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Echinoderm Faunas from the Bromide Formation (Middle Ordovician) of Oklahoma

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Editor

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CONTENTS

Abstract....1
INTRODUCTION....3
Introduction, James Sprinkle....3
Depositional Setting and Regional Characteristics, Mark W. Longman....6
Stratigraphic Studies, Robert O. Fay and A. Allen Graffham....11
Depositional Environments, Mark W. Longman....17
Biostratigraphic and Paleontological Studies, Robert O. Fay and A. Allen Graffham....31
Previous Studies of Bromide Echinoderms, Robert O. Fay, A. Allen Graffham, and James Sprinkle....34
Collection of Echinoderms, 1965-1967, Robert O. Fay and A. Allen Graffham....44
Echinoderm Zones and Faunas, James Sprinkle....47
Holdfasts, Ronald D. Lewis....57
Age and Correlation Using Bromide Echinoderms, James Sprinkle....65
Echinoderm Paleoecology, James Sprinkle and Mark W. Longman....68
SYSTEMATIC PALEONTOLOGY....77
Phylum ECHINODERMATA Bruguiere, 1791
Subphylum CRINOZOA Matsumoto, 1929
Class CRINOIDEA Miller, 1821
Subclass INADUNATA Wachsmuth and Springer, 1885
Order DISPARIDA Moore and Laudon, 1943
Long-Armed Disparid Inadunates, John M. Warn....77
Phylogeny of Primitive Calceocrinids, James C. Brower....90
Acolocrinus, James Sprinkle....111
Order HYBOCRINIDA Jaekel, 1918
Hybocrinus, James Sprinkle....119
Order CLADIDA Moore and Laudon, 1943
Suborder DENDROCRININA Bather, 1899
Long-Armed Cladid Inadunates, James C. Brower and Julia Veinus....129
Suborder CYATHOCRININA Bather, 1899
Superfamily GASTEROCOMACEA Roemer, 1854
Large-Calyx Cladid Inadunates, James Sprinkle....145
Subclass CAMERATA Wachsmuth and Springer, 1885
Camerates, Dennis R. Kolata....170
"Rhomb-Bearing" Camerate, James Sprinkle and Dennis R. Kolata....206
Class PARACRINOIDEA Regnéll
Paracrinoids, Ronald L. Parsley....212
"Golf-Ball" Paracrinoid, James Sprinkle and Ronald L. Parsley....224
Subphylum BLASTOZOA Sprinkle, 1973
Class RHOMBIFERA Zittel, 1879, emend. Paul 1968
Order DICHOPORITA Jaekel, 1899
Superfamily GLYPTOCYSTITIDA Bather, 1899
Cylindrical and Globular Rhombiferans, James Sprinkle....231
Pleurocystitids, Ronald L. Parsley....274
Class DIPLOPORITA Müller, 1854, nom. transl. Paul, 1968
Eumorphocystis, Ronald L. Parsley....280

Class EOCRINOIDEA Jaekel, 1918
Family PALAEOCYSTITIDAE Ubaghs, 1968
Palaeocystitids, James Sprinkle.....289
Subphylum INDETERMINATE
Class EDRIOASTEROIDEA Billings, 1858
Edrioasteroids, Bruce M. Bell.....297
Subphylum ECHINOZOA Zittel, 1895
Class EDRIOBLASTOIDEA Fay, 1962
Astrocystites, James Sprinkle.....307
Class CYCLOCYSTOIDEA Miller and Gurley, 1895
Cyclocystoids, Dennis R. Kolata.....309
Class ECHINOIDEA Leske, 1778
Echinoids, Porter M. Kier.....310
Class HOLOTHUROIDEA
Holothurians, James Sprinkle.....315
Subphylum ASTEROZOA Zittel, 1895
Class STELLEROIDEA Lamarck, 1816
Subclass ASTEROIDEA de Blainville, 1830
Asteroids, Jon W. Branstrator.....316
Subphylum HOMALOZOA Whitehouse, 1941
Homalozoans, Ronald L. Parsley.....322
REFERENCES.....324
APPENDIX: Measured Sections and Other Collecting Localities, Robert O. Fay, A. Allen Graffham, and James Sprinkle.....335
1. Johnston Ranch, Murray County.....336
2. Mountain Lake, Carter County.....338
3A. Tulip Creek, Chapman Ranch, Carter County.....339
3B. Tulip Creek, Cornell Ranch, Carter County.....341
4. Daube Ranch, Johnston County.....342
5. Bromide, plus McLish Ranch, Coal County.....343
6. Lick Creek, Murray County.....346
7. Amis Ranch, Murray County.....349
8. Nebo, Murray County.....350
9. Buckhorn Ranch, Murray County.....351
10. Sulphur, Murray County.....354
11A. Fittstown Roadcut, Pontotoc County.....355
11B. Fittstown Quarry, Pontotoc County.....358
12. North Criner Hills, Carter County.....359
13A. Rudd Quarry, Carter County.....359
13B. Dunn Quarry, Carter County.....359
14. Culley Creek, Carter County.....361
15A. Rock Crossing, Carter County.....361
15B. Southeast Rock Crossing, Carter County.....364
16A. North Interstate 35, Murray County.....365
16B. North-Central Interstate 35, Murray County.....366
Other Collecting Localities.....368

FIGURES

1. Isopach map of the Bromide Formation in south-central Oklahoma.....6
2. Paleogeographic reconstruction of Oklahoma and northern Texas at the beginning of Bromide deposition.....7
3. Four stages in the evolution of the southern Oklahoma aulacogen.....8
4. Idealized facies distribution on a carbonate ramp profile.....9
5. Idealized facies distribution on a carbonate platform.....9
6. Composite measured section of the Bromide Formation.....18
7. Lithofacies relationships and inferred water depths of the upper and lower shoreface sandstones.....19
8. Deposition of the basinal lithofacies.....23
9. Lithofacies map of the shelf-edge biosparite relative to the major echinoderm localities.....26
10. Lithofacies relationships early in Pooleville deposition.....27
11. Lithofacies relationships of the regressive limestones in the Pooleville Member...28
12. Stratigraphic distribution of echinoderm zones and beds in the Bromide Formation....46
13. Geographic distribution of echinoderm genera in the Lower Echinoderm Zone around the Arbuckle Mountains and Criner Hills.....48
14. Geographic distribution of echinoderm genera in the Upper Echinoderm Zone around the Arbuckle Mountains and Criner Hills.....50
15. Geographic distribution of echinoderm genera in the Pooleville Echinoderm Zones around the Criner Hills and Arbuckle Mountains.....52
16. Proximal and lateral views of the eight common holdfast morphotypes.....58
17. Plate diagram of *Apodasmocrinus daubei*.....80
18. Br and food groove shape in *A. daubei*.....80
19. Pinnular of *A. daubei*.....81
20. Cross section of the column of *A. daubei*...81
21. Plate diagram of *Penicillicrinus parvus*....83
22. Plate diagram of *Praecursoricrinus sulphurensis*.....84
23. Plate diagram of *Doliocrinus pustulatus*....85
24. Two types of food groove shapes in the arms of *Doliocrinus pustulatus*.....86
25. Plate diagram of unknown Cincinnaticrinidae.....87
26. Plate diagram of *Peltacrinus sculptatus*....88
27. Arm branching pattern of *P. sculptatus*.....88
28. Cover plate arrangement in the arms of *P. sculptatus*.....88
29. Cross section of the column of *P. sculptatus*.....89
30. Plate diagrams of primitive calceocrinid genera and homocrinid ancestor.....94
31. Drawings of representative primitive calceocrinids from the Bromide Formation...96
32. Drawings of representative primitive calceocrinids from stratigraphic units other than the Bromide Formation.....97
33. Plot of scores of first two principal components for calceocrinid data.....98
34. Wagner network for calceocrinids based on 21 species and 17 characters.....100
35. Wagner networks for calceocrinids, including 13 species with 4 arm-bearing rays and 14 characters and 8 species of *Calceocrinus* with 10 characters.....101
36. Wagner networks for calceocrinids, characters weighted proportional to consistencies.....103
37. Prim network in which links constrained to be consistent with stratigraphy.....104
38. Phylogeny for calceocrinids.....107
39. Morphology of Bromide specimens of *Acolocrinus*.....112
40. Morphology of *Hybocrinus nitidus* Sinclair and *H. crinerensis* Strimple and Watkins.....120
41. Morphology of *Merocrinus impressus* Brower and Veinus, n. sp.....131
42. New species of dendrocrinids from the Lower Echinoderm Zone of the Mountain Lake Member, Daube Ranch.....133
43. Morphology of *Quinquecaudex glabellus* Brower and Veinus, n. gen., n. sp.....137
44. Morphology of *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp.....141
45. Morphology of *Carabocrinus treadwelli* Sinclair.....147
46. Morphology of *Palaeocrinus hudsoni* Sinclair, plus *P.* sp. and *P.* sp. cf. *P. planobasalis* Brower and Veinus.....158
47. Slit spacing in Bromide species of *Palaeocrinus*.....161
48. Morphology of *Porocrinus bromidensis* Sprinkle, n. sp.....167
49. Diagrammatic representation of calyx of *Reteocrinus depressus* Kolata, n. sp.....176
50. Plate diagram of *Anthracocrinus primitivus* Strimple and Watkins (1955).....179
51. Plate diagram of *Bromidocrinus nodosus* Kolata, n. gen., n. sp.....187
52. Plate diagram of posterior side of *Crinerocrinus parvicostatus* Kolata, n. gen., n. sp.....190
53. Plate diagram of aboral cup of *Diabolocrinus arbucklensis* Kolata, n. sp.....193
54. Diagrammatic representation of posterior side of *Pararchaeocrinus decoratus* Strimple and Watkins (1955).....199
55. Plate diagram of posterior side of *Paradiabolocrinus stellatus* Kolata, n. sp.....202
56. Plate diagram of *Abludoglyptocrinus laticostatus* Kolata, n. gen., n. sp.....203
57. Morphology of *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp.....207
58. Diagram of thecal plates and their nomenclature in *Platycystites levatus* Bassler.....221
59. Anterior and posterior plate patterns of *Arbucklecystis pyriformis* Parsley and Sprinkle, n. gen., n. sp.....223
60. Morphology of *Bistomiacystis globosa* Sprinkle and Parsley, n. gen., n. sp.....225
61. Morphology of *Glyptocystella loeblichi* (Bassler).....236
62. Morphology of *Pirocystella strimplei* Sprinkle, n. gen., n. sp., *P. cooki* Sprinkle, n. gen., n. sp., and *P. bassleri* Sprinkle, n. gen., n. sp.....244
63. Morphology of *Hesperocystis deckeri* Sinclair.....256
64. Morphology of *Strabocystis fayi* Sprinkle, n. gen., n. sp.....260
65. Morphology of *Tanaocystis watkinsi* Sprinkle, n. gen., n. sp.....266
66. Morphology of *Quadrocystis graffhami* Sprinkle, n. gen., n. sp.....271
67. Reconstruction of the dorsal face of *Praepleurocystis watkinsi* (Strimple).....275
68. Plate outlines of the distal ventral surface of *Praepleurocystis watkinsi* (Strimple).....276
69. Composite partial reconstruction of a mature *Eumorphocystis multiporata*.....281
70. Partial diagrammatic reconstruction of the adoral surface of *Eumorphocystis multiporata*.....286

71. Side and oral views of *Eumorphocystis multiporata*.....287
72. Morphology of *Bromidocystis bassleri* Sprinkle, n. gen., n. sp., and *B. sinclairi* Sprinkle, n. gen., n. sp.....290
73. Morphology of *Unibothriocidaris bromidensis* Kier, n. gen., n. sp.....311
74. Morphology of *Bothriocidaris kolatai* Kier, n. sp.....313
75. General orientation terminology of asteroid theca.....317
76. Two species of *Petraster* with axillary interbrachial series in each shaded.....318
77. Names and locations of measured sections and collecting locatlies in the Arbuckle Mountains and Criner Hills of southern Oklahoma.....335
78. Correlation diagrams and isopach map of Bromide Formation in Arbuckle Mountains and Criner Hills.....pocket, back cover
79. Geologic map showing Bromide Formation and location of Measured Section 1 at Johnston Ranch.....336
80. Spring Creek exposure, Murray County.....337
81. Close-up view of Spring Creek exposure, Murray County.....338
82. Geologic map showing Bromide Formation and location of Measured Section 2 at Mountain Lake.....339
83. Geologic map showing Bromide Formation and location of Measured Section 3 at Tulip Creek.....340
84. Cornell Ranch exposure, Carter County.....341
85. Geologic map showing Bromide Formation and location of Measured Section 4 at Daube Ranch.....343
86. Daube Ranch exposure, Johnston County.....344
87. Geologic map showing Bromide Formation, location of Measured Section 5 at Bro-Bromide, and collecting localities to west on McLish Ranch.....345
88. Bromide exposure, Coal County.....345
89. Geologic map showing Bromide Formation and location of Measured Section 6 at Lick Creek.....347
90. Upper Echinoderm Zone at Lick Creek exposure, Murray County.....347
91. Lower Echinoderm Zone at Lick Creek exposure, Murray County.....348
92. Geologic map showing Bromide Formation and location of Measured Section 7 at Amis Ranch.....349
93. Amis Ranch exposure, Murray County.....350
94. Geologic map showing Bromide Formation and location of Measured Section 8 at Nebo.....351
95. Geologic map showing Bromide Formation and location of Measured Section 9 at Buckhorn Ranch.....352
96. Buckhorn Ranch exposure, Murray County....352
97. Geologic map showing Bromide Formation and location of Measured Section 10 at Sulphur.....353
98. Sulphur exposure, Murray County.....353
99. Close-up of Sulphur exposure, Murray County.....354
100. Geologic map showing Bromide Formation and location of Measured Section 11A at Fittstown Roadcut.....356
101. Fittstown Roadcut exposure, Pontotoc County.....357
102. Geologic map showing Bromide Formation and location of Measured Section 11B at Fittstown Quarry.....358
103. Geologic map showing Bromide Formation and location of Measured Section 12 at North Criner Hills.....358
104. Geologic map showing Bromide Formation and location of Measured Section 13 at Rudd (south) and Dunn (north) Quarries....359
105. Rudd Quarry exposure, Carter County.....360
106. Dunn Quarry exposure, Carter County.....360
107. Geologic map showing Bromide Formation and location of Measured Section 14 at Culley Creek.....361
108. Culley Creek exposure, Carter County.....362
109. Geologic map showing Bromide Formation and location of Measured Sections 15A and 15 B at Rock Crossing.....363
110. Contact between Pooleville Member and Mountain Lake Member at Rock Crossing exposure, Carter County.....364
111. Upper Pooleville Member at Rock Crossing exposure, Carter County.....365
112. Middle Pooleville Member at Rock Crossing exposure, Carter County.....366
113. Geologic map showing Bromide Formation, related units, and location of Measured Sections 16A and 16B along Interstate 35..367

PLATES

1. Outcrop and petrographic features of the lower Bromide Formation.....21
2. Outcrop and petrographic features of the upper Bromide Formation.....24
3. Echinoderm specimens overgrown by bryozoan colonies, holdfasts and distal stem terminations, and specimens with borings....63
4. Morphology of *Doliocrinus pustulatus* Warn, n. gen., n. sp., *Apodasmocrinus daubei* Warn and Strimple, and *Cyclocystoides* sp.....79
5. Morphology of *Peltacrinus sculptatus* Warn, n. gen., n. sp., *Penicillicrinus parvus* Warn, n. gen., n. sp., *Praecursoricrinus sulphurnesis* Frest, Strimple, and McGinnis, and an unknown Cincinnaticrinidae.....82
6. Morphology of *Acolocrinus crinerensis* Sprinkle, n. sp., *A. arbucklensis* Sprinkle, n. sp., and *Acolocrinus?* sp.....114
7. Morphology of *Hybocrinus nitidus* Sinclair..122
8. Morphology of *Hybocrinus nitidus* Sinclair and *H. crinerensis* Strimple and Watkins....124
9. Morphology of *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp., *Merocrinus pressus* Brower and Veinus, n. sp., *Dendrocrinus villosus* Brower and Veinus, n. sp., and *D.? bibrachialis* Brower and Veinus, n. sp.....130
10. Morphology of *Quinquecaudex glabellus* Brower and Veinus, n. gen., n. sp.....139
11. Morphology of *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp.....143
12. Morphology of *Carabocrinus treadwelli* Sinclair and *Carabocrinus* sp.....148
13. Morphology of *Carabocrinus treadwelli* Sinclair and *Palaeocrinus hudsoni* Sinclair.....150
14. Morphology of *Palaeocrinus hudsoni* Sinclair, *Palaeocrinus* sp. cf. *P. planobasalis* Brower and Veinus, and *Palaeocrinus* sp.....156
15. Morphology of *Porocrinus bromidensis* Sprinkle, n. sp.....164
16. Morphology of *Cleiocrinus bromidensis* Kolata, n. sp. and *C. ornatus* Kolata, n. sp..172
17. Morphology of *Anthracocrinus primitivus* Strimple and Watkins (1955), *Reteocrinus depressus* Kolata, n. sp., *Archaeocrinus conicus* Kolata, n. sp., *A. buckhornensis*

Kolata, n. sp., *A. subovalis* Strimple (1953b), and *Archaeocrinus* sp.....178
18. Morphology of *Archaeocrinus subovalis* Strimple (1953b) and *Pararchaeocrinus decoratus* Strimple and Watkins (1955).....184
19. Morphology of *Bromidocrinus nodosus* Kolata, n. gen., n. sp., Rhodocrinitid species A, and *Diabolocrinus oklahomensis* Kolata, n. sp.....188
20. Morphology of *Diabolocrinus arbucklensis* Kolata, n. sp., *Pararchaeocrinus?* sp., *Diabolocrinus constrictus* Kolata, n. sp., and Camerate species A.....192
21. Morphology of *Diabolocrinus poolevillensis* Kolata, n. sp., *Abludoglyptocrinus laticostatus* Kolata, n. gen., n. sp., *Crinerocrinus parvicostatus* Kolata, n. gen., n. sp., and *Paradiabolocrinus stellatus* Kolata, n. sp.....194
22. Morphology of *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp., and *Colpodecrinus* sp.....208
23. Thecal morphology of *Sinclairocystis praedicta* Bassler and *Oklahomacystis bibrachiatus* Parsley, n. sp.....214
24. Thecal morphology of *Oklahomacystis tribrachiatus* (Bassler), *Platycystites levatus* Bassler, *P. cristatus* Bassler, *Arbucklecystis pyriformis* Parsley and Sprinkle, n. gen., n. sp., and *Oklahomacystis bibrachiatus* Parsley, n. sp.....216
25. Morphology of *Bistomiacystis globosa* Sprinkle and Parsley, n. gen., n. sp.....226
26. Morphology of *Glyptocystella loeblichi* (Bassler).....232
27. Morphology of *Glyptocystella leoblichi* (Bassler), *Pirocystella?* sp., *Cheirocrinus ardmorensis* (Bassler), and an unknown rhombiferan.....238
28. Morphology of *Pirocystella strimplei* Sprinkle, n. gen., n. sp.....242
29. Morphology of *Pirocystella cooki* Sprinkle, n. gen., n. sp., *P. bassleri* Sprinkle, n. gen., n. sp., and *P. ornatus* (Bassler).....249
30. Morphology of *Hesperocystis deckeri* Sinclair.....254
31. Morphology of *Strabocystis fayi* Sprinkle, n. gen., n. sp.....258
32. Morphology of *Tanaocystis watkinsi* Sprinkle, n. gen., n. sp.....265
33. Morphology of *Quadrocystis graffhami* Sprinkle, n. gen., n. sp.....268
34. Thecal morphology of *Praepleurocystis watkinsi* (Strimple) and *Pleurocystites squamosus* Billings.....278
35. Thecal morphology of *Eumorphocystis multiporata* Branson and Peck.....282
36. Morphology of the theca, column, and exothecal tribrachials of *Eumorphocystis multiporata* Branson and Peck.....284
37. Morphology of *Bromidocystis bassleri* Sprinkle, n. gen., n. sp., *B. sinclairi* Sprinkle, n. gen., n. sp., and *Astrocystites* sp. A and B.....293
38. Morphology of *Foerstediscus splendens* Bassler.....298
39. Morphology of *Foerstediscus splendens* Bassler, *Cyathocystis americanus* Bassler, *Edriophus* sp. cf. *E. laevis* (Bather), *Pyrgocystis* sp. B, and *Pyrgocystis* sp. A...301
40. Morphology of *Cyathocystis americanus* Bassler.....304
41. Morhpology of *Bothriocidaris kolatai* Kier, n. sp., and *Unibothriocidaris bromidensis* Kier, n. gen., n. sp.....312
42. Morphology of *Petraster wigleyi* Branstrator, n. sp., *Protopalaeaster narrawayi* Hudson, and *Urasterella* sp.....319

TABLES

1. Distribution of ostracods in the Bromide Formation.....30
2. Distribution of trilobites in the Bromide Formation.....30
3. Distribution of brachiopods in the Bromide Formation.....30
4. Distribution of bryozoa in the Bromide Formation.....32
5. Distribution of graptolites in the Bromide Formation.....32
6. Distribution of conodonts in the Bromide Formation.....33
7. Distribution of microphytoplankton (acritarchs) in the Bromide Formation.....33
8. Stratigraphic position of Bromide echinoderms as used by authors from 1903 to 1980..40
9. List of Bromide echinoderm genera identified from the Lower Echinoderm Zone.....49
10. List of Bromide echinoderm genera identified from the Upper Echinoderm Zone.....51
11. List of Bromide echinoderm genera identified from the Pooleville Echinoderm Zones...53
12. List of Bromide echinoderm genera found as complete specimens in the *Carabocrinus* Beds.....54
13. List of Bromide echinoderm genera found as complete specimens in the *Bromidocystis* Bed.....55
14. Comparison of calyx and holdfast data for the Lower Echinoderm Zone at Lick Creek.....59
15. Comparison of calyx and holdfast data for the Lower Echinoderm Zone at Fittstown Quarry.....59
16. Comparison of calyx and holdfast data for the Lower Echinoderm Zone at McLish Ranch...60
17. Comparison of calyx and holdfast data for the *Carabocrinus* Beds for North-Central I-35, North I-35, and Lick Creek, combined..60
18. Comparison of calyx and holdfast data for the Upper Echinoderm Zone at North-Central I-35 and North I-35, combined.....61
19. Comparison of calyx and holdfast data for the Pooleville Member at six localities.....64
20. Summary of environmental, sedimentological, and time differences between the various Bromide echinoderm zones and beds that may have affected the compostion of echinoderm faunas.....70
21. Possible reasons for the occurrence of Bromide echinoderms in thin, rich zones.....73
22. Calceocrinid species used in phylogeny study.....92
23. Characters measured for species used in phylogeny study.....95
24. First three principal components for calceocrinids.....99
25. Character consistencies for various calceocrinid data sets.....102
26. Character states for primitive calceocrinids.....109
27. Data on the food-gathering system of *Eopinnacrinus pinnulatus*, n. gen., n. sp...142
28. Stratigraphic distribution of camerate crinoids in the Bromide Formation.....171
29. Measurements of *Cleiocrinus bromidensis* Kolata, n. sp.....174

30. Measurements of *Reteocrinus depressus* Kolata, n. sp.....177
31. Measurements of *Anthracocrinus primitivus* Strimple and Watkins (1955).....180
32. Characteristic features of rhodocrinitid genera occurring in the Bromide Formation of southern Oklahoma.....181
33. Measurements of *Archaeocrinus buckhornensis* Kolata, n. sp.....182
34. Measurements of *Archaeocrinus subovalis* Strimple (1953b).....185
35. Measurements of *Diabolocrinus arbucklensis* Kolata, n. sp.....191
36. Measurements of *Diabolocrinus poolevillensis* Kolata, n. sp.....198
37. Measurements of *Pararchaeocrinus decoratus* Strimple and Watkins (1955).....201
38. Measurements of *Abludoglyptocrinus laticostatus* Kotata, n. gen., n. sp.....204
39. Measurements of the two partly complete specimens of *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp.....209
40. Thecal and ambulacral measurements for the best preserved specimens of *Bistomiacystis globosa* Sprinkle and Parsley, n. gen., n. sp.....229
41. Comparison of pectinirhomb positions in all Bromide cylindrical or globular rhombiferans known from several complete specimens plus *Glyptocystites*.....234

Echinoderm Faunas from the Bromide Formation (Middle Ordovician) of Oklahoma

James Sprinkle
Editor

ABSTRACT

The Middle Ordovician Bromide Formation of southern Oklahoma contains perhaps the largest and most diverse echinoderm fauna ever collected from a single Ordovician formation. Over 11,000 complete specimens representing at least 61 echinoderm genera and 13 classes have been collected from 16 measured sections and 8 other collecting localities in the Arbuckle Mountains and Criner Hills of southern Oklahoma. Three rich zones and two other beds making up about 16 percent of the Bromide section have produced nearly all of these echinoderm specimens.

A 1- to 2-m shaly interval called the Lower Echinoderm Zone in the middle Mountain Lake Member of the Bromide has yielded a rich but patchy echinoderm fauna containing over 6,800 specimens and 31 genera at 18 localities throughout the Arbuckle Mountains and perhaps into the Criner Hills. The Lower Echinoderm Zone is dominated by the inadunate crinoid *Hybocrinus* (51 percent of the echinoderm fauna) and the paracrinoid *Platycystites* (23 percent), but also contains several cladid and disparid inadunate crinoids, rhombiferans, edrioasteroids, camerate crinoids, and other groups. A 1- to 4-m series of shaly beds called the Upper Echinoderm Zone near the top of the Mountain Lake Member is widespread in the Arbuckle Mountains, where it has produced about 3,700 echinoderm specimens and 20 genera at 15 localities. The Upper Echinoderm Zone is strongly dominated by the paracrinoid *Oklahomacystis* (93 percent of the echinoderm fauna), but also contains two other paracrinoids, some inadunate and camerate crinoids, rhombiferans, and a few other groups. The upper 14 m of the overlying Pooleville Member has produced a rich echinoderm fauna from a series of thin zones mostly in the Criner Hills. About 650 specimens and 30 genera have been collected from this interval at four localities. These Pooleville zones are dominated by the camerate crinoid *Archaeocrinus* (29 percent of the echinoderm fauna), but also contain several other camerate crinoids, disparid and cladid inadunate crinoids, a stylophoran, rhombiferans, edrioasteroids, starfish, and several other groups. Two other thin intervals in the middle and upper Mountain Lake Member (the *Carabocrinus* Beds and the *Bromidocystis* Bed) have produced a few complete echinoderms at two or three localities in the Arbuckle Mountains and may represent additional zones.

These echinoderm faunas and some other fossil groups indicate that most or all of the Bromide Formation is probably of Blackriveran (or Porterfieldian) age in the Middle Ordovician. Bromide echinoderms correlate most closely with those of the Benbolt and Hogskin formations of Virginia and Tennessee, the Lebanon Limestone of central Tennessee, the Stones River Formation of Alabama, and the Platteville and lower Galena groups of Illinois and adjacent states.

The Bromide Formation represents a single transgressive-regressive cycle deposited on the northeastern margin of the subsiding Southern Oklahoma aulacogen. The echinoderm-bearing zones in the Bromide were deposited in a variety of warm water shelf environments with water depths ranging from about 3 m at times on the platform in the central and northeastern Arbuckles to about 75 m in the aulacogen in the southwestern Arbuckles and Criner Hills. Echinoderms were most common in environments having a mixture of clay (or lime mud) and skeletal debris, especially where small bryozoan buildups in shaly units of the Mountain Lake Member provided favorable attachment sites. The richest echinoderm localities in the Mountain Lake

Member occur along the aulacogen margin at moderate water depths; shallow-water areas to the northeast and deeper water areas to the southwest have less abundant echinoderm faunas characterized by rare and perhaps opportunistic genera and species. The especially rich echinoderm faunas probably resulted from favorable living conditions (including slow deposition, abundant food in the plankton, and available attachment sites), stratification of suspension feeders using stem height, and the appearance of several new ways of life for echinoderms. The major collecting method (trenching) has probably accentuated the occurrence of echinoderms in a few thin rich zones, and the gregarious nature of many echinoderms has increased the abundance and patchiness within these zones.

About one-quarter of the genera and one-third of the echinoderm species now known from the Bromide are newly described here. These new taxa, totaling 2 new families, 17 new genera, and 39 new echinoderm species, include: the disparid inadunate crinoids *Penicillicrinus parvus* Warn, n. gen., n. sp., *Doliocrinus pustulatus* Warn, n. gen., n. sp., *Peltacrinus sculptatus* Warn, n. gen., n. sp., *Acolocrinus crinerensis* Sprinkle, n. sp., and *A. arbucklensis* Sprinkle, n. sp.; the cladid inadunate crinoids *Merocrinus impressus* Brower and Veinus, n. sp., *Dendrocrinus villosus* Brower and Veinus, n. sp., *D.? bibrachialis* Brower and Veinus, n. sp., *Quinquecaudex glabellus* Brower and Veinus, n. gen., n. sp., *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp., and *Porocrinus bromidensis* Sprinkle, n. sp.; the camerate crinoids *Cleiocrinus bromidensis* Kolata, n. sp., *C. ornatus* Kolata, n. sp., *Reteocrinus depressus* Kolata, n. sp., *Archaeocrinus buckhornensis* Kolata, n. sp., *A. conicus* Kolata, n. sp., *Bromidocrinus nodosus* Kolata, n. gen., n. sp., *Crinerocrinus parvicostatus* Kolata, n. gen., n. sp., *Diabolocrinus arbucklensis* Kolata, n. sp., *D. constrictus* Kolata, n. sp., *D. oklahomensis* Kolata, n. sp., *D. poolevillensis* Kolata, n. sp., *Paradiabolocrinus stellatus* Kolata, n. sp., *Abludoglyptocrinus laticostatus* Kolata, n. gen., n. sp., and the new family Colpodecrinidae Sprinkle and Kolata containing *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp.; the paracrinoids *Oklahomacystis bibrachiatus* Parsley, n. sp., *Arbucklecystis pyriformis* Parsley and Sprinkle, n. gen., n. sp., and the new family Bistomiacystidae Sprinkle and Parsley containing *Bistomiacystis globosa* Sprinkle and Parsley, n. gen., n. sp.; the rhombiferans *Pirocystella strimplei* Sprinkle, n. gen., n. sp., *P. cooki* Sprinkle, n. sp., *P. bassleri* Sprinkle, n. sp., *Strabocystis fayi* Sprinkle, n. gen., n. sp., *Tanaocystis watkinsi* Sprinkle, n. gen., n. sp., and *Quadrocystis graffhami* Sprinkle, n. gen., n. sp.; the palaeocystitid eocrinoids *Bromidocystis bassleri* Sprinkle, n. gen., n. sp. and *B. sinclairi* Sprinkle, n. sp.; the echinoids *Unibothriocidaris bromidensis* Kier, n. gen., n. sp. and *Bothriocidaris kolatai* Kier, n. sp.; and the asteroid *Petraster wigleyi* Branstrator, n. sp. Redescriptions of many other echinoderms, originally described from one or a few specimens, are based on much larger and better preserved samples of specimens. However, the presence of some unidentified but distinctive plates and stems indicates that additional Bromide echinoderms still remain to be collected and described.

INTRODUCTION

James Sprinkle

University of Texas at Austin

In many ways, echinoderms are unusual and distinctive fossils. Complete and well-preserved fossil echinoderms often have considerable scientific value and intrinsic beauty to both professional and amateur collectors. Part of this appeal is in the complex and sometimes unusual skeletal morphology shown by many fossil echinoderms. Echinoderms also have a long and rich fossil record both in the number of classes known (20 at present) and in the number of fossil genera and species that have been described (now totaling about 7,500 species). But perhaps the most intriguing aspect of many echinoderms is the way in which they occur in the fossil record. Echinoderms tend to be gregarious and become common only under optimal environmental conditions. Also, their multiplated skeletons break down fairly easily after death unless buried quickly on the sea floor. Because of these ecologic and preservational factors, many fossil echinoderms occur only rarely as complete specimens in the fossil record, but these rare occurrences often yield a large number of excellent specimens in a very restricted stratigraphic interval. Perhaps one of the best examples of this distinctive occurrence is the echinoderm faunas from the Middle Ordovician Bromide Formation of southern Oklahoma, the subject of this monograph. The Bromide has several rich and diverse echinoderm faunas containing many spectacular and unusual specimens mostly confined to thin zones scattered throughout the stratigraphic section. Specimens are so abundant in these rich zones at some localities that trenching these intervals yielded thousands of complete specimens in only a few weeks of work.

The Bromide Formation contains an enormous echinoderm fauna, including representatives of 13 of the 17 echinoderm classes living during the Middle Ordovician, at least 61 echinoderm genera, and over 11,000 partial or complete specimens. This may represent the largest and most diverse echinoderm fauna ever collected and studied from a single Ordovician formation. Many specimens are excellently preserved, and about 10 to 15 percent have some of the attachment or food-gathering appendages still preserved. In addition, many hundreds of holdfasts, root systems, and arm fragments, plus thousands of stem segments and separate plates, were recovered in the search for complete specimens. They have increased our knowledge about the morphology of many of these echinoderms and in some cases indicated that certain genera were much more common in the rich zones than is shown by the number of calyces recovered.

Bromide echinoderms lived at the time of maximum class diversity and of very high generic diversity for echinoderms (see Sprinkle, 1980). As many as 31 genera may occur together in a single bed in the Bromide, in contrast to Cambrian faunas with abundant echinoderms, which are characterized by one to three genera occurring together in any unit (Sprinkle, 1976). Many new and more advanced classes of echinoderms had appeared in the Early and Middle Ordovician, and diversity within most echinoderm classes had greatly increased over that of the Cambrian (Sprinkle, 1980). The Bromide represents the time of maximum diversity of paracrinoids (5 to 6 genera), rhombiferans (6 to 7 genera), and perhaps edrioasteroids (4 genera); it represents a critical time in the initial radiation of crinoids (28 genera) and perhaps asteroids (5 genera); and it contains the earliest record, perhaps tied with other coeval units, of echinoids (2 genera), holothurians (1 to 3 genera), and possibly edrioblastoids (1 genus). Thus, study of the Bromide echinoderm faunas is critical for understanding the evolution of many of these echinoderm groups.

Echinoderms have been known and illustrated from the Bromide Formation in the Arbuckle Mountains of southern Oklahoma for about 50 years (Decker, 1931b), although a few specimens may date back to the early 1900's. Many echinoderm genera and species were described from one or a few

specimens during the 1940's and 1950's, primarily by Ray Bassler, G. Winston Sinclair, and Harrell Strimple. Several of these authors commented on the variety of echinoderms found in the Bromide, but until now almost no work has been done on the entire echinoderm fauna and its occurrence. During the mid-1960's, Robert O. Fay of the Oklahoma Geological Survey, Norman, and Allen Graffham of Ardmore, Oklahoma, restudied all of the known localities where scattered echinoderms had previously been reported from the Bromide (Fay and Graffham, 1969) and collected three large echinoderm faunas totaling about 9,000 specimens by trenching rich beds in this formation. These collections included as many as 3,500 specimens of the most abundant echinoderms, hundreds of specimens of many other species, and scattered specimens of many rare and unusual forms. These extensive collections form the basis of the present monograph, along with nearly 2,000 specimens collected by the author between May, 1974, when work on this monograph began, and May, 1979. Type and other specimens in older museum collections, principally the National Museum of Natural History in Washington, D. C., and the University of Oklahoma at Norman, as well as scattered specimens in several private collections, were also studied. Summaries of a few echinoderm groups based on these collections have already been published (Parsley and Mintz, 1975; Brower, 1977; Parsley, 1979), but most echinoderm groups are newly restudied here.

Despite these extensive collections, new echinoderms will almost certainly be discovered in the Bromide Formation by future collectors. The chances for finding entirely new echinoderms in the three well-collected zones are not very good; most forms have already been collected and described from these intervals. Desirable specimens from these zones will more likely include well-preserved examples of rare forms or calyces with rarely preserved appendages still attached. The chances of finding new echinoderms are much better outside the well-sampled zones in the Bromide. Some forms occurring here are known only from plates, and these intervals have not been widely sampled. The present study, although extensive, is obviously not the final word on this rich and spectacular echinoderm fauna.

This monograph on Bromide echinoderms is divided into three major parts. The first has short introductory and general chapters reviewing the setting of the Bromide, its deposition, the history of study, its invertebrate fauna, the echinoderm zones and beds, its age and correlation to other areas, and the paleoecology of the echinoderms. Second are longer chapters on the systematics of the echinoderm groups; this part contains the bulk of the plates. The third and concluding part is an appendix containing 16 detailed measured sections plus locations for 8 other collecting sites that were not measured.

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The Oklahoma Geological Survey, under the direction of the late Carl C. Branson, supported Fay during field and laboratory work in 1965-1967 and purchased many of the specimens found by Graffham in the early 1960's. Allen Graffham, owner of Geological Enterprises, Ardmore, Oklahoma, paid for a fulltime field assistant, C. R. (Sonny) Smith, during the major collecting work in 1965-1967.

We are indebted to many property owners and foremen who allowed access to property in the Arbuckles and Criner Hills and, in some cases, permission to dig for specimens. These include: the Daube Cattle Co., Ardmore (Daube Ranch); W. D. Amis of the Amis Construction Co., Oklahoma City, and Homer Ratchford (Amis Ranch); Pete York of the Phil Cornell Ranch; Tom Jack and Melborn Jones (Buckhorn Ranch); Don and Dana Cook and Bill and Pauline Keichler (Fittstown Quarry); Grant Adams, Jr. (Culley Creek); Bill Johnston and Mr. and Mrs. Virgil Johnston of the old Joins Ranch (Johnston Ranch); J. A. Chapman of Chapman Ranch; Robert Howe of Cedarvale Gardens (Cedar Village); Harold Rudd (Rudd Quarry); Will Rhynes, Jr. (Rhynes Ranch); Elmer and Elia Pickens (Pickens Ranch); and Mrs. Hershel Putman (Putman Ranch).

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Individual chapters in this monograph were reviewed by: Harrell L. Strimple and Terry Frest, University of Iowa, Thomas W. Broadhead, University of Tennessee, Carlton Brett, University of Rochester, Parsley, Kolata, Graffham, and Fay (Sprinkle's chapters); Bill Rose, Oklahoma Geological Survey (Fay and Graffham's chapters); N. Gary Lane, Indiana University (Kolata's chapter); D. Bradford Macurda, Jr., The Energists, Houston, Thomas W. Broadhead, and Bell (Parsley's chapters); Earle McBride, University of Texas at Austin (Longman's chapters); Daniel B. Blake, University of Illinois (Branstrator's chapter); R. I. C. Hansell, University of Toronto, Peter Sneath, University of Leichester, George C. McIntosh, University of Michigan, Carlton E. Brett, and Kolata (Brower's and Brower and Veinus' chapters); Kolata (Warn's, Kier's, and Bell's chapters); J. Wyatt Durham, University of California, Berkeley (Kier's chapter); and Carlton E. Brett (Lewis' chapter).

Sprinkle was assisted in picking and sorting specimens and cleaning them with an air abrasive machine by Raymond C. Pilcher, Charles E. McKemie, Adna H. Underhill, Jr., and Margaret Sipple, present or former students at the University of Texas at Austin. David Stevens copied many of the plates, and Debbie Magner, Connie Warren, Nancy Bessent, Teresa Reyes, and Maria Brito typed several versions of grant proposals and intermediate and final copies of the manuscript at the University of Texas at Austin. Fay was assisted in sorting specimens and cleaning them with an air abrasive machine by Rosalind Kelly and Shirley Crossland, the latter a student at the University of Oklahoma. Roy Davis, Mrs. Chris Pflegel, and Mrs. Marion Clark drafted illustrations and the fence diagrams at the Oklahoma Geological Survey, and Roger Burkhalter measured the section at the Fittstown Quarry. Susan Foster, Tulane University, drew the reconstructions for Parsley's chapters.

DEPOSITIONAL SETTING AND REGIONAL CHARACTERISTICS

Mark W. Longman

Buttercup Energy, Denver

The thickness of the Bromide Formation varies considerably across the Arbuckle Mountain region. Figure 1 is an isopach map of the formation based on data from measured sections and electric logs. The formation is thinnest to the northeast of the Arbuckle Mountains on what was apparently a relatively stable platform during deposition. It is thickest in an elongate area that trends northwestward and lies just south of the Arbuckle Mountains. Between these two areas, thickness of the Bromide changes rapidly along an apparent hingeline that trended northwestward roughly parallel with the Washita Valley fault zone (this fault zone was active mainly during the Pennsylvanian, not the Ordovician), and syndepositional subsidence along the hingeline was apparently responsible for the thickening of the formation. Down-to-the-coast faulting did not occur or was of minor importance because no abrupt changes in thickness of the Bromide were observed between closely spaced data points.

TOPOGRAPHIC ELEMENTS DURING DEPOSITION

The isopach map shows that the Bromide Formation was deposited in and along a slowly subsiding northwesterly trending trough. This trough persisted throughout much of the Paleozoic and had a

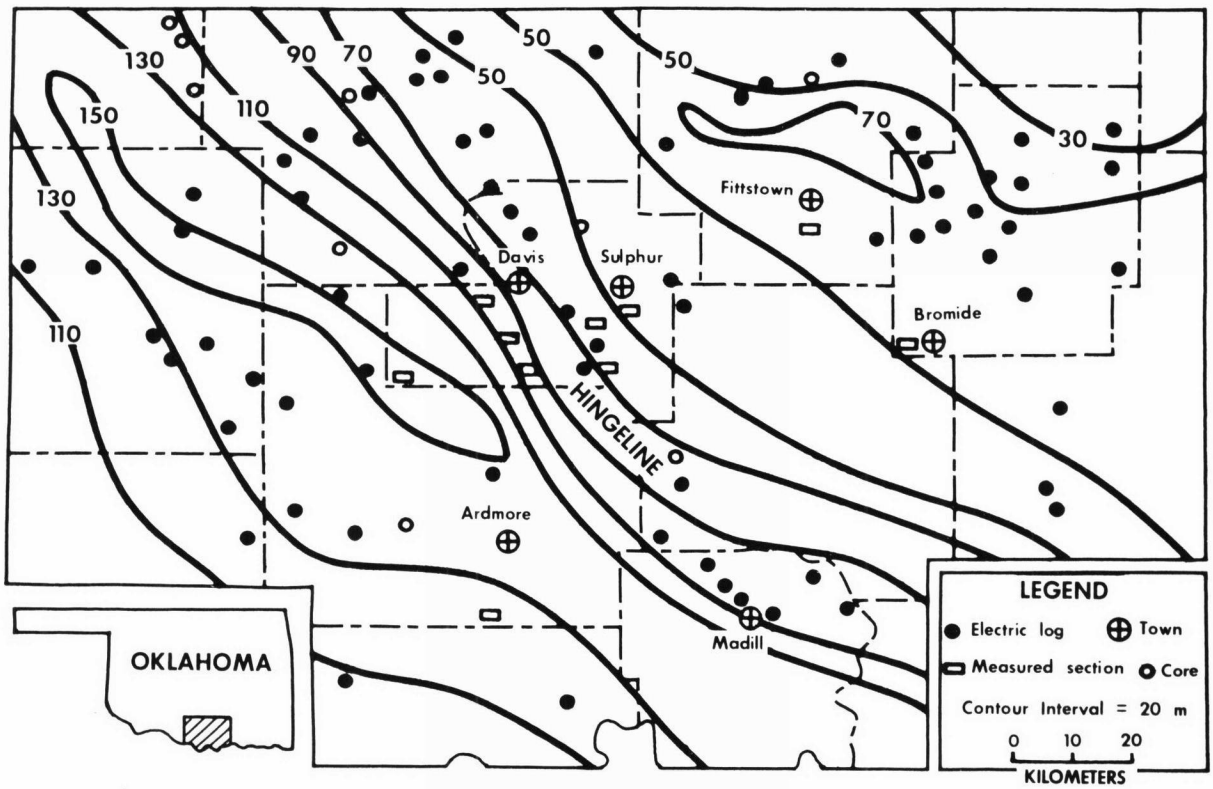

Fig. 1. Isopach map of the Bromide Formation in south-central Oklahoma.

strong influence on the deposition of many lower Paleozoic formations in south-central Oklahoma. The trough has been called the Southern Oklahoma geosyncline (Ham and others, 1964) and, more recently, with the growth of plate tectonics theory, the Southern Oklahoma aulacogen (Hoffman and others, 1974; Webster, 1977) or Wichita aulacogen (Walper, 1977).

The paleogeographic setting of Bromide deposition is shown in Figure 2. The Southern Oklahoma aulacogen was bordered on the north by the stable Arbuckle platform (new name), which occupied the northern two-thirds of Oklahoma during the early Paleozoic. To the south of the aulacogen, the Bromide Formation is considerably thinner where it laps onto the Concho arch (term from Nicholas and Rozendal, 1975). This topographic high has also been called the Texas peninsula (Adams, 1954) and evolved in part into the Muenster, Electra, and Bend arches in the late Paleozoic. Presumably open ocean occupied the present Gulf of Mexico to the southeast, and the elongate embayment shallowed and gradually died out to the northwest in the Texas Panhandle or southern Colorado (Ross, 1976).

The paleogeographic reconstruction in Figure 2 is intended to represent the position of the sea at the beginning of Bromide deposition. At this time, the center of the aulacogen was definitely submerged and the Concho arch was probably covered by very shallow water. Because it was submerged and capped by the Ellenburger Limestone, the Concho arch was the source of little, if any, sediment in the aulacogen. Almost all terrigenous sand in the basin was derived from the broad, low-lying desert north of the aulacogen. Evidence that the area to the north was an arid desert includes: 1) the ubiquity of very well-rounded quartz grains in the lower Bromide (such extreme rounding is produced only under eolian conditions according to Kuenen, 1960); 2) the presence of extremely fresh, unaltered feldspar in the sandstones (feldspar weathers rapidly in humid climates); and 3) the presence of some distinctly bimodal sandstones locally in the Bromide. (Such bimodal sandstones are characteristic of some types of eolian sediment according to Folk, 1968.)

With passing time, the sea transgressed from the aulacogen onto the desert and the eolian sands were reworked and deposited in shallow marine and tidal flat environments. Eventually the transgression extended far enough to prevent the influx of more terrigenous clastic material (except for clay and wind-blown silt) into the Southern Oklahoma aulacogen, and shales and limestones of the middle and upper Bromide were deposited.

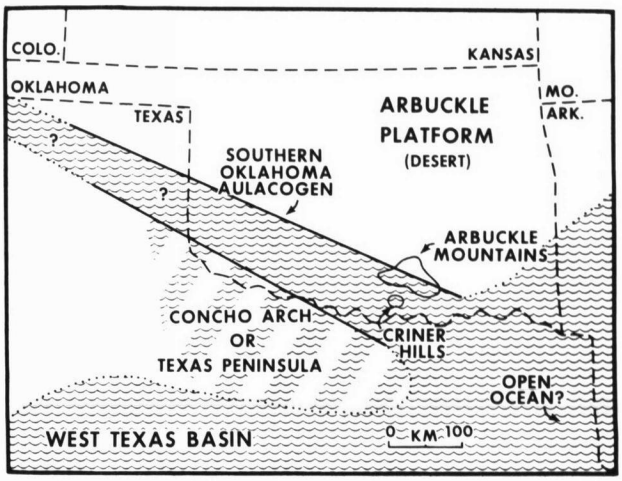

Fig. 2. Paleogeographic reconstruction of Oklahoma and northern Texas at the beginning of Bromide deposition. The aulacogen was submerged but the Arbuckle platform to the north was emergent. The Concho arch was covered by very shallow water.

CHARACTERISTICS OF AULACOGEN DEPOSITION

Characteristics of the Southern Oklahoma geosyncline have been described by Walper (1977) and Webster (1977) and are similar to those of aulacogens described by Salop and Scheinmann (1969). Aulacogens are large, grabenlike downwarps in the continental platform that extend landward from ocean basins. One end of the aulacogen abuts a geosyncline and the opposite end dies out in the platform. Subsidence, sediment thickness, sediment diversity, and tectonic activity are greatest near the mouth of the aulacogen, where it merges with the miogeosyncline from which it is indistinguishable. Aulacogens always form at the apex of a reentrant angle of the ocean into the platform and may be accompanied by basic volcanism (Salop and Scheinmann, 1969).

Shatski (1946) was the first to recognize aulacogens and also the first to recognize the Southern Oklahoma geosyncline as an aulacogen. American geologists were slow to recognize the significance of Shatski's work, however, and it was not until Salop and Scheinmann (1969), Burke and Dewey (1973), and Hoffman and others (1974) that the concept of aulacogens was clearly presented in English. Hoffman and others stressed how well the Southern Oklahoma aulacogen fits the definition of Shatski and used the work of Ham and others (1964) to discuss the geologic history of the structure

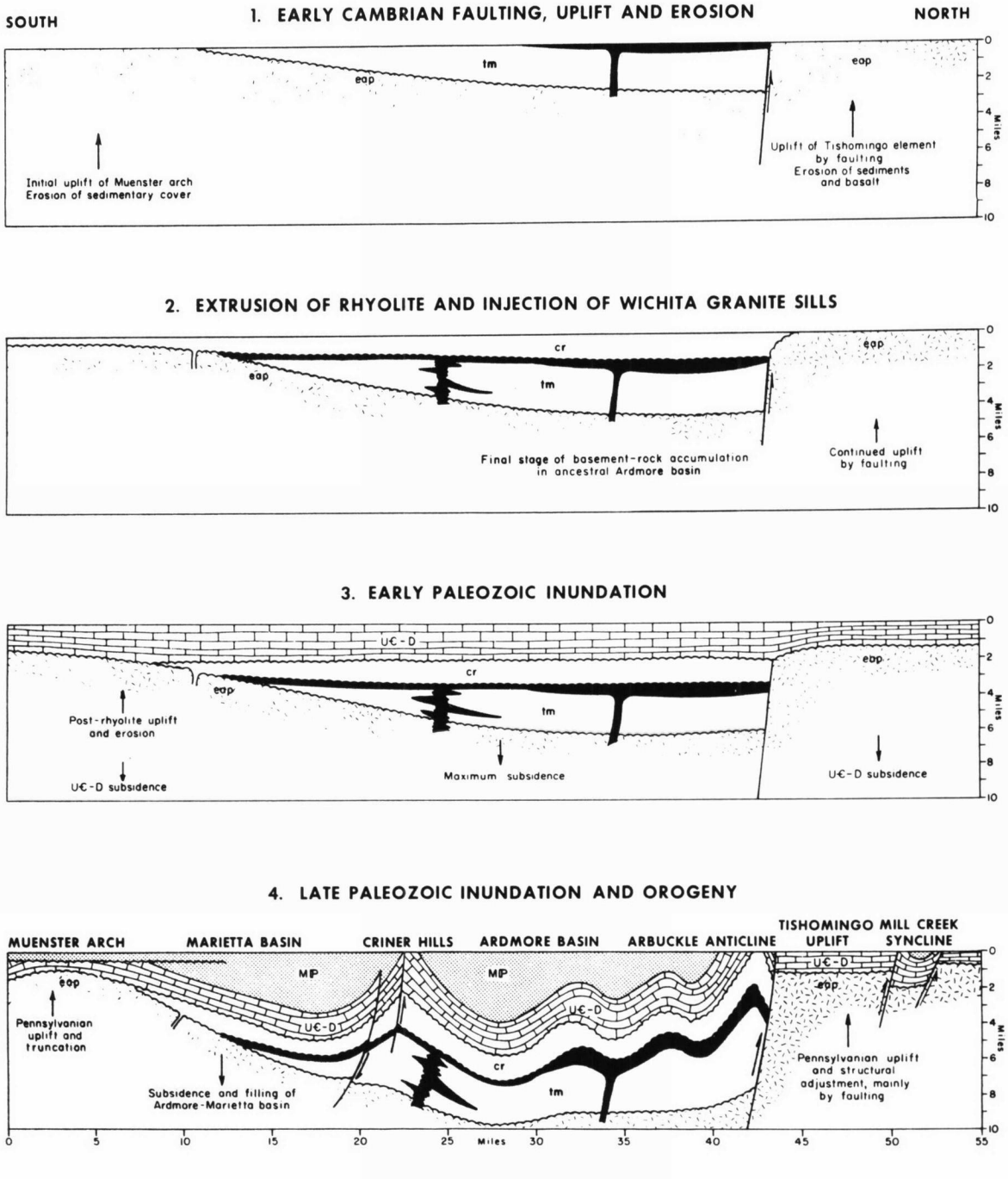

Fig. 3. Four stages in the evolution of the Southern Oklahoma aulacogen (from Ham and others, 1964). The Bromide Formation was deposited during stage 3.

(Fig. 3). According to Ham and others (1964) and Hoffman and others (1974), the aulacogen began as a graben underlain by Precambrian granite. Filling of the graben occurred in three major stages. During the first stage in the Early and Middle Cambrian, up to 5,000 m of coarse immature clastics, basalt, spilite, rhyolite, and hypabyssal sills accumulated during rapid subsidence. This was followed by a stage of shallow shelf carbonate and terrigenous deposition that lasted from the Late Cambrian to the Mississippian. Sediments deposited during this stage are about 3,000 m thick. Toward the end of this stage the rate of subsidence decreased and during the Late Silurian and Devonian only 355 m of shale, limestone, and chert accumulated. Rocks deposited in Late Silurian to Mississippian time are the only formations that are not thicker in the basin than on the platform, indicating that the aulacogen and craton were subsiding at roughly the same rate (Webster, 1977).

The third stage was characterized by major tectonic activity and resulted in a complex pattern of paired uplifts and fault basins such as the Arbuckle uplift and the neighboring Ardmore basin. The basins received as much as 7,000 m of late Paleozoic terrigenous sediment, almost as much as some geosynclines. Most of the tectonic activity took place during the Pennsylvanian.

APPLICATION OF THE AULACOGEN MODEL TO BROMIDE DEPOSITION

The Bromide Formation was deposited during an intermediate stage of aulacogen development. This stage was characterized by sporadic slow subsidence and little, if any, faulting. The tectonic stability provided ample time for storms to distribute terrigenous sediment throughout the basin during the early stages of deposition of the Bromide. Because the rate of influx of terrigenous clastics was low during these early stages, the rate of subsidence exceeded the rate of deposition and a generally transgressive sequence dominated by sandstone and shale was deposited. However, conditions eventually changed and became more stable. During deposition of the upper Bromide, this stability combined with a decrease in the influx of clastic material to expedite filling of the basin with a regressive limestone sequence.

Two models are available for interpreting gross aspects of deposition, particularly carbonate deposition, along margins of epeiric seas: the traditional "shallow shelf" model characterized by a nearly flat platform and a clearly defined shelf-slope break (Wilson, 1975, p. 22), and the carbonate ramp proposed by Ahr (1973), in which the platform is replaced by an inclined ramp that extends basinward with no pronounced break in slope. Facies are distributed very differently in these two models (Bay, 1977; Figs. 4, 5). Because of the gentle subsidence in the aulacogen, almost the entire Bromide Formation was deposited in a ramp setting as indicated by the distribution of higher energy facies to the northeast on the shallow and stable Arbuckle platform (Longman, 1976). Only for a short interval near the middle of Bromide deposition did the carbonate ramp evolve into a more typical shelf-edge depositional setting. This change was brought about largely by a crinoid-bryozoan carbonate buildup and resulted in the deposition of carbonate grainstones along the shelf-edge (hingeline) simultaneously with the deposition of grainstones in the shallow water on the

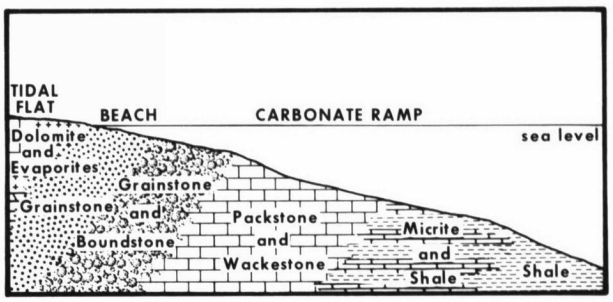

Fig. 4. Idealized facies distribution on a carbonate ramp profile. The carbonate ramp is characterized by (1) concentric facies belts that follow bathymetric contours, (2) grainstones updip passing into pelagic mudstones downdip, and (3) wedge-shaped units thickening seaward. Deposition of most of the Bromide Formation occurred in such a setting with shallow water to the northeast. Drawn from Ahr's (1973) written description.

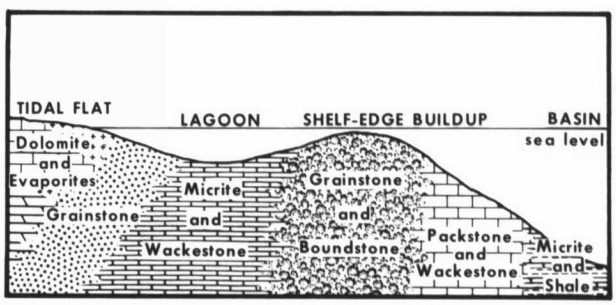

Fig. 5. Idealized facies distribution on a carbonate platform. Only during a brief interval in the middle of Bromide deposition did such a profile develop via a crinoid/bryozoan carbonate buildup.

northeastern part of the Arbuckle platform. Deposition in a ramp setting seems to have been common throughout the history of the Southern Oklahoma aulacogen and may well be a normal characteristic of aulacogen deposition except where reef-building organisms were abundant.

Summary.—The Bromide Formation was deposited in and adjacent to the Southern Oklahoma aulacogen during a period of slow, steady subsidence. Early deposition was in a storm-dominated epeiric sea in a ramp setting with shallowest water to the northeast. The rate of subsidence exceeded the rate of deposition and the lower Bromide represents a generally transgressive sequence dominated by sandstone and shale. Eventually conditions stabilized and the ramp evolved for a brief time into a shelf-margin carbonate buildup. In the later stages of Bromide deposition, tectonic stability increased, influx of clastic material was cut off, and relatively rapid carbonate accumulation began, which resulted in the deposition of a regressive limestone sequence at the top of the formation. Echinoderms occur in subtidal facies of both the transgressive and regressive sequences.

STRATIGRAPHIC STUDIES

Robert O. Fay and A. Allen Graffham

Oklahoma Geological Survey;
Geological Enterprises

The Bromide Formation (Middle Ordovician, Blackriveran) consists of over a hundred meters of sandstones, shales, and limestones (ascending) that crop out in the Arbuckle Mountains, Criner Hills, and two isolated areas in the Wichita Mountains of southern Oklahoma. The Bromide is the uppermost formation in the Simpson Group; it appears conformable with the Tulip Creek Formation below, but is probably unconformable with the Viola Limestone above.

The Bromide is subdivided into two members, the Mountain Lake Member below and the Pooleville Member above. The Mountain Lake is a transgressive sequence, with quartz-arenite sandstone at the base and biosparite and shale above. The Pooleville is a regressive sequence of biomicrite, with some birdseye micrite at the top in the northern Arbuckles. The upper Pooleville lithofacies is subtidal in the Criner Hills but intertidal or supratidal in most of the Arbuckles. The overlying basal Viola lithofacies is deep subtidal in both areas.

Ordovician rocks were first recognized in the Arbuckle Mountains and Criner Hills in 1891 and in the Wichita Mountains in 1890. The first geologic maps of these areas were published from 1901 to 1904. The Bromide was named in 1911, and modern terminology was established in 1931. The following sections review early studies on the Ordovician of southern Oklahoma and later stratigraphic work on the Simpson Group and Bromide Formation.

EARLY STUDIES ON THE ORDOVICIAN OF SOUTHERN OKLAHOMA

Arbuckle Mountains.—One of the earliest references to Ordovician geology of the Arbuckle Mountains is that of Shumard (1853-1854, p. 184-185), who mentioned that a bluish-gray nonfossiliferous crystalline limestone occurred above the granite between Fort Arbuckle and Fort Washita. The route was along the northeastern side of the Washita River, through the northeastern Arbuckle Mountains. The limestone was probably part of the Arbuckle Group. At that time, the Arbuckle Mountains were the area west of the Washita River. The Arbuckles were named for Fort Arbuckle in the SE¼ sec. 25, T. 1 N., R. 1 W., Garvin County, according to Shirk (1966, p. 10). Fort Arbuckle was named for Brigadier General Matthew Arbuckle, and the fort was established by Captain Randolph B. Marcy in April, 1851. In 1870, Initial Point was established about one mile south, for surveying Oklahoma, and in 1871 the fort was abandoned and moved to the new Fort Sill in the Wichita Mountains. A Lieutenant Grant who served at Fort Arbuckle later purchased the land and established a home. The Arbuckle Post Office was in operation from August 20, 1884, to January 15, 1906. The Grant family still owns the property.

Hill (1891a, p. 119) mentioned that he collected fossils in the Arbuckle Mountains and sent the fossils to Professor H. S. Williams for identification. This was the first mention that Ordovician rocks existed in the Arbuckle Mountains. Hill (1891b, p. 117-122) published further information, mentioning an *Orthis testudinaria* that was collected on Bill Jackson's ranch along Delaware Creek west of Boggy Depot (near Viola and Bromide). A Mr. J. T. Munson of Denison, Texas, collected specimens in this area, and Professor Alpheus Hyatt identified the fossils as belonging to the Hudson River Group (p. 117). Hill (p. 121) measured a section and collected fossils between Dougherty and Berwyn and collected fossils near Woodford. Williams identified the fossils as Trentonian to Helderbergian in age. These were the first Ordovician fossils to be named in the Arbuckle Mountains. No echinoderms are mentioned, and no precise localities are recorded. Vaughan (1897, p. 559) mentioned that Ordovician limestones occurred on the north flank of the "Arbuckle Hills." Vaughan (1899, p. 52) stated that he

collected Ordovician fossils on the south side of Boggy Creek, 13 to 16 km above Stonewall, but no echinoderms are mentioned.

In 1897, a program was initiated by the U.S. Geological Survey to study the segregated coal lands of the Choctaw and Chickasaw nations. Dr. Joseph Alexander Taff was in charge of the project until 1910, using four mules for transportation. Girty (1899, p. 539-540, 551-552) mentioned that Taff collected Ordovician fossils in 1897 at two places in the Arbuckles, one in the SE¼ sec. 6, T. 3 S., R. 9 E., and the other through the center of T. 1 S., Rs. 7-8 E., along an east-west line. A Mr. Francois E. Matthes prepared a profile along the latter line (pl. 69, p. 540), showing Beds 12 to 25 as Ordovician: Bed 12 contained *Rhynchotrema capax* (a Fernvale marker), Bed 16 contained *Rafinesquina alternata* (?Bromide), Bed 19 contained *Monotrypa* (Bromide), and Bed 25 contained *Maclurea bigsbyi* (?McLish). At the first locality, *Orthis tricenaria* (a Pooleville marker) was collected. No fossils are described, and no echinoderms are mentioned. Taff (1901a, p. 271) estimated the thickness of the Ordovician rocks in the Arbuckles to be 2,000 m and the same year (1901b) mapped a small part of the Arbuckles on the Coalgate Folio. Taff (1904) prepared the first geologic map of the Arbuckle Mountains, with assistance from G. I. Adams, S. H. Ball, and G. B. Richardson. Dr. Edward O. Ulrich and Dr. George H. Girty did the paleontology, with Ulrich being responsible for the pre-Carboniferous fossils. Taff (1904, p. 23) published the first measured section of the Simpson, in the Arbuckle anticline west of the Washita River. Ulrich (pp. 24-25) listed fossils from this section, which included Bromide forms. With Taff's publications, the concept of the Arbuckle Mountains was changed to a geological meaning, to include also the area east of the Washita River.

Wichita Mountains.—Comstock (1890, p. 323-324) first mentioned the occurrence of lower Paleozoic limestones in the Wichita Mountains, naming the ranges "Silurian Hills." Vaughan (1897, p. 559) mentioned that the limestones north of the Wichitas contained Ordovician fossils. Vaughan (1899, p. 49) listed some Ordovician fossils from the limestones on the north flank of the Wichitas and noted Ordovician limestones on the south flank (p. 51). Dr. Girty (p. 53) identified some fossils from the Fort Sill quarry as probably Trentonian in age. A Lieutenant Savill of Fort Sill first reported that limestones occurred in the Rainy Mountains, north of the main limestone hills.

Bain (1900, p. 135) named the "Rainy Mountain limestone" for the Ordovician limestones in the Wichita Mountains. The limestones in Rainy Mountain were identified as being probably Trentonian in age by Dr. Stuart Weller (p. 144), based on fossils collected by Bain and Professor Rollin D. Salisbury. Some of these fossils were probably from the Bromide Formation, but no echinoderms were mentioned.

Taff (1904), with the help of Dr. Charles Newton Gould and E. O. Ulrich on geology and paleontology, prepared the first geologic map of the Wichita Mountains, beginning work in 1901. Taff (1904, p. 71) devoted one page to the Rainy Mountain section, having mapped three isolated Viola Limestone areas. No echinoderms were mentioned in the report.

Criner Hills.—Hill (1891b, p. 120) named the Red Bird Mountains (now Criner Hills) after the Red Bird Post Office and first recognized lower Paleozoic rocks there. Taff (1904, p. 47) was the first to map and describe the geology of the Criner Hills and to use the name Criner Hills in the geological literature. He also recognized the Simpson in the Criner Hills (p. 49), but no echinoderms are mentioned.

The Criner Hills were named for John Criner, a prominent settler whose ranch was in Tps. 5-6 S., R. 1 E. The Criner Post Office, in sec. 28, T. 5 S., R. 1 E., Carter County, was established on November 10, 1885, and discontinued October 31, 1887, according to Shirk (1966, p. 57).

Summary.—Ordovician rocks were first identified in southern Oklahoma in 1890-1891, but Simpson rocks were not mapped and studied until 1901-1904. These early reconnaissance studies lacked both detailed measured sections and descriptions of fossils.

HISTORY OF THE SIMPSON GROUP

Taff (1902, p. 3, columnar section) first named and mapped the "Simpson formation" in his Atoka Folio report, which included part of the Arbuckle Mountains. He did not designate a type locality or a type section. The name comes from the town of Simpson (now Pontotoc) in secs. 1 and 12, T. 1 S., R. 6 E., Johnston County, east of which are good exposures below the Viola Limestone and above the Arbuckle Group. The old town of Pontotoc was in the SW¼ sec. 12, T. 1 S., R. 6 E., and the post office was established September 22, 1858, according to Shirk (1966, p. 170). On the Tishomingo Quadrangle, surveyed in 1897-1898 and used by Taff

(1903), the Simpson townsite was shown in the north half of sec. 12 and the south-central part of sec. 1, T. 1 S., R. 6 E., and Pontotoc was shown in the SW¼ sec. 12. Taff (1904, p. 20, pl. 1) showed the town of Simpson in the same position as on the Tishomingo Quadrangle, but he did not show Pontotoc. Later maps show Pontotoc where Simpson used to be, and modern maps only show Pontotoc in the same position as Simpson. The original concept of the "Simpson formation" of Taff (1902, 1903, 1904) was that of Middle Ordovician sandstones, shales, and limestones about 490 m thick, with the "Viola limestone" above and the "Arbuckle limestone" below.

The "Arbuckle limestone" was named by Taff (1902, p. 3) and was elevated to group rank by Decker (1933b, p. 55-57), with the type locality and section presumably being the Arbuckle anticline in T. 2 S., Rs. 1-2 E., Murray and Carter counties.

Taff (1902, p. 3) named the "Viola limestone" presumably for exposures near Viola, in the SW¼ sec. 13, T. 2 S., R. 7 E., Johnston County. Taff's Viola was 230 m thick, the lower part now being included in the Bromide Formation. Viola was named for Viola Jackson, daughter of Judge William H. (Bill) Jackson, who operated the post office from June 30, 1890, to July 17, 1906, when the name was changed to Springbrook. Springbrook Post Office was discontinued November 15, 1910. Ulrich in Taff (1904, p. 26) listed "lower Viola" fossils from the area of Double Mound, about 9.5 km northwest of Roff, and mentioned "lower Viola" as being very fossiliferous. The fossils are those of the Bromide Formation. Sprinkle (pers. commun.) attempted to relocate these exposures northeast of Roff during field work in 1977, but was unsuccessful. Thus, Taff's orginial map and usage of the term "Viola limestone" included the Bromide Formation (in part) in different areas.

Taff (1902-1904) did not designate type localities or type sections for the Arbuckle, Simpson, and Viola units. Not until Decker (1930, 1931b, 1933b) restudied and remapped these units were sections and type localities named. Decker (1930, p. 1493-1505; 1931b, p. 5) raised the Simpson to group rank and mentioned the location of old Simpson. Decker's usage of formation names subdividing the Simpson is currently followed: Bromide, Tulip Creek, McLish, Oil Creek, and Joins (descending).

Harris (1957) summarized the history of Simpson studies. Cramer (1965) gave a bibliography of the Simpson Group. In a symposium on the Simpson published in 1965, Holden, Huffman, Ireland, Schramm (1965a), and Statler summarized the regional stratigraphy of the Simpson. In the same publication, Coffman, Green, Kornfeld, Neumann, Rupnik, Schramm (1965b), and Wright reported on petroleum aspects of the Simpson. Alberstadt (1973, p. 15) showed that the Viola is Trentonian to Richmondian in age, based on studies of articulate brachiopods.

HISTORY OF THE BROMIDE FORMATION

Name and nomenclatural history.—Ulrich (1911, pl. 27) listed the term "Bromide formation" in a chart for a unit unconformable above the "Simpson formation" and unconformable below the "Viola limestone." He assigned a Trentonian age to the Viola and a Blackriveran-Chazyan age to the Bromide (or "lower Viola" of Taff). No type locality or type section was designated.

Ulrich (1927, p. 21-32) included the Bromide in the top of the Simpson. Edson (1927, p. 967-975; 1930) proposed that the type locality was the SW¼ sec. 32, T. 1 S., R. 8 E., just north of Bromide, Coal County, and that the section had been mapped by Taff (1902) as "lower Viola limestone" (Measured Section 5 of this report).

The town of Bromide lies mostly in secs. 5 and 6, T. 2 S., R. 8 E., Johnston County, with a northern part in secs. 31 and 32, T. 1 S., R. 8 E., Coal County. Before 1906 the town was named Juanita. On April 27, 1906, the post office was changed to Zenobia, named for Zenobia Jackson, daughter of Judge William H. Jackson, who operated a local store and hotel. On June 8, 1907, the name was changed to Bromide, which comes from the nearby mineral springs that resulted from wells drilled in the Simpson formations (Shirk, 1966, p. 29). Many of the wells in the area were drilled by Mr. Robert Galbreath of Tulsa, who built a two-story hotel in Bromide in 1909. In previous publications this hotel is spelled Galbraith, but according to Hoig (1976, p. 10) the correct spelling is Galbreath. Galbreath's interest in Bromide was first oil and then a health spa. The hotel, most of which has been torn down, is located in the northwestern corner of Bromide, and the type section of the Bromide was given by Decker (1931b) as that north of the hotel along an old road. The road is closed and partly washed out, but the exposures are still good. Loeblich (1942) measured a section through the Bromide here.

Decker (1930, p. 1498-1505; 1931b, p. 11-12, 98) first studied the Bromide Formation in detail

and included it in the Simpson Group, between the Tulip Creek Formation below and the Viola Limestone above. Edson (1930, p. 947) mentioned that the Bromide was unconformable above the Tulip Creek and below the Viola, based upon subsurface studies. For many years, Decker was unable to separate the Tulip Creek from the Bromide in the eastern Arbuckle Mountains.

Ulrich (December 1928, unpublished chart) first introduced the term Tulip Creek, with the upper Simpson Group being subdivided into the Bromide, Criner, and Tulip Creek members (descending). Ulrich (1930, p. 73) used the same nomenclature. No type locality and no type section was designated. Decker (1930, p. 1498-1505) redefined the Tulip Creek Formation for beds between the McLish Formation below and the Bromide Formation above, a usage currently followed. The type locality and type section for the Tulip Creek is along Tulip Creek in the NE¼ sec. 25, T. 2 S., R. 1 E., Carter County (Measured Section 3 of this report). On the 30-minute Ardmore Quadrangle (1898), the name Tulip Creek is applied to the entire stream running southward to Caddo Creek. On the current 7½-minute Springer Quadrangle, this stream is named Philips Creek, after a Mr. Philips who lived in the NE¼SE¼ sec. 36, T. 2 S., R. 1 E., having settled in the area after the Civil War. In order to preserve the name Tulip Creek, the Oklahoma Geological Survey petitioned the National Board on Geographic Names to validate the name Tulip Creek for that portion of Philips Creek that drains through the Arbuckle Mountains in sec. 25, T. 2 S., R. 1 E. From that point southward, the name Philips Creek would be valid. This petition was passed. We were unable to find the derivation of the name Tulip Creek. Local residents have always used the term Philips Creek, dating back to Civil War days.

Decker (1941, p. 650, 655) first recognized that the lower part of the Bromide Formation at some sections in the eastern Arbuckles may belong to the Tulip Creek Formation. In the section south of Fittstown (Measured Section 11A of this report), he recognized the basal 6.7 m as Tulip Creek, and at Bromide he revised the thickness of the Bromide from 89 m to 39 m. Gillert (1952) showed 89 m of beds between the Viola and McLish south of Fittstown but did not distinguish between the Tulip Creek and Bromide formations. Ham and McKinley (1954) and Ham (1955) restudied and remapped the Arbuckle Mountains, but they did not distinguish between the Tulip Creek and Bromide formations in the eastern Arbuckle Mountains. Harris (1957) also had difficulty at the Fittstown section, where he showed 38 m of Tulip Creek, the upper 11 m of which is probably Bromide. Frederickson (1957b) mapped the Bromide and Tulip Creek formations in the Criner Hills, but the contact between these units is covered here. Statler (1965, p. 200) classed the Tulip Creek with the basal Bromide.

Mountain Lake Member.—Cooper (1956, p. 120) proposed the name Mountain Lake Member for the lower sequence of the Bromide Formation, below the Pooleville Member. Although not mentioned, the basal sandstone should be included in the Mountain Lake. The type section is along Spring Creek in secs. 8 and 17, T. 2 S., R 1 W., Murray County (Measured Section 1 of this report). Mountain Lake is a municipal water supply for Ardmore, in the E½ sec. 22, T. 2 S., R. 1 W., Carter County. The basal sandstone is conformable with the underlying Tulip Creek Formation, and the upper limestones and shales are conformable with the overlying Pooleville Member.

The Mountain Lake Member has a basal tan to greenish-gray fine-grained quartz arenite sandstone, with well-rounded and frosted grains, overlain by a sandstone and greenish-gray illitic-chloritic shale sequence with interbedded biospartite limestone and greenish-gray shale above. The sandstone sequence is thickest (more than 37 m) along Lick Creek in the northwestern Arbuckles and thinnest (less than 9 m) in the eastern Arbuckles, losing sand at the top of the section. The overlying shale and limestone is thickest (more than 60 m) along the axis of the aulacogen and is mostly shale. In a comparable section in the northeastern Arbuckles, limestone predominates with some sand, and the section is 24 to 31 m thick (see Fig. 78 in pocket, back cover).

Ulrich (1933, p. 105) proposed a new term, Cool Creek, for a shaly member above the Tulip Creek and below his Criner Member. No type locality and no type section was given, but it is presumed that Ulrich's type locality was along Cool Creek in secs. 35 and 36, T. 2 S., R. 2 E., Carter County, in the Arbuckle Mountains. Decker (1933b, p. 55-57) proposed the term Cool Creek for a formation of the Arbuckle Group, and Ulrich's name Cool Creek was discarded. Ulrich's Cool Creek is the same as Cooper's (1956) Mountain Lake Member.

Cooper (1956) correlated the lower Mountain Lake with the Lincolnshire Formation (upper Ashbyan Stage) and the upper Mountain Lake with the Benbolt Formation (lower Porterfieldian Stage). Generally the entire Bromide is now considered to be Blackriveran in age. In northeastern Oklahoma,

the upper Tyner Dolomite may correlate with the Mountain Lake Member.

Pooleville Member.—Cooper (1956, p. 121) also proposed the name Pooleville Member for the fine-grained limestone in the upper part of the Bromide Formation. The type section is along Spring Creek in secs. 8 and 17, T. 2 S., R. 1 W., Murray County (Measured Section 1, this report). Pooleville (formerly Elk) is in the south-central part of sec. 34, T. 1 S., R. 2 W., and the north-central part of sec. 3, T. 2 S., R. 2 W., Carter County. Elk was established January 15, 1893, and the name was changed to Pooleville on July 20, 1907, after an Ardmore banker, E. S. Poole, according to Shirk (1966, p. 170).

The Pooleville Member is mainly biomicrite and microspar limestone, interbedded with greenish-gray calcareous shale along the axis of the aulacogen. The type section in the southwestern Arbuckles is 71 m thick, with much greenish-gray calcareous shale, and probably represents an area close to the Pooleville depocenter. In most of the Arbuckle Mountains, the upper 5 m of Pooleville is a massive burrowed micrite or calcilutite of the intertidal facies. In the Criner Hills, the Pooleville is about 40 m thick and is mainly a thin-bedded to medium-bedded mudstone or microspar limestone, deposited along the southern margin of the aulacogen. In the northeastern and northern Arbuckles, the Pooleville is less than 21 m thick, with some birdseye micrite in the upper part. This latter facies, prevalent on the northern platform, was named the Corbin Ranch Formation by Harris (1957) but is probably a supratidal facies of the Pooleville.

Several different names have been proposed for the Pooleville Member, such as Criner, Webster, Corbin Ranch, and Bromide dense (subsurface).

Ulrich (April 1928, unpublished chart) first used the term Criner Member of the West Spring Creek Formation for a unit lying unconformably above the Bromide Member and below the Viola Limestone. No type locality and no type section was designated, but the type area was presumed to be in the Criner Hills. It is assumed that Ulrich's type locality was Rock Crossing (?Hickory Gap) in the N½S½ sec. 35, T. 5 S., R. 1 E., in the Criner Hills, Carter County (Measured Section 15 of this report). Ulrich (December 1928, unpublished chart) dropped the term West Spring Creek and showed the Criner Member unconformably below the Bromide and above the Tulip Creek. Ulrich published an abstract in 1929 and repeated this usage in 1930 (p. 73). Decker (1930, p. 1495) published Ulrich's December 1928 chart, discarding the term Criner, having recognized that it was a slightly different facies of the upper Bromide Formation. Ulrich (1933, p. 105) retained the term Criner and proposed a new term, Cool Creek, for a shaly member below the Criner and above the Tulip Creek. Decker (1931b, p. 98-99; 1933, p. 55-57) did not use the term Criner and rejected the term Cool Creek, recognizing that both were facies of the Bromide. Ulrich thought that the fine-grained limestones in the Criner Hills, the shaly beds in the western Arbuckles, and the coarse-grained limestones at Bromide in the eastern Arbuckles were different formations of different ages, but Decker correctly recognized these as facies of the Bromide Formation.

The term Webster Formation was proposed by Ulrich (December 1932, unpublished chart) for a unit below the Viola Limestone and above the Bromide Formation. It is Blackriveran to Trentonian in age. No type locality and no type section was given. Edson (1935, p. 1122-1130) first published Ulrich's chart. Harris (1957, pl. 94) suggested that the Webster may have been his Corbin Ranch. We have been unable to find the derivation of the name Webster, and the term has been dropped.

Harris (1957, p. 94) named the Corbin Ranch Formation for exposures near the Carleton W. Corbin Ranch on the west side of Oklahoma Highway 99, about 5 km south of Fittstown, in the SW¼ sec. 12, T. 1 N., R. 7 E., Pontotoc County. About 16 m of dense Pooleville is exposed below the Viola, the upper 6 m of which is a birdseye micrite and was designated Corbin Ranch. Harris (p. 95) recognized this facies on Colbert Creek southwest of Davis, where about 9 m is exposed below the Viola. Harris (p. 100, 103) considered the Corbin Ranch to be unconformable with beds above and below and to be Blackriveran to Trentonian in age, based on ostracod studies. No mention was made of this being a possible supratidal facies, slightly different from the Pooleville intertidal facies or different from the deeper subtidal facies of the Viola. Schramm (1964, 1965a) correlated the Corbin Ranch with the upper Tyner and Fite of northeastern Oklahoma. Statler (1965, p. 200) recognized the Corbin Ranch to be the same as the "Bromide dense" of subsurface terminology. He suggested (p. 209) that the pre-Fernvale part of the Viola may correlate with the Fite, following Disney and Cronenwett (1955, p. 110) and Cronenwett (1956), and implied that the fossils in the Fite may be facies holdovers of the Viola. Huffman (1965, p. 120) correlated the Fite with the Corbin Ranch or

"Bromide dense." Frezon (1962, p. 42) correlated the Corbin Ranch with the Fite and with the Platin Limestone of Arkansas. The Fite Limestone of northeastern Oklahoma contains the coral *Tetradium* and ostracods like those of the Pooleville birdseye micrite, according to Harris (1957) and Huffman (1965).

Statler (1965, p. 200) stated that he was unable to trace the Mountain Lake and Pooleville members into the subsurface, but his electric log cross sections show characteristics of both of these members.

The Viola Limestone may be unconformable above the Pooleville Member (Wengerd, 1948), but the hiatus is not great, according to Decker (1936a, p. 306; 1943, p. 1392; 1952, p. 100, 136). Northeastward from the Arbuckles, the hiatus increases.

Present studies suggest that the Corbin Ranch is a supratidal facies of the Pooleville, and so the name Corbin Ranch is here dropped.

Cooper (1956) correlated the Pooleville with the Wardell and Ridley formations (upper Porterfieldian and lower Wildernessian stages) in the southern Appalachians; these are generally Blackriveran in age.

Summary.—The Bromide Formation is at the top of the Simpson Group, below the Viola Limestone and above the Tulip Creek Formation. It is subdivided into two units, the Mountain Lake Member at the base, consisting of a basal sandstone overlain by shale and biosparite, and the Pooleville Member at the top, consisting of biomicrite. Each member has different facies, extending from subtidal mudstones and shales of the Ardmore basin to supratidal birdseye micrites and dolomites on the platform north of the Arbuckle Mountains. Each facies is characterized by a different dominant fauna of Blackriveran age, including some Chazyan holdovers and Trentonian forerunners. The upper Tyner and Fite formations of northeastern Oklahoma may correlate with the Mountain Lake and Pooleville members, respectively.

DEPOSITIONAL ENVIRONMENTS

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The systematic paleontology and stratigraphy of the Bromide Formation have received much attention during the past 75 years because of the fortuitous preservation of abundant fossils and the relatively isolated position of this Middle Ordovician formation in the southern midcontinent region. However, detailed analyses of the Bromide depositional environments have lagged far behind the study of the fossils. The reasons for this include the relatively poor exposures in the deeply weathered Arbuckle Mountains and the changing emphasis in stratigraphy through time. Until the early 1960's, emphasis in stratigraphy was on fossils and correlation of time-equivalent units. More recently, however, the definition of stratigraphy has broadened to include interpretation of depositional environments and recognition of time-transgressive units. This change in the concept of stratigraphy is largely the result of the increasing knowledge of recent depositional environments and processes.

This study of Bromide depositional environments was undertaken to complement the studies on systematic paleontology of the echinoderms. Its basis is a bed-by-bed analysis of the rocks and fossils throughout the formation. Sedimentary structures, lithic characteristics such as grain size, sorting, and abrasion (in both terrigenous and biogenic grains), and vertical facies relationships were used to interpret the environments of deposition. As with all studies of ancient depositional environments, analogy with recent depositional processes is an important part of the interpretation process.

CHARACTERISTICS OF THE FORMATION

In a gross sense, the Bromide Formation consists of a basal sandstone, an intermediate mixed shale-limestone sequence, and an upper limestone. The basal sandstone and intermediate shale-limestone sequence have been named the Mountain Lake Member; the upper limestone is called the Pooleville Member (Cooper, 1956). These members can be traced throughout the Arbuckle Mountain region of south-central Oklahoma.

Thickness variation of the Bromide Formation was discussed in a previous chapter. The formation is thinnest to the northeast on what was the relatively stable Arbuckle platform during the time of deposition. It thickens fairly abruptly from about 70 m to as much as 150 m along a "hingeline" that trended northwestward through the center of the Arbuckle Mountain region. Further to the southwest in the Criner Hills region, the formation again becomes somewhat thinner. Much of the thickening of the Bromide Formation is in the Mountain Lake Member, but the Pooleville is also thickest in the center of the aulacogen to the south of the hingeline.

The sequence of rock types in the Bromide Formation is shown in Figure 6. This composite measured section, which is typical of those along the hingeline, contains a complex assemblage of interbedded rock types. In spite of the complexity, these rocks can be grouped into correlative packages or lithofacies assemblages. In a previous report on the Bromide (Longman, 1976), I divided the Mountain Lake Member into six lithofacies and the Pooleville into five. General characteristics of these lithofacies are presented in Figure 6.

DESCRIPTION OF LITHOFACIES

Stratigraphic correlation can be done using either lithic characteristics (most commonly used on a local scale) or apparent time markers such as fossils (usually used to correlate over large distances). Use of lithic characteristics independent of fossils is inadequate because migrating facies can produce time-transgressive rock units. On the other hand, correlation based on fossils alone may be inadequate because of the paleoenvironmental controls on fossil distribution. Even the distribution of the best Ordovician index fossils (graptolites) is largely controlled by facies. Thus, if the goal of a study is to provide an integrated picture of lithofacies relationships through time

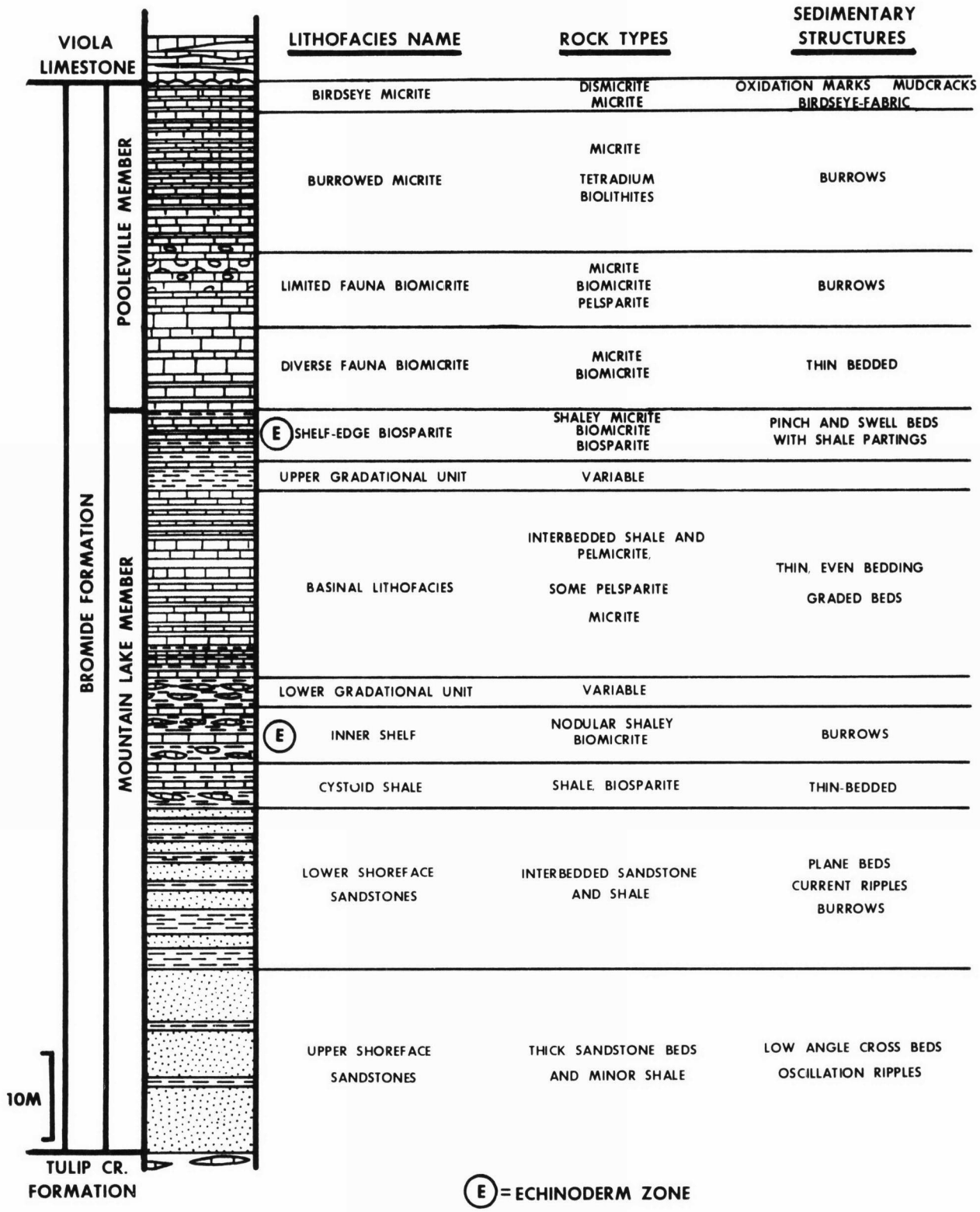


Fig. 6. Composite measured section of the Bromide Formation along hingeline showing the various lithofacies and some of their characteristics. The basinal lithofacies of the Pooleville, which occurs only in the Criner Hills, is not shown.

as it is here, the best approach is to combine the lithic and paleontologic methods of correlation.

In the Bromide Formation, correlation of lithologies is relatively easy. The basal sandstone, the upper limestone, and many units within the formation can be correlated over most of the study area. Recognition of time lines is more difficult, but five have been interpreted within the Bromide Formation. The easiest to describe are the two echinoderm zones in the Mountain Lake Member. Each of these thin zones contains abundant echinoderms and can be correlated throughout the Arbuckle Mountain region. Furthermore, these echinoderm zones transcend lithic boundaries as true time lines should (see Fig. 9b), and this indicates that they did not form as the result of lateral migration of a particularly optimal environment through time. In addition, the Upper Echinoderm Zone is closely associated with the boundary between the Pooleville and Mountain Lake members. This boundary represents a sudden drastic reduction in the amount of terrigenous shale deposition in the Bromide and is probably a time line itself. Because storms can rework shale basinward across a shelf, this boundary probably represents a major event in the source area of the shales (such as submergence) rather than a migrating environmental boundary. All three of these time lines, i.e., the two echinoderm zones and the Mountain Lake-Pooleville contact, represent broad (perhaps as much as several hundred thousand years), but correlative time lines and provide a way to recognize which of the lithofacies in the Bromide were deposited synchronously.

The other time lines occur at the base and at the top of the Bromide Formation. Although these boundaries are more difficult to defend as time lines, they do cut across lithofacies boundaries as true time lines should. For example, the base of the Bromide consists of thin sandstone storm beds with abundant shale in the center of the aulacogen, lower shoreface sandstones near the hingeline, and coarse, well-sorted upper shoreface sandstones on the Arbuckle platform (Fig. 7). These sandstones were clearly deposited in different water depths and do not represent a single migrating facies. Instead, they can reasonably be interpreted as time-correlative lithofacies that formed when a supply of sand became available. However, it should be noted that different processes operated across the Arbuckle platform because of its considerable width and that a migrating upper shoreface environment probably was responsible for the great lateral extent of some of

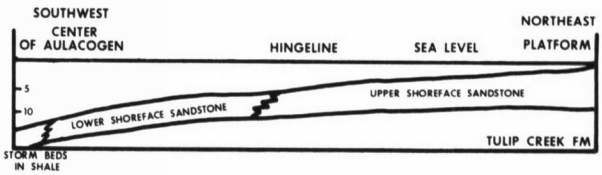


Fig. 7. Lithofacies relationships and inferred water depths of the upper and lower shoreface sandstones near the base of the Bromide Formation.

the upper shoreface sandstones there. At the top of the Bromide the contact with the overlying Viola Formation crosses facies boundaries in a similar logical way, but postdepositional erosion may have had some effect on this boundary.

By combining lithofacies correlations in the Bromide with apparent time lines, we can observe the shelf-to-basin sediment transitions from the Arbuckle platform across the hingeline into the center of the aulacogen. These relationships are shown in a series of diagrams in the following sections.

In descriptions that follow, sedimentary and paleontologic characteristics of the various lithofacies are presented. For convenience, similar lithofacies are described together. These descriptions are followed by an interpretation of depositional environment. Sandstone and limestone classification is based on Folk (1974), and terminology of sandstone depositional environments is from Reineck and Singh (1975). A much more detailed discussion of both lithofacies characteristics and criteria for interpreting the environments of deposition has been presented by Longman (1976).

UPPER AND LOWER SHOREFACE SANDSTONES

Sandstones near the base of the Bromide vary both laterally and vertically. On the Arbuckle platform, the sandstones as revealed in electric logs typically occur in massive units 1 to 20 m thick interbedded with shales. The thick sandstones are characterized by low-angle foreset cross beds (Pl. 1, fig. 1), plane beds, current ripplemarks, and some oscillation ripplemarks. Bioturbation is locally extensive. Compositionally and texturally, the sandtones are very mature quartzarenites. Quartz averages more than 98 percent of the terrigenous grains in the sandstones and occurs as well-rounded grains (Pl. 1, fig. 2). Grains are generally well sorted. Feldspar, tourmaline, and zircon occur in very minor amounts, and some glauconite is present locally. Abraded

and well-rounded fossil fragments, mainly from echinoderms and bryozoans, are abundant in some sandstone beds. Associated with some of the thick sandstone beds in cores from northeastern and northwestern parts of the study area are units characterized by interbedded thin (on a millimeter scale) shales and sandstones with flaser bedding (Pl. 1, fig. 3), sparse vertical burrows (Pl. 1, fig. 4), poorly preserved desiccation cracks, and small ripplemarks.

The thick sandstone beds grade upward in the section and change facies southward into thinner bedded (10 to 200 cm) sandstones with significantly more shale. Grain size in these is typically finer than that found in the thicker sandstone beds, but overall composition is very similar (except for abundance of shell fragments). Bioturbation is much more extensive, and in most beds no primary sedimentary structures are preserved. Those beds with sedimentary structures typically have planar bedding and some current ripplemarks (Pl. 1, fig. 5). Beds 10 to 50 cm thick with sharp bases and gradational tops are common. Tops of these beds commonly contain some burrows.

Fossils are more common in the thinner sandstones than in the more massive beds. Extensive burrowing has completely homogenized some beds, but where individual burrows can be observed, horizontal *Planolites* burrows are the most common type. *Teichichnus* and *Dictyodora* (compare Frey and Chowns, 1972) are also present (Pl. 1, fig. 6). Ostracods are locally abundant, and large, slightly abraded fragments of brachiopods, echinoderms, and bryozoans are fairly common.

Depositional Environments.—Lithofacies relationships and the interpreted depositional environments of the sandstones near the base of the Bromide are summarized in Figure 7. Petrographic evidence, sedimentary structures such as low-angle cross beds, abraded marine fossil fragments, and glauconite indicate that the thick sandstone beds on the Arbuckle platform were deposited in shallow marine upper shoreface and associated environments. The thin-bedded, flaser-bedded, interbedded sandstone and shale are interpreted as tidal flat deposits.

The thinner sandstones present in the aulacogen and above the massive sandstones on the Arbuckle platform are interpreted as lower shoreface sandstones. Sandstones from the lower shoreface environment have been described from both the Holocene (see Howard and Reineck, 1972, for an excellent discussion), and ancient deposits (compare Cotter, 1975). Sediments deposited in the lower shoreface environment bear evidence of having been disturbed both by burrowing organisms and by storms. The beds, 10 to 50 cm thick, with sharp bases and plane beds near the base grading upward into burrows and ripplemarks in the lower shoreface sandstones of the Bromide, are similar to storm beds described by Kumar and Sanders (1976) from other shoreface areas. The *Planolites* and *Teichichnus* burrows are also typical of lower shoreface environments (Frey and Chowns, 1972). The abundance of bioturbation and clay-size material in these lower shoreface sandstones suggests that the Bromide coastline was characterized by low to moderate wave and tide energy.

PLATE 1.

Fig. 1. Low-angle foreset crossbeds in upper shoreface sandstone at the Fittstown exposure. Such structures are common in foreshore and upper shoreface environments. Hammer at center is 29 cm long. Unit 7ML-F.

Fig. 2. Calcite-cemented upper shoreface sandstone showing the excellent rounding typical of quartz sand in the Bromide. Average grain size is 0.6 mm.

Fig. 3. Tidal flat sandstone showing characteristic very thin bedding, clay drapes, and burrows. This facies occurs at the top of small regressive cycles in the transgressive upper shoreface sandstone. Sample from Allen well, depth 1,920 m. Bar scale is 1 cm long.

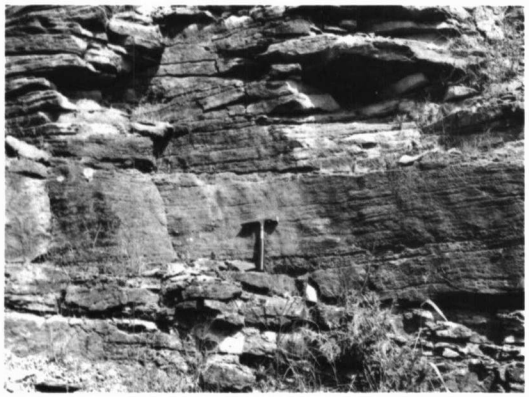
Fig. 4. Another tidal flat sandstone showing part of a "U" shaped burrow and typical flaser bedding. Sample from Lane well, depth 4,811 m. Bar scale is 1 cm long.

Fig. 5. Plane beds, ripple laminations, and burrows in lower shoreface sandstone, Fittstown outcrop. Burrowing is slightly more common near the top of the bed, which was probably deposited during a major storm. Coin is 2.5 cm in diameter.

Fig. 6. Two bedding planes only cm apart show distinctly different trace fossil assemblages. Lower bed contains *Dictyodora;* upper bed contains *Planolites* and perhaps *Trichophycus*. Most sandstone beds in the lower shoreface sandstone are characterized by only one ichnogenus. Sample from Rock Crossing in the Criner Hills. Lens cap is 6.0 cm in diameter.

Fig. 7. Basinal lithofacies along hingeline. Note the regularity of the bedding. Resistant light-colored beds are limestone and the darker beds are shale. The limestone beds average about 5 cm thick.

Fig. 8. Closeup of alternating limestone and shale couplets in the basinal lithofacies. The shale is soft and weathers easily, making this unit difficult to find in weathered outcrops. The dark layers visible in the limestone beds are pelsparite layers, some of which are graded. The lower limestone bed is about 5 cm thick.



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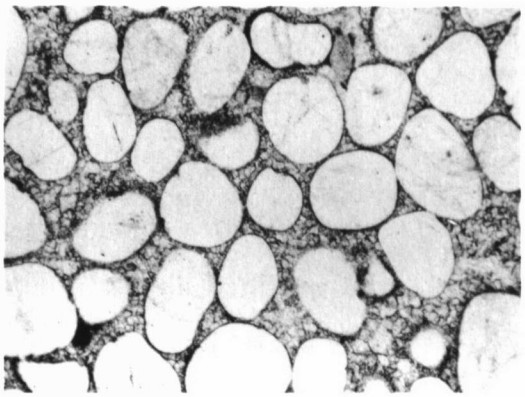

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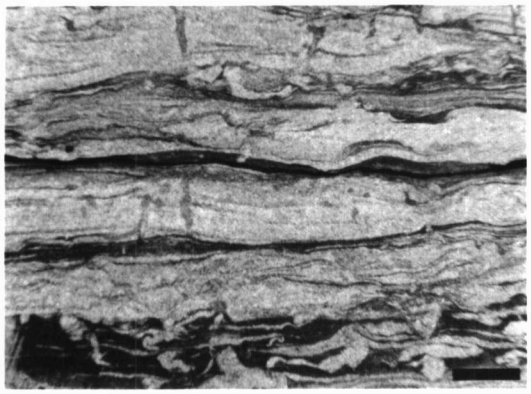

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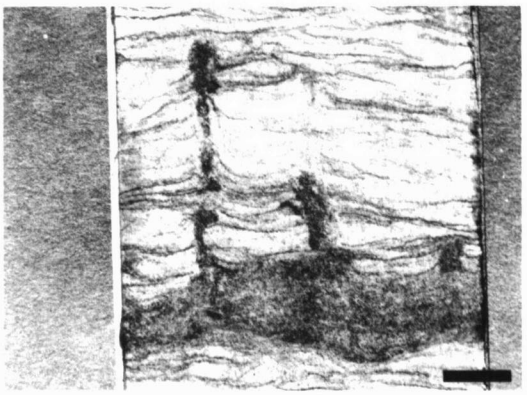

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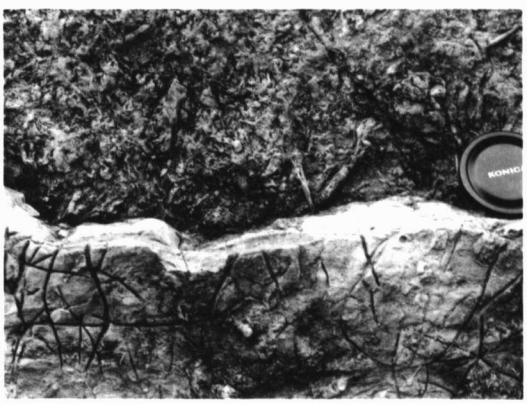

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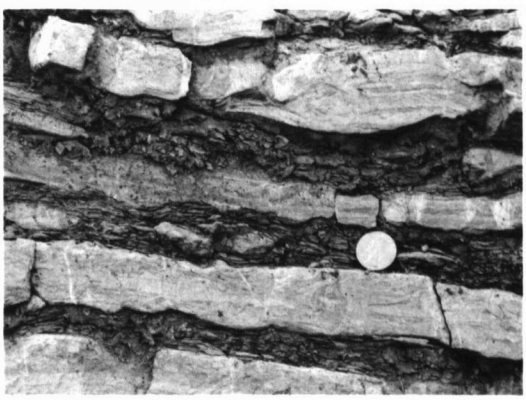

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Upper shoreface sandstones in the Bromide are present only along the hingeline and on the Arbuckle platform. In the aulacogen, lower shoreface sandstones rest directly on the shales of the Tulip Creek Formation. Water depth apparently shallowed to the northeast, as shown by the greater abundance of tidal flat deposits there and the coarser grain sizes. With time, the sea transgressed to the north and water deepened on the Arbuckle platform until lower shoreface sandstones were deposited over the upper shoreface sandstones there. At this time, deeper water must have been present in the center of the aulacogen and other types of sediments were being deposited there. Complexities in the simplified transgressive sequence described here occurred frequently, and stacked sequences of upper and lower shoreface sandstones are found in some places on the platform.

CYSTOID SHALE AND INNER SHELF LITHOFACIES

Gradationally overlying the lower shoreface sandstones throughout the study area is a sequence of interbedded shale and limestone. These beds were divided into the cystoid shale and the inner shelf lithofacies by Longman (1976) but are described together here to save space. The shales are dark green when fresh and weather to limonitic yellow-brown. Chlorite, illite, and quartz are the dominant minerals. The limestones are dominantly biomicrites and biosparites. Fossils are common. Strophomenid brachiopods are present in some shale beds. Rhombiferan cystoid columnals and thecal plates, ramose bryozoans, and massive bryozoans are common in some limestone beds near the base of this sequence. Near the top of the sequence, a greater diversity of fossils is present. The Lower Echinoderm Zone is present in this part of the section and contains abundant echinoderms, bryozoans, and brachiopods.

Sedimentary structures are rare in this lithofacies. Many limestone beds have a slightly nodular appearance. Burrows are abundant and have probably obscured most of the primary sedimentary structures.

Except for the brachiopods, fossils in the lower part of this sequence are generally disarticulated and concentrated into distinct beds by currents. There is some sorting of fossil fragments in limestone beds associated with the Lower Echinoderm Zone, but articulated fossils, including complete echinoderm calyces, are present in the zone itself. Current energy apparently decreased as this sequence of interbedded shale and limestone was deposited because articulated fossils become more common while grainstones become less common toward the top of the sequence.

Depositional Environment Interpretation.—This sequence of beds was deposited in inner shelf, shallow marine environments during a transgression. The position of the shales containing cystoid fragments between the lower shoreface sandstones and the more normal marine biomicrites suggests that the shales were deposited in a transition zone environment. Strong storms were probably responsible for the concentration of fossils into distinct beds. Shale accumulated during the relatively quiet times during the waning of storms. As the water deepened, the normal marine assemblage of echinoderms (other than cystoids), brachiopods, and bryozoans replaced the cystoid fauna. During this time, the Lower Echinoderm Zone was deposited in an inner shelf environment. Terrigenous clay was carried into the depositional environment by sporadic storms and was mixed with the biogenically produced limestones by burrowers.

The Lower Echinoderm Zone contains fewer complete echinoderm calyces and a somewhat different echinoderm fauna on the Arbuckle platform than along the hingeline. This apparently reflects the shallower water on the platform during deposition. More frequent storms created less stable conditions and more turbidity that favored an opportunistic fauna over a more diverse and stable community.

BASINAL LITHOFACIES

This unit takes its name from a distinctive sequence of regularly interbedded thin shales and limestones (Pl. 1, fig. 7, 8) along the hingeline that has been interpreted (Longman, 1976) as a basinal deposit. Although the name is somewhat misleading because of the variability of the unit across the study area, it is a convenient way to refer to the mixed assemblage of rock types between the Lower and Upper Echinoderm zones in the Mountain Lake Member. This unit thickens from about 5 m on the Arbuckle platform to about 30 m along the hingeline.

The basinal lithofacies is separated from both the underlying and overlying echinoderm zones by interbedded shales, biomicrites, and biosparites of quite variable character. These mixed assemblages have been called gradational units because

of their positions between the echinoderm zones and basinal sediments. The basinal lithofacies itself is quite variable. Far to the northeast on the Arbuckle platform, interbedded sandy dismicrites and grainstones consisting of large (1 cm) oncolites are present. Nearer the hingeline but still on the platform, the dismicrites grade into silty micrite with a sparse fauna of brachiopods. Thin shale partings are present between these limestones.

Along the hingeline, the characteristic limestone-shale couplets of the lithofacies are present. These couplets average about 5 cm thick and are remarkably even bedded (Pl. 1, fig. 7). Except for disarticulated ostracods, fossils are relatively rare, but a few burrows, trilobite and echinoderm fragments, and sponges have been found. The limestones are dominantly pelmicrites and pelsparites. Typically several thin (less than 1 cm thick) graded beds are present in each limestone bed (Pl. 1, fig. 8). Rare burrow escape structures through some of the limestones indicate that the beds were deposited rapidly. Several apparent submarine hardgrounds are present in this lithofacies and these probably formed during times of very slow deposition.

Further to the south in the center of the aulacogen, the thin shale is typicaly splintery and green, consisting of chlorite, illite, and quartz, as do most of the shales in the Bromide.

Except for the thin graded beds and the regular nature of the bedding in the limestone-shale couplets along the hingeline, sedimentary structures are sparse in the basinal lithofacies. Massive limestone beds are present far to the northeast and grade into thinner and thinner beds with more shale partings to the southwest.

Depositional Environment Interpretation.—Lithofacies relationships and depositional environments are represented in Figure 8. The dismicrites on the Arbuckle platform are interpreted as shallow subtidal to intertidal deposits. The associated algal oncolite grainstones were probably deposited in very shallow lagoonal environments. The absence of a normal marine fauna suggests that hypersaline conditions may have existed.

Nearer the hingeline, micrite with sparse brachiopods was deposited in a more normal marine environment, probably on a turbulent shallow shelf. Conditions such as turbidity or salinity must have been too variable for a normal marine fauna to become established. The paucity of articulated fossils suggests that storms may have frequently worked the bottom.

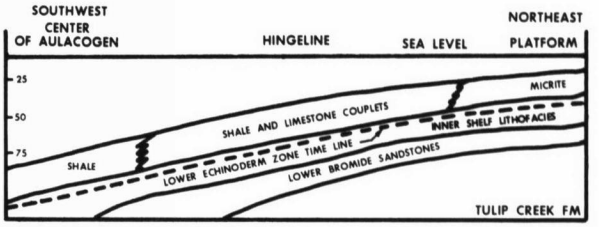

Fig. 8. Deposition of the basinal lithofacies occurred on a gently sloping carbonate ramp. The various component rock types were deposited simultaneously in different water depths. The shallowest water facies, the oncolitic and birdseye micrites, are not shown but were deposited farther to the northeast.

Along the hingeline, the limestone-shale couplets were deposited in a restricted basinal environment. However, the association with relatively shallow-water deposits suggests that this basin was not very deep. Apparently the periodic storms that worked the shallow-shelf carbonates to the north carried carbonate mud, pellets, and intraclasts basinward until they were deposited in the somewhat deeper water there. During quiet periods, shale accumulated on top of the storm-deposited limestone beds. The paucity of shale on the Arbuckle platform indicates that the shale was probably derived from a different source area and was carried to the site of deposition by some mechanism other than storms. Perhaps it was carried by contourite-type currents (see Reineck and Singh, 1975, p. 388) that flowed parallel with the edges of the aulacogen from either the southeast or northwest.

In the deeper water in the center of the aulacogen, no limestone was deposited by the storms; only shale accumulated.

SHELF-EDGE BIOSPARITE

The term shelf-edge biosparite is something of a misnomer because this lithofacies contains a wide variety of rocks deposited in several environments. However, it is a term of convenience for a sequence of biomicrites and biosparites that includes the Upper Echinoderm Zone. Rock type varies across the study area and so does thickness of the unit. This lithofacies is about 2 m thick on the Arbuckle platform and about 15 m thick along the hingeline.

On the Arbuckle platform, this lithofacies consists of biomicrite with some interbedded shale. Much of the shale has been mixed into the limestones by burrowing. Farther to the northeast,

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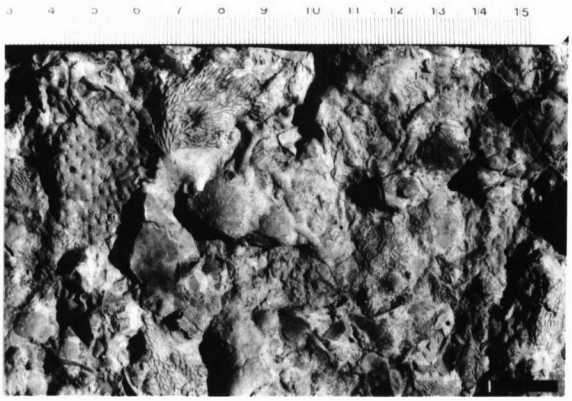

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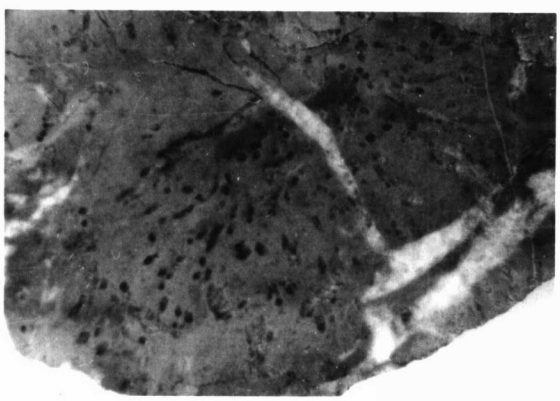

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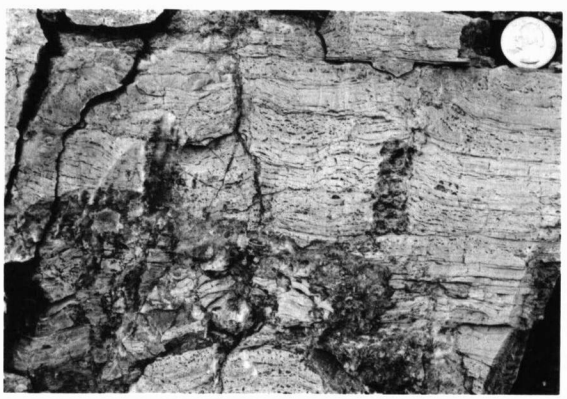

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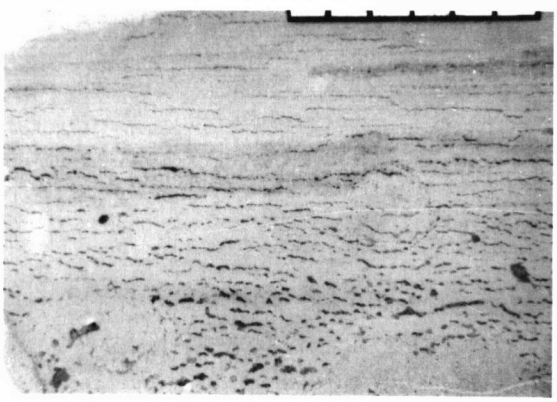

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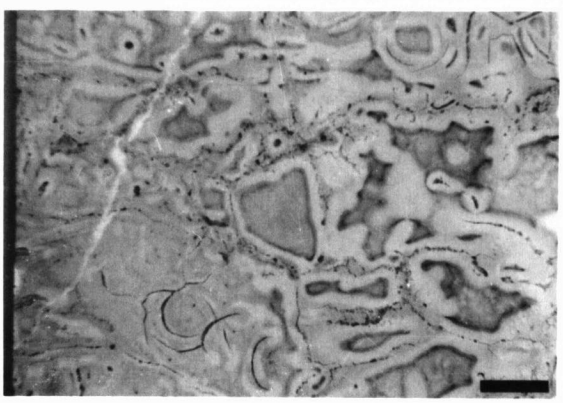

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some beds of oolites are present.

Along the hingeline, this lithofacies consists of biosparite with thin shale partings. The biosparites occur in irregular beds 5 to 10 cm thick with pinch-and-swell structures (Pl. 2, fig. 1). Abraded echinoderm and bryozoan fragments are the dominant components of the biosparites, but some articulated echinoderm calyces and abraded trilobite and brachiopod fragments are also present.

The biosparites give way basinward to micrite and shale with some echinoderms, bryozoans, and brachiopods. In the center of the aulacogen, shale with nodular limestones is present. Fossils are sparse but some echinoderms, nautiloids, and bryozoans are present.

Fossils are most abundant along the hingeline in the biosparites. They become less common toward the platform and toward the basin. Except for the pinch-and-swell bedding of the biosparites, sedimentary structures are rare. Burrowing is widespread and has obscured most primary structures.

Depositional Environment Interpretation.—Two models are available for interpreting gross aspects of carbonate deposition along margins of epeiric seas; the traditional "shallow shelf" model characterized by a nearly flat platform and a clearly defined shelf-slope break (Wilson, 1975, p. 22), and the carbonate ramp proposed by Ahr (1973), in which the platform is replaced by an inclined ramp that extends basinward with no pronounced break in slope. These models were discussed briefly in a previous chapter. Lithofacies described previously from the Bromide Formation were apparently deposited in a ramp setting as indicated by the distribution of higher energy facies to the northeast on the Arbuckle platform. However, after deposition of the basinal lithofacies, higher energy facies became common along the hingeline as well as far to the northeast on the platform. This suggests that the ramp evolved into a typical carbonate platform with a distinct shelf-edge buildup (Fig. 9).

In the platform model, wave energy is dissipated on the shelf edge where the waves first encounter shallow water. This higher energy environment is rich in oxygen and nutrients brought in from the open sea and is ideal for organisms capable of withstanding turbulent conditions. Attached Bromide echinoderms seem to have thrived in this shelf-edge environment, and they contributed skeletal material to a significant carbonate buildup.

Because wave energy was dissipated on the buildup at the shelf edge, a low-energy protected lagoonal environment formed behind the buildup. The micrite and shale beds of the upper Mountain Lake Member on the Arbuckle platform were deposited in a lagoonal environment of this type. In spite of being somewhat enclosed, salinity in this lagoon was apparently normal because many organisms, including echinoderms, bryozoans, and brachiopods, thrived in the quiet shallow water. Be-

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PLATE 2.

Fig. 1. Bedding in shelf-edge biosparite lithofacies along I-35 south of Davis. Biosparite beds are separated by thin shale beds and show slightly irregular bedding. Frequent reworking by storms is probably responsible for bedding of this type. Divisions on right side of scale are cm.

Fig. 2. Slab of diverse fauna biomicrite containing abundant bryozoans and brachiopods. None of these organisms has been moved far from its original habitat; probably they simply fell over and were buried where they had been living. Sample from I-35 exposure south of Davis. Bar scale is about 1 cm long.

Fig. 3. Exposure of basinal lithofacies in the Pooleville Member. Like the basinal lithofacies in the Mountain Lake Member, this one is characterized by thin (5 to 10 cm) beds of limestone separated by calcareous shale. Fossils are sparse but include brachiopods and trilobites. This outcrop is at Rock Crossing. About 2 m of section are exposed.

Fig. 4. Burrowed micrite lithofacies showing small spar-filled tubes that are probably *Tetradium* corallites. Note also the large gastropod in upper left corner. From I-35 exposure. Coin is 2.5 cm in diameter.

Fig. 5. Burrowed micrite lithofacies showing 1-mm-diameter, spar-filled tubes that are characteristic of the upper part of this lithofacies. Examination of the tubes shows that some have a four-sided pattern and indicates that these are *Tetradium* corallites rather than burrows. From I-35 exposure.

Fig. 6. Birdseye micrite showing characteristic birdseye texture, which was probably formed by decaying algal mats and trapped gas bubbles. This structure is typical of supratidal deposits in some areas. Sample from I-35 where this facies is about 0.5 m thick. Coin is 2.5 cm in diameter.

Fig. 7. Slab of birdseye micrite showing remarkable fenestral fabric. This sample is from the Fittstown exposure and is part of what Harris (1957) called the Corbin Ranch Formation. Actually the Corbin Ranch is simply the supratidal facies of the Pooleville. Birdseye micrite is about 6 m thick at Fittstown. Scale in cm.

Fig. 8. Oxidation marks (bleach marks) in the birdseye micrite at the Fittstown exposure. Such structures form when water or air moves along fractures and oxidizes organic material in the sediment in adjacent areas. This structure only occurs in supratidal environments. Bar scale is about 1 cm long.

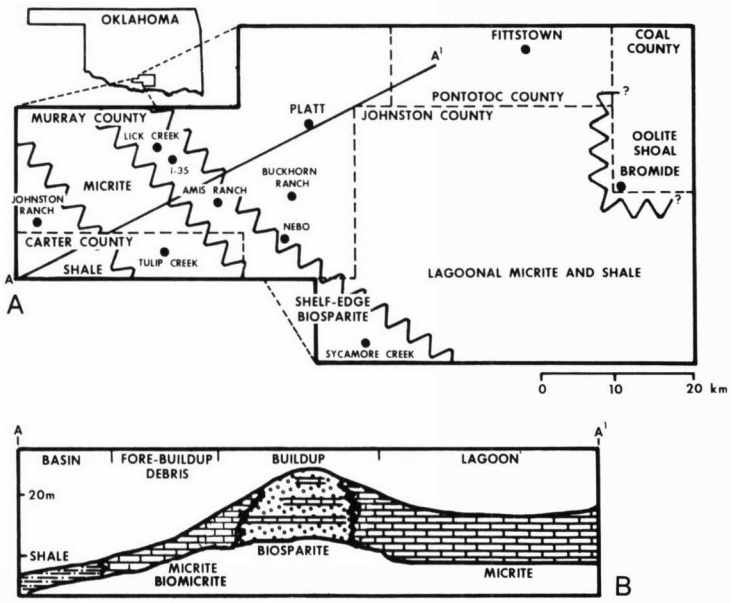

Fig. 9. A, Lithofacies map of shelf-edge biosparite relative to the major echinoderm localities, and B, cross section showing the distribution and relative water depths of the component facies.

cause of the quiet conditions, preservation of whole organisms was common.

Deeper water in front of the shelf edge was also characterized by quiet conditions that favored the deposition of shale and micrite. This deeper water environment contained fewer organisms than the lagoonal environment, but nautiloids were more common there than elsewhere.

DIVERSE-FAUNA AND LIMITED-FAUNA BIOMICRITE LITHOFACES

As discussed earlier, the contact of the Mountain Lake and Pooleville members is marked by a rapid and significant decrease in the amount of detrital shale and probably represents a time line. Thus, facies at the base of the Pooleville throughout the study area are probably time correlative.

On the Arbuckle platform the lower Pooleville consists of micrite with a sparse fauna of brachiopods and echinoderm fragments. Along the hingeline, biomicrite with a diverse fauna of brachiopods and bryozoans (Pl. 2, fig. 2) is present in thin beds separated by shale partings. Some trilobites and echinoderm fragments are also present. These fossils show no evidence of major postdepositional transport and are probably nearly in life position. Similar biomicrites are present well into the aulacogen but fossils are somewhat more sporadically distributed. In the Criner Hills near the center of the aulacogen, limestone and shale couplets in beds 2 to 10 cm thick are present (Pl. 2, fig. 3).

Limestone in the lower Pooleville on the Arbuckle platform is distributed in thick burrowed beds, whereas along the hingeline it occurs in thin unburrowed beds. The thin-bedded biomicrites along the hingeline grade upward into more massive beds like those on the platform. Primary sedimentary structures in all the limestone beds have been obscured by diagenesis and burrowing. Broken and abraded fossil fragments are more common low in the unit and in the biomicrites deposited in the aulacogen.

Depositional Environment Interpretation.—In all previously described lithofacies of the Bromide, it is apparent that shallower water was present to the northeast on the Arbuckle platform and deeper water occupied the aulacogen. This same trend is indicated by the limestones of the lower Pooleville, and a facies reconstruction is presented in Figure 10. The abundance of abraded fossil fragments on the platform and the preservation of articulated and nontransported fossils in the aulacogen indicate that current energy increased to the northeast. Apparently some relict relief was present along the hingeline from the buildup of the self-edge biosparite, and this relief created favorable environments for a diverse community of brachiopods and bryozoans. Preservation of unbroken, fragile forms indicates that this community lived beneath the zone of storm-induced turbulence. Shallower water on the platform resulted

in bottom sediments being frequently reworked by storms in that area.

In the Criner Hills region in the central part of the aulacogen, the lower Pooleville rocks appear to represent basinal deposits with the same characteristic even bedding observed in the basinal lithofacies of the Mountain Lake Member along the hingeline. However, fossils such as small brachiopods and trilobite fragments are much more common in the Pooleville basinal facies. This fact may result from the decreased abundance of terrigenous shale in these beds.

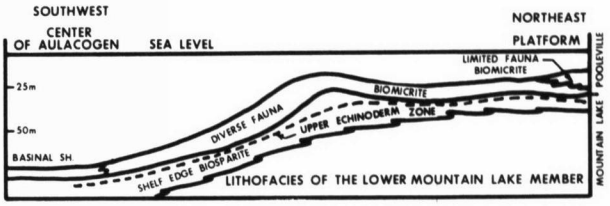

Fig. 10. Lithofacies relationships early in Pooleville deposition. The diverse fauna biomicrite was deposited along and north of the hingeline. The basinal shale and limestone was deposited in deeper water to the southwest, while the limited fauna biomicrite was deposited farther to the northeast.

BURROWED MICRITE AND BIRDSEYE MICRITE LITHOFACIES

Limestones of the upper Pooleville on the platform grade upward from unfossiliferous micrites and pelsparites into thin-bedded micrites with desiccation cracks, oxidation marks, birdseye texture, and sparse algal-laminated sediment. Along the hingeline, the sparsely fossiliferous micrites grade upward through burrowed micrites into pelleted biolithites with common tubes of the tabulate coral *Tetradium* (Pl. 2, fig. 4, 5). The sequence contains some algal stromatolites with birdseye textures near the top (Pl. 2, fig. 6, 7). Near the center of the aulacogen, in the southwestern Arbuckles *Tetradium* and stromatolites are absent; micrites and biomicrites with a diverse fauna of bryozoans, brachiopods, and echinoderms are present.

Fossils show a biased distribution in these rocks. Whole bryozoans, brachiopods, and echinoderms are most common in the southwestern Arbuckles near the center of the aulacogen. Only a limited fauna of ostracods, trilobites, and small brachiopods is found on the Arbuckle platform and most of these occur as disarticulated fragments. *Tetradium* bioherms are present only along the hingeline.

The most interesting sedimentary structures in this lithofacies are the oxidation marks in the platform area (Pl. 2, fig. 8). These are lightened (bleached) rims along fractures and desiccation cracks that formed by oxidation of organic material and pyrite shortly after deposition (late-stage fractures are not surrounded by oxidized aureoles). Dixon (1976) has described similar structures and interpreted them as forming in tidal flat sediments.

Depositional Environments.—Rocks at the top of the Pooleville on the Arbuckle platform were clearly deposited in tidal flat environments at or slightly above sea level as is shown by the oxidation marks, birdseye structures, and desiccation cracks. Algal mats along the hingeline were probably also deposited in a tidal flat environment. The position of the algal mats in close proximity with the *Tetradium* buildups indicates that the buildups formed in very shallow water, perhaps even in lower intertidal environments.

The more massive micrites beneath the tidal flat deposits contain only fragments of fossils and appear to have been frequently worked by storms. Later burrowing homogenized the sediments and destroyed bedding. The beds of pelsparite represent current sorting of some kind, perhaps by waves in a shoreface environment.

In the aulacogen, the abundance of brachiopods, bryozoans, and echinoderms and the absence of any features indicative of tidal flat conditions show that these rocks were deposited in open marine environments. Thus, while the tidal flat micrites were accumulating on the Arbuckle platform, water still filled the center of the aulacogen (Fig. 11).

DEPOSITIONAL SEQUENCES IN THE BROMIDE

The sequence of lithofacies in the Mountain Lake Member indicates that this member was deposited in a generally transgressive sea. On the Arbuckle platform eolian sands were reworked by the transgressing sea and deposited in tidal flat and shoreface environments. Continued transgression resulted in deeper water and the deposition of shales and biomicrites in shelf environments. Eventually the transgression cut off the supply of terrigenous clastic material and the limestones of the Pooleville Member began to accumulate. In the absence of terrigenous material, carbonate deposition was apparently relatively rapid (compare

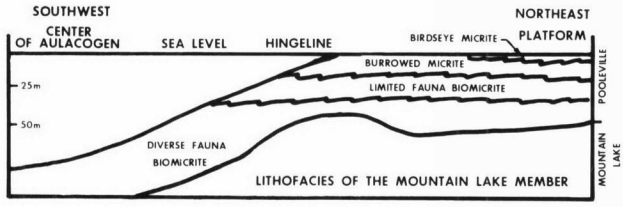

Fig. 11. Lithofacies relationships of the regressive limestones in the Pooleville Member. The rate of carbonate accumulation greatly exceeded the rate of subsidence and the limestones began filling the basin from the northeast.

Ginsburg and James, 1976) and limestones began filling the basin from the northeast. Cessation of subsidence accelerated the regressive cycle of the Pooleville and permitted limestones to accumulate to slightly above sea level on the Arbuckle platform. The absence of tidal flat rocks in the center of the aulacogen indicates that either the sea never completely left the basin in the late stages of Bromide deposition or the shallow-water facies were eroded prior to deposition of the Viola Formation.

Complications were present in this simplified transgressive-regressive cycle. Vertical stacking of upper and lower shoreface sandstones on the platform indicates that early stages of the transgression were episodic and the rate of deposition of sand occasionally exceeded the rate of subsidence. After deposition of the sand, the transgression continued with moderate regularity during deposition of the basinal lithofacies. After deposition of the basinal lithofacies, the water shallowed along the hingeline by the accumulation of bioclastic limestones. This buildup trapped sediments in a low-energy lagoon on the Arbuckle platform.

Relatively abrupt subsidence after deposition of the shelf-edge biosparite is indicated by the sudden change from well-sorted biosparites along the hingeline to biomicrite biocoenoses with unabraded fossils. This subsidence marked the end of the transgressive phase of sedimentation and the beginning of the regressive phase. The Pooleville apparently represents a relatively simple regressive sequence. On the Arbuckle platform where deposition occurred close to sea level, storms and minor fluctuations in sea level resulted in slightly different depositional sequences.

WATER DEPTHS DURING DEPOSITION

Interpretation of paleobathymetry is always difficult, but this should not inhibit careful speculation. The approximate water depths during deposition of the Pooleville can be inferred because of several favorable circumstances. One of these is the relatively simple regressive sequence of limestones. Another is the "cap" of tidal flat sediments that was clearly deposited at about sea level. This provides a known depth data point. Third is the tectonic setting, in this case an aulacogen. Throughout most of their depositional history, aulacogens are characterized by sporadic slow subsidence and little, if any, uplift.

Thickness of the Pooleville Member changes only slightly across the Arbuckle platform, whereas the Mountain Lake, which was deposited during subsidence and transgression, changes significantly in thickness across the same area. This suggests that the Pooleville was deposited during a time of little subsidence. If the assumption is made that there was no subsidence during deposition of the Pooleville, then the thickness of rock between a given bed and the overlying tidal flat deposits should represent approximately the depth of water during deposition of that bed (disregarding for the moment the potentially very significant role of sediment compaction). This would suggest that the diverse bryozoan-brachiopod community at the base of the Pooleville along the hingeline was deposited in about 25 m of water.

Interpreting the amount of sediment compaction now becomes critical. If sediment compaction occurred, the inferred depth obtained by measuring the thickness between a given bed and the tidal flat deposits represents a minimum depth value. However, a number of carbonate petrologists have observed that, in distinct contrast with terrigenous shale, which can undergo up to 70 percent compaction, carbonate mud was frequently lithified prior to significant compaction (Weller, 1959; Bathurst, 1971, p. 439). Evidence in the Pooleville supports the idea that there was little postdepositional compaction of the carbonate muds. Horizontal burrows generally have a nearly round cross section, pellets are always nearly spherical even though they were probably quite soft originally, and geopetal shelter cavities containing calcite spar above micrite are locally common under (and within) shell fragments in micrite. These shelter cavities clearly indicate that cementation of the rock occurred prior to compaction; if not, mud would have been packed around the shell fragments. Thus, a liberal percentage for sediment compaction in the Pooleville limestones would be about 20 percent, implying that a 25 percent cor-

rection factor must be added to final thickness to obtain original thickness. Adding this correction for compaction to the measured "depths" based on rock thickness implies that the minimum depth of the bryozoan-brachiopod community in the lower Pooleville along the hingeline was probably between 25 and 32 m. According to this approach, storms induced turbulence to depths of as much as 20 m and *Tetradium* formed buildups in water 0 to 4 m deep. All of these values are based on the assumption that no significant subsidence occurred during Pooleville deposition.

Interpreting the depths of water during deposition of the Mountain Lake is more difficult because of the transgressive character of the sequence and the observation that deposition occurred during a period of gradual subsidence. However, analogy with similar Holocene environments is possible. Evidence presented earlier indicated that the Bromide sandstones were deposited along a coast characterized by low to moderate wave and tide energy. Sandstones in a similar Holocene setting have been described by Howard and others (1973), who found that upper shoreface sandstones occurred in water between 0 and 7 m deep. Lower shoreface sandstones extended to depths of about 12 m. The Bromide shoreface sandstones were probably deposited in water of approximately these depths.

The transition zone between the lower shoreface and inner shelf environments along low-energy Holocene coastlines occurs at depths between 10 and 15 m (Reineck and Singh, 1975, p. 308). Parts of the cystoid-rich shale immediately above the lower shoreface sandstones in the Bromide were probably deposited at these depths. The position of the Lower Echinoderm Zone above the cystoid shales suggests that this unit was deposited in depths of 15 to 25 m along the hingeline, assuming that there were no major breaks in the transgressive sequence.

The position of the basinal lithofacies in gradational contact with the relatively shallow-water deposits of the underlying inner-shelf lithofacies and the overlying shelf-edge biosparite indicates that it was not deposited in very deep water. Taking into consideration the position of this lithofacies in the transgressive sequence, the thickness of the gradational zones surrounding it, and the sedimentary characteristics, the limestone-shale couplets along the hingeline were probably deposited in 35 to 60 m of water. The associated shales in the center of the aulacogen probably accumulated in water as much as 80 m deep. These depths are significantly less than the 100 to 600 m estimated by Wilson (1969) for similar limestone-shale couplets, but the Bromide Formation provides better control via associated facies than Wilson had. This is not to imply, however, that all basinal couplets are deposited in such shallow depths.

The shelf-edge biosparite at the top of the Mountain Lake was deposited in shallower water than the basinal lithofacies as indicated by the well-sorted grainstones along the hingeline. Water depth was probably on the order of 15 to 20 m along the hingeline. The lagoon may have been slightly deeper immediately behind the buildup but shallowed to the northeast across the Arbuckle platform. The oolites far to the northeast on the platform near Bromide probably formed in water less than 5 m deep. Water depths indicated in Figures 7 to 11 are based on the information presented here.

CONCLUSIONS

Analysis of rock types, fossils, and sedimentary structures indicates that the Bromide Formation was deposited during a major transgressive-regressive cycle. Sandstones near the base of the formation were deposited in upper and lower shoreface shallow marine environments and grade upward into shale and limestone deposited on a shallow marine shelf. Continued subsidence resulted in carbonate deposition in a ramp setting with high-energy carbonate grainstones accumulating in shallow water to the northeast while basinal shale and limestone accumulated in deeper water in the aulacogen. Eventually subsidence ceased and regressive carbonates of the upper Bromide began filling the basin from the northeast.

The regressive limestone was deposited during a period of little, if any, subsidence and is capped by tidal flat deposits. Sediment compaction was probably less than 20 percent. This combination of circumstances permits interpretation of paleobathymetry of the limestones. A diverse community of brachiopods and bryozoans inhabited water about 30 m deep, storm base was between 15 and 20 m, and *Tetradium* corals formed buildups in up to 4 m of water. Although the transgressive sequence and higher amount of compaction in the lower Bromide prevent similar interpretations of paleobathymetry, analogy with Holocene environments indicates water depths ranging between 0 and 80 m.

Table 1. Distribution of ostracods in the Bromide Formation (modified from Harris, 1957).

Name	Measured section of this report: Mountain Lake Member	Pooleville Member
Acanthobolbina loeblichi	1, 11A	15
Aparchites maccoyii	1, 11A, 15	1, 15
A. millepunctatus	1, 11A, 15	1, 11A, 15
Balticella deckeri	1, 11A	1, 15
B. d. elongata	11A	-----
Bromidella reticulata	11A, 15	-----
Bythocypris cylindrica	1, 11A, 15	1, 15
B. spinosa	1, 11A, 15	1, 15
Coelochilina alata	-----	11A
Cryptophyllus gibbosum	1, 11A, 15	1
C. nuculopsis	11A	-----
C. simpsoni	1, 11A, 15	1, 11A, 15
Ctenobolbina abrupta	-----	11A
C. bispinata	1	15
C. cancellata	11A, 15	-----
C. c. varicata	1, 11A	1
C. inflata	11A	-----
C. parva	1, 11A	1
C. percarinata	1, 11A	-----
Dicranella fragilis	1, 11A	1
D. macrocarinata	1, 11A, 15	1
Echinoprimitia imputata	-----	15
Eohollina depressa	1, 11A	1
E. d. papillata	11A, 15	-----
Eoleperditia fabulites	-----	1, 11A
E. inflativentralis	-----	1
Eoprimitia bailyana	11A, 15	15
E. cooperi	1, 11A, 15	1, 15
E. quadrata	1, 11A, 15	1, 15
?E. subnodosa	15	-----
Eurychilina papillata	-----	15
E. subradiata	1, 11A, 15	15
E. ventrosa	1, 11A, 15	15
Glymmatobolbina quadrata	11A	-----
Halliella labiosa	1, 11A, 15	1, 15
Hyperchilarina nodosimarginata	1, 11A, 15	15
Kayina hybosa	11A	-----
?K. porosa	11A	-----
Krausella arcuata	1, 11A, 15	15
Leperditella aequilatera	-----	11A
L. altiforma	11A	-----
L. incisa	1, 11A	1, 15
?L. jonesinoides	-----	11A
L. porosa	-----	11A
L. rex	-----	11A
L. r. minima	1, 11A, 15	1, 15
L. tumida	-----	11A
Monoceratella brevispinata	11A	-----
?Paraparchites circulantis	1, 11A, 15	15
Platyrhomboides quadratus	1	-----
Primitiella constricta varicata	1, 11A, 15	15
Primitiopsis bassleri	1, 11A	1
P. elegans	1, 11A, 15	-----
P. excavatus	11A	-----
P. minutus	1, 15	1, 15
Punctaparchites rugosus	1, 11A, 15	15
Rayella calvini	11A	-----
R. c. parva	11A, 15	-----
Schmidtella affinis	1, 15	-----
S. asymmetrica	11A, 15	-----
S. brevis	15	-----
S. crassimarginata	1, 11A, 15	1
S. excavata	11A, 15	-----
S. minuta	11A	-----
S. ovalis	11A, 15	-----
S. transversa	1, 11A, 15	1
Tetradellina henningsmoeni	1	-----
Thomasatia auricula	-----	15
T. bromidensis	1, 11A	-----
T. simplex	1, 11A	-----
Winchellatina cornuta	11A	-----
W. longispina	1, 11A	1

Table 2. Distribution of trilobites in the Bromide Formation (after Shaw, 1974; Ludvigsen, 1978).

Name	Mountain Lake Member	Pooleville Member
Amphilichas subpunctatus	-	x
Apianurus sp.	-	x
Bathyurus superbus	-	x
Bumastoides cf. B. milleri	-	x
Calyptaulax annulata	x	x
Ceratocephala graffhami	-	x
Ceraurus ruidus	-	x
Cybeloides sp.	x	-
Dolicoharpes reticulata	-	x
Encrinuroides capitonis	-	x
Eomonorachus divaricatus	-	x
Lonchodomus mcgeheei	-	x
Nanillaenus cf. N. punctatus	x	x
Otarion sp.	-	x
Pandaspinapyga salsa	-	x
Platillaenus cf. P. limbatus	-	x
Pliomerops cf. P. canadensis	x	-
Probolichas sp.	-	x
Remopleurides sp.	-	x
Sphaerocoryphe sp.	-	x
Vogdesia bromidensis	x	x

Table 3. Distribution of brachiopods in the Bromide Formation (after Cooper, 1956).

Name	Mountain Lake Member	Pooleville Member
Acanthocrania erecta	x	-
A. oklahomensis	-	x
A. subquadrata	x	x
Ancistrorhyncha costata	-	x
A. globularis	-	x
Atelelasma oklahomense	x	-
Bellimurina compressa	x	-
B. subquadrata	x	-
Camerella anteroplicata	-	x
C. oklahomensis	-	x
Chaulistomella crassa	x	-
?C. magna	-	x
C. mira	x	-
C. mundula	x	-
C. nitens	x	-
C. obesa	x	-
Craniops tenuis	-	x
Cyclospira parva	-	x
Dactylogonia sculpturata	x	-
D. subaequicostellata	x	-

BIOSTRATIGRAPHIC AND PALEONTOLOGICAL STUDIES

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Few authors have made biostratigraphic studies of the Bromide Formation, attempting to relate paleontology to depositional environments. Merritt (1931), Fischer (1948), Dapples (1955), Schramm (1964), Green (1965), Ireland (1965), and Moore and Albano (1965) have made physical studies of the sediments, but these are vaguely related or unrelated to fossils. Trout (1913) and Eckert (1951) studied Bromide fossils, but these works are unpublished, contain many misidentifications, and are uncoordinated with depositional environments. Decker (1931b) attempted an overall study of the paleontology of the Bromide, but his studies consisted of lists of fossil names, many of which were invalid. Nevertheless, he was able to differentiate facies of the Bromide and to correlate the same species over wide areas. Ulrich, in his many studies of the Bromide, recognized the dominant facies of the different rock units, and used a different name for each lithofacies: Criner (for subtidal Pooleville), Webster (for supratidal Pooleville), Cool Creek (for subtidal Mountain Lake), and Bromide (for shallow subtidal Mountain Lake). Ulrich's studies resulted mostly in unpublished charts and fossil lists. Loeblich (1942), Branson and Mehl (1943), Cooper (1956), and Shaw (1974) described many new species of bryozoans, conodonts, brachiopods, and trilobites, respectively, but these were unrelated to facies. Shaw (1974) noted that all of the Bromide trilobite genera are found in Chazyan rocks, but he interpreted the Bromide fossils to be Blackriveran holdovers. The trilobite *Vogdesia bromidensis* (formerly *Homotelus; Isotelus*) occurs in many zones from the bottom to the top of the Pooleville in the Criner Hills and southwestern Arbuckles, reflecting recurring deep-subtidal facies. Harris (1957) gave the best information with his study of

Table 3. Continued.

Doleroides compressus	x	-	Pachyglossa biconvexa	-	x
D. oklahomensis	-	x	Paurorthis macrodeltoidea	x	x
?Ectenoglossa sculpta	-	x	Petrocrania inflata	-	x
Fascifera dalmanelloidea	x	-	Petrocrania sp. 3	x	-
Glosella liumbona	-	x	Philhedra sp. 1	x	-
Glyptorthis costellata	-	x	?Platymena bellatula	-	x
G. crenulata	x	-	Plectambonites sericeus	-	x
G. obesa	x	-	Plectoglossa oklahomensis	-	x
G. uncinata	x	-	Plectorthis symmetrica	-	x
Hesperorthis crinerensis	x	-	Protozyga costata	x	-
H. sulcata	-	x	P. elongata	x	-
Lingula cf. L. elegantula	-	x	P. loeblichi	-	x
L. eva	-	x	P. magnicostata	x	-
Lingulasma oklahomense	-	x	Pseudolingula imperfecta	-	x
Lingulella galba	x	-	Rostricellula cuneata	x	-
?L. glypta	-	x	Rostricellula sp. 1	-	x
Macrocoelia bella	x	-	Schizambon perspinosum	-	x
Mimella extensa	x	-	Skenidioides oklahomensis	x	-
M. subquadrata	x	-	S. perfectus	-	x
Multicostella convexa	x	-	Sowerbyella indistincta	x	-
M. sulcata	x	-	S. plicatifera	x	-
Murinella partita	x	-	S. variabilis	-	x
Neostrophia gregaria	-	x	S. vulgata	x	-
Onychoplecia tenuis	x	x	Sowerbyella sp. 1	-	x
Oepikina expatiata	x	-	Sowerbyites hami	-	x
O. extensa	-	x	S. lamellosus	x	x
O. formosa	-	x	Strophomena costellata	-	x
O. gregaria	x	-	S. crinerensis	-	x
Oepikina sp. 2	-	x	S. oklahomensis	-	x
Orbiculoidea eximia	-	x	S. trentonensis	-	x
Oxoplecia filosa	x	-	Valcourea transversa	x	-
O. gouldi	-	x			

ostracods, but almost all of his fossils were collected from shales, and many species have long ranges.

Sweet and Bergström (1973) indicated that the age of the Bromide is Blackriveran (Middle Ordovician), with the lower Mountain Lake being transitional Chazyan, based upon regional biostratigraphic studies of Middle and Upper Ordovician conodonts and graptolites in North America and Europe. *Polyplacognathus sweeti* occurs in the lower Mountain Lake, and *Phragmodus inflexus* and *Prioniodus gerdae* occur in the upper Mountain Lake. The middle Mountain Lake corresponds closely with the *Prioniodus variabilis-P. gerdae* and the *Nemagraptus gracilis-Diplograptus multidens* boundaries of North America and Europe. The Pooleville contains fibrous conodonts that are typically wide spread in Blackriveran rocks. The Tulip Creek contains *Polyplacognathus friendsvillensis* of Chazyan age, and the Viola Limestone contains *Phragmodus undatus* of Trentonian age.

Table 4. Distribution of bryozoans in the Bromide Formation (after Loeblich, 1942).

Name	Measured sections of this report: Mountain Lake Member, lower	Mountain Lake Member, upper	Pooleville Member
Anolotichia deckeri	---	---	1
A. impolita	---	---	1
A. spinulifera	---	---	1
Atactoporella bellula	---	---	1
Batostoma chapparsi	---	---	1
B. cumingsi	---	---	1
B. winchelli	---	---	1
Dekayella praenuntia var. echinata	---	---	1
Eridotrypa abrupta	---	---	1
?Fistulipora bassleri	4,8,15	---	---
Hallopora dubia	---	---	1
H. macrostoma	---	---	1
H. pachymura	3	---	---
Hemiphragma irrasum	---	---	Rainy Mtn.
H. pulchra	---	---	1
Heterotrypa taffi	---	3	1,3
Homotrypa callitoecha	8	---	---
H. multitabulata	4,11A, 15	---	---
H. sagittata	3	---	---
H. ulrichi	---	---	1
Mesotrypa favosa	1	---	---
M. tubulifera	3	---	---
Monticuliporella croneisi	---	---	1
M. peculiaris	---	3	3
M. shideleri	---	---	1
Nicholsonella irregularis	---	5	---
N. laminata	4	---	---
N. moniliformis	1,8	10	---
Pachydictya bromidensis	---	---	Rainy Mtn.
Prasopora fritzae	---	3	3
Stromatotrypa frondosa	11A, McLish R.	---	---

Table 5. Distribution of graptolites in the Bromide Formation (after Decker, 1935, 1936a, b, 1941, 1943).

Name	Measured sections of this report: Pooleville Member
Dicellograptus gurleyi	15
D. mensurans*	15
Dictyonema francesiae	15
D. rockcrossingensis	15
Diplograptus (Amplexograptus) maxwelli#	4, 8, 15

* Equals upper Normanskill.
\# Equals Platteville.

Certain conodonts are common in particular facies, as pointed out by Sweet, Ethington, and Barnes (1971), Bergström (1971a, b), Barnes (1973), and Barnes, Rexroad, and Miller (1973). Such fibrous conodonts as *Cardiodella*, *Chirognathus*, *Erismodus*, *Leptochirognathus*, *Polycaulodus*, and *Polyplacognathus* are common in intertidal facies. Cancellate (or lamellar) conodonts are common in subtidal to deep-shelf or basin facies, with such forms as *Bryantodina*, *Ozarkodina*, and *Plectodina* occurring in shallow-shelf facies, and *Amorphognathus*, *Cordylodus*, *Drepanodus*, *Icriodella*, *Phragmodus*, and *Prioniodus* occurring in deep-shelf or basin facies.

Maerz (1972) was the first person who attempted a paleoecologic study of the Bromide Formation, restricting his studies to the Pooleville Member in the Criner Hills. Most of the Pooleville there consists of low-intertidal to shallow-subtidal facies at the base and top, with a diverse fauna of brachiopods, bryozoans, and echinoderms. The middle Pooleville is mostly deep-subtidal facies with trilobites and graptolites.

Beechler (1974) studied the Pooleville in the Arbuckle Mountains, showing that a diverse fauna occurs in the subtidal facies, a restricted fauna in the intertidal facies, and almost no fauna in the supratidal facies.

Longman (1976) studied the entire Bromide Formation, showing that the Mountain Lake was a transgressive sequence and that the Pooleville was part of a regressive sequence. In each sequence, the subtidal, intertidal, and supratidal facies were different from each other and from comparable

facies of the opposite sequence (Longman and Sprinkle, 1976). In the transgressive sequence, sand was deposited in the supratidal zone, but in the regressive sequence, birdseye micrite was deposited. In a transgressive sequence, high-energy biosparite and greenish-gray shale was deposited in the subtidal zone, but in a regressive sequence, low-energy biomicrite was formed. In both sequences, the deep-basin facies was graptolitic shale, such as that of the upper Womble in the Ouachita basin. Both sequences may have been interrupted by high areas, such as the Seminole uplift, Central Oklahoma arch, Blaine arch, and Woodward arch, with washed clean sands on the uplifts and lagoonal dolomites occurring in the embayments, as shown by Green (1965) and Schramm (1964, 1965b). In the Seminole area, the basal Viola may even be a sandstone (Seminole Sandstone) according to Disney and Cronenwett (1955).

Table 6. Distribution of conodonts in the Bromide Formation; X, fibrous conodonts, widespread in Blackriveran rocks; (V), Viola only (after Branson and Mehl, 1943; Bergström, 1971b; Sweet and Bergström, 1973; Sweet, Bergström, and Carnes, 1973).

Name	Measured sections of this report: Mountain Lake Member, lower	Mountain Lake Member, upper	Pooleville Member
Cardiodella abbreviatus	---	---	11A
C. arcuatus	11A	---	---
C. densus	---	---	11A
C. robustus	11A	---	---
Cordylodus sp. indet.	11A	---	---
Curtognathus cordiformis	---	---	11A
C. coronata	11A	---	---
C. limitaris	11A	---	11A
Curtognathus sp.	---	---	11A
Dichognathus extensa	---	---	11A(V)
D. typica	---	---	11A(V)
?Erismodus sp.	---	---	11A
Leptochirognathus extensa	11A	---	---
?Leptochirognathus sp.	11A	---	---
Microcoelodus asymmetricus	11A	---	---
M. inornatus	11A	---	---
M. intermedius	11A	---	---
M. minutidentatus	11A	---	---
M. typus	11A	---	11A
?Microcoelodus sp.	11A	---	---
Oistodus abundans	---	---	11A(V)
O. inclinatus	---	---	11A(V)
O. suberectus	---	---	11A
Paltodus compressus	---	---	11A(V)
P. gracilis	---	---	11A(V)
Phragmodus inflexus	---	X	---
P. undatus	---	---	11A
Phragmodus n. sp.	X	---	---
Polycaulodus bidentatus	11A	---	11A
P. tridentatus	11A	---	11A
Polyplacognathus sweeti	X	---	---
Polyplacognathus n. sp.	X	---	---
Prioniodus gerdae	---	X	---
?Pteroconus abbreviatus	---	---	11A(V)
Trichonodella obtusa	---	---	11A
Trucherognathus distorta	11A	---	---
T. irregularis	11A	---	---

Table 7. Distribution of microphytoplankton (acritarchs) in the Bromide Formation (after Loeblich and Tappan, 1969, 1971a, b, 1976, 1978).

Name	Measured sections of this report: Mountain Lake Member
Actinotodissus longitaleosus	1
Adornofusa microhapsis	1
Asketopalla formosula	1
Baltisphaeridium accinctum	1
B. bystrentos	1
B. disparicanale	1
B. parvigranosum	1
B. trophirhapium	1
Cleithronetrum cancellatum	1
Disparifusa hystricosa	1
Gorgonisphaeridium antiquum	1
Gyalorhethium chondrodes	1
Gyalorhethium sp.	4
Leiovalia scaberula	1
L. teretis	1
Orthosphaeridium vibrissiferum	1
Poikilofusa plethysticha	16B
Polyancistrodorus columbariferus	1
Rhiptosocherma improcera	1
Veryhachium bromidense	1
V. irroratum	1
Villosacapsula entriche	1

Certain fossils are found associated with each facies. Longman (1976, p. 165: see also Longman and Sprinkle, 1976) gave a general analysis of fossil communities of the Bromide Formation. Corals and algae, such as *Tetradium and Ischadites*, favored intertidal environments, whereas brachiopods, bryozoans, echinoderms, and cephalopods favored subtidal environments. Trilobites and graptolites favored deep-subtidal environments. Conodonts and ostracods ranged into diverse environments, but certain genera and species favored one particular environment.

Bromide fossils described by various authors are listed by taxonomic group in Tables 1 to 7, which also show distribution in the Mountain Lake and Pooleville members. Numbers, if present, refer to collecting localities at the measured sections of this report. The lists are incomplete and include only published information on the major groups of fossils; most have not been updated with later taxonomic or nomenclatural changes.

PREVIOUS STUDIES OF BROMIDE ECHINODERMS

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Echinoderms from the Bromide Formation of southern Oklahoma were first mentioned in the literature in 1903, the first specimens were figured in 1931, and the first new echinoderm taxon was described in 1940. Since then about 36 generic names and 70 specific names have been assigned to or newly proposed for Bromide echinoderms (see Table 8). Undoubtedly, some of these names are synonyms, but probably a much greater number of new echinoderm taxa await naming and description. Correcting both of these problems is a major objective of this monograph.

Studies of Bromide echinoderms can be roughly divided into three periods. Early studies (1903-1931) cover the interval between the first discovery and report of echinoderms in the Bromide to Decker's (1931b) summary of Bromide stratigraphy and paleontology. Descriptive studies (1940-1961) cover the period from the first description of a new Bromide echinoderm (Branson and Peck, 1940) through the major taxonomic works of Bassler, Sinclair, Strimple, and several other workers; most of the common Bromide echinoderms were named and described during this period. Recent studies (1964-1980) cover the period of gradually renewed interest in Bromide echinoderms, the major excavations by Fay and Graffham (1965 to 1967), work revising and completing older collections, and work in preparation for this monograph. The following historical review groups taxonomic and general studies of Bromide echinoderms into these three periods.

EARLY STUDIES

The first mention of Bromide echinoderms is that of J. A. Taff (1903, p. 3), who listed "*Platycystites* sp. nov." and "*Amygdalocystites* sp. nov." from the upper 92 m of the Simpson Formation in the Arbuckle Mountains. Taff also mentioned that the best outcrops were on the south side of the Arbuckle anticline, and presumably E. O. Ulrich collected the fossils in that area. The geologic investigation of the Tishomingo Quadrangle was completed from 1900 to 1903, so presumably Ulrich collected the echinoderms at or before that time.

Taff (1904, p. 24-25) listed "plates of cystidian *(?Glyptocystites)*" from the lower Simpson, and "*Archaeocrinus* sp. undetermined, *Platycystites* (?) sp. nov., *Amygdalocystites* sp. nov., and *Glyptocystites* sp. nov." from the upper 92 m of the Simpson Formation. Ulrich collected and identified the fossils, which were found mostly west of the Washita River (p. 24). The only measured section given is on the south flank of the Arbuckle anticline (p. 23). Thus, most of these echinoderms may have been collected from the Lower and Upper Echinoderm zones of the Mountain Lake Member on the south flank of the Arbuckle anticline. Morgan (1924, p. 27) repeated Taff's list of fossils. Taff (1904, p. 26) listed fossils from the "lower Viola" (now Bromide), especially near the base of Double Mound, 9.5 km northeast of Roff, but no mention was made of finding any echinoderms.

The next reference to Bromide echinoderms was that of Trout (1913, p. 172-176), who listed from the upper Simpson *Amygdalocystites*, *Glyptocystites* (probably *G. multiporus* and *G. forbesi*), *Platycystites* (several new species), and *Archaeocrinus*. These were mainly after Taff (1904), so Trout may not have collected echinoderms himself. Most of Trout's collections came from outcrops along the Gulf, Colorado, and Santa Fe Railroad cut about 0.8 km south of Crusher, presumably in the SW¼ sec. 30, the NW¼ sec. 31, T. 2 S., R. 2 E., and the NE¼ sec. 36, T. 2 S., R. 1 E., Murray County.

Charles E. Decker (1931b, p. 40-86, pl. 13) gave the first detailed measured sections of the Bromide Formation in the Arbuckle Mountains, Criner Hills, and Wichita Mountains. He first recognized two cystid zones in the Simpson: a "lower cystid zone" about 11 m above the top of the basal

McLish sandstone, and an "upper cystid zone" about 9 m above the top of his basal Bromide sandstone sequence. The "lower cystid zone" of the McLish Formation has never been studied, and only one complete cystoid has been collected from this zone: *Caryocystites tappani* Bassler (1943, p. 699), from sec. 31 [not 3], T. 1 S., R. 1 W., on West Spring Creek, Murray County.

The "upper cystid zone" (now the Lower Echinoderm Zone of the Mountain Lake Member) was recognized by Decker as being widespread, but Decker incorrectly correlated this zone between the Criner Hills and the Arbuckle Mountains. Decker did not realize that a third zone (now the Upper Echinoderm Zone of the Mountain Lake Member) existed well above his "upper cystid zone." Some of Decker's echinoderm identifications were incorrect, but he must receive credit for the modern concept of facies changes and for echinoderm zonation of the Bromide Formation.

Decker (1931b, pl. 13B) published the first illustration of a Bromide echinoderm, which he identified as *Glyptocystites logani*, from his "upper cystid zone" on the west branch of Sycamore Creek (his locality 13) (Measured Section 4 of this report).

Decker (1931b, p. 47, 51) first mentioned the discovery of complete specimens on the east side of U. S. Highway 77, the west branch of Sycamore Creek, and on the east side of McLish Ranch 3.2 km northwest of Bromide, all from his "upper cystid zone" 9 to 12 m above the top of his basal sandstone sequence.

Decker (1931b, p. 42, 47-48, 83) first mentioned the occurrence of Bromide echinoderms in the Criner Hills. Judging from his lists (p. 48), he must have mixed a zone number with a locality number for *Amygdalocystites florealis:* instead of locality 8 (our Culley Creek), he must have meant locality 7, zone 8 (Rock Crossing), which may have the Upper Echinoderm Zone of the Mountain Lake Member just below the Pooleville Member. Decker thought that this was his "upper cystid zone" and incorrectly correlated this zone in the Criner Hills with the "upper cystid zone" in the Arbuckle Mountains. Decker listed other echinoderms from the Criner Hills: *Archaeocrinus subglobosus* (his localities 7, 8), *Carabocrinus tumidus* (his locality 8), *Carabocrinus* cf. *C. vancortlandi* (his locality 7), *Dendrocrinus rusticus* (his locality 8), and *Periglyptocrinus priscus* (his locality 8). Decker's locality 8 is in sec. 26, T. 5 S., R. 1 E. (now Culley Creek, Measured Section 14 of this report), and all specimens are from the Pooleville Member. Decker's locality 7 is Rock Crossing in sec. 35, T. 5 S., R. 1 E. (Measured Section 15, this report), and *Archaeocrinus subglobosus* is from the Pooleville Member; but *Carabocrinus* cf. *C. vancortlandi* and *Amygdalocystites florealis* are from the Lower and Upper Echinoderm zones, respectively, of the Mountain Lake Member. Decker did not describe or illustrate any of the above echinoderms, and it is impossible to know exactly where the specimens were collected stratigraphically.

In the Arbuckle Mountains, Decker (1931b, p. 48) listed from his localities *Cheirocrinus logani* (13, 19), *Lepadocystites moorei?* (19), *Carabocrinus tumidus* (4, 11, 13, 20), *Carabocrinus* cf. *C. vancortlandi* (13), *Cleiocrinus regius* (20), and *Periglyptocrinus priscus* (13). Decker's locality 4 is the east side of U.S. Highway 77 north of Springer (p. 62), bed 22, 8.5 m above the basal sandstone sequence, and is the Lower Echinoderm Zone of the Mountain Lake Member (Measured Section 3, this report). *Cheirocrinus logani* is also listed elsewhere from this locality. Decker's locality 11 is 3.2 km west of the Nebo Store and is generally the Upper Echinoderm Zone of the Mountain Lake Member (Measured Section 8, this report). Decker's locality 13 is the west branch of Sycamore Creek on Daube Ranch and is the Lower Echinoderm Zone of the Mountain Lake Member, where Decker (p. 71) also listed *Dendrocrinus* cf. *D. latibranchiatus* from a 2.2-m bed (no. 16) about 14 m above the basal sandstone sequence (Measured Section 4, this report). Decker's locality 19 is the east side of McLish Ranch about 3.2 km northwest of Bromide and is the Lower Echinoderm Zone of the Mountain Lake Member. Decker's locality 20 is the type Bromide at Bromide (Measured Section 5, this report), where Decker (p. 81) had zones 12 and 13 (now the Lower Echinoderm Zone of the Mountain Lake Member) about 6 m above the basal sandstone sequence. This sandstone is here correlated as the basal Bromide sandstone, but Decker included this sandstone and the underlying 37 m of beds in the Bromide. The underlying rock is here classified as Tulip Creek. Decker identified his zones 12 and 13 as his "upper cystid zone" and correctly correlated this with the same zone on the west branch of Sycamore Creek (his beds 15, 16, locality 13), and on Highway 77 (bed 22, locality 4), but incorrectly correlated this zone with bed 8 at Rock Crossing, which may be the Upper Echinoderm Zone of the Mountain Lake Member.

In the eastern Arbuckle Mountains, Decker (1931b, p. 77) had difficulty distinguishing the

Bromide from the Tulip Creek. On the P. A. Norris Ranch south of Fittstown in sec. 2, T. 1 N., R. 6 E., Decker recognized the "upper cystid zone" (bed 8 with *Carabocrinus*) (Lower Echinoderm Zone of the Mountain Lake Member) about 6 m above a 8.3-m sandstone. Decker did not identify this sandstone as the basal Bromide sandstone but included the underlying 18 m of beds (beds 14, 15) in the Bromide. These underlying beds should be classed as Tulip Creek. Thus, the Tulip Creek is about 37 m thick near Bromide and about 18.5 m or more thick near Fittstown, with the overlying basal Bromide sandstone being less than 9.2 m thick.

Decker (1931b, p. 84) measured a section on Lick Creek in the northwestern part of the Arbuckle Mountains, correctly showing the "upper cystid zone" (bed 7) about 9.2 m above the basal sandstone. This is the Lower Echinoderm Zone of the Mountain Lake Member (Measured Section 6, this report).

Decker's studies established a basic stratigraphic framework for studies of the Bromide Formation, and his observations on echinoderms made it possible for others to collect many thousands of complete specimens more than 35 years later.

DESCRIPTIVE STUDIES

Previous to 1940, Bromide echinoderms were listed but not described. E. B. Branson and R. E. Peck (1940, p. 89-92) figured and described *Eumorphocystis multiporata*, collected by E. B. Branson in 1939 from the outcrop on Oklahoma Highway 99 south of Fittstown (Measured Section 11A, this report). The complete type specimen was collected from the Lower Echinoderm Zone of the Mountain Lake Member, as later determined by Carl C. Branson in company with R. O. Fay, and published by C. C. Branson (1958, p. 178). The type specimen, which still represents the largest *Eumorphocystis* ever collected from the Bromide (see Parsley, this volume), is at the University of Missouri (Columbia).

Carey Croneis (1942, p. 1828) briefly described in an abstract a microcrinoid from the Bromide Formation at Rock Crossing in the Criner Hills (Measured Section 15, this report) collected by W. H. Shideler of Miami University. As far as can be determined, nothing else was published on this specimen, and its whereabouts are unknown.

The next published work is that of Ray S. Bassler (1943, p. 694-703), who obtained most of his studied specimens from Alfred R. Loeblich, Jr., who had just completed his doctoral dissertation on Bromide bryozoans at the University of Chicago. Most specimens were collected from 1936 to 1942 by Loeblich, his wife, Helen Tappan Loeblich, and her father, Professor Frank G. Tappan of the University of Oklahoma, but a few specimens came from much older USGS collections made by E. O. Ulrich and others. Eleven new species were described under seven known genera: *Amygdalocystites*, *Caryocystites*, *Cheirocrinus*, *Echinoencrinites*, *Enoploura*, *Glyptocystites*, and *Platycystites*. All types were deposited at the National Museum of Natural History, Washington, D. C. Bassler used the names Cool Creek and Falls for units of the Simpson, but his Cool Creek is now the Mountain Lake Member of the Bromide Formation, and his Falls is the McLish Formation. *Caryocystites* occurs in the McLish, whereas the remainder of his genera occur in the Bromide. *?Exoploura papillata* came from Rock Crossing, Criner Hills, from a zone 13 m below the top of the Bromide (now Pooleville Member, Measured Section 15, this report). *Amygdalocystites tribrachiatus* was collected from the Upper Echinoderm Zone of the Mountain Lake Member, from the Nebo area (sec. 22, T. 2 S., R. 3 E.; type specimen), and the SW¼ sec. 3, T. 2 S., R. 3 E., and sec. 11, T. 1 S., R. 3 E. (Measured Section 8, this report). Also, this species was recorded from sec. 14 (probably the NE¼), T. 6 N., R. 16 W., and represents the only reference to a Bromide echinoderm from the Wichita Mountains of southwestern Oklahoma. *?Echinoencrinites ornatus* came from an unknown zone in the Mountain Lake Member at Rock Crossing, Criner Hills. The remainder of Bassler's specimens probably all came from the Lower Echinoderm Zone of the Mountain Lake Member: *Cheirocrinus ardmorensis*, north end of Hickory Gap (?Rock Crossing), 13 km south-southwest of Ardmore; *?Cheirocrinus loeblichi*, sec. 12, T. 1 N., R. 6 E., south of Fittstown; *Glyptocystites loeblichae* and *Platycystites bromidensis*, at Bromide; *P. cristatus*, southern Arbuckles, possibly U.S. Highway 77; and *P. fimbriatus* and *P. levatus*, both from the area 13 km south-southwest of Ardmore (?Rock Crossing). Bassler did not attempt to collect new material, did not correlate echinoderm zones, and did not give precise data on collecting localities and zones. His was the first major paper on Bromide echinoderms.

In another major paper on Ordovician echinoderms, Bassler (1950, p. 273-277) described *Sinclairocystis praedicta* from the Upper Echinoderm Zone of the Mountain Lake Member, south of Sulphur (Measured Section 10, this report), and *Strimple-*

cystis oklahomensis from the Lower Echinoderm Zone of the Mountain Lake Member about 43 m below the top of the Bromide, on Oklahoma Highway 99 south of Fittstown (Measured Section 11A, this report). The specimens were collected by G. Arthur Cooper and William Allen, and the types are in the National Museum of Natural History. Bassler also proposed the new genus *Kirkocystis* for the old *?Enoploura papillata*, described in his previous article.

Another early publication was that of G. Winston Sinclair (1945, p. 707-716), who studied specimens collected over many years by C. E. Decker of the University of Oklahoma. Sinclair withheld publication until Bassler's 1943 article was published. The types were originally in collections at the University of Oklahoma, but later were transferred to the National Museum of Natural History. Eight species (seven new) of five genera (one new) were described, all probably from the Lower Echinoderm Zone of the Mountain Lake Member. *Carabocrinus treadwelli*, sec. 27, T. 2 S., R. 3 E., southwest of Nebo store (not sec. 2, T. 2 S., R. 7 E.); *Hesperocystis deckeri*, east edge of McLish Ranch in sec. 36, T. 1 S., R. 7 E.; *Hybocrinus nitidus*, west branch of Sycamore Creek; *H. pyxidatus*, west branch of Sycamore Creek and U.S. Highway 77, east side; *Palaeocrinus hudsoni*, west branch of Sycamore Creek, and sec. 22, T. 2 S., R. 3 E., west of Nebo; *Platycystites* cf. *P. bromidensis* and *P. bassleri*, west branch of Sycamore Creek in sec. 27, T. 3 S., R. 4 E.; and *P.* cf. *P. levatus*, U.S. Highway 77, east side, were described. No attempt was made to collect new material, and no correlation or zonation of echinoderms was attempted.

In another paper, Sinclair (1948, p. 312) mentioned that *?Glyptocystites loeblichae* Bassler, 1943, may belong to *Cheirocrinus*. No attempt was made to collect new material or to restudy the type specimen.

In 1948, Harrell L. Strimple of Bartlesville, Oklahoma (now at the University of Iowa), described *Pleurocystites watkinsi* from the Pooleville Member of the Bromide at Rock Crossing, Criner Hills (Measured Section 15, this report). In 1949, Strimple and William T. Watkins, now of San Antonio, Texas, described *Hybocrinus crinerensis* from the Pooleville Member at Rock Crossing. The two type specimens were collected a few years previously by Watkins and are in the National Museum of Natural History.

In 1952, Strimple described *Sinclairocystis angulatus* and *S. sulphurensis* from the Upper Echinoderm Zone of the Mountain Lake Member, just south of Sulphur in the road cut on the east side of U.S. Highway 177 (old Highway 18). The types are in the National Museum of Natural History. In April, 1953, Strimple described *Myeinocystites natus* from the upper Pooleville on Culley Creek (formerly Spring Creek and West Spring Creek of authors) in sec. 26, T. 5 S., R. 1 E., Criner Hills (Measured Section 14, this report). The type is in the National Museum of Natural History. In July, 1953, Strimple described *Archaeocrinus subovalis* from the upper Pooleville at Rock Crossing and Culley Creek, Criner Hills. The holotype came from Rock Crossing. About 100 metatypes came from Culley Creek and were collected by Watkins and Strimple. The types are in the National Museum of Natural History.

In 1955, Strimple and Watkins described *Anthracocrinus primitivus* and *Pararchaeocrinus decoratus* from the upper Pooleville on Culley Creek, Criner Hills, based upon material collected by them and A. Allen Graffham, dating back to 1948. One slab of paratypes is at the University of Oklahoma. In an accompanying paper Strimple and Graffham (1955) described *Cyathocystis oklahomae* from Culley Creek, Criner Hills. All type specimens of these authors are in the National Museum of Natural History.

In 1961, Strimple published a short paper with a camera lucida drawing of *Myeinocystites natus* and listed one additional specimen plus *Anthracocrinus primitivus*, *Archaeocrinus subovalis*, *Pararchaeocrinus decoratus*, and *Cyathocystis oklahomae* from Culley Creek in the Criner Hills.

In 1951, Eckert completed a Master of Science thesis at the University of Oklahoma on Bromide fossils. From Lick Creek (C), Rock Crossing (D), and south of Fittstown (G; Measured Sections 6, 15, and 11A, this report), he listed or figured *Amygdalocystites* cf. *A. florealis* (D6, 7; G3b, 8), *A. tribrachiatus* (C3a, b), *Archaeocrinus* cf. *A. lacunosus* (C8; D7; one whole specimen), *?Carabocrinus* sp. (C6; G3b), *Echinospaerites aurantium* (D3f, D7; one whole specimen), *Glyptocystites* cf. *G. regnelli* (C3a; D7), *Hybocrinus conicus* (C3a; one whole specimen), *?Paleocystites* sp. (C8; D9; G6, 8b), and *Platycystites* cf. *P. bassleri* (G7; one whole specimen). Only four complete echinoderms were collected, the remainder of the specimens being fragments that may be misidentified. His *Echinospaerites* looks like *Archaeocrinus*, and his *Archaeocrinus* looks like *Diabolocrinus*. No zonation was noted. Eckert's collections were moved from storage in 1976 to the University of

Oklahoma. The four echinoderm specimens now at the University of Oklahoma are: *Archaeocrinus* cf. *A. lacunosus* (sec. 22, T. 1 S., R. 1 E.), *Echinosphaerites aurantium* (sec. 35, T. 5 S., R. 1 E.), *Platycystites* cf. *P. bassleri* (sec. 12, T. 1 N., R. 6 E.), and *Hybocrinus conicus* from Lick Creek, the first two specimens having been misidentified.

Caster (1952, p. 27) presented a key to some of the carpoids, which shows the relationships of *Kirkocystis*.

Cooper (1956, p. 120-123) proposed the names Mountain Lake Member and Pooleville Member, and mentioned that *Platycystites* and *Cheirocrinus* occur in the upper Mountain Lake (Upper Echinoderm Zone) on Spring Creek in the western Arbuckles.

RECENT STUDIES

Reso and Wegner (1964, p. 89-94) described a collection of 35 microscopic holothurian sclerites from the upper Pooleville at Rock Crossing (Measured Section 15, this report). Three species of *Thuroholia* were figured and described, *T. croneisi* Gutschick and *T. crinerensis* and *T. overbrookensis* (both new). These sclerites were collected from shaly interbeds at the north end of the exposure approximately 8 to 11 m below the Pooleville-Viola contact.

Brower (1966) described *Anulocrinus* sp. aff. *A. drummuckensis* from the Pooleville Member on Culley Creek, Criner Hills (Measured Section 14, this report). He studied 41 specimens, mostly from the Strimple Collection at the National Museum of Natural History, and mentioned that five specimens of *Calceocrinus* were also present in the Strimple Collection.

More recently, Brower (1977) published on all known Bromide calceocrinids, including one new genus and three new species. Many of the specimens were collected by Fay and Graffham. *Paracremacrinus laticardinalis* was newly described from the Lower Echinoderm Zone of the Mountain Lake Member from the west branch of Sycamore Creek, Lick Creek, Tulip Creek, and Amis Ranch (Measured Sections 4, 6, 3B, 7, this report). *Anulocrinus ramifer* came from Culley Creek, 8 to 10 m and 11 to 13 m below the Viola Limestone, and from Rudd Quarry, 2.4 m below the Viola Limestone, in the Criner Hills (Measured Sections 14 and 13A, this report). *Calceocrinus longifrons* came from Culley Creek 9 to 10 m below the Viola Limestone, Criner Hills. It is postulated that these echinoderms reposed on the bottom in a "runner" fashion. They are among the oldest calceocrinids now known.

Ubaghs (1968a, p. S555) assigned *Kirkocystis* to *Anatiferocystis* Chauvel, 1941. This assignment is supported provisionally by Parsley (herein).

In 1967, Paul proposed a new genus, *Praepleurocystis*, with *Pleurocystites watkinsi* Strimple, 1948, as the type species. Parsley (1970, p. 142) reassigned this species to *Pleurocystites*, noting that it may be the oldest known species of the genus. However, Parsley herein assigns this species to *Praepleurocystis*, in agreement with Paul. Strimple (1972) published a short paper describing the collection of the original type specimen and its subsequent history.

Fay and Graffham (1969) presented a measured section through the Bromide Formation at Tulip Creek (see Measured Section 3, herein) and briefly described the stratigraphic occurrence, geographic distribution, and dominant genera in the Lower and Upper Echinoderm zones of the Mountain Lake Member. They also mentioned the occurrence of echinoderms in the Pooleville Member in the Criner Hills.

In 1972, Paul referred *Cheirocrinus ardmorensis* of Bassler to a new genus *Cheirocystis*, and placed Bassler's other three cheirocrinid species in *Glyptocystella loeblichi* (new genus). In addition to the type specimens, Paul studied a large group of specimens collected by Strimple, which are at the National Museum of Natural History.

Maerz (1972), in a master's thesis at Texas Christian University, showed zonation of the Pooleville Member in the Criner Hills, with an *Archaeocrinus subovalis* Zonule at the base and top of the Pooleville. This zonule probably represents organisms that lived under subtidal conditions.

Parsley (1972, p. 341-347) restudied and refigured *Myeinocystites natus* Strimple 1953, placing it in the class Homoiostelea, order Soluta, and family Belemnocystitidae. He also assigned a specimen from the Benbolt Formation of northeastern Tennessee to this species. Kolata (1975, p. 14-15), in a memoir on Platteville and Galena echinoderms from northwestern Illinois, also assigned two Galena Group specimens to *Myeinocystites natus* described from the Bromide, and used this occurrence to argue for a similar age for the Galena Group and Bromide Formation. Two years later, Kolata, Strimple, and Levorson (1977) decided that the Galena *Myeinocystites* belonged to a new species (*M. crosslandi*), redescribed *M. natus* from the Bromide, considered synonymizing *Myeinocystites* with *Belemnocystites* Miller and Gurley, 1894, and transferred both genera to the family

Iowacystidae.

Brower and Veinus (1974, p. 19) noted that *Ectenocrinus* occurs in the Bromide Formation, based on a specimen seen in the National Museum of Natural History.

In 1975, Parsley and Mintz revised the Paracrinoidea, including *Sinclairocystis*, *Platycystites*, and a new genus, *Oklahomacystis*. The latter genus was proposed for *Amygdalocystites tribrachiatus* of former authors. The genera are referred to the Blackriveran Stage. Many of the illustrated specimens were collected by Fay and Graffham. They recognized only one species of *Sinclairocystis*, *S. praedicta*, based upon studies of specimens from the locality south of Sulphur. All previous species of Bromide *Platycystites* were referred to *P. cristatus*. One specimen of *Platycystites faberi* was figured from the Bromide Formation on Tulip Creek (see pl. 7, fig. 4, 5; at the National Museum of Natural History).

In 1975, Strimple began a new series of papers on Bromide echinoderms, completing work he had begun many years earlier. Strimple (1975a) reviewed his previous studies of Bromide echinoderms in a summary of work then under way on Ordovician echinoderms in other areas. Strimple (1975b) discussed the paleoecology of *Hybocrinus* at Bromide, concluding that this genus probably sat upright on the sea floor with a short trailing stem. These observations were based on seven specimens in the National Museum of Natural History, which Strimple had collected many years earlier, supposedly from "about 15-20 feet below the top of the formation" (p. 51). This stratigraphic position may be in error because all of the small asymmetric specimens of *Hybocrinus* that we have seen from Bromide come from the Lower Echinoderm Zone much lower in the formation (see Measured Section 5, this report). Frest and Strimple (1978) repeated this ecologic analysis and figured a specimen of *Hybocrinus nitida* [sic] from the Bromide.

Frest and Strimple (1976) published on abnormal specimens of *Platycystites cristatus* with three epithecal arms. The two specimens are at the University of Iowa. The collecting locality and zone are not given, but both specimens apparently came from the Lower Echinoderm Zone along the west branch of Sycamore Creek on Daube Ranch. In an accompanying paper, Frest, Strimple, and McGinnis (1976) described *Platycystites infundus*, new species, from the Upper Echinoderm Zone south of Sulphur. The single type specimen is at the University of Iowa.

Warn and Strimple (1977, p. 91-96) described *Apodasmocrinus daubei*, new genus, new species, from the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation at Daube Ranch. This is the crinoid previously referred to as *Ectenocrinus* by Brower and Veinus (1974). The two type specimens, one at the University of Iowa, the other at the National Museum of Natural History, were illustrated only by line drawings; photographs of these specimens are included here in the chapter by Warn.

Frest, Strimple, and Coney (1979, p. 390-398) referred several Bromide species of *Platycystites* to their new genus *Globulocystites*, including *G. cristatus* from the Lower Echinoderm Zone and *G. infundus* from the Upper Echinoderm Zone. They also argued that *Globulocystites* probably had a recumbent mode of life. Parsley (herein) has rejected this taxonomic assignment and has returned all previously named Bromide species to *Platycystites*. Frest, Strimple, and McGinnis (1979) described *Praecursoricrinus sulphurensis*, new genus, new species, from the Upper Echinoderm Zone south of Sulphur. The two type specimens are at the University of Iowa. Finally, Frest, Strimple, and Witzke (1980) described *Oklahomacystis spissus*, new species, from the Upper Echinoderm Zone south of Sulphur, and figured specimens of *O. tribrachiatus* and *Sinclairocystis praedicta* from the same zone and locality. The poorly preserved holotype and separate plates are at the University of Iowa. Parsley (herein) has rejected this species.

Sprinkle and Longman (1977, p. 26) briefly described the location and composition of the three echinoderm zones in the Bromide and some of the environmental factors responsible for the occurrence of abundant echinoderms. In another paper, Sprinkle and Bell (1978) figured a specimen of *Cyathocystis oklahomae* from the Lower Echinoderm Zone at Rhynes Ranch in the northeastern Arbuckles and discussed the ecology and distribution of this unusual paedomorphic edrioasteroid.

Table 8 shows the probable stratigraphic position and collection locality of all previously reported and named echinoderms from the Bromide Formation.

Table 8. Stratigraphic position of Bromide echinoderms as used by authors from 1903 to 1980.

Echinoderm Name and Author Usage	Stratigraphic Member and Collecting Locality of This Report		
	Mountain Lake Member		Pooleville Member Zones
	Lower Zone	Upper Zone	
Amygdalocystites of authors (now = Oklahomacystis of Parsley and Mintz, 1975, which see)			
Amygdalocystites sp. nov. Taff, 1903; Taff, 1904; Trout, 1913; Morgan, 1924	-----	3	-----
A. florealis Decker, 1931b	-----	15	-----
A. cf. A. florealis Eckert, 1951 (?misidentified fragments).	?11A, ?15	11A	-----
A. tribrachiatus Bassler, 1943	-----	8, 9, 10; sec. 14, T6N-R16W	-----
Eckert, 1951 (?misidentified fragments)	-----	6, (14-6N-16W)	?6
Anatiferocystis papillata Ubaghs, 1968a (formerly Enoploura and Kirkocystis)	-----	-----	15
Anthracocrinus primitivus Strimple and Watkins, 1955; Strimple, 1961;	-----	-----	14
Maerz, 1972	-----	-----	12, 15
Anulocrinus sp. aff. A. drummuckensis Brower, 1966 (later A. ramifer Brower, 1977	-----	-----	13, 14
Apodasmocrinus daubei Warn and Strimple, 1977	4	-----	-----
Archaeocrinus sp. undet. Taff, 1904; Trout, 1913; Morgan, 1924	-----	-----	?W. Arbuckles
Archaeocrinus sp. Eckert, 1951 (some specimens may not be Archaeocrinus; one specimen was named Echinosphaerites aurantium)	?15	?15	15
A. cf. A. lacunosus Eckert, 1951 (may be a Diabolocrinus)	6	15	-----
A. subglobosus Decker, 1931b	-----	-----	14, 15
A. subovalis Strimple, 1953b;	-----	-----	14, 15
Strimple, 1961;	-----	-----	14
Maerz, 1972	-----	-----	12, 14, 15, N. Stevens Ranch

Calceocrinus sp. Brower, 1966 (later C. longifrons Brower, 1977)	-----	-----	14
Carabocrinus sp. Decker, 1931b	Norris Ranch (2-1N-6E)	-----	-----
C. treadwelli Sinclair, 1945	8	-----	-----
C. tumidus Decker, 1931b	3, 4, 5, 8	-----	14
C. cf. C. vancortlandi Decker, 1931b	4	15	-----
Cheirocrinus Cooper, 1956	-----	1	-----
C. ardmorensis Bassler, 1943 (changed to Cheirocystis by Paul, 1972b)	?15	-----	-----
?C. loeblichae Sinclair, 1948 (formerly Glyptocystites of Bassler, 1943; changed to Glyptocystella by Paul, 1972b)	5	-----	-----
C. loeblichi Bassler, 1943	11A	-----	-----
C. logani Decker, 1931b	4	-----	-----
Cheirocystis ardmorensis Paul, 1972b (formerly Cheirocrinus of Bassler, 1943)	?15	-----	-----
Cleiocrinus regius Decker, 1931b	5	-----	-----
Cyathocystis oklahomae Strimple and Graffham, 1955; Strimple, 1961;	-----	-----	14
Sprinkle and Bell, 1978	Rhynes Ranch	-----	-----
Dendrocrinus cf. D. latibranchiatus Decker, 1931b	4	-----	-----
D. rusticus Decker, 1931b	-----	-----	14
Diabolocrinus Maerz, 1972	-----	-----	14
?Echinoencrinites ornatus Bassler, 1943	-----	15	-----
Ectenocrinus Brower and Veinus, 1974	?x	-----	-----
?Enoploura papillata Bassler, 1943 (changed to Kirkocystis by Bassler, 1950, then to Anatiferocystis by Ubaghs, 1968a)	-----	-----	15
Eumorphocystis multiporata Branson and Peck, 1940	11A	-----	-----
Globulocystites cristatus Frest, Strimple, and Coney, 1979	?4	-----	-----
G. infundus Frest, Strimple, and Coney, 1979	-----	10	-----
Glyptocystella Paul, 1972b (formerly Glyptocystites loeblichae of Bassler, 1943)	5	-----	-----
Glyptocystites sp. nov. Taff, 1904; Morgan, 1924	3	-----	-----
G. forbesi Trout, 1913	3	-----	-----
G. loeblichae Bassler, 1943 (may be Cheirocrinus of Sinclair, 1948; changed to Glyptocystella by Paul, 1972b)	5	-----	-----

Echinoderm Name and Author Usage	Stratigraphic Member and Collecting Locality of This Report		
	Mountain Lake Member		Pooleville Member Zones
	Lower Zone	Upper Zone	
G. logani, Decker 1931b	4	-----	-----
G. multiporus, Trout 1913	3	-----	-----
G. cf. G. regnelli Eckert, 1951 (?unidentified plates)	6, 15	11	6
Glyptocystites sp. of Maerz, 1972	-----	-----	12, 14, 15
Hesperocystis deckeri Sinclair, 1945	McLish Ranch (36-1S-7E)		
Hybocrinus conicus Eckert, 1951	-----	-----	6
H. crinerensis Strimple and Watkins, 1949	-----	-----	15
H. nitidus Sinclair, 1945; Frest and Strimple, 1978	4	-----	-----
H. pyxidatus Sinclair, 1945	3	-----	-----
Hybocrinus sp. Strimple, 1975b	-----	-----	?5
Kirkocystis papillata Bassler, 1950 (formerly Enoploura Bassler, 1943, now Anatiferocystis of Ubaghs, 1968a); Caster, 1952	-----	-----	15
Lepadocystites ?moorei Decker, 1931b	McLish Ranch (36-1S-7E)	-----	-----
Myeinocystites natus Strimple, 1953a; Strimple, 1961; Parsley, 1972; Kolata, Strimple, and Levorson, 1977	-----	-----	14
Oklahomacystis tribrachiatus Parsley and Mintz, 1975 (formerly Amygdalocystites of authors)	-----	(14-6N-16W), 3, 8, 9, 10, 15	-----
O. spissus Frest, Strimple, and Witzke, 1980	-----	10	-----
Palaeocrinus hudsoni Sinclair, 1945	4, 8	-----	-----
?Paleocystites sp. Eckert, 1951 (may be Carabocrinus; unidentified)	6, 11A, 15	-----	-----
Paracremacrinus laticardinalis Brower, 1977	3, 4, 6, 7	-----	-----

Pararchaeocrinus decoratus Strimple and Watkins, 1955; Strimple, 1961	-----	-----	14
Maerz, 1972	-----	-----	14, 15
Periglyptocrinus priscus Decker, 1931b	4	-----	14
Platycystites sp. nov. Taff, 1903; Taff, 1904; Trout 1913; Morgan, 1924	3	-----	-----
Platycystites Cooper, 1956	-----	1	-----
P. bassleri Sinclair, 1945	4	-----	-----
P. cf. P. bassleri Eckert, 1951.	11A	-----	-----
P. bromidensis Bassler, 1943	5	-----	-----
P. cf. P. bromidensis Sinclair, 1945	4	-----	-----
P. cristatus Bassler, 1943; Parsley and Mintz, 1975 (all previous Bromide species of Platycystites belong here)	3	-----	-----
P. faberi Parsley and Mintz, 1975	-----	3	-----
P. fimbriatus Bassler, 1943	12	-----	-----
P. infundus Frest, Strimple, and McGinnis, 1976	-----	10	-----
P. levatus Bassler, 1943	12	-----	-----
P. cf. P. levatus Sinclair, 1945	3	-----	-----
Pleurocystites watkinsi Strimple, 1948, 1972; (changed to Praepleurocystis by Paul, 1967b, but changed back by Parsley, 1970)	-----	-----	15
Praecursoricrinus sulphurensis Frest, Strimple, and McGinnis, 1979	-----	10	-----
Sinclairocystis angulatus Strimple, 1952	-----	10	-----
S. praedicta Bassler, 1950; Parsley and Mintz, 1975 (all other species are synonyms)	-----	10	-----
S. sulphurensis Strimple, 1952	-----	10	-----
Strimplecystis oklahomensis Bassler, 1950	11A	-----	-----
Thuroholia crinerensis Reso and Wegner, 1964	-----	-----	15
T. croneisi Reso and Wegner, 1964	-----	-----	15
T. overbrookensis Reso and Wegner, 1964	-----	-----	15

COLLECTION OF ECHINODERMS, 1965-1967

Robert O. Fay and A. Allen Graffham

Oklahoma Geological Survey;
Geological Enterprises

Although Decker (1931b) first recognized that whole echinoderms occurred in certain "cystid zones" in the Simpson Group, it was not until Graffham, Strimple, Watkins, and others began digging in the zones below the weathered surface that many hundreds of specimens were discovered. The exact zones were located by a careful search for whole specimens at places where Decker mentioned that he had found complete echinoderms. By digging directly below the surface and noting the exact placement of other whole specimens, workers delineated certain echinoderm zones. Three localities that yielded specimens early were the west branch of Sycamore Creek on Daube Ranch, the Sulphur locality, and Rock Crossing in the Criner Hills.

Beginning in the 1950's and until 1965, A. A. Graffham, owner of Geological Enterprises, Ardmore, sent Bromide echinoderms to the University of Oklahoma. Dr. Carl C. Branson, then Director of the Oklahoma Geological Survey, asked Robert Fay to make a stratigraphic study of the Bromide Formation and to try to find the exact placement of echinoderms in the Bromide members.

From 1965 to 1967, we restudied the Bromide Formation. We first visited the commonly known localities and dug some fossil echinoderms to reestablish the zones. We then measured detailed sections at these localities, noting exact placement of all previously collected echinoderms by Graffham. We then studied all parts of each section equally, without bias, trying to find any new zones or any new echinoderms. We dug in many places along each measured section, and we treated the Pooleville Member the same as we did the Mountain Lake Member at all localities. When we finally exhausted our search at a measured section, we dug each identified echinoderm zone for several months until we could find no new echinoderm taxa. Digging was not terminated because of a lack of echinoderms.

After studying the classical localities that Graffham had worked, we decided to study new localities at regularly spaced intervals. We did not attempt to exhaust the knowledge from every square kilometer of the Arbuckles, Criner Hills, and Wichitas, and it is likely that some new collecting localities and zones will be found in the future. We selected widely spaced localities in order to give a wide geographic spread to our knowledge.

We found that most of the Pooleville echinoderms came only from the Criner Hills and that the Mountain Lake echinoderms came from the Arbuckle Mountains, with little overlap. The Wichitas were not productive. In the Pooleville in the Criner Hills, most of the echinoderms were found in thin biostromes mainly in the upper part. Whole echinoderms were rare or lacking outside of two predictable echinoderm zones of the Mountain Lake, in spite of repeated meticulous efforts to collect from all units of the Mountain Lake. We found that a thin echinoderm zone occurs about 6.4 m above the top of the basal sandstone sequence of the Mountain Lake. Another echinoderm zone with different dominant genera occurs at the top of the Mountain Lake Member. These two echinoderm zones were designated the Lower Echinoderm Zone and the Upper Echinoderm Zone by Fay and Graffham (1969, p. 37-39). Their positions were found to be predictable throughout the Arbuckle Mountains. Many thousands of complete echinoderms were collected from these thin zones, especially where bryozoan- and brachiopod-rich biostromes were present, and where there was an even balance between shale and limestone, with a low-energy environment.

At each "dig" we tried to select a flat spot along a creek at the base of the echinoderm zone. Most of the zones are on edge, and so we dug a flat-bottomed trench into the zone laterally along the bedding planes. The main digs where we had water were Lick Creek, Daube Ranch, and Culley Creek. We constructed some fine-wired screens for washing, and we built small drying racks for the screens. We constructed a small dam across the creek at the site, and washed the specimens in the water. We dug several cubic meters of rock a day by hand, after removing up to a few meters of weathered overburden. We used miners' picks for

loosening large pieces of limestone and shale, placing the rock in the sieves. If a complete specimen was exposed, we collected all of the specimen that was possibly preserved in the rock and wrapped the specimen in metal foil. If the specimen was so delicate that it would fall to pieces, we glued the specimen and rock together and then wrapped the specimen in metal foil. In spite of all this precaution, there was still about 20 percent breakage. After washing the rock in sieves, and drying excess water on a rack, we carefully picked out all fossils, including echinoderms, keeping everything that was identifiable. We then placed the waste rock in a dump for later examination. We also placed the weathered surface material on the dump. Approximately 10 percent of the fossils that were missed in digging or sorting were later found on these dumps. We kept a record of the total amount of rock removed from each dig, so that we could estimate the relative abundance of the various fossils per cubic foot or meter. At many of the digs, water was not available, so we picked out the fossils we could see, throwing the excess rock on the dump. About 25 percent of the echinoderms were missed, and were later found on the dump after weathering. We bulldozed the Lower Echinoderm Zone dig at Daube Ranch, first by removing trees and shrubs for a hundred meters along the strike of the zone and then by removing about a meter of weathered zone. This was the only site bulldozed.

We removed about 14 cubic meters of rock from the Lower Echinoderm Zone at Lick Creek, about 11 cubic meters at Daube Ranch, and lesser amounts of 7 cubic meters at Tulip Creek and 5 cubic meters at Amis Ranch. The Lower Echinoderm Zone at most localities was less than a meter thick, with a bounding massive limestone below. The zone contained many loose echinoderm plates, along with abundant bryozoans and brachiopods. The echinoderms occurred in small groups along the same bedding plane, separated by barren intervals from an adjacent bedding plane. It was difficult to predict the exact position of a rich bed within the main zone, and sometimes we would strike a specimen with our pick. The upper parts of small thin limestone slabs sometimes contained delicately preserved specimens, and we would place these face-up on the dumps and return after a rainfall. Although we tested many adjacent units, we were unable to find complete specimens outside the main zone. At Lick Creek we found many specimens in the overlying meter, but this may be part of the main zone. Smaller digs were made at several localities of the Upper Echinoderm Zone near the top of the Mountain Lake Member and at Culley Creek, where the top of the Pooleville Member is exposed. The exact position of each echinoderm zone and the amount of rock removed by digging are shown in Figure 78 and are described in the measured sections in the Appendix.

The specimens were unpacked from collecting bags, and each one removed from metal foil and lightly washed or scrubbed in water. All hard matrix was removed by use of an air abrasive machine loaded with sodium bicarbonate. Each specimen was placed in a tray or vial or plastic box with cotton and carefully labeled. All nonechinoderm fossils were treated similarly and placed in the collections at the University of Oklahoma. Graffham retained several thousand specimens of the most common genera, such as *Hybocrinus*, *Platycystites*, and *Oklahomacystis*, to compensate for his assistance and time in collecting and preparation. All rare specimens and most of the common specimens were kept by the University of Oklahoma, amounting to almost 6,100 specimens belonging to over 60 genera and 13 classes of echinoderms. The last of the specimens was unpacked and cleaned in 1973, although the last digging was in 1967. In 1974, Graffham traded a collection of about 200 well-preserved and rare specimens to the University of Texas at Austin from his later collecting at the digs and dumps on Daube Ranch and Culley Creek.

In November, 1973, Fay asked James Sprinkle of the University of Texas at Austin to coordinate a study of the Bromide echinoderm faunas. Since 1973, Sprinkle has asked many echinoderm experts to help write certain sections of the monograph. Some authors, such as Parsley and Brower, borrowed material in advance to help them with other publications on echinoderms (see Parsely and Mintz, 1975; Brower, 1977; Parsley, 1979). The present study is a summary of all authors' work on Bromide echinoderms.

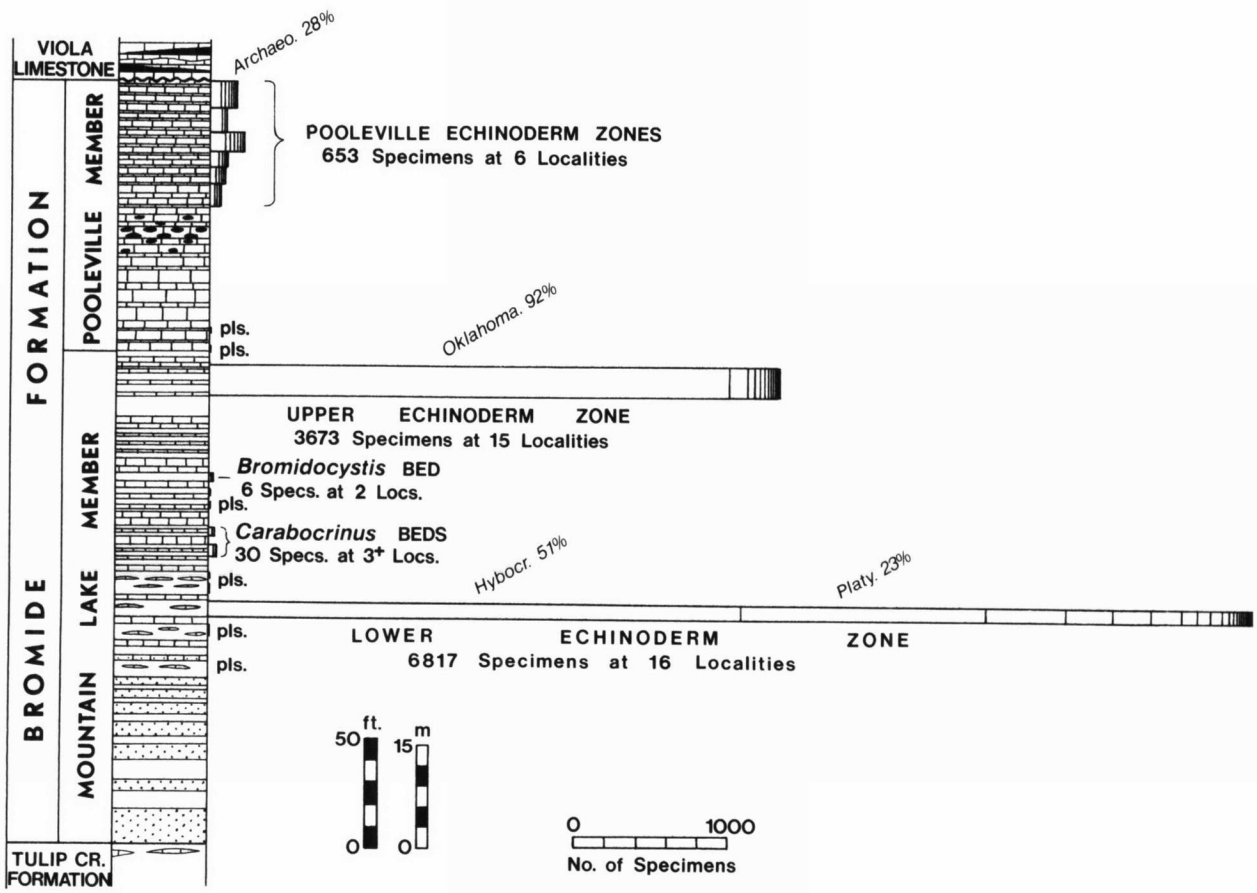

Fig. 12. Composite section of the Bromide Formation showing the location of the three rich echinoderm zones, which have produced thousands of complete specimens, and the two other beds in the Mountain Lake Member, which have each produced a few complete echinoderms.

ECHINODERM ZONES AND FAUNAS

James Sprinkle

University of Texas at Austin

The complete echinoderms studied in this project are not equally distributed throughout the Bromide stratigraphic section; they are concentrated in several thin zones in different parts of the Bromide with the adjacent beds having few complete echinoderms or only disarticulated plates. Three main zones with hundreds or thousands of complete echinoderms were extensively collected during this project (Fig. 12), and two other beds have also yielded a few echinoderms at two or more sections. These rich intervals were termed "zones" by Fay and Graffham (1969), who named and correlated the Lower Echinoderm Zone and the Upper Echinoderm Zone, both in the Mountain Lake Member. This usage of "zone" as a thin stratigraphic interval containing a rich and distinctive fauna of complete echinoderms is continued here and extended to include at least six thin intervals containing abundant echinoderms in the upper part of the Pooleville Member, which are here termed the Pooleville Echinoderm Zones (Fig. 12). Two other thin intervals in the Mountain Lake Member have also produced a few complete echinoderms; these are here termed "beds" because they usually contain one or a few lithologic units of bed size. These have been named after the dominant echinoderm genus present (*Carabocrinus* Beds and *Bromidocystis* Bed; see Fig. 12). Future collecting may show that these beds represent true echinoderm zones that are widespread and contain their own distinctive echinoderm faunas. The stratigraphic position of these Bromide echinoderm zones and beds is approximately shown on the composite section in Figure 12; exact positions at each locality are shown on Figure 78 and in the measured sections in the Appendix.

LOWER ECHINODERM ZONE

The Lower Echinoderm Zone is located near the middle of the Mountain Lake Member, usually about 6.5 to 8.0 m above the highest sandstone bed in the basal sequence (Fig. 12). It is a single shaly unit usually less than 1 m thick and often bounded above and below by thick limestone beds. In particular, the bounding limestone bed just below is often a very distinctive "mottled bed"; it is a thick, massive, rusty-weathering, fine-grained calcarenite with numerous large apparent burrows, giving it a mottled texture. In some sections (such as Cornell Ranch), several beds of this type are present in the middle Mountain Lake, but the one immediately below the Lower Echinoderm Zone is usually the thickest. This resistant and distinctive bed can often be traced long distances across the countryside and serves as a marker for the Lower Echinoderm Zone. Decker (1931b) was the first to recognize this zone in the Arbuckle Mountains, and named it the "upper cystid zone."

The Lower Echinoderm Zone is very widespread in the Arbuckles, occurring at 15 localities spread over the entire area, but has not been conclusively identified in the Criner Hills. The largest faunas have been recovered from this zone along a northwest-southeast hingeline extending through the central Arbuckles (Fig. 13), closely following the trend of the Washita Valley fault. This region was at the northeastern edge of the aulacogen and had favorable shallow-water conditions during deposition of this zone. Localities with much smaller echinoderm collections occur in between the three largest ones (Fig. 13), probably indicating that this rich zone is patchy in its distribution. Several collections from the Lower Echinoderm Zone have been made in the northeastern Arbuckles, particularly at Fittstown Quarry where the zone is especially well exposed. One locality in the southwestern Arbuckles also has a small echinoderm collection from the Lower Echinoderm Zone.

At the rich localities for the Lower Echinoderm Zone, echinoderm specimens and fragments make up approximately 30 percent of the total fauna. Bryozoans are very abundant in this zone, with ramose, ribbonlike, and domal forms making up more than 35 percent of the fauna. Brachiopods (mostly *Mimella*) are also common and equal about 30 percent. Other fossil groups, including a few trilobites, ostracods, gastropods, and bivalves, are uncommon, and

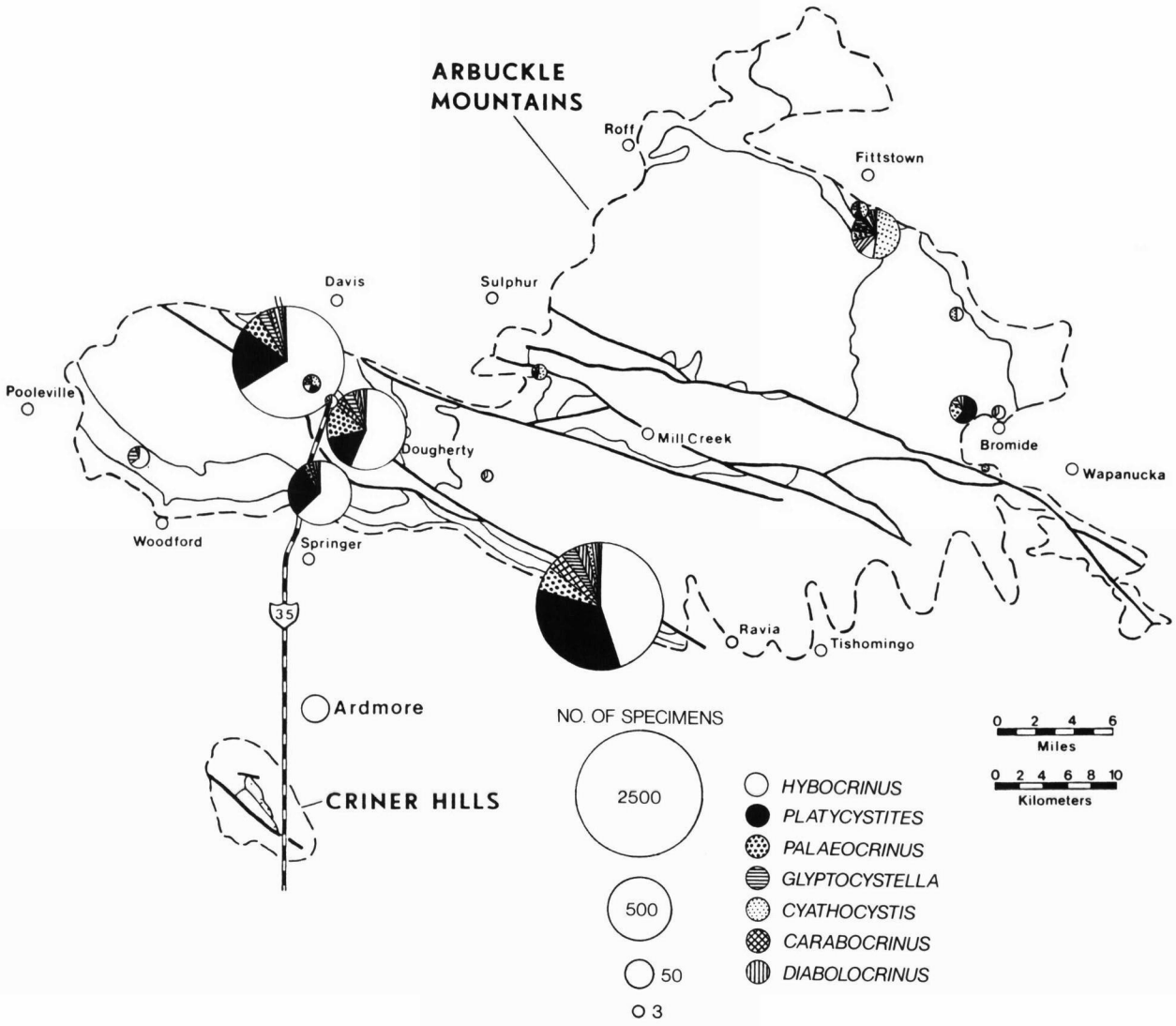

Fig. 13. Distribution of the Lower Echinoderm Zone around the Arbuckle Mountains and composition at each locality. Note that the richest localities lie along a northwest-southeast hingeline through the western and central Arbuckles, that most of the hingeline localities have a similar echinoderm composition, and that localities in the eastern and northeastern Arbuckles have a different echinoderm composition. Base map from Lewis (1982), redrawn from Ham (1969, fig. 13).

probably total about 5 percent. Thus, bryozoans, brachiopods, and echinoderms are almost equally common at rich localities of the Lower Echinoderm Zone. Adjacent shaly beds up- and downsection from this zone tend to be strongly dominated by bryozoans, with fewer brachiopods, fewer echinoderm fragments, and almost no complete echinoderm specimens. Echinoderm plates and stems seem to become especially common as the rich zone is approached from up- or downsection, and represent another marker for the zone.

The Lower Echinoderm Zone is predominantly a green shale containing thin lenses or stringers of calcarenitic limestone made up mostly of bryozoan and echinoderm fragments. Larger bryozoans and brachiopods are scattered throughout this matrix, and at some sections domal bryozoans become so abundant that they form small layered buildups or bioherms 0.3 to 1.0 m in size; these are sometimes covered with echinoderm root systems and holdfasts (see Pl. 3, fig. 32). Echinoderms seem most abundant at sections where the amount of shale approximately equals the amount of limestone stringers plus fossils (Fay and Graffham, 1969). Echinoderm plates are scattered throughout the zone, but complete echinoderms seem to occur in thin intervals

Table 9. Bromide echinoderm genera identified from the Lower Echinoderm Zone [based on complete specimens (6,817) and plates collected through November, 1977].

Genus	Group	Number Complete Specimens	Percent Echino. Fauna	Number Localities	Rank
Hybocrinus	inadunate crinoid	3,447	51	13	1
Platycystites	paracrinoid	1,589	23	12	2
Palaeocrinus	inadunate crinoid	511	7.5	6	3
Cyathocystis	edrioasteroid	306	4.5	13	4
Glyptocystella	rhombiferan	305	4.5	7	5
Carabocrinus	inadunate crinoid	194	2.9	6	6
Diabolocrinus	camerate crinoid	108	1.6	6	7
Paracremacrinus	inadunate crinoid	99	1.5	5	8
Pirocystella	rhombiferan	88	1.3	6	9
Apodasmocrinus	inadunate crinoid	39	0.6	5	10
Archaeocrinus	camerate crinoid	25	0.4	3	11
Bromidocystis	eocrinoid	24	0.4	5	12
Eumorphocystis	diploporan	22	0.3	7	13
Eopinnacrinus	inadunate crinoid	14	0.2	2	14
Bistomiacystis	paracrinoid	11	0.2	4	15
Doliocrinus	inadunate crinoid	5	0.1	2	16
Promopalaeaster	asteroid	4	< 0.1	1	17-19
Edriophus	edrioasteroid	4	< 0.1	3	17-19
Foerstediscus	edrioasteroid	4	< 0.1	3	17-19
Hesperocystis	rhombiferan	3	< 0.1	1	20
Reteocrinus	camerate crinoid	2	< 0.1	2	21-26
Cleiocrinus	camerate crinoid	2	< 0.1	2	21-26
Bromidocrinus	camerate crinoid	2	< 0.1	1	21-26
Dendrocrinus	inadunate crinoid	2	< 0.1	1	21-26
Hudsonaster	asteroid	2	< 0.1	1	21-26
Pyrgocystis	edrioasteroid	2	< 0.1	2	21-26
Camerate sp. A	camerate crinoid	1	< 0.1	1	27-29
Petraster	asteroid	1	< 0.1	1	27-29
Protopalaeaster	asteroid	1	< 0.1	1	27-29
Astrocystites	edrioblastoid	plates	< 0.1	2	30-31
Cyclocystoides	cyclocystoid	1 plate	< 0.1	1	30-31

in which one or two species dominate. Sometimes many echinoderm specimens will occur on a single bedding plane over a small area, perhaps representing a small "garden" of individuals that were living together; however, this type of occurrence is less common here than in the Pooleville Echinoderm Zones.

At the richest Lower Echinoderm Zone localities along the hingeline, the normal echinoderm fauna is very diverse (16 to 18 genera and species) and, based on counts of complete calyces, is dominated by the small inadunate crinoid *Hybocrinus nitidus* (about 51 percent of the fauna) and the large lens-shaped paracrinoid *Platycystites levatus* (about 23 percent; see Fig. 12, 13; Table 9). Although several other types of inadunate and camerate crinoids, rhombiferan cystoids, and an edrioasteroid are fairly common, no other species makes up more than 8 percent of the echinoderm fauna at these localities. More than 2,500 echinoderm specimens have been collected from this thin zone at Daube Ranch, about 2,100 at Lick Creek, more than 1,000 at Amis Ranch, and nearly 500 at Cornell Ranch (Tulip Creek) (Fig. 13). In contrast, several small echinoderm collections have been made along the hingeline at localities between these rich ones; these include North-Central I-35 (7 specimens), Cedar Village (13 specimens), and Nebo (3 specimens). The shale band containing the Lower Echinoderm Zone can be identified at these localities but does not appear to have a rich echinoderm fauna as it does at localities only a few kilometers away. The sparse echinoderm fauna at some of these localities contains echinoderms that are very rare at the nearby rich localities; for example, Cedar Village has produced a total of only 13 complete echinoderms, but among these are five specimens (in two groups) of *Cyathocystis* (4.5 percent of the entire Lower Zone fauna), two specimens of *Eumorphocystis* (0.3 percent), and a specimen each of *Bromidocystis* (0.4 percent) and *Edriophus* (less than 0.1 percent).

Localities in the northeastern or eastern Arbuckles (Fittstown Roadcut and Quarry, Rhynes Ranch, McLish Ranch, Bromide, and Pickens Ranch) have most of the same echinoderm species, but in different proportions than at the rich hingeline localities (Fig. 13). *Cyathocystis* (63 percent

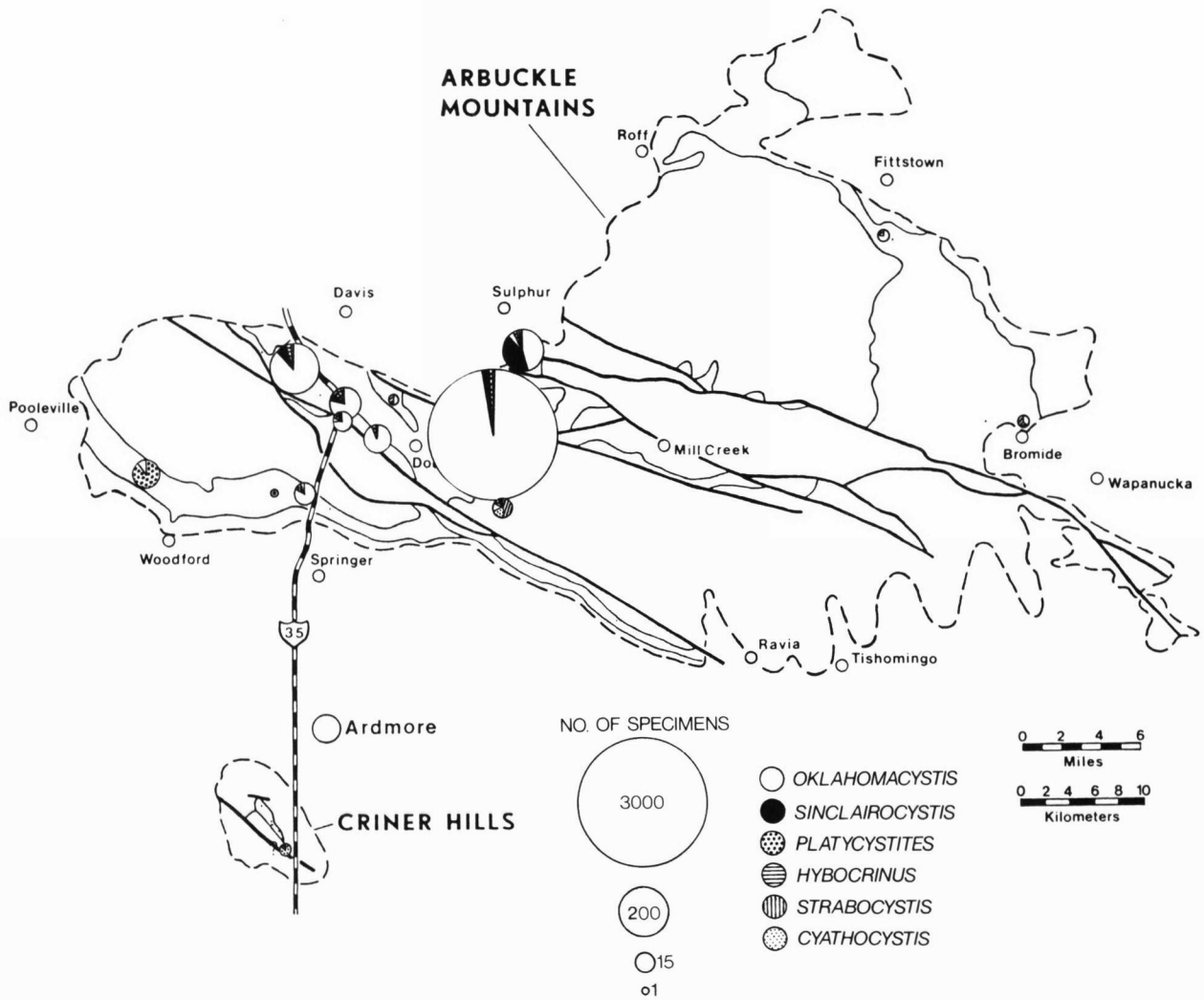

Fig. 14. Distribution of the Upper Echinoderm Zone around the Arbuckle Mountains and Criner Hills and composition at each locality. Note one very rich locality (Buckhorn Ranch) and dominance by *Oklahomacystis* at most localities. Base map from Lewis (1982), redrawn from Ham (1969, fig. 13).

vs. 4.5 percent overall) and *Bromidocystis* (6.6 percent vs. 0.4 percent overall) are especially common at the Fittstown localities, and *Hesperocystis* and *Bromidocrinus* have been found as complete specimens only at McLish Ranch. The shales of these northeastern and eastern localities were deposited in very shallow water (perhaps 3 to 5 m; see Longman, 1976) on the Arbuckle platform. They were closer to shore, more affected by storms, and in general had less than optimal conditions for echinoderms during deposition of the Lower Echinoderm Zone. Genera like *Cyathocystis* and *Bromidocystis* probably used an r-strategy (Pianka, 1971; Sprinkle and Bell, 1978) to colonize this marginal and frequently disturbed environment; other genera such as *Hesperocystis* and *Bromidocrinus* were probably well adapted to these very shallow-water conditions and occur only here.

Localities in the southwestern Arbuckles that were in deeper water near the center of the aulacogen during deposition of the Lower Echinoderm Zone have produced a small but fairly normal fauna dominated by *Hybocrinus*. The Lower Echinoderm Zone has not been found for certain to the south in the Criner Hills, but several complete specimens and many plates characteristic of this zone have been collected from the middle or upper Mountain Lake Member at Rock Crossing, the only place where this unit is well exposed in the Criner Hills (see Measured Section 15A, Appendix).

Table 10. Bromide echinoderm genera identified from the Upper Echinoderm Zone [based on complete specimens (3,673) and plates collected through November, 1977].

Genus	Group	Number Complete Specimens	Percent Echino. Fauna	Number Localities	Rank
Oklahomacystis	paracrinoid	3,365	92	12	1
Sinclairocystis	paracrinoid	128	3.5	7	2
Platycystites	paracrinoid	56	1.5	5	3
Hybocrinus	inadunate crinoid	38	1.0	4	4
Cyathocystis	edrioasteroid	16	0.4	7	5
Strabocystis	rhombiferan	15	0.4	5	6-7
Cleiocrinus	camerate crinoid	15	0.4	8	6-7
Archaeocrinus	camerate crinoid	11	0.3	2	8-9
Foerstediscus	edrioasteroid	11	0.3	3	8-9
Praecursoricrinus	inadunate crinoid	3	0.1	1	10-11
Pyrgocystis	edrioasteroid	3	0.1	1	10-11
Edriophus	edrioasteroid	2	< 0.1	2	12-15
Colpodecrinus	camerate crinoid	2	< 0.1	1	12-15
Carabocrinus	inadunate crinoid	2	< 0.1	1	12-15
Palaeocrinus	inadunate crinoid	2	< 0.1	1	12-15
Diabolocrinus	camerate crinoid	1	< 0.1	1	16-19
Paradiabolocrinus	camerate crinoid	1	< 0.1	1	16-19
Cyclocystoides	cyclocystoid	1	< 0.1	1	16-19
Pleurocystites	rhombiferan	1	< 0.1	1	16-19
Astrocystites	edrioblastoid	plates	< 0.1	1	20-21
Bromidocystis	eocrinoid	plates	< 0.1	3	20-21

UPPER ECHINODERM ZONE

The Upper Echinoderm Zone is located near the top of the Mountain Lake Member just below the contact with the overlying Pooleville Member (Fig. 12). This zone usually includes several alternating biosparite and shale beds ranging from 0.8 to 4.3 m in total thickness. In the southwestern and central Arbuckles, this zone occurs just above a thick, nearly barren shale unit as much as 10 m thick at Johnston Ranch.

The Upper Echinoderm Zone is widespread in the Arbuckle Mountains, occurring at 14 localities extending over much of the area (Fig. 14). This zone may also occur in the Criner Hills (questionably at Rock Crossing) and in the Wichita Mountains in southwestern Oklahoma, where a single specimen of *Oklahomacystis* has been reported (Bassler, 1943, p. 696). Most localities in the Arbuckles have produced fairly small collections of echinoderms (see Fig. 14), but one medium-sized dig at Buckhorn Ranch in the central Arbuckles has yielded over 3,000 specimens, the largest single collection of echinoderms from any Bromide locality or zone.

Where thick and well developed, the Upper Echinoderm Zone includes several different lithologic units. Shale and shaly limestone beds alternate with medium-bedded calcarenite or biosparite units made up mostly of echinoderm fragments. Complete echinoderms are found in both of these lithologies, although they seem somewhat more common and diverse in the shaly units. At the North I-35 section, a distinctive 0.3-m stromatoparoid bed occurs near the middle of the zone, but this bed is absent at the North-Central I-35 section just 1.6 km to the south.

Bryozoans (especially disc-shaped *Prasopora*) and complete and fragmentary echinoderms are the most common fossils in the Upper Echinoderm Zone, probably each contributing about 40 percent of the total fauna. Brachiopods are less common, probably about 10 percent, but *Multicostella* and *Oxoplecia* are often found in different parts of the zone. Other groups, including stromatoparoids, receptaculitids, bivalves, gastropods, nautiloids, trilobites, and ostracods, have also been found at one or more sections and usually make up 8 to 10 percent of the fauna. These minor groups seem to be more common and diverse here than in the Lower Echinoderm Zone.

The small to medium-sized globular paracrinoid *Oklahomacystis* strongly dominates the Upper Echinoderm Zone, making up about 92 percent of the total echinoderm fauna (Table 10). Two other paracrinoids, *Sinclairocystis* (3.5 percent) and *Platycystites* (1.5 percent), also occur in this zone, along with the compact inadunate crinoid *Hybocrinus* (1.0 percent); all other echinoderms (at least 13 genera) are rare (less than 1 per-

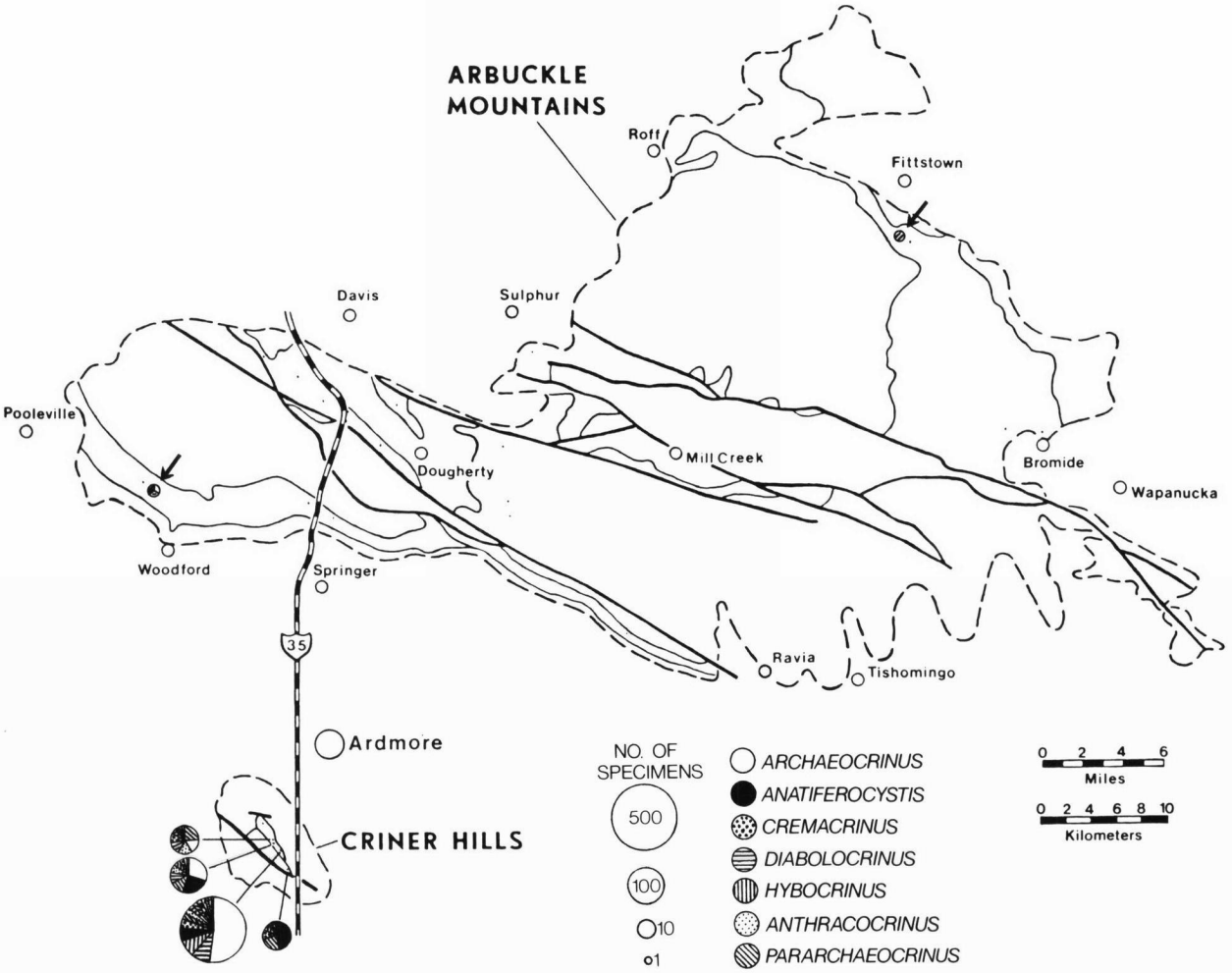

Fig. 15. Distribution of the Pooleville Echinoderm Zones around the Arbuckle Mountains and Criner Hills and composition at each locality. Note that very few specimens come from the Arbuckle Mountains (two arrows), which had unfavorable conditions during most of Pooleville deposition. Base map from Lewis (1982), redrawn from Ham (1969, fig. 13).

cent). The three paracrinoid genera vary considerably in their relative abundance across the Arbuckles (Fig. 14). At Sulphur on the Arbuckle platform, which probably had lagoonal conditions, *Sinclairocystis* is nearly as abundant as *Oklahomacystis*, and *Platycystites* is very rare. *Oklahomacystis* strongly dominates the echinoderm fauna at Buckhorn Ranch, which was also on the Arbuckle platform. Along the hingeline at Lick Creek, the I-35 sections, and Amis Ranch, *Oklahomacystis* again dominates over *Sinclairocystis*, but *Platycystites* becomes more common. In the southern and southwestern Arbuckles, where water was deeper, *Platycystites cristatus* (a different species from the hingeline localities) becomes dominant over *Oklahomacystis bibrachiatus* (a different species also), and *Sinclairocystis* is absent. Thus, *Sinclairocystis* and perhaps *Oklahomacystis* seem to have favored shallow-water environments in the central Arbuckles, whereas *Platycystites* was more common in deeper water to the southwest. Other echinoderms in the Upper Echinoderm Zone are too rare and limited in distribution for any pattern to be apparent.

POOLEVILLE ECHINODERM ZONES

Almost all echinoderms collected from the Pooleville have come from the upper half of this member in the Criner Hills (see Fig. 12, 15). Only seven echinoderm specimens have been found in the Pooleville from the Arbuckle Mountains. Nearly 650 complete echinoderms have been found at four lo-

Table 11. Bromide echinoderm genera identified from the Pooleville Echinoderm Zone [based on complete specimens (654) and plates collected through November, 1977].

Genus	Group	Number Complete Specimens	Percent Echino. Fauna	Number Localities	Rank
Archaeocrinus	camerate crinoid	180	28	4	1
Anatiferocystis	stylophoran	79	12	4	2
Cremacrinus	inadunate crinoid	65	10	2	3
Diabolocrinus	camerate crinoid	42	6.4	1	4
Hybocrinus	inadunate crinoid	40	6.1	3	5
Anthracocrinus	camerate crinoid	35	5.4	2	6
Pararchaeocrinus	camerate crinoid	27	4.1	2	7
Praepleurocystis	rhombiferan	21	3.2	3	8-9
Porocrinus	inadunate crinoid	21	3.2	4	8-9
Urasterella	asteroid	19	2.9	3	10
Peltacrinus	inadunate crinoid	18	2.8	2	11
Cyathocystis	edrioasteroid	16	2.4	3	12
Calceocrinus	inadunate crinoid	15	2.3	1	13
Cleiocrinus	camerate crinoid	14	2.1	1	14
Quadrocystis	rhombiferan	13	2.0	3	15
Pyrgocystis	edrioasteroid	12	1.8	3	16
Tanaocystis	rhombiferan	11	1.7	4	17
Abludoglyptocrinus	camerate crinoid	7	1.1	2	18
Pleurocystites	rhombiferan	3	0.5	2	19
Penicillicrinus	inadunate crinoid	2	0.3	1	20-24
Platycystites	paracrinoid	2	0.3	2	20-24
Myeinocystites	homoiostelean	2	0.3	2	20-24
Promopalaeaster	asteroid	2	0.3	1	20-24
Foerstediscus	edrioasteroid	2	0.3	2	20-24
Acolocrinus	inadunate crinoid	1	< 0.2	1	25-29
Rhodocrinid	camerate crinoid	1	< 0.2	1	25-29
Crinerocrinus	camerate crinoid	1	< 0.2	1	25-29
Bothriocidaris	echinoid	1	< 0.2	1	25-29
Unibothriocidaris	echinoid	1	< 0.2	1	25-29

calities in the Criner Hills (Culley Creek, Rudd Quarry, Dunn Quarry, and Rock Crossing) between 1 and 19 m below the top of the Pooleville Member. The echinoderms occur here in thin intervals or biostromes throughout this sequence with one or a few echinoderm genera occurring together. The matrix through this whole sequence is an alternating light gray to tan biomicrite and shaly micrite in thin beds.

Several types of brachiopods (especially *Oxoplecia*) and bryozoans are about as common as the echinoderms in the thin rich zones; each of these groups makes up about 25 percent of the total fauna. Trilobites (including *Vogdesia* and *Lonchodomus*) make up about 15 percent of the fauna, and horizontal burrows are also present in many of the limestone beds. Most other invertebrates are rare or absent in these zones.

The Pooleville Echinoderm Zones are almost as diverse (about 30 echinoderm genera) as the Lower Echinoderm Zone, even though far fewer specimens have been collected. The fauna is dominated by crinoids, especially the large camerate *Archaeocrinus*, which makes up about 28 percent of the fauna. The small stylophoran *Anatiferocystis* is also fairly abundant (12 percent) and several other camerate and inadunate crinoids, rhombiferan cystoids, and edrioasteroids are fairly common (see Table 11).

Many of the crinoids in these zones are well-preserved crowns with nearly complete stem and arms. They occur together in patches about 1 m in diameter on the bottoms of biomicrite beds, often with much stem and plate debris in the yellow-stained shaly bed immediately below. These patches probably represent small "gardens" of crinoids or other echinoderms with many individuals living together for a long period until catastrophically smothered by a sudden influx of limy sediment. Many specimens of *Archaeocrinus*, *Pararchaeocrinus*, and *Cremacrinus* occur in this manner; some groups of *Cremacrinus* are tightly packed and all facing the same way as if they were attached together to some object lying on the sea bottom. Some of these apparent gardens contain mostly one genus and species; others contain several different types of echinoderms occurring together.

The four localities in the Criner Hills are close enough together that it is nearly impossible to see any geographic variation in the occurrence

Table 12. Bromide echinoderm genera found as complete specimens in the *Carabocrinus* Beds.

Genus	Group	Number Complete Specimens	Percent Echino. Fauna	Number Localities	Rank
Carabocrinus	inadunate crinoid	11	37	2	1
Diabolocrinus	camerate crinoid	5	17	1	2
Platycystites	paracrinoid	4	13	1	3
Hybocrinus	inadunate crinoid	2	7	2	4-7
Palaeocrinus	inadunate crinoid	2	7	1	4-7
Acolocrinus	inadunate crinoid	2	7	2	4-7
Apodasmocrinus	inadunate crinoid	2	7	1	4-7
Pirocystella	rhombiferan	1	3	1	8-9
Urasterella	asteroid	1	3	1	8-9

of specific echinoderms. However, some variation in stratigraphic occurrence by zone was noted for some echinoderm genera. Most specimens of *Porocrinus*, *Hybocrinus*, *Praepleurocystis*, *Pararchaeocrinus*, *Anthracocrinus*, *Pyrgocystis*, *Anatiferocystis*, and *Urasterella* occur in the top 1 to 6 m of the Pooleville, including one large colony with over 100 echinoderms 2.5 to 3.0 m below the top at Rudd Quarry. If Zone 1 at Culley Creek is faulted up from lower in the Pooleville, then most specimens of *Archaeocrinus*, *Peltacrinus*, *Calceocrinus*, *Cremacrinus*, *Diabolocrinus*, *Quadrocystis*, and the two echinoids come from 9 to 13 m below the top of the Pooleville. Although the entire Pooleville sequence in the Criner Hills appears to be offshore subtidal (below wave base), water depth may gradually have become shallower during deposition of the upper Pooleville, so that the first fauna cited above may have been living in somewhat shallower water than the second.

CARABOCRINUS BEDS

The *Carabocrinus* Beds include at least two shaly limestone units that have produced complete echinoderms in the middle Mountain Lake about 11 to 13 m above the Lower Echinoderm Zone at the North-Central I-35 section, where this unit is best exposed. These beds also occur at North I-35, at Lick Creek, and perhaps at Amis Ranch at nearly the same stratigraphic position, but have not been located at other sections. The matrix is an alternating thin-bedded tan biomicrite and gray shale, bounded by thicker limestone beds, some of which contain hardgrounds. A lower shaly unit about 0.7 to 0.9 m thick has produced most of the complete echinoderms; another 0.6-m-thick, thin-bedded, shaly unit about 2.2 m higher has also yielded a few echinoderms. These beds can be identified by the gray to tan color of the matrix, which differs from the dark green shales found both above and especially below, and by the abundance of separate echinoderm plates (in particular *Carabocrinus*) which are characteristically overgrown by a thick layer of brown diagentic calcite (see Pl. 12, fig. 13). Plates of complete specimens are usually overgrown also, making identification and study more difficult.

This possible echinoderm zone was first discovered by Sprinkle in mid-1976 at the well-exposed North-Central I-35 section. However, two earlier specimens had apparently been collected from these beds at this section without their significance being realized: a specimen of *Acolocrinus* (Pl. 6, fig. 17-21) collected by Graffham in the late 1960's soon after the Interstate opened apparently came from these beds (based on its preservation and matrix), although mislabeled as coming from the Lower Echinoderm Zone; and a complete specimen of *Carabocrinus* collected here by Sprinkle in 1974 was also questionably assigned to the wrong zone. Measurement of this section, discovery of more complete echinoderms, and restudy of these early specimens resulted in their assignment to this possible new zone.

The *Carabocrinus* Beds have now produced 30 complete echinoderms from three localities (Table 12). *Carabocrinus* dominates this fauna with nearly 37 percent of the complete specimens, and *Carabocrinus* plates and stem segments are by far the most abundant fragmentary material found in these beds. The overall fauna in these beds is rather similar to that found in the underlying Lower Echinoderm Zone. Most of the genera and species appear to be the same in these two adjacent zones. *Hybocrinus* is much less common in the *Carabocrinus* Beds (7 percent) than in the Lower Echinoderm Zone

Table 13. Bromide echinoderm genera found as complete specimens (6 total) in the *Bromidocystis* Bed. (No complete specimens of *Bromidocystis* have yet been found, even though it is the most abundant plate type.)

Genus	Group	Number Complete Specimens	Percent Echino. Fauna	Number Localities	Rank
Sinclairocystis	paracrinoid	2	33	2	1
Arbucklecystis	paracrinoid	1	17	1	2-5
Acolocrinus	inadunate crinoid	1	17	1	2-5
Apodasmocrinus	inadunate crinoid	1	17	1	2-5
Diabolocrinus	camerate crinoid	1	17	1	2-5

(51 percent), while *Carabocrinus* and *Diabolocrinus* are more common in these beds. The *Carabocrinus* Beds have much less in common with the overlying *Bromidocystis* Bed and the Upper Echinoderm Zone, and very little in common with the Pooleville Echinoderm Zones.

The *Carabocrinus* Beds were probably deposited under fairly shallow-water shelf conditions along the hingeline at or just above wave-base. However, the water was probably deeper and the clay input less than in the underlying Lower Echinoderm Zone. Perhaps this is why different echinoderm genera dominate these two zones, even though the overall fauna is very similar.

BROMIDOCYSTIS BED

This 1-m shaly interval occurs immediately below a massive limestone ledge in the upper Mountain Lake Member about 13 m above the main *Carabocrinus* Bed, about 20 m below the base of the Upper Echinoderm Zone, and about 25 m below the top of the Mountain Lake at the North-Central I-35 locality. It also occurs in the creek bottom at Daube Ranch in the southern Arbuckles, where it is about 24 m below the top of the Mountain Lake Member. This bed was first recognized as a possible echinoderm zone by Sprinkle, who collected four complete echinoderms and many plates in mid-1977 from the North-Central I-35 locality; another echinoderm specimen from the same bed at Daube Ranch was found later that year. However, Fay had collected a single specimen of *Sinclairocystis* from this bed at Daube Ranch during the mid-1960's, and Graffham (pers. commun., July, 1977) also knew of this bed with its abundant plates and had tried digging here without success.

This bed is a distinctive interval of green shale alternating with thin limestone beds usually containing numerous large bryozoan colonies and the brachiopod *Sowerbyella*. Echinoderm plates are abundant, dominated by a distinctive large species of *Bromidocystis* (Pl. 37, fig. 36-45) that is known only from plates but gives the bed its name. Only six complete echinoderms have been collected from this bed (Table 13); the most common form is form is the paracrinoid *Sinclairocystis*, which in this bed has distinctive concave plates lacking pores. The new paracrinoid *Arbucklecystis* is also described from this zone based on a single well-preserved specimen.

The meager echinoderm fauna from the *Bromidocystis* Bed is not very similar to that of any other Bromide echinoderm zone. Several distinctive genera and species occur only here, but several genera are shared with other zones or beds in the Mountain Lake Member. This bed appears to represent a distinctive new echinoderm zone that should be searched for (and perhaps trenched) at other localities.

DISTRIBUTION OF BROMIDE ECHINODERM GROUPS

The three echinoderm zones and two additional echinoderm beds in the Bromide show gradual and abrupt changes in their echinoderm content. Different environmental conditions, sediment types, and time differences may be responsible for this. Crinoids in general are abundant and diverse in the Lower Echinoderm Zone and even more so in the Pooleville Zones, but drop off considerably in the intervening Upper Echinoderm Zone. Both inadunate and camerate crinoids show the same pattern through the Bromide. Paracrinoids are fairly common but not very diverse in the Lower Echinoderm Zone through the *Bromidocystis* Bed, then become extremely common and somewhat more diverse in the Upper Echinoderm Zone, but are almost completely absent from the Pooleville Echinoderm Zones. Edrioasteroids and rhombiferans are present through-

out the Bromide but make up only 1 to 5 percent of the echinoderm fauna. Some echinoderm groups do not appear until near the top of the Bromide; carpoids (homalozoans), echinoids, and holothurians first appear in the Pooleville although they remain rare.

Several echinoderm genera extend throughout the entire Bromide section, but only a few echinoderm species show this distribution. Genera ranging throughout the Bromide include *Hybocrinus*, *Archaeocrinus*, *Cleiocrinus*, *Diabolocrinus*, *Platycystites*, *Cyathocystis*, *Promopalaeaster*, and *Urasterella*, but this represents only about 14 percent of the echinoderm genera present. Most species seem to be confined to only a single zone; however, other species range through several zones in the Mountain Lake Member. Only three species (about 4 percent) extend throughout the Bromide from the Lower Echinoderm Zone in the Mountain Lake to the Pooleville Echinoderm Zones; these include *Cleiocrinus bromidensis*, *Cyathocystis americanus*, and questionably *Promopalaeaster* sp.

HOLDFASTS

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Holdfast is the general term for the structure used by stemmed echinoderms to attach to the substrate (Ubaghs, 1978, p. T88). The morphology of holdfasts ranges from simple attachment discs with circular or lobate outlines to complexly branching rootlike systems (radicular holdfasts). Holdfast morphology was in part genetically determined and in part controlled by the type of substrate to which the larvae attached. Hard, relatively smooth surfaces resulted in simple discs or radicular holdfasts with short "roots," while soft substrates or loose skeletal sand fostered the development of more elaborate radicular holdfasts (Halleck, 1973; Brett, 1978).

Early studies that included descriptions of holdfasts were primarily concerned with taxonomy (Hall, 1866; Sardeson, 1899, 1908; Springer, 1905; Ehrenberg, 1929; Faber, 1929; and Fenton, 1929a,b). Holdfasts are currently being reexamined because of their paleoecologic importance (Franzén 1976; Palmer and Palmer, 1977; Brett, 1978; Brett and Liddell, 1978). The site and mode of fixation are critical factors for attached echinoderms. For example, recent crinoid larvae do not develop normally if they are unable to find suitable attachment substrates (Mortensen, 1920). These substrates must have been especially important for species destined to spend all of their lives at the site of the original spat-fall. Other species apparently broke free from their holdfasts after an attached juvenile stage (Warn and Strimple, 1977). Because the holdfasts are often relatively solid, cemented masses of calcite, they tended to remain at the attachment site, while the stem and calyx commonly became disarticulated and scattered by currents and scavengers. If large enough attachment surfaces are available, holdfasts can yield information on the spatial distribution of individuals within populations, and of populations within communities (e.g., Franzén, 1976; Brett and Liddell, 1978).

Assignment of holdfasts to known taxa, which is a prerequisite for their use in paleoecologic studies, is made difficult by a number of factors. Specimens complete with calyx, stem, and holdfast are very rare because of the rapid disarticulation of echinoderm skeletons after death. Possible changes in morphology along the length of the stem make it difficult to match up the calyx and proximal part of the stem to its holdfast and attached distal stem if the morphology of the stem is incompletely known. Another problem is that many holdfasts are probably not distinct enough morphologically to be recognized at the genus or species level; two or more species may have holdfasts that are indistinguishable.

BROMIDE DATA

The collection of holdfasts from the Bromide Formation, over 1,200 specimens, is probably the largest ever made from one formation. In addition, many of the samples are probably relatively unbiased by the collection procedure, especially samples from such localities as Lick Creek, where productive zones were trenched and essentially all echinoderm material was recovered. In the Lower Echinoderm Zone at Fittstown Quarry and McLish Ranch, the holdfasts are distinctive and more abundant than calyces. Therefore, a special effort was made to collect all holdfasts during surface collecting of talus piles.

Early investigators named genera and species based only upon holdfasts and attempted to assign these form taxa to calyx material by means of compatible morphologies and mutual occurrences (e.g., Sardeson, 1908). The large samples from a number of localities and zones in the Bromide Formation allow a somewhat more quantitative approach than has been used in the past to relate holdfasts to known taxa. Nevertheless, taxonomic assignments are provisional, and therefore the holdfasts are described as morphotypes.

MORPHOTYPES

Only eight morphotypes account for the vast majority of well-preserved holdfast specimens in

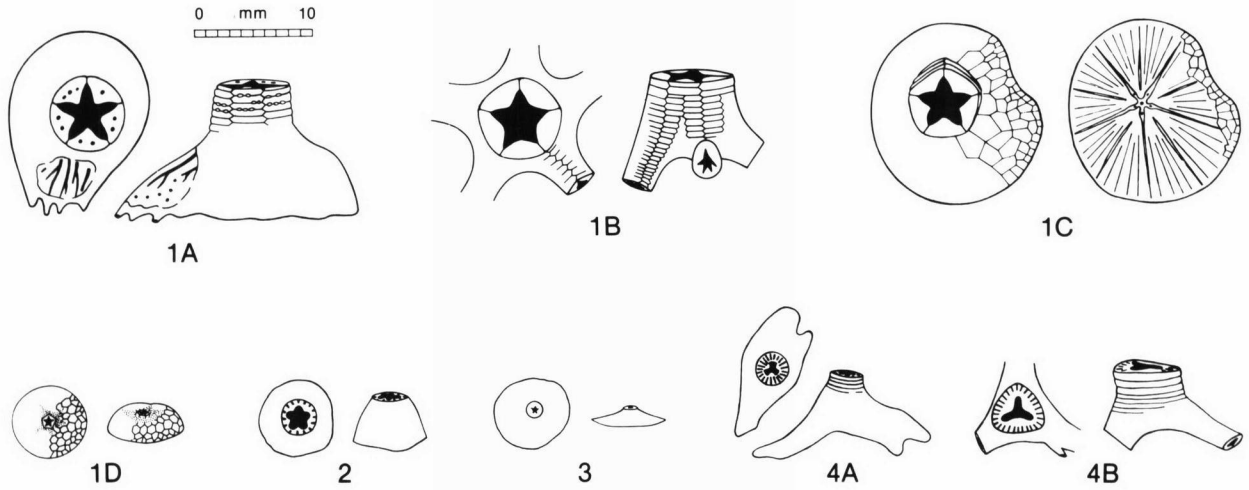

Fig. 16. Proximal and lateral (except 1C) views of each of the eight common holdfast morphotypes. In types 1A to 1D the attached stem is divided into pentameres and has a stellate axial canal. This pentaradial symmetry extends into the multiplated holdfast in types 1B to 1D, while type 1A is irregular in shape and is not multiplated. The stem of type 1A has platelets intercalated between some of the pentameres, and the stem facets and holdfast are penetrated by many small canals (shown in cut-away view). Type 1B has large, multiplated radicles extending from the points of the stellate axial canal. Each radicle is compressed laterally and has a modified pentalobate axial canal. Type 1C (*Podolithus*) consists of a multiplated upper part and a one-piece basal attachment plate with prominent radiating septa. Type 1D (*Lichenocrinus*) is a small holdfast similar to type 1C, but with a depressed area surrounding the base of the stem. Type 2 is a small, conical, one-piece holdfast with a relatively large, pentalobate lumen. It is similar to the holdfast of *Hybocrinus nitidus*. Type 3 is a very small disc-shaped to low conical holdfast with a shallow, concave stem cicatrix. Types 4A and 4B are characterized by their triradial symmetry and unipartite columnals. Type 4A is a small, digitate holdfast with an angular axial canal. Type 4B is larger, has a trilobate axial canal, and has three large radicles, one extending outward from each lobe.

all of the Bromide samples (Fig. 16). The attached stem is divided into pentameres in types 1A through 1D. The axial canal is stellate in cross section. Types 1C and 1D have a basal attachment plate (flooring plate), whereas types 1A and 1B do not. Types 2 and 3 are small, one-piece holdfasts with pentalobate lumens. Types 4A and 4B are one-piece holdfasts with stems made up of unipartite columnals with triradial axial canals.

TYPE 1A

Description.—This holdfast type is represented by hundreds of well-preserved specimens and is common in the major echinoderm zones of the Mountain Lake Member (Tables 14-18). It is a relatively large holdfast that is not multiplated and is penetrated throughout by small canals (approximately 0.2 mm in diameter). These canals are evident in weathered specimens (Pl. 3, fig. 10, 11) and also appear as small holes in the facets of attached columnals (Fig. 16). At the distal margin of the holdfast, some specimens have small, rootlike extensions (radicles), each with a small axial canal.

The attached stem is pentapartite with exceptionally well-preserved specimens showing small platelets between pentameres. The axial canal is sharply stellate.

Discussion.—The abundance of this holdfast type in the Lower Echinoderm Zone is puzzling when compared to the data based on complete or nearly complete calyces (Table 14). The size and morphology of type 1A is incompatible with *Hybocrinus*, the most abundant genus based on the calyx data. Pentapartite stems with stellate axial canals are virtually restricted to crinoids, so it is reasonable to eliminate the noncrinoid taxa from consideration. Holdfast type 1A must therefore correspond to one or more fairly large crinoids that have a pentapartite column, at least at the distal end. The stem is probably also fairly long, allowing for changes in morphology along its length. In several early Paleozoic crinoids, seemingly unipartite columnals in the proximal part of the column give way to pentapartite stems with offset pentameres distally (e.g., Warn and Strimple, 1977, text-fig. 11, 13; Lewis, 1981, text-fig. 2). A specimen of *Carabocrinus treadwelli* from the

Table 14. Whole calyx and holdfast incidence in the Lower Echinoderm Zone, Lick Creek. (Some taxa without holdfasts omitted.)

Genus	Calyx Data		Holdfast Data		
	No.	Percent	Morphotype	No.	Percent
Palaeocrinus	121	6.1	1A	417	71.8
Carabocrinus	30	1.5	--	--	--
Porocrinus	0	--	--	--	--
Cleiocrinus	0	--	1B	18	3.1
Reteocrinus	0	--	1C	11	1.9
Bromidocrinus	0	--	--	--	--
Apodasmocrinus	2	0.1	1D	0	--
Doliocrinus	0	--	--	--	--
Peltacrinus	0	--	--	--	--
Acolocrinus	0	--	--	--	--
Hybocrinus	1,371	69.5	2	19	3.2
	--	--	3	8	1.4
Diabolocrinus	8	0.4	--	--	--
Paracremacrinus	36	1.8	--	--	--
Archaeocrinus	4	0.2	--	--	--
Eumorphocystis	2	0.1	4A	43	7.4
Bromidocystis	3	0.15	4B	65	11.2
Platycystites	397	20.1	--	--	--
Total	1,974			581	

Lower Echinoderm Zone at Amis Ranch also demonstrates this pattern, although the distal part of the stem appears to be missing (Pl. 12, fig. 14). The holdfast is unknown for *Carabocrinus*, although it has been inferred to have had a *Podolithus* (type 1C) holdfast (Brower and Veinus, 1978).

I suggest that holdfast type 1A was formed by both *Carabocrinus* and *Palaeocrinus*, which are closely related, large-calyx, cladid, inadunate crinoids. In the *Carabocrinus* Beds, so called because of the abundance of large *Carabocrinus* calyx plates, the only holdfasts known are type 1A (Table 17) and they are especially large. The calyx and holdfast abundance data for the Lower Echinoderm Zone at Lick Creek (Table 14) suggest that holdfast type 1A can also be attributed to *Palaeocrinus*. The relative decrease in the number of type 1A holdfasts at the Fittstown Quarry locality (Table 15) corresponds to the decrease in *Palaeocrinus* calyces and dissociated plates.

Indirect evidence from other faunas also indicates that both genera have this type of holdfast. Type 1A holdfasts are known from the Lebanon Formation in Tennessee, which contains *Carabocrinus* but not *Palaeocrinus* (Thomas Guensburg, pers. commun.), and from the Oil Creek Formation, which has *Palaeocrinus* but not *Carabocrinus* (Lewis, 1982). This two-genus origin for type 1A helps to explain its dominance in Lower Echinoderm Zone exposures and suggests that *Palaeocrinus* and *Carabocrinus* are underrepresented in the calyx data.

TYPE 1B

Description.—Large radicles branching from the distal part of the holdfast give this morphotype a pronounced pentaradial symmetry. On such hard substrates as bryozoan colonies, only five large radicles are developed, although smaller radicles may branch from these major ones. Free specimens of this holdfast type, which were collected from shale beds, consist of an elongated holdfast with five major radicles given off at several levels (Pl. 3, fig. 21,22).

The attached column is pentapartite with a large, broadly stellate axial canal. Radicles extend outward from five points of the axial canal. Each is typically compressed laterally and has a modified pentalobate canal. The holdfast is made up of many small plates, but lacks the attachment plate found in types 1C and 1D. Pentameres of the most distal part of the stem divide in half to produce two prominant rows of biserially arranged, elongated plates on each major radicle (Fig. 16).

Discussion.—Morphotype 1B cannot be assigned with confidence to any of the known Bromide echinoderms. However, some circumstantial evidence suggests that it may belong to *Cleiocrinus*. The large axial canal of some specimens of this hold-

Table 15. Whole calyx and holdfast incidence in the Lower Echinoderm Zone, Fittstown Quarry. (Some taxa without holdfasts omitted.)

Genus	Calyx Data		Holdfast Data		
	No.	Percent	Morphotype	No.	Percent
Palaeocrinus	2	1.9	1A	48	14.7
Carabocrinus	2	1.9	--	--	--
Porocrinus	0	--	--	--	--
Cleiocrinus	1	0.9	1B	46	14.1
Reteocrinus	0	--	1C	30	9.2
Bromidocrinus	1	0.9	--	--	--
Apodasmocrinus	21	19.8	1D	0	--
Doliocrinus	4	3.8	--	--	--
Peltacrinus	0	--	--	--	--
Acolocrinus	0	--	--	--	--
Hybocrinus	21	19.8	2	4	1.2
	--	--	3	6	1.8
Diabolocrinus	1	0.9	--	--	--
Paracremacrinus	15	14.15	--	--	--
Archaeocrinus	12	11.3	--	--	--
Eumorphocystis	3	2.8	4A	142	43.3
Bromidocystis	16	15.1	4B	51	15.6
Platycystites	7	6.6	--	--	--
Total	106			327	

Table 16. Whole calyx and holdfast incidence in the Lower Echinoderm Zone, McLish Ranch. (Some taxa without holdfasts omitted.)

Genus	Calyx Data		Holdfast Data		
	No.	Percent	Morphotype	No.	Percent
Palaeocrinus	0	--	1A	49	19.1
Carabocrinus	1	2.7	--	--	--
Porocrinus	0	--	--	--	--
Cleiocrinus	1	2.7	1B	7	2.7
Reteocrinus	0	--	1C	38	14.8
Bromidocrinus	2	5.4	--	--	--
Apodasmocrinus	0	--	1D	1	0.4
Doliocrinus	1	2.7	--	--	--
Peltacrinus	0	--	--	--	--
Acolocrinus	0	--	--	--	--
Hybocrinus	2	5.4	2	11	4.3
	--	--	3	42	16.4
Diabolocrinus	0	--	--	--	--
Paracremacrinus	0	--	--	--	--
Archaeocrinus	0	--	--	--	--
Eumorphocystis	0	--	4A	79	31.0
Bromidocystis	0	--	4B	29	11.3
Platycystites	30	81.1	--	--	--
Total	37			256	

fast type are comparable to the axial canal of *Cleiocrinus* stems. Also, type 1B is found together with *Cleiocrinus* in the Upper Echinoderm Zone (see Pl. 3, fig. 29,30), where the morphotype is represented by many segments of radicles in addition to the data shown in Table 18.

If type 1B is *Cleiocrinus*, the holdfast appears to be atypical for the genus. Springer (1905, p. 111, pl. 5) described *Cleiocrinus regius* Billings as having a pentagonal to rounded stem with a very large, pentagonal, axial canal and terminating in a large, rounded holdfast not bearing radicles. Based partly on their unusually large size, holdfasts resembling type 1C from the Bobcaygeon Formation in Ontario have been ascribed to *Cleiocrinus* (Brett and Liddell, 1978), as have similar holdfasts from the Lebanon Formation of Tennessee (Thomas Guensburg, pers. commun.). However, no large holdfasts similar to those described from the Bobcaygeon and Lebanon formations have been found in the Bromide Formation.

TYPE 1C

Description.—Named *Podolithus* by Sardeson (1908) and *Disconia* by Westphal (1974a,b), this morphotype consists of two parts: a septate attachment plate at the base, which is apparently a single plate, and an upper portion made up of a large number of very small, polygonal plates. In side view, the holdfast is subconical and lacks the depression near the stem which characterizes the smaller *Lichenocrinus*. In top view, the outline is subcircular to lobate depending upon the configuration of the substrate.

The attachment plate displays marked pentameral symmetry because the large septa are arranged in orders of five septa each (Fig. 16). A small canal is located in the center of the plate, and a canal is also found in the proximal part of each of the five major septa. The attached stem is pentapartite, apparently lacks the platelets found in some specimens of type 1A, and has a stellate axial canal. The ridge formed by the inner projections at the middle of the pentameres connects with each of the five major septa on the attachment plate.

Discussion.—Sardeson (1908) described five species of *Podolithus* and assigned each to a different genus of crinoid based upon the mutual occurrence of holdfasts and calyx remains. He considered *P. strophocrinus* to be the holdfast of *Carabocrinus* (=*Strophocrinus*). Brower and Veinus (1978, text-fig. 3) also found this association convincing and reconstructed carabocrinids with very short stems and type 1C holdfasts. However, as discussed above, *Carabocrinus* in the Bromide Formation is known to have had a much longer stem

Table 17. Whole calyx and holdfast incidence in the *Carabocrinus* Beds, North-Central I-35, North I-35, and Lick Creek. (Some taxa without holdfasts omitted.)

Genus	Calyx Data		Holdfast Data		
	No.	Percent	Morphotype	No.	Percent
Palaeocrinus	2	7.1	1A	9	100
Carabocrinus	11	39.3	--	--	--
Porocrinus	0	--	--	--	--
Cleiocrinus	0	--	1B	0	--
Reteocrinus	0	--	1C	0	--
Bromidocrinus	0	--	--	--	--
Apodasmocrinus	2	7.1	1D	0	--
Doliocrinus	0	--	--	--	--
Peltacrinus	0	--	--	--	--
Acolocrinus	2	7.1	--	--	--
Hybocrinus	2	7.1	2	0	--
	--	--	3	0	--
Diabolocrinus	5	17.9	--	--	--
Paracremacrinus	0	--	--	--	--
Archaeocrinus	0	--	--	--	--
Eumorphocystis	0	--	4A	0	--
Bromidocystis	0	--	4B	0	--
Platycystites	4	14.3	--	--	--
Total	28			9	

and probably had a type 1A holdfast.

Sardeson was probably correct in concluding that this type of holdfast was formed by several genera of crinoids. These stems were probably fairly long with pentapartite distal regions. For example, a new species of the camerate crinoid *Reteocrinus* from the Lebanon Formation of Tennessee has a short, pentapartite dististele and a type 1C holdfast (Thomas Guensburg, pers. commun.). *Reteocrinus* is known in the Bromide Formation from one calyx at Lick Creek and another at Daube Ranch, but the multiplated calyx probably disarticulated quickly upon death of the crinoid. Such inadunate crinoids as *Doliocrinus* may also have had a type 1C holdfast if the stem was still attached to the substrate in the adult stage.

TYPE 1D

Description.—Type 1D is well known as *Lichenocrinus*, a small holdfast similar in general construction to type 1C (Warn and Strimple, 1977, review extensive literature on *Lichenocrinus;* Brower and Veinus, 1978). Like type 1C, it has a one-piece attachment plate, a multiplated upper portion, and a pentapartite stem with a stellate axial canal. It is distinguished from type 1C by its small size and by a depressed area at the base of the stem (Sardeson, 1908). It is commonly found attached to such hard substrates as bryozoans and brachiopod valves.

Discussion.—There is good evidence that type 1D holdfasts *(Lichenocrinus)* are the attachment structures for a variety of juvenile cincinnaticrinids and homocrinids (Kolata, 1975, p. 27; Warn and Strimple, 1977, p. 49-53). In the Bromide Formation, such small disparid inadunates are represented by *Apodasmocrinus* and *Doliocrinus* in the Mountain Lake Member and by *Peltacrinus* in the Pooleville Member.

TYPE 2

Description.—This small, cone-shaped holdfast has a subcircular to lobate outline depending on the configuration of the substrate. It seems to be of one-piece construction and not penetrated by canals. No attached stem is known, but the lumen of the holdfast itself is relatively large and pentalobate.

Discussion.—Because *Hybocrinus* is so abundant in collections from the Lower Echinoderm Zone, I made a special effort to identify its holdfast. Two specimens of *Hybocrinus nitidus* complete with cup, stem, and holdfast establish the general characteristics of the holdfast (Pl. 7, fig. 34-36). Morphotype 2 represents all holdfasts that have a comparable size and morphology.

As shown in Table 14, the small number of holdfasts does not correspond with the huge collections of *Hybocrinus* from many exposures of the Lower Echinoderm Zone; however, the holdfasts are small and rather nondescript. They could easily have been overlooked during trenching or surface collecting, whereas the compact calyces probably did not disarticulate readily and would have been conspicuous. It is noteworthy that the decrease in the relative number of *Hybocrinus* specimens at Fittstown Quarry (Table 15) is accompanied by a decrease in the percentage of the type 2 holdfast.

Table 18. Whole calyx and holdfast incidence in the Upper Echinoderm Zone, North-Central I-35 and North I-35. (Some taxa without holdfasts omitted.)

	Calyx Data		Holdfast Data		
Genus	No.	Percent	Morphotype	No.	Percent
Palaeocrinus	0	--	1A	9	28.1
Carabocrinus	0	--	--	--	--
Porocrinus	0	--	--	--	--
Cleiocrinus	2	2.4	1B	19	59.4
Reteocrinus	0	--	1C	1	3.1
Bromidocrinus	0	--	--	--	--
Apodasmocrinus	0	--	1D	0	--
Doliocrinus	0	--	--	--	--
Peltacrinus	0	--	--	--	--
Acolocrinus	0	--	--	--	--
Hybocrinus	2	2.4	2	1	3.1
	--	--	3	0	--
Diabolocrinus	2	2.4	--	--	--
Paracremacrinus	0	--	--	--	--
Archaeocrinus	0	--	--	--	--
Eumorphocystis	0	--	4A	1	3.1
Bromidocystis	0	--	4B	1	3.1
Platycystites	2	2.4	--	--	--
Oklahomacystis	71	85.5	--	--	--
Sinclairocystis	4	4.8	--	--	--
Total	83			32	

TYPE 3

Description.—Morphotype 3 is a very small, discoid to low conical holdfast found attached to such hard substrates as bryozoan colonies or brachiopod valves. Its stem cicatrix is a low pit with an ill-defined but probably pentalobate lumen. No attached columnals have been found, but

the cicatrix seems to indicate they were unipartite.

Discussion.—This relatively rare holdfast type is difficult to assign to a particular genus. Virtually any small or juvenile crinoid may have formed this morphotype. It is most abundant at McLish Ranch.

TYPE 4A

Description.—The shape of this small, lobate to digitate holdfast is quite variable and depends largely on the nature of the substrate. It is of one-piece construction and is not penetrated by canals. The attached stem is circular in cross section and consists of unipartite columnals. The axial canal is distinctive because it is triradial with three angular, wedge-shaped lobes.

Discussion.—This holdfast type is most abundant in the Lower Echinoderm Zone at Fittstown Quarry and McLish Ranch. It is very similar to the attachment structure of the rhombiferan cystoid *Caryocrinites* (Brett, 1978). Although the holdfast of *Caryocrinites* differs from morphotype 4A because of the development of numerous radicles, its angular triradial axial canal is virtually identical to that of the Bromide holdfasts. This provides a clue to the identity of the morphotype, but definite assignment to genus is not possible at this time. Apparently, none of the Bromide rhombiferans (except perhaps *Hesperocystis)* was attached distally to the substrate. The stem of the diploporan cystoid *Eumorphocystis* consists of unipartite columnals with an axial canal that is circular in cross section in the proximal and mid-

PLATE 3.

Fig. 1-9. Echinoderm specimens overgrown by bryozoan colonies, Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1-3 from Daube Ranch, 4-9 from Lick Creek. 1, 2. Side and oral views of specimen 1221TX35 of *Hybocrinus nitidus* almost completely overgrown by an adjacent bryozoan colony (right); X1.3. 3. Side view of large cup OU 8838 of *Carabocrinus treadwelli* overgrown by a bryozoan; note characteristic plate ridges still visible through thin bryozoan cover near exposed spot; X1.5. 4. Oral view of *Hybocrinus nitidus* cup OU 8855 overgrown by a highly digitate bryozoan; note proximal brachials also overgrown; X1.4. 5. Side view of overgrown calyx OU 8861 of *Hybocrinus nitidus* showing proximal arms still attached and overgrown; X1.3. 6, 7. Side and basal views of elongate theca OU 9175 of *Bromidocystis bassleri*, n. gen., n. sp., showing traces of plate sutures and internal epitaxial calcite crystals at base; X1.3. 8, 9. Side and oral views of cup OU 8920 of *Hybocrinus nitidus;* note covered oral region and proximal brachials; X1.3.

Fig. 10-17, 21-35. Holdfasts and distal stem terminations, Bromide Formation, southern Oklahoma; 10, 11, 15, 16, 32, 33 from the Lower Echinoderm Zone, Mountain Lake Member, McLish Ranch; 12, 21, 22, 24, 27 from the Lower Echinoderm Zone, Mountain Lake Member, Fittstown Quarry; 13, 14, 17, 23, 25, 26, 28 from the Lower Echinoderm Zone, Mountain Lake Member, Lick Creek; 29, 30 from the Upper Echinoderm Zone, Mountain Lake Member, Buckhorn Ranch; 31 from the top 6.0 m of the Pooleville Member, Rock Crossing; 34, 35 from the top 7.5 m of the Pooleville Member, Dunn Quarry. 10, 11. Proximal (top) and distal (bottom) views of weathered type 1A holdfast 1113TX33 showing one-piece construction and many small canals; X1.3. 12. Proximal view of attachment plate of type 1C holdfast 1279TX319 exposed by weathering of upper, multiplated part of holdfast; note pentameral symmetry shown by different orders of radiating septa; X1.3. 13. Oblique proximal view of type 1C holdfast 1107TX8 showing multiplated upper part of holdfast and attached stem with stellate axial canal; X1.2. 14. Proximal view of type 1B holdfast 1107TX9 showing stellate axial canal and 5 major radicles; X1.4. 15, 16. Lateral and proximal views of type 1C holdfast 1113TX34 wrapped around a bryozoan; note pentameres in stem and polygonal plates in holdfast; X1.3. 17. Proximal view of a cluster of type 1A holdfasts (1107TX10) attached to bryozoan colony; X1.3. 21, 22. Proximal and lateral views of large type 1B holdfast 1279TX322 showing rootlike morphology with major radicles arranged in 5 tiers; X1.6. 23. Proximal view of type 1B holdfast 1107TX11 attached to a possible hardground substrate; note small rootlets spreading out on surface; X1.3. 24. Oblique proximal view of small type 1A holdfast 1279TX323 wrapped around a bryozoan; X1.3. 25. Small type 4A holdfast 1107TX12 attached to a ramose bryozoan; note triradial axial canal; X1.4. 26. Small type 4B holdfast 1107TX13 showing trilobate lumen and 3 associated large radicles; X1.3. 27. Empty *Cyathocystis* cup and a very small possible type 2 holdfast 1279TX324 cemented to a small ramose bryozoan; X1.4. 28. Large type 1A holdfast OU 8928 cemented to a pile of bryozoan fragments; note pentameres and intervening platelets in attached stem; X1.3. 29, 30. Lateral and proximal views of large type ?1B holdfast OU 9181; note broken proximal end of this multiplated holdfast shows large lumen similar to holdfasts attributed to *Cleiocrinus;* X1.4. 31. Very small type 1D holdfast 1281TX13 cemented to a brachiopod; note small pentagonal stem and depressed area in holdfast at base of stem; X5.6. 32. Numerous, small, weathered, type ?4A holdfasts (1113TX35) attached to a large bryozoan colony; X0.95. 33. Two large type 1C holdfasts (1113TX36) cemented to a large domal bryozoan colony; upper, multiplated part of holdfast weathered away exposing septate attachment plate in top holdfast; X1.3. 34, 35. Distal and lateral views of large, flanged archaeocrinid stem OU 9182 wrapped around a spicular sponge ?holdfast; over 195 mm of distal stem are present here; X1.2

Fig. 18-20. Specimens with borings; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Fittstown Quarry, northeastern Arbuckle Mountains, southern Oklahoma. 18, 19. Exterior and enlarged edge view of *Carabocrinus treadwelli* radial 1279TX320 showing small hemispherical pits not penetrating to interior; X1.2, X2.6. 20. Aboral side of *Carabocrinus treadwelli* arm 1279TX321 showing multiple pits on interbrachial sutures; X2.5.

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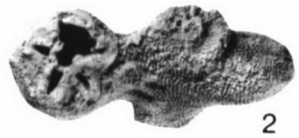
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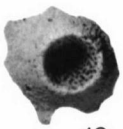
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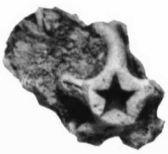
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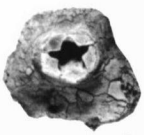
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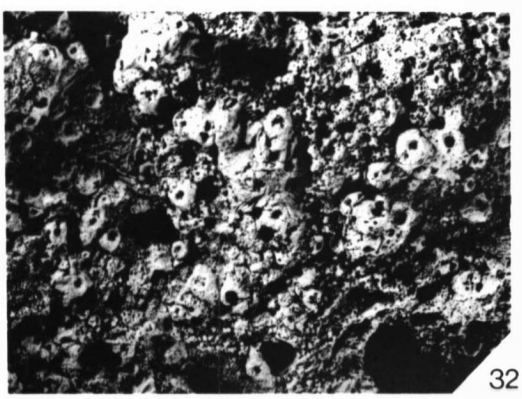
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Table 19. Whole calyx and holdfast incidence in the Pooleville Member, six localities. (Some taxa without holdfasts omitted.)

	Calyx Data		Holdfast Data		
Genus	No.	Percent	Morphotype	No.	Percent
Palaeocrinus	0	--	1A	0	--
Carabocrinus	0	--	--	--	--
Porocrinus	21	4.6	--	--	--
Cleiocrinus	14	3.0	1B	0	--
Reteocrinus	0	--	1C	0	--
Bromidocrinus	0	--	--	--	--
Apodasmocrinus	0	--	1D	1	100
Doliocrinus	0	--	--	--	--
Peltacrinus	18	3.9	--	--	--
Acolocrinus	1	0.2	--	--	--
Hybocrinus	40	8.7	2	0	--
	--	--	3	0	--
Diabolocrinus	42	9.1	--	--	--
Calceocrinus	15	3.2	--	--	--
Cremacrinus	65	14.1	--	--	--
Paracremacrinus	0	--	--	--	--
Archaeocrinus	180	39.1	--	--	--
Pararchaeocrinus	27	5.9	--	--	--
Anthracocrinus	35	7.6	--	--	--
Eumorphocystis	0	--	4A	0	--
Bromidocystis	0	--	4B	0	--
Platycystites	2	0.4	--	--	--
Total	460			1	

dle portions. Unfortunately, the distal stem of *Eumorphocystis* is unknown at present.

TYPE 4B

Description.—Morphotype 4B is a medium-sized, digitate holdfast displaying marked triradial symmetry. It is apparently not multiplated and consists of three main radicles at angles of approximately 120 degrees from each other.

The attached stem is composed of unipartite columnals with a rounded triangular outline. The axial canal is large and trilobate. Each of the three lobes of the axial canal becomes the axial canal of a major radicle.

Discussion.—Holdfast types 4A and 4B are both quite variable in morphology. In general, type 4B seems to be larger, has well-developed radicles, and has a lobate, rather than an angular, axial canal. It is possible that they represent different ontogenetic stages of the same echinoderm.

Morphotype 4B is tentatively assigned to the eocrinoid *Bromidocystis*. Large specimens of this holdfast type are found in the *Bromidocystis* Bed together with abundant dissociated calyx plates of this genus. Although the axial canal of *Bromidocystis* is oval in the proximal part of the stem, a long stem fragment from the *Bromidocystis* Bed demonstrates the change necessary to link *Bromidocystis* with holdfast type 4B. The axial canal of this specimen is subcircular in cross section on one end and trilobate on the other. This change in shape of the axial canal is also known in *Caryocrinites* (Brett, 1978).

SUMMARY

In spite of the great diversity of the echinoderm fauna in the Bromide Formation, only eight holdfast morphotypes are recognized. Part of the explanation for this is that some of the taxa lacked holdfasts. The near absence of holdfasts from the Pooleville Member (Table 19) reflects the dominance of archaeocrinids, which probably lacked holdfasts at maturity (Pl. 3, fig. 34, 35). The taxa believed to be responsible for most of the Mountain Lake holdfasts—*Palaeocrinus*, *Carabocrinus*, and *Bromidocystis*—are not found in the Pooleville Member.

The small number of holdfast types is probably also a result of indistinct morphotypes shared by two or more taxa. In addition, some small and nondescript holdfasts (such as those of *Hybocrinus*) may not have been collected.

Classification of the eight morphotypes, although artificial, leads to some interesting generalizations. Many Ordovician inadunate and camerate crinoids probably had distal stems made up of alternating pentameres even though the proximal parts of the stems appear to consist of unipartite columnals. This type of distal stem could terminate in any of the type 1 holdfasts. Other crinoids (such as *Hybocrinus*) have a multiplated distal stem and others have single-piece columnals. The triradial symmetry shown in the axial canals of morphotypes 4A and 4B is in marked contrast to the circular or pentaradial axial canals of crinoids. This trilobate cross section of the axial canal in the distal stem may prove to be restricted to noncrinoid taxa.

AGE AND CORRELATION USING BROMIDE ECHINODERMS

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Echinoderms have not been used often to determine the age of a formation. They are usually too rare and patchy throughout a stratigraphic section, too provincial in their geographic extent, and not well enough studied in many areas. However, the Bromide Formation has a very large and well-known echinoderm fauna divided into several zones, each characterized by a particular assemblage of echinoderms that might be useful in correlation. In addition, other fossil groups in the Bromide have been fairly well studied, so that much biostratigraphic information is available. These lines of evidence lead to the conclusion that the Bromide Formation is most likely of Blackriveran (or Porterfieldian) age.

AGE OF BROMIDE BASED ON OTHER GROUPS

Several different groups of marine fossils have been used to date the Bromide Formation, including brachiopods (Cooper, 1956, 1976), ostracods (Harris, 1957), bryozoans (Loeblich, 1942), conodonts (Sweet and Bergström, 1973, 1976; Sweet, Bergström, and Carnes, 1973), graptolites (Decker, 1936a, 1952), trilobites (Shaw, 1974; Shaw and Fortey, 1977; Ludvigsen, 1978), and acritarchs (Loeblich and Tappan, 1978). Almost all of these authors considered a large part of the Bromide to be Blackriveran (or Porterfieldian) in age. The only exceptions to this were Loeblich (1942), who considered the Bromide to be of younger Trentonian age based on bryozoans (but see Loeblich and Tappan, 1978, for a later, different opinion), and Decker (1952), who assigned a Trentonian age based on graptolites. About 25 percent of the remaining authors considered the Bromide to be entirely of Blackriveran (or Porterfieldian) age based on trilobites (Shaw, 1974), graptolites (Decker, 1936a), acritarchs (Loeblich and Tappan, 1978), or correlation of insoluble residues (Ireland, 1965). Nearly 40 percent of the authors believed the lower Bromide is of Chazyan (or Marmoran) age based on trilobites (Shaw and Fortey, 1977; Ludvigsen, 1978), conodonts (Sweet and Bergström, 1973), all fossils (Twenhofel and others, 1954), or physical stratigraphy (Dapples, 1955). A few authors believed the upper Bromide to be Trentonian (or Wildernessian) in age based on ostracods (Harris, 1957), bryozoans (Farmer, 1974), or subsurface data (Schramm, 1965a). Finally, a few authors believed the Bromide Formation ranges all the way from Chazyan to Wildernessian in age based on brachiopods (Cooper, 1956, 1976) and conodonts (Sweet and Bergström, 1976). This extended range of time includes the British Llandeilian and early Caradocian, and most authors (for example, see Twenhofel and others, 1954; Ross, 1976) would probably agree that the Bromide falls somewhere in this interval.

AGE OF BROMIDE BASED ON ECHINODERMS

Known echinoderm faunas in general indicate a Blackriveran (or Porterfieldian) age for the entire Bromide Formation. Paracrinoids are abundant in the Mountain Lake Member, and elsewhere in North America these forms range from the Chazyan to Trentonian. The Bromide paracrinoids (especially *Platycystites* as used by Parsley here and *Oklahomacystis)* correlate with the Benbolt and Hogskin formations of the central Appalachians, with the Lebanon Limestone of Tennessee, and with the Stones River Formation of central Alabama. Early crinoids are common in the middle Mountain Lake and become even more diverse in the Pooleville. Such genera as *Hybocrinus, Carabocrinus, Palaeocrinus, Porocrinus, Archaeocrinus, Cremacrinus, Diabolocrinus, and Cleiocrinus* are found in many other Chazyan, Blackriveran, and Trentonian units as part of the initial crinoid radiation in the Middle Ordovician. The Bromide lacks some of the most characteristic echinoderms found elsewhere in the Chazyan, such as rhipidocystid eocrinoids and parablastoids. However, both of these archaic blastozoan groups do occur in the Arbuckle Mountains of Oklahoma in the underlying Oil Creek For-

mation (Lewis, 1982), which is considered to be of Whiterockian age. Finally, the top of the Pooleville has the earliest echinoids and holothurian sclerites similar to those found in the Platteville Group, which is also considered to be Blackriveran in age (Kolata, 1975; Willman and Kolata, 1978).

The echinoderm fauna of the Bromide Formation shows perhaps the greatest similarity to the Benbolt and Hogskin formations (Ottosee Group) of southwestern Virginia and northeastern Tennessee (see Brower and Veinus, 1974; Parsley and Mintz, 1975; Frest, Strimple, and McGinnis, 1979). Many of the crinoid and paracrinoid genera listed above occur in both faunas, as do similar species of the following echinoderm genera: the new camerate *Colpodecrinus*, the inadunate *Acolocrinus*, the diploporan *Eumorphocystis* (=*Regnellicystis* in the Benbolt), the edrioasteroid *Cyathocystis*, the stylophoran *Anatiferocystis*, the rhombiferan *Pleurocystites*, and plates of the edrioblastoid *Astrocystites*. However, only two species (*Palaeocrinus planobasalis* and *Cyathocystis americana*) are thought to occur in both areas although some other species are very similar. The Benbolt and Hogskin may be slightly older than the Bromide because they contain the eocrinoid *Batherocystis* and the parablastoid *Meristoschisma*.

The Bromide echinoderm fauna shares many genera and perhaps a few species with a large, mostly undescribed fauna from the Lebanon Limestone of central Tennessee, based on work by Tom Guensburg of the University of Illinois. The Lebanon fauna includes such forms as *Cleiocrinus*, *Archaeocrinus*, *Ablutoglyptocrinus*, *Apodasmocrinus* cf. *A. daubei*, *Doliocrinus*, *Hybocrinus*, *Porocrinus*, *Carabocrinus*, *Quinquecaudex*, *Bothriocidaris*, *Unibothriocidaris*, *Oklahomacystis* (similar to the two-armed *O. bibrachiatus*, n. sp.), *Cyathocystis*, *Tanaocystis*, and *Praepleurocystis* cf. *P. watkinsi*. Guensburg (pers. commun., August 26, 1980) has noted that, in the Lebanon echinoderm fauna: "...echinoids plus some cystoids and camerate crinoids closely resemble Pooleville forms, while long-armed disparid inadunates better coincide with Mountain Lake forms." He believes that the Lebanon Limestone is early Blackriveran in age based on the entire fauna. The Lebanon echinoderm fauna lacks all eocrinoids, parablastoids, and edrioblastoids, but does contain several paracrinoids, which may help in correlations to other areas. Based on available information, the Lebanon Limestone correlates best with the upper half of the Bromide, including the Upper Echinoderm Zone and the Pooleville Member.

Another echinoderm fauna similar to that of the Bromide is found in the Birmingham, Alabama, area in the Stones River Formation (see Drahovzal and Neathery, 1971), especially the reef-bearing Gate City Member and the underlying Carters Member (local usage; equivalent to the Carters Formation of Tennessee). Based on collecting by Gorden L. Bell, Jr., and other workers in the Birmingham region, the unpublished fauna of the Gate City Member, which is closely associated with small algal and stromatoparoid reefs, contains *Platycystites* sp., *Oklahomacystis tribrachiatus*, *Cyathocystis* sp., *Cleiocrinus* cf. *C. tesselatus*, *Hybocrinus* sp., *Carabocrinus* sp., and a possible *Colpodecrinus*. The underlying Carters Member contains *Pleurocystites* sp., *Carabocrinus* sp., and a small inadunate crinoid resembling *Apodasmocrinus* or *Praecursoricrinus*. The Gate City fauna closely resembles that from the Upper Echinoderm Zone at the top of the Mountain Lake Member of the Bromide, and is the only fauna outside southern Oklahoma in which *Oklahomacystis* and specifically *O. tribrachiatus* is known. The Carters fauna is less diagnostic but shows some resemblance to faunas of both the Lower and Upper Echinoderm zones of the Mountain Lake. Local workers in the Birmingham area (G. L. Bell, Jr., pers. commun., March 29, 1980) consider the Gate City and Carters members to be Blackriveran in age based on abundant brachiopods and trilobites, although the Carters Formation of Tennessee has been assigned in the past to the Trentonian (Wildernessian) (Twenhofel and others, 1954).

The Bromide echinoderm fauna also shares a number of genera with the Platteville and Galena groups of northern Illinois and adjacent areas (Kolata, 1975). Several of the crinoid genera (but no paracrinoids) listed above occur in both faunas as do similar species of the following echinoderm genera: the homoiostelean *Myeinocystites;* the rhombiferans *Praepleurocystis*, *Pleurocystites*, and *Tanaocystis* (=*Coronocystis durandensis* in the Platteville); the echinoids *Bothriocidaris* and *Unibothriocidaris;* and the holothurian *Thuroholia* (represented by sclerites). The Platteville and Galena groups may be slightly younger (or represent somewhat different environments) than the Bromide because paracrinoids and *Cyathocystis* are apparently missing. The Platteville is generally considered to be of Blackriveran age whereas the Galena is early Wildernessian (Kolata, 1975; Willman and Kolata, 1978).

The Bromide echinoderm fauna also shows many

similarities to that of the Ottawa Group (Hull, Sherman Falls, and Cobourg formations) of southeastern Ontario (Wilson, 1946), which is Trentonian (Wildernessian) in age. All of the crinoid genera (except *Diabolocrinus*) listed above occur in both faunas, but none of the species are the same. The following genera also occur in both faunas: the rhombiferan *Pleurocystites;* the edrioblastoid *Astrocystites;* the cyclocystoid *Cyclocystoides;* and the starfish *Hudsonaster, Petraster, Promopalaeaster,* and *Urasterella.* However, the Ottawa Group contains different paracrinoids and many cystoids and crinoids more advanced than those of the Bromide, probably implying a younger age.

Other Middle Ordovician echinoderm faunas are much more poorly known or share few genera with the Bromide, clearly implying an older or younger age. Thus, the Bromide echinoderm faunas seem to correlate best with those of the Benbolt and Hogskin formations in Virginia and Tennessee, which appear to be the same age or slightly older, the Lebanon Limestone in central Tennessee and the Stones River Formation in Alabama, which may be about the same age, the Platteville and lower Galena groups in Illinois and adjacent states, which appear to be the same age or slightly younger, and the Ottawa Group in southeastern Ontario, which is probably younger. Based on these correlations using echinoderms, I favor a Blackriveran (or Porterfieldian) age for the entire Bromide, in agreement with correlations based on several other fossil groups, but not with all.

ECHINODERM PALEOECOLOGY

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The Bromide Formation is well-suited for paleoecologic interpretations for a number of reasons. Its fossils are abundant and its sediment shows a wide variety of textures. Good outcrops permit study of continuous lithostratigraphic sequences both vertically and laterally, and its depositional setting across the margin of an aulacogen included both a stable platform and a subsiding basin. Detailed analysis of lithofacies in the Bromide on the basis of sediment textures, sedimentary structures, fauna, and vertical sequences reveals that the Mountain Lake Member of the Bromide Formation was deposited in a storm-dominated epeiric sea during a slow marine transgression whereas the overlying Pooleville Member was deposited during a period of relatively stable sea level that allowed sediment to fill in the platform adjacent to the aulacogen and begin filling the basin (Longman, 1976; this volume).

Correlation of lithofacies in measured sections reveals that deposition of the Mountain Lake Member began on a ramp that dipped gently to the southwest (present coordinates) across the northern margin of the Southern Oklahoma aulacogen. With continued slow transgression and more rapid subsidence in the aulacogen, this ramp eventually evolved into a carbonate shelf-to-basin profile when a shelf-edge buildup constructed by carbonate-producing organisms formed near the end of deposition of the Mountain Lake. Pooleville deposition began on the same shelf-to-basin profile but eventually changed back into a simple ramp when the platform adjacent to the aulacogen was filled with sediment.

This chapter summarizes the paleoecology of Bromide echinoderms. Within the depositional framework presented above, it is possible to interpret the paleoecology of the echinoderm zones with a fair degree of accuracy and without the vulnerability created by using the fauna alone to determine paleoenvironments. Other factors influencing the distribution of echinoderms in the Bromide, such as preservation and collecting biases, are also discussed. The chapter concludes with a discussion of possible explanations for the nonhomogeneous distribution of echinoderms in the Bromide.

PRESERVATION OF ECHINODERM SPECIMENS

Specimens from the echinoderm zones in the Mountain Lake Member generally occur in a green or tan shale or on the surface of thin slabs of bryozoan or crinoid calcarenite interbedded within the shale. Specimens from echinoderm zones in the Pooleville Member occur in a soft shaly biomicrite or on surfaces of the interbedded, harder biomicrites. Only in the Upper Echinoderm Zone along the hingeline are complete calyces preserved in biosparites, and even here echinoderms are easily collected only on bedding planes in contact with shale laminae.

The shaly nature of most of the echinoderm-rich beds facilitates specimen preparation, and many echinoderms have well-preserved exteriors with delicate ornamentation and appendages. Some specimens, however, show weathering, or diagenetic alteration of the exterior surface. In the Upper Echinoderm Zone beds at Nebo where the bedding is nearly horizontal (unusual for Bromide exposures), several specimens of the rhombiferan *Strabocystis* (Pl. 31, fig. 1-4, 17-19) have the uppermost side of the theca weathered and the opposite side covered with caliche that has obscured much of the surface morphology. Most specimens (and some separate plates) from the *Carabocrinus* Beds, a few specimens and plates from the *Bromidocystis* Bed, and a few specimens and plates from the Lower Echinoderm Zone in the northeastern Arbuckles have thick epitaxial overgrowths of dark gray or brown diagenetic calcite on the exterior surface (Pl. 24, fig. 13; Pl. 28, fig. 26-28) in optical continuity with the underlying plates (see Müller, 1979, p. A63). Small plates or appendages in complete specimens do not show these overgrowths, but

large plates have thick layers and are separated by deeply depressed V-shaped sutures where the overgrowths from adjacent plates have grown apart. These calcite overgrowths are similar (except in their darker color) to those found in the calyx interior of many complete specimens.

Sediment compaction has also significantly affected echinoderm preservation. Some specimens from the Mountain Lake had holes punched in their thecal wall by ramose bryozoans or stem segments during compaction (Pl. 25, fig. 9,10; Pl. 26, fig. 11; see also Frest, Strimple, and McGinnis, 1976, fig. 1,8). The amount of calyx deformation during compaction was controlled in part by calyx size and shape, plate thickness and ornament, number and size of plates, and type of calyx filling. Large calyces were more easily crushed than small ones. Globular or ellipsoidal calyces were more easily crushed than conical, lens-shaped, or nearly flat calyces. Calyces with thin, unornamented, or only slightly ornamented plates were more easily crushed than calyces with thick plates and heavy ornament that extended from plate to plate.

Probably the most important factor in the preservation of whole uncrushed echinoderm calyces in the Bromide was the filling of the interior cavity with epitaxial calcite cement in thick scalenohedral crystals prior to sediment compaction (Longman, 1980, p. 477). Complete specimens having a shale filling that entered the coelomic cavity during burial lack thick calcite crystals and were usually crushed during compaction because of the lack of rigid internal support for the plates. Calyx size and shape are also important in the growth of shape-preserving internal calcite crystals; small calyces and lens-shaped or flattened calyces have a shorter distance for these calcite crystals to grow to meet in the center. These factors have probably increased the preservability of *Hybocrinus*, which has a fairly small, compact, somewhat conical calyx with a few plates, aiding the growth of internal calcite crystals to support the fairly thin, slightly ornamented plates. *Hybocrinus* is also easy to pick out of the matrix during digging, another factor which has increased its percentage in several zones. *Platycystites* is a large thin-plated genus whose thecal shape (lens-shaped to flattened) has made it easier for calcite crystals to grow across the coelomic cavity, thus forming a solid interior and preserving many specimens uncrushed and complete. This may explain why *Platycystites* is the second most abundant genus in the Lower Echinoderm Zone (23 percent of the fauna based on calyces). *Oklahomacystis*, the most common echinoderm in the Upper Echinoderm Zone (92 percent of the calyx fauna), was commonly preserved because it had a medium-sized globular calyx composed of heavily ornamented and tightly sutured plates that held together well even if transported by currents or internally filled with shale. At the opposite extreme, *Bromidocystis* is rare as complete specimens (only 0.4 percent of the fauna in the Lower Echinoderm Zone), even though its plates are common to abundant at most localities and its inferred holdfast (see chapter by Lewis, this volume, and Pl. 3, fig. 25, 26) may make up 15 percent of the total holdfast fauna in this zone. This genus has a large, club-shaped theca with numerous medium-sized plates; even though these plates are thick and heavily ornamented, the sutural pores weakened connections and allowed most thecae to fall apart easily after death unless buried rapidly or overgrown by encrusting bryozoans.

The completeness of Bromide echinoderms, including preservation of delicate appendages, must have been closely related to the rate of burial as well as the early precipitation of internal epitaxial crystals. Well-preserved specimens with delicate appendages attached were probably buried either alive or within a few hours of death (Liddell, 1975; Sprinkle and Gutschick, 1967, p. 400) and escaped disarticulation by burrowing organisms after burial. Complete calyces lacking appendages may have been exposed on the sea floor for a somewhat longer time. Most separate plates probably originated from specimens that were not buried rapidly and were disarticulated by scavengers or currents. Burrowing organisms, although rare in the Bromide, probably also contributed to the disarticulation of a few echinoderms, and some separate plates probably came from crushed or even whole specimens that fell apart during weathering or excavation.

DEPOSITIONAL ENVIRONMENTS OF ECHINODERM ZONES

Southern Oklahoma was in the Southern Hemisphere Tropics during the Middle Ordovician (Ziegler and others, 1979), implying a warm climate with little seasonal temperature variation. The presence of abundant echinoderms, brachiopods, trilobites, and cephalopods implies normal marine salinity for all of the Bromide except for the uppermost Pooleville to the northeast on the Arbuckle platform where tidal flat deposits are present. The Southern Oklahoma aulacogen acted much

Table 20. Environmental, sedimentological, and time differences among Bromide Echinoderm zones and beds that may have affected composition of echinoderm faunas (data adapted from Longman, 1976).

Zone	Part of Cycle	Shelf Setting	Water Depth	Sediment Type	Time
Pooleville Echinoderm zones	regressive	carbonate ramp (platform filled in)	medium to deep, below wave base	carbonate mud-dominated	late
Upper Echinoderm zone	end of transgression	carbonate platform with influx of clays	shallow to deep, above to below wave base	shale dominated, locally biosparite	middle
Lower Echinoderm zone plus Carabocrinus and Bromidocystis beds	transgressive	carbonate ramp with influx of clays	shallow to medium, above storm wave base	shale dominated	early

like a stable continental shelf except that it subsided more rapidly than most shelves during the early part of Bromide deposition; this implies the presence of waves, tides, bottom currents, and periodic storms. The presence of benthic calcareous algae indicates that the sea bottom in most areas was in the photic zone.

Using the lithostratigraphic analysis of Longman (1976) as a basis, it is clear that the three echinoderm-rich intervals in the Bromide were deposited under significantly different conditions, both in terms of regional setting and local bottom conditions (Table 20). The Lower Echinoderm Zone occurs near the middle of the Mountain Lake Member about 6 to 8 m above the uppermost sandstone beds, which are interpreted as having been deposited in a lower shoreface environment. Deposition of the Lower Echinoderm Zone occurred on a gently sloping ramp during a marine transgression. Much terrigenous clay was mixed with the carbonate sediment in the early stages of the transgression. Water depth during deposition of the Lower Echinoderm Zone probably ranged from only 3 to 5 m on the updip portion of the ramp in the northeastern Arbuckles to about 30 m in the southwestern Arbuckles and Criner Hills. The richest echinoderm localities occur along the hingeline in water depths inferred to have been about 15 to 20 m. Deposition occurred below the zone of normal wave base as shown by the predominance of muddy sediment, but above storm wave base as indicated by the local occurrence of well-sorted thin beds of calcarenite.

The Upper Echinoderm Zone occurs just below the top of the Mountain Lake Member, in many places just above a thick, nearly barren shale interval. It is also a mixed carbonate-clastic unit, but was deposited in a carbonate platform setting near the maximum of Bromide transgression. Water depths ranged greatly across the area, from perhaps 10 m in the shallow lagoon to the northeast to about 75 m in the fairly deep-water basin to the southwest according to evidence discussed by Longman (1976). The entire Arbuckle Mountain region was probably submerged below normal wave base during deposition of the Upper Echinoderm Zone, but an extensive carbonate buildup composed mainly of echinoderm debris formed along the hingeline and rose above storm wave base. This buildup separated the lagoon from the basin and absorbed most wave energy during storms. Thus, micrite and shale accumulated in the low-energy lagoon and basin while calcarenite accumulated in the buildup.

The Pooleville Zones occur in the upper half of the Pooleville Member, mostly in the Criner Hills. They occur in a sequence of biomicrites deposited in moderate- to deep-water conditions on a carbonate ramp near the end of the upper Bromide regression. Water depth in the Criner Hills area was below storm wave base, probably somewhere between 25 and 60 m. The wide range reflects the uncertainty about where the Criner Hills were located in the Southern Oklahoma aulacogen (Longman, 1976; Walper, 1977).

SUBSTRATE

All three echinoderm zones contain fossils in a muddy matrix, implying that a soft bottom composed of clay or carbonate mud was present during deposition. When currents were present, there was probably some turbidity in the water column near the sea floor. In only a few places did "floating brachiopods" colonize a soft bottom in a short-term ecologic succession such as that described by Walker and Alberstadt (1975). One such sequence of beds occurs immediately above the Lower Echinoderm Zone in the northeastern Arbuckles. Also, the

abundance of suspension feeding echinoderms in these zones argues against much turbidity in the water column, except perhaps during storms.

On such a soft bottom, attachment sites may have been an important control on the distribution of Bromide echinoderms. Between 70 and 95 percent of the echinoderms in each of the rich zones in the Bromide were attached forms. Nearly all of the Bromide inadunate and camerate crinoids, including such unusual forms as the short-stemmed calceocrinids and *Cleiocrinus*, probably had a branched root system or cemented disclike holdfast for attachment. The stemmed paracrinoids (except perhaps *Bistomiacystis*), diploporans, palaeocystitids, and edrioblastoids were apparently attached to the substrate also, as were the edrioasteroids. The rhombiferans (except perhaps *Hesperocystis*) and the stylophorans and homoiosteleans were unattached as adults and may have been able to swim or wriggle across the sea bottom.

Hard substrates in the Bromide were provided by submarine hardground surfaces, massive bryozoans, and fossil fragments. Some samples of these collected from the Lower Echinoderm Zone are covered with root systems and disclike holdfasts (see Pl. 3, fig. 32,33). Fay and Graffham also noted during their excavation work that complete echinoderms were most abundant adjacent to, and on one side of, small buildups composed of ramose bryozoans, suggesting that these either were used for attachment sites or provided other especially favorable conditions, such as sheltering from high currents.

FOOD SUPPLY AND OXYGEN

The abundance of low- and high-level attached suspension feeders in the various Bromide echinoderm zones implies a rich suspended food supply carried along by currents near the sea floor. This food probably consisted of microphytoplankton, including acritarchs which are present in the Mountain Lake Member (see Table 7; Loeblich and Tappan, 1978), clay-sized detrital grains containing organic material and perhaps coated with bacteria, and probably dissolved organic matter in the water (see Brett, 1980). The top layer of sediment was probably rich in organic matter (Walker and Bambach, 1974), which was used by epifaunal and shallow infaunal detritus-feeding echinoderms. Although there is no direct evidence, marine plants (brown algae) probably grew on the sea floor and provided food for some epifaunal herbivores.

Suspended food supply, turbidity, and current velocity probably were all directly related, but high values of all three may actually have been detrimental to suspension feeding echinoderms. Their ambulacral tracts could rapidly become clogged under turbid and plankton-laden water conditions, and their attachment might be threatened by rapid currents generated by storms or tides. Slow to moderate unidirectional currents with moderate plankton densities and fairly low turbidity probably produced the most favorable conditions (see Meyer, 1973, p. 124-127; Macurda and Meyer, 1974, for a comparison with modern crinoids).

Oxygen content in the sea water was probably low to moderate during Bromide deposition. This inference is based on the argument by Paul (1976) about oxygen concentrations in the Middle Ordovician tropics, and the presence in the Bromide of many groups (crinoids, rhombiferans, diploporans, paracrinoids, and palaeocystitids) with specialized calyx respiratory structures or else very thin calyx plates.

ECHINODERM PALEOENVIRONMENTS

As expected, different echinoderms preferred to inhabit different environments as a result of their tolerance for currents, turbidity, substrate, and so on. In the Lower Echinoderm Zone, the optimum environment for echinoderms occurred along the northern margin of the aulacogen in water depths inferred on the basis of position in the stratigraphic section to have been a few tens of meters and probably between 10 and 20 m. Abundant *Hybocrinus* and *Platycystites* (both relatively easily preserved genera) grew in association with *Palaeocrinus*, *Carabocrinus*, *Glyptocystella*, and *Diabolocrinus* (Fig. 12) in this area. Updip on the ramp where wave energy was undoubtedly greater because of the shallower water depths (several meters), the fauna was dominated by the edrioasteroid *Cyathocystis* and the omnipresent *Platycystites*.

This shallow northeastern area was periodically (perhaps frequently) disturbed by storms, and probably had conditions that prevented the normal Lower Echinoderm Zone fauna from becoming established. Instead, a group of such opportunistic genera as *Cyathocystis* and *Bromidocystis*, which are rare elsewhere, became quite common. Surprisingly, though, the total diversity of echinoderms in this suboptimal environment is just as great as at localities along the hingeline, where almost 15

times as many echinoderms have been collected.

The Upper Echinoderm Zone near the Mountain Lake-Pooleville contact was deposited in three distinct environments: in a relatively deep-water (several tens of meters) basin in the center of the aulacogen, in a small carbonate buildup along the margin of the aulacogen, and in a lower energy lagoon behind the buildup to the northeast. *Oklahomacystis* is by far the most common genus in most environments, but this is probably a result of its high potential for preservation. It is the only common, intact echinoderm found in the shelf-margin buildup, even though the limestones in the buildup are composed almost entirely of disarticulated echinoderm fragments belonging to it and other genera. In the lagoonal environment *Oklahomacystis* occurs in shaly biomicrites with *Sinclairocystis* and some *Platycystites*. Comparison of the sections behind the shelf-margin buildup (Nebo, Sulphur, Fittstown) suggests that *Sinclairocystis* preferred the deeper portions of the lagoon where terrigenous shale accumulated while *Oklahomacystis* preferred more micritic bottoms closer to the buildup. Far to the northeast, in what must have been shallower water, the Upper Echinoderm Zone is very poorly developed, and only a few specimens have been found.

In the basin in front of the buildup, *Platycystites* is the dominant form in the deep-water shales while *Oklahomacystis*, *Cleiocrinus*, and *Strabocystis* inhabited an intermediate zone closer to the buildup. However, echinoderms were not nearly so common in the basin as in the shelf-margin buildup and lagoon.

The echinoderms in the upper part of the Pooleville Member inhabited a moderately deep-water environment (tens of meters) dominated by micrite below wave base. The most common forms are such archaeocrinid camerate crinoids as *Archaeocrinus*. Diversity in this apparently stable environment was comparable to that in the Lower Echinoderm Zone, but with much lower abundance of echinoderms. Pooleville echinoderms occur almost exclusively in the Criner Hills; indeed, only seven specimens are known from the entire Arbuckle Mountains, two from Fittstown and five from Johnston Ranch. While most of the Arbuckle Mountain area had intertidal to supratidal conditions during deposition of the upper Pooleville, the southwestern Arbuckles and Criner Hills had subtidal conditions favorable to many groups of echinoderms. Most of the Bromide starfish and carpoids and the only known echinoids and holothurian sclerites occur in the upper Pooleville in the Criner Hills.

ECHINODERM COMMUNITIES

Most Bromide crinoids, paracrinoids, rhombiferans, diploporans, edrioasteroids, cyclocystoids, edrioblastoids, and perhaps stylophorans were high- or low-level attached or stationary suspension feeders. Only a few Bromide echinoderms were mobile epifaunal or infaunal detritus feeders (such as homoiosteleans, holothurians, and perhaps stylophorans), mobile epifaunal herbivores (echinoids), or mobile epifaunal carnivores (asteroids). Even where these mobile groups were most abundant in the Pooleville, they make up less than 15 percent of the echinoderm fauna.

The many attached echinoderms partitioned space and suspended food by living at different heights above the bottom and perhaps by selecting different-sized food particles. Three general living heights can be distinguished: high, medium, and low (see Ausich, 1980, for a similar analysis of a Mississippian echinoderm fauna). High-level suspension feeders had long stems and fed from currents 30 to 90 cm above the sea floor; these included some large camerate and inadunate crinoids (*Archaeocrinus*, *Cleiocrinus*, *Carabocrinus*, *Colpodecrinus*) and probably such other echinoderms as *Bromidocystis* and *Eumorphocystis*. No other preserved organisms in the Bromide fauna competed with these high-level suspension feeding echinoderms. Medium-level suspension feeders fed from currents 10 to 30 cm above the sea floor and included paracrinoids like *Oklahomacystis* and perhaps *Platycystites*, small crinoids like *Palaeocrinus* and *Diabolocrinus*, and larger rhombiferans. Large ramose bryozoans and perhaps a few domal or encrusting bryozoans forming small buildups may have competed with these echinoderms as medium-level suspension feeders. Low-level suspension feeders had a short or recumbent stem or were attached on or near the sea bottom. These forms fed from slow currents very near the bottom and included small, short-stemmed crinoids like *Hybocrinus* and *Paracremacrinus*, paracrinoids such as *Bistomiacystis* and perhaps *Platycystites* (see Frest, Strimple, and Coney, 1979), edrioasteroids such as *Cyathocystis*, and perhaps small rhombiferans and other groups. Competition was much more severe at this level, because all except the largest bryozoans and nearly all the brachiopods found in the Bromide were also attached or stationary low-level suspension feeders. These two groups usually comprise between 50 and 70 percent of the total fauna in the rich echinoderm zones.

OCCURRENCE IN ZONES

One of the most striking features about the occurrence of complete echinoderms in the Bromide Formation is their abundance in thin, discrete, stratigraphic zones and paucity immediately up- and downsection. This applies primarily to the zones in the Mountain Lake Member where the echinoderms are concentrated in one or a few thin shaly units separated by limestone beds. However, in a slightly different sense, it also applies to the whole upper Pooleville in the Criner Hills where several thin shaly intervals are dominated by a few echinoderm species that probably lived in patches or gardens. Echinoderms occur in similar discrete, rich zones at several other Paleozoic echinoderm localities (for example, see Koch and Strimple, 1968; Sprinkle, 1973, p. 51-52, 68, 90; Van Sant and Lane, 1964, p. 23), but have a more even distribution throughout an appreciable stratigraphic section in other occurrences (Kolata, 1975, p. 7-10).

Two important questions need to be answered before an explanation for the Bromide echinoderm zones can be offered. First, are the complete echinoderms really occurring only in thin, rich zones instead of being spread out through a thicker stratigraphic section? Second, are we dealing with the same zones throughout the Arbuckle Mountains? Although many large excavations have been made in single shaly units where a zone is best developed (see Fay and Graffham, 1969, and herein), no large excavations have been made across an interval containing a rich zone and the adjacent beds. Small "test holes" and surface picking of beds adjacent to a zone (including the well-exposed I-35 roadcuts) indicate that a few complete echinoderms and some plates, stems, and holdfasts are present in adjacent beds, and that the amount of fragmentary echinoderm material increases toward the zone over a distance of a few meters. Although abundance of complete echinoderms markedly decreases away from a rich zone, the decrease is not so rapid as indicated in Figure 12, which has a strong collection bias from the trenches that were dug.

In answer to the question of correlation, it is fairly easy to trace specific zones from one section to another along the depositional hingeline that runs diagonally through the central Arbuckles, but much more difficult to correlate between a hingeline locality and the somewhat isolated exposures in the northeastern and southwestern Arbuckles because lithofacies and thicknesses change considerably in these directions. Correlation is supported by the fact that the two rich Mountain Lake echinoderm zones have the same genera present to the northeast and southwest across the hingeline, although different forms dominate these zones (see Fig. 13, 14). However, correlating the shaly Lower Echinoderm Zone interval in the northeastern Arbuckles to the east from Fittstown, and the "same" zone with its associated hardgrounds to the north from McLish Ranch, resulted in the discovery that these two echinoderm-bearing intervals did not correlate exactly but were about 1.5 to 2.5 m apart at Rhynes Ranch, which is almost equidistant from these localities (see Fig. 13). This indicates that in the northeastern and eastern Arbuckles, several closely spaced but distinct shaly intervals have been identified as the Lower Echinoderm Zone and that more than one bed is involved.

Table 21. Possible reasons for the occurrence of Bromide echinoderms in thin, rich zones.

Reason	Applicable to Bromide?
1. Migrating facies with optimal environmental conditions	unlikely
2. Periodic preservational factors in environment (storms, mud slides, long period with no storms)	possible (Longman), unlikely (Sprinkle)
3. Collecting methods for echinoderms ("diggers" vs. "pickers")	yes; accentuates occurence in zones
4. Gregarious nature of echinoderms (necessary for reproduction, clustered at attachment sites)	yes; makes zones rich but patchy
5. Optimal ecologic conditions for an extended period	yes; causes development of rich and diverse communities

Previous echinoderm workers have proposed several reasons why Paleozoic echinoderms might occur in thin, rich zones, and we have modified and added to this list to explain the pattern of occurrence in the Bromide (Longman, 1976; Sprinkle and Longman, 1977). Explanations fall into the five major categories listed in Table 21.

Probably the least likely explanation for the occurrence of echinoderms in thin, rich zones is the migrating facies hypothesis, which states that each of the Mountain Lake zones represents a nar-

row environmental zone of optimal conditions that migrated across the Arbuckles from southwest to northeast during the slow transgression. Adjacent beds represent somewhat different environments with suboptimal conditions that limited echinoderm populations. If this were true, it would imply that 1) each of the rich zones in the Mountain Lake is younger to the northeast, 2) the sequence of lithologies near each of the zones should be nearly the same everywhere, 3) each of the zones was deposited under specific water depths as that environment reached a certain locality, and 4) the Upper Echinoderm Zone was deposited everywhere under deeper water conditions than the Lower Echinoderm Zone.

Several of these implications are known to be incorrect (see Longman, 1976; Sprinkle, herein), and each of the zones is thought to represent a time line rather than a specific facies migrating through time. The best evidence for this is the Upper Echinoderm Zone, which: 1) occurs everywhere within a few meters of the abrupt transition to the Pooleville Member, 2) contains markedly different facies deposited at considerably different water depths across the Arbuckles (Longman, 1976), and 3) is dominated by different echinoderms in the different environments. The lower Echinoderm Zone shows some of these same features although less conclusively, because it was deposited on a gently sloping ramp. Unfortunately, we still lack the critical time markers (for example, bentonites or diagnostic index fossils) that could conclusively disprove the migrating facies hypothesis, but we believe migrating facies did not create the widespread Bromide echinoderm zones.

More difficult to evaluate is the hypothesis that periodic preservational factors in the environment (such as absence of storms for a long period, or sediment layers dumped by storms or underwater mudslides) produced the rich echinoderm zones. We have been unable to agree how important this factor may have been in the Bromide (see Table 21). Longman (1976, p. 104-106) proposed that the Lower Echinoderm Zone may represent an interval of Bromide deposition characterized by few severe storms. Lack of storms could have produced a shaly interval with near-optimal growth conditions for echinoderms and led to the gradual accumulation of numerous complete specimens which escaped disarticulation, whereas adjacent beds were deposited under suboptimal growth conditions because of periodic storms. On the other hand, Longman now recognizes that periodic storms may have helped preserve complete echinoderms in the Lower Echinoderm Zone (rather than destroy them) by uprooting and transporting complete specimens a short distance and then burying them rapidly under a layer of shaly sediment. In either case, he believes that storms (or their absence) contributed to the preservation of intact echinoderm calyces in the Lower Echinoderm Zone.

In contrast, Sprinkle does not believe that any of these preservational factors were important in the deposition of the echinoderm-rich zones in the Mountain Lake Member of the Bromide (see Table 21). Although the absence of storms or deposits formed by storms or underwater mudslides may have been responsible for preserving echinoderms in some Pooleville beds and in other occurrences, evidence for these preservational factors is rare in the lower Bromide. Adjacent shaly beds probably were not deposited under much different conditions (storms or no storms) than the zone beds. These shaly beds have a similar appearance and contain much the same fauna, although more bryozoans and fewer complete (and fragmented) echinoderms are usually present. If each 1-m shaly interval represents several hundred to several thousand years of deposition, it seems unreasonable to propose that more storms than usual or no storms at all would affect this marine nearshore area in the Ordovician tropics over that long a period. Today the Texas Gulf Coast is hit by a major hurricane on the average once every 4.5 years (Hayes, 1967). Finally, storm-deposited shale beds preserving complete echinoderms are known from the Oil Creek Formation lower in the Simpson Group (Lewis, 1982), but none of the rich echinoderm zones in the Mountain Lake Member of the Bromide have beds similar to these distinctive units.

The remaining three hypotheses (Table 21) have all played a part in producing a zoned occurrence for Bromide echinoderms. The collecting method for specimens in this project has accentuated their apparent occurrence in thin, rich zones. Nearly 9,000 specimens were collected between 1965 and 1967 by A. Allen Graffham and Robert O. Fay, two field paleontologists whom we might designate as "diggers." They used information on museum labels and discoveries made by amateur collectors to find localities that had produced a few complete echinoderms, carefully searched the surface for the most productive bed at these localities, and then dug large trenches along this rich bed, sometimes recovering as many as 3,000 complete specimens in about five cubic meters of excavated material (Fay and Graffham, herein). At many of these locali-

ties, beds in the Bromide are steeply dipping or nearly vertical, making it easier to follow and trench a single shaly bed. Trenching is time-consuming, often hard work, and requires great patience, but some Bromide localities in the rich zones were so productive that this collecting strategy worked quite well.

In contrast, we might be characterized as "pickers," searching for complete echinoderms in the surface material along an outcrop or in piles of debris from the trenches. Picking requires luck and a different type of persistence to return repeatedly to a locality looking for one or a few rare specimens, but it has resulted in some spectacular finds (see Pl. 6, fig. 1-10; Pl. 19, fig. 1-4). Picking works best where trenching would be difficult (for example in cliffed roadcuts or in thin, shale beds with massive bounding limestones), where specimens are uncommon or scattered over a wide area (such as at McLish Ranch), or for reconnaissance work to located productive beds in a section (often before trenching). Picking has probably resulted in the collection of about 2,000 echinoderm specimens during this project.

Although picking has indicated that some specimens occur in beds adjacent to rich zones and that several new zones may be present in the Bromide section, the total number of specimens collected by this method is small compared to that recovered by trenching the few rich zones. This has resulted in a "trenchers bias" (see Fig. 12) in which most of the specimens collected from the Bromide (and especially from the Mountain Lake Member) appear to come from a few thin beds. The true distribution of echinoderms throughout the Bromide is probably more equable than that shown, although it is far from even.

The echinoderm zones in the Mountain Lake and Pooleville members are not continuous and equally productive everywhere, but appear to be patchy or clumped. At several localities in the northern Arbuckles (Cedar Gardens, North-Central I-35, and Nebo) the Lower Echinoderm Zone contains few echinoderms and is hard to find, in contrast to nearby localities (Lick Creek, Amis Ranch) where the zone has yielded numerous echinoderms (see Fig. 13). Many echinoderms today and throughout the fossil record were gregarious, occurring in large numbers in local areas under especially favorable environmental conditions (for example, see Van Sant and Lane, 1964; Sprinkle and Gutschick, 1967; Brett and Liddell, 1978). Because most echinoderm species have separate sexes and external fertilization, echinoderms may have needed to live close together and coordinate their breeding activity (probably by chemical stimulus) to ensure successful reproduction (Brower, 1973). In addition, many Paleozoic stemmed echinoderms probably could not attach directly to a muddy substrate, but needed a firm bottom or hard objects lying on the sea floor. Favorable attachment sites (fossil debris, bryozoan colonies, small bryozoan buildups) are often covered with holdfasts and root systems (see Pl. 3, fig. 32, 33) in the shaly Bromide zones (Sprinkle and Longman, 1977). Near favorable attachment sites the zones are often very rich, in contrast to other nearby areas lacking suitable sites, which are echinoderm-poor.

Probably the most important factor in the formation of the echinoderm zones (but also the hardest to document) was the condition of the total environment; echinoderms only became abundant (a "zone") when conditions were optimal for a significant period of time. Under suboptimal or fluctuating conditions, echinoderms were only a minor part of the total faunal community (a "non-zone"). Many conditions for echinoderm survival, such as a warm climate and fully marine conditions, existed during all or most of Bromide deposition and cannot be used to explain the zones. However, factors such as clastic input, food supply, water depth, depth of photic zone, and bottom currents varied during deposition and could have combined to create an optimal environment for echinoderms only at certain times. Bryozoans, brachiopods, and other invertebrate fossils that occur outside the echinoderm zones in great abundance may not have been as susceptible to these factors or may have had different optimal conditions. Unfortunately, one can only postulate that the most abundant echinoderms occurred under the most favorable local conditions.

The identification of three or four different causes (Table 21), which probably contributed in different ways to the zoned occurrence of echinoderms in the Bromide, is undoubtedly less satisfying than finding a single controlling cause. However, it points out a major problem confronting paleoecologists: even with excellent fossil collections, detailed lithofacies analysis, and an understanding of regional depositional setting and processes, it is often difficult to explain why certain organisms thrived at certain times while others were excluded.

SYSTEMATIC PALEONTOLOGY

The following chapters are set up in a taxonomic sequence based on a commonly used classification of echinoderms (see Sprinkle, 1980, table 1) with subphyla and classes generally in their order of abundance in the Bromide: Crinozoa (crinoids and paracrinoids), Blastozoa (rhombiferans, diploporans, and eocrinoids), Echinozoa (edrioasteroids, edrioblastoids, cyclocystoids, echinoids, and holothurians), Asterozoa (stelleroids), and Homalozoa (stylophorans and homoiosteleans). All groups are studied in detail except for holothurians and homalozoans, both of which are briefly summarized. For purposes of counting, the term "specimen" is used either for a complete theca or a portion representing more than one-fourth to one-third of a theca that could not be matched with any other fragment at the locality. Smaller pieces of an echinoderm are termed fragments, plates, arm segments, stems, holdfasts, and root systems; these were usually not counted in the number of specimens, except when a rare and distinctive plate indicated the presence of a group at a locality. Museum abbreviations for studied specimens are as follows: OU, Stovall Museum of Science and History, University of Oklahoma, Norman; TX, Texas Archive for Geologic Research, University of Texas at Austin; USNM, National Museum of Natural History, Washington, D. C.; UM, University of Missouri, Columbia; UCMP, University of Cincinnati Museum of Paleontology; MCZ, Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts; ROM, Royal Ontario Museum, Toronto, Ontario, Canada; and SUI, University of Iowa Paleontology Collection, Iowa City. [—Ed.]

LONG-ARMED DISPARID INADUNATES

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Long-armed disparid inadunates are represented in the Bromide collection by more than 70 specimens distributed among three superfamilies (Homocrinacea, Cincinnaticrinacea, and Myelodactylacea), three families (Homocrinidae, Cincinnaticrinidae, and Iocrinidae), and at least five genera and species. Three genera and species (*Penicillicrinus parvus*, *Doliocrinus pustulatus*, and *Peltacrinus sculptatus*) are new. Two other genera and species, *Apodasmocrinus daubei* Warn and Strimple, 1977, and *Praecursoricrinus sulphurensis* Frest, Strimple, and McGinnis, 1979, have only recently been described. All forms are closely related primitive disparid inadunates. They are found as minor constituents in all Bromide echinoderm zones.

Phylum ECHINODERMATA Bruguiere, 1791

Subphylum CRINOZOA Matsumoto, 1929

Class CRINOIDEA Miller, 1821

Subclass INADUNATA Wachsmuth and Springer, 1885

Order DISPARIDA Moore and Laudon, 1943

Superfamily HOMOCRINACEA Kirk, 1914

Family HOMOCRINIDAE Kirk, 1914

Subfamily HOMOCRININAE Kirk, 1914

Genus APODASMOCRINUS Warn and Strimple, 1977

Type species.—*Apodasmocrinus daubei* Warn and Strimple, 1977, by original desgination.

Diagnosis.—Homocrininae with barrel-shaped dorsal cup.

Discussion.—*Apodasmocrinus* at present contains two species, *A. daubei* Warn and Strimple, 1977, from the Mountain Lake Member of the Bromide Formation of Oklahoma and *A. punctatus* (Brower and Veinus), 1974, from the Hogskin Member of the Lincolnshire Formation and the Benbolt Formation of Tennessee and Virginia.

Apodasmocrinus is apparently most closely related to *Ectenocrinus*. They have similar cup-plate shapes and arrangements. Both have two IBrr per ray supporting 10 long, stout, pinnulate arms with pinnules given off every other Br on alternate sides, the first given off abradially. *Apodasmocrinus* differs from *Ectenocrinus* in having a much wider, lower cup with basal concavity and a heteromorphic, pentagonal, proximal column lacking distal taper. *Ectenocrinus* has a round column with marked distal taper proximally, after which columnals are of uniform size for some length before its column becomes heteromorphic (see Warn and Strimple, 1977, pl. 13-15).

Frest, Strimple, and McGinnis (1979, p. 399-400) suggested a close relationship between *Apodasmocrinus* and their new genus *Difficilicrinus* and erected the new family Apodasmocrinidae to receive both genera. Both have similarly shaped cups and basal concavities. The arms of *Difficilicrinus* are unknown, but *Difficilicrinus* is unique in having simple RR in the A, C, and D rays and compound RR in the B and E rays. I consider cup-plate arrangement to be an important familial taxobasis (it is certainly a convenient one) in inadunate classification. In this respect, *Apodasmocrinus* fits well in the Homocrinidae, and perhaps *Difficilicrinus* deserves its own family.

APODASMOCRINUS DAUBEI Warn and Strimple, 1977

Plate 4, figures 13-30; Figures 17-20

Apodasmocrinus daubei Warn and Strimple, 1977, p. 93-96, text-fig. 21, 22a-c.

Apodasmocrinus daubei Warn and Strimple, 1977; Frest, Strimple, and McGinnis, 1979, text-fig. 7d.

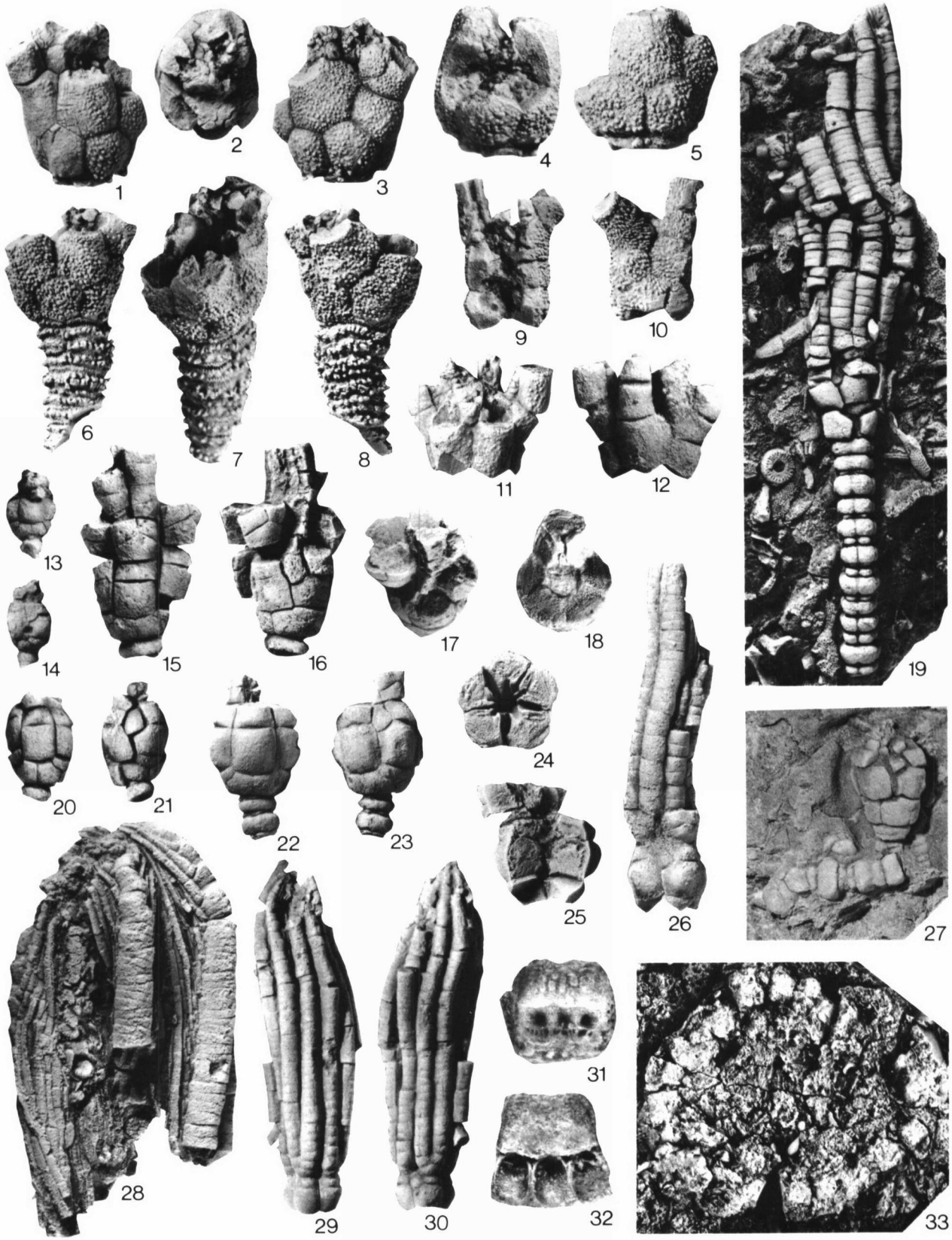
Material.— Although *A. daubei* was originally described from only 2 specimens, holotype SUI 39593 and paratype USNM 164106, 37 additional specimens are now known from the Mountain Lake Member of the Bromide Formation of south-central Oklahoma. The following additional specimens are illustrated here: 1276TX5, 1279TX17-19, 1279TX-165-166, 1279TX181, 1404TX4 (Watkins Coll.), and OU 9052.

PLATE 4.

Fig. 1-12. *Doliocrinus pustulatus* Warn, n. gen., n. sp; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, southern Oklahoma; 1-3 from shale band immediately below Lower Echinoderm Zone at Lick Creek Road; 4, 5, 9-12 from Fittstown Quarry; 6-8 from McLish Ranch. 1-3. A-ray, oral (with C ray at top), and D-ray views of holotype 1391TX3; X3. 4, 5. CE-interray and A-ray views of paratype 1279TX23; X3. 6-8. AB-interray, oblique B-ray, and D-ray views of paratype 1113TX-51; X3. 9, 10. B-ray and DE-interray views of longitudinally broken paratype 1279TX177; X3. 11, 12. AB-interray and D-ray views of paratype 1279-TX176; X3.

Fig. 13-30. *Apodasmocrinus daubei* Warn and Strimple, 1977; Mountain Lake Member, Bromide Formation, southern Oklahoma; 13, 14, 18, 22-26, 28 from Lower Echinoderm Zone at Fittstown Quarry; 15-17, 27, 29, 30 from Lower Echinoderm Zone at Daube Ranch; 19 from Lower Echinoderm Zone at Lick Creek; 20, 21 from the *Carabocrinus* Beds at North-Central I-35. 13, 14. A-ray and CD-interray views of 1279TX19; X3. 15-17. A-ray, CD-interray, and oblique oral (A ray on top) views of 1404TX4, 16 and 17 showing XX, triangular in cross section; X3. 18. Oral view (D ray at top) of 1279TX166, showing shape of food groove in D-ray R, articular facets on B-, C-, and E-ray RR and EA-AB interray BB, and size of proximal coelomic cavity; X3. 19. CD-interray view of OU 9052, showing crown and pentameric, pentagonal, heteromorphic column; X3. 20, 21. A-ray and CD-interray views of 1276TX5; X3. 22, 23. A-ray and CD-interray views of 1279-TX17; X3. 24. View of tops of RR (A ray at top) of 1279TX18 showing food grooves, articular facets, and coelomic cavity; X3. 25. EA-interray view (of inner edges of B- and D-ray RR) of broken specimen 1279TX178; X3. 26. CD-interray view of crown 1279TX165 missing BB; X3. 27. CD-interray view of holotype SUI 39593 (negative supplied by H. L. Strimple, University of Iowa); X3. 28. Lateral view of distal crown of complete but disintegrated specimen 1279TX181 showing 2 large arms tapering rapidly at tips, numerous pinnules, some with food grooves and cover plates visible, and polyplated anal tube in left center of photo; X4. 29, 30. A- and C-ray views of paratype crown USNM 164106, missing BB and iRR (negatives supplied by H. L. Strimple, University of Iowa); X2.

Fig. 31-33. *Cyclocystoides* sp.; 31, 32, Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, McLish Ranch, eastern Arbuckle Mountains; 33, Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, North-Central I-35, northern Arbuckle Mountains. 31, 32. View of interior edge showing submarginal pore and row of closely spaced pits and view of upper surface showing cupules, 1113TX15; X6.5. 33. View of upper surface of poorly preserved ring 1222TX3; X4.



Diagnosis.—*Apodasmocrinus* with broad cup; with large BB flexed upward to form an appreciable portion of sides of cup; and with cup plates tumid and smooth.

Description.—Cup 2 to 3 times as broad as column; column inserted into narrow, but moderately deep, basal cup concavity; cup barrel-shaped, sides of cup diverging only slightly distally before converging rapidly at prominent constriction at junction of cup and arms; cup widest just above mid-height of RR; 10 stout arms, when folded, only

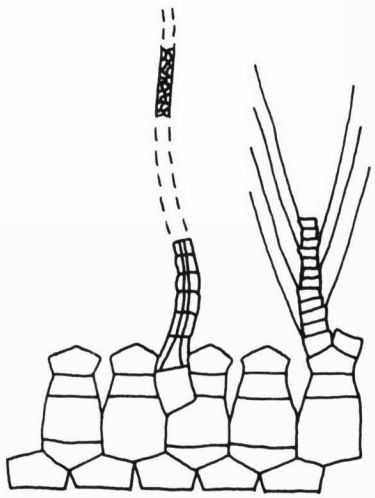


Fig. 17. Plate diagram of *Apodasmocrinus daubei*. Only a portion of one arm (left branch of A ray) is shown, but complete arms have been observed and continue the pattern portrayed. Lines off Brr represent pinnules. Lines down the middle of XX demarcate triangular (in cross section) ridge. Dashed areas of anal series unknown.

slightly broader than cup but quite long (about 5 to 7 times as long as cup is tall); cup heights (base of BB to top of $IBrr_1$) of known specimens ranging from 2.8 to 6.9 mm, with small specimens having globose cups and larger specimens having steeply conical to barrel-shaped cups; cup composed of thick plates making for relatively small coelomic cavity (Pl. 4, fig. 18, 24, 25).

BB 5, similar in size in single individuals but among different individuals ranging from about half the size of the sRR to nearly the same size as the sRR; 1 symmetrically pentagonal B occupying the BC interray with 2 steeply sloping upper sides beneath the 2 adjacent compound RR; other BB asymmetrically pentagonal with steeply sloping upper sides beneath compound RR and gently sloping upper sides (nearly horizontal) beneath simple RR; lateral sides of BB diverging only slightly; bottoms of BB (base of cup) possessing 5 radial hollows at their junctions for accommodating insertion of

Fig. 18. Br and food groove shape in *Apodasmocrinus daubei*, greatly enlarged. A-C, proximal to distal.

pentameres of proximal columnal.

RR 5, 2 simple (in A and D rays) and 3 compound (in B, C, and E rays); tops of RR at about same level of cup, but bases of compound RR inserted more deeply than simple RR into basal circlet of cup; iRR shorter inverted symmetrical pentagons about a third as tall as overlying sRR (smallest specimens have iRR and sRR closer in size; apparently sRR grew faster than iRR); sRR tall rectangles, about seven-eighths as tall as simple RR; simple RR inverted symmetrical pentagons, about one and one-fourth as tall as wide with 2 gently sloping (nearly horizontal) lower sides; distal surfaces of RR (Pl. 4, fig. 24) having triangular facets; raised lips on insides of RR making fluted food grooves that rapidly become shallow proximally (Pl. 4, fig. 18, 24).

Anal series composed of at least 6 or 7 plates proximally and a polyplated anal tube distally; X_1 an inverted irregular pentagon with apex inserted into shallow notch formed by steeply sloping truncated right shoulder of D-ray R and more gently sloping truncated left shoulder of C-ray sR; X_1 taller than broad, narrowing distally, its 5 sides abutting against (starting with X_2 and moving clockwise) X_2, C-ray IBr_1, C-ray sR, D-ray R, and D-ray IBr_1; X_1 extending to tops of, or just beyond, $IBrr_1$; X_{2-7} distally tapering trapezoids diminishing in size distally, triangular in cross section, with scalloped lateral edges (Pl. 4, fig. 16, 17); distal anal tube (known from a single specimen) round, polyplated, about half the diameter of arms, extending nearly to arm tops; tube composed of numerous irregularly polygonal interlocking plates (Pl. 4, fig. 28); relation of proximal XX to distal anal tube unknown.

IBrr 2 per ray; $IBrr_1$ short trapezoids tapering rapidly distally; $IBrr_2$ short pentagonal axillaries expanding rapidly distally, that combination causing a prominent constriction in the crown; each IBr_2 bearing 2 equal-sized, long, stout arms not tapering over their length until near arm tips (Pl. 4, fig. 28); arms bearing long pinnules about one-sixth the diameter of arms; pinnules branching off every other Br on alternate sides with the

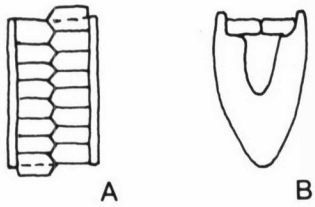


Fig. 19. Pinnular of *Apodasmocrinus daubei*, greatly enlarged. A. Plan view showing biseries of cover plates between lateral edges of pinnular (dashed lines are edges of pinnular below overlapping cover plates). B. Cross section showing depressed cover plates over food groove.

first given off away from the ray axis (rarely adjacent Brr with pinnules branching off alternate sides); Brr round in cross section with wedge-shaped food groove incised from one-third to one-sixth of the way into Brr (Fig. 18).

Pinnulars tall and thin rectangles in side view, 4 to 5 times as tall as wide and 3 to 4 times as tall as Brr; wedge-shaped in cross section with inner broad edge carrying deep U-shaped food groove covered by biserial arrangement of tiny polygonal interlocking cover plates, 7 to 8 per pinnular on each side; cover plates slightly wider than tall to equidimensional, sunken slightly below edges of pinnulars (Fig. 19).

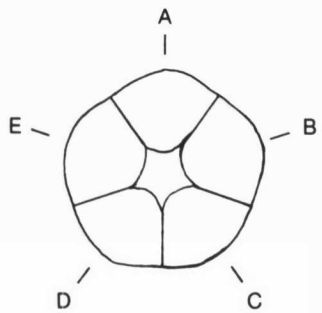


Fig. 20. Cross section of the column of *Apodasmocrinus daubei*, greatly enlarged, showing radial arrangement of pentameres and column angles and interradial disposition of interpentameric sutures and lumen angles (letters denote the five rays).

Column (Pl. 4, fig. 19) composed of alternating series of large equal-sized nodals and smaller equal-sized internodals; pentagonal proximally, becoming round distally; column pentapartite with radially disposed pentameres and column angles; lumen star-shaped with interradially disposed points (Fig. 20); column articulatory surface (at least that joining cup) marked with numerous striae arranged in petaloid fashion.

Occurrence.—*A. daubei* is known only from the Mountain Lake Member of the Bromide Formation in south-central Oklahoma. Most specimens are from the Lower Echinoderm Zone at Fittstown Quarry, Daube Ranch, and Lick Creek; a few specimens are also known from the *Carabocrinus* Beds and the *Bromidocystis* Bed at North-Central I-35.

Discussion.—*Apodasmocrinus daubei* is closely related to *A. punctatus*, known from a few specimens from the Benbolt Formation of southwestern Virginia and northeastern Tennessee. *A. punctatus* differs in having punctate prosopon and shorter basals that do not form an appreciable portion of the sides of the cup. Both species are Blackriveran in age.

Genus PENICILLICRINUS Warn, new

Type species.—*Penicillicrinus parvus* Warn, n. sp.

Diagnosis.—Homocrininae with 1 short symmetrically pentagonal B (in the BC interray) and 4 taller asymmetrically hexagonal BB; with isotomously branching arms; and with round column tapering only slightly distally below cup.

Etymology.—The name for this crinoid is derived from *penicillum*, Latin for tuft or painter's brush, which *Penicillicrinus* resembles in gross form.

PENICILLICRINUS PARVUS Warn, n. sp.

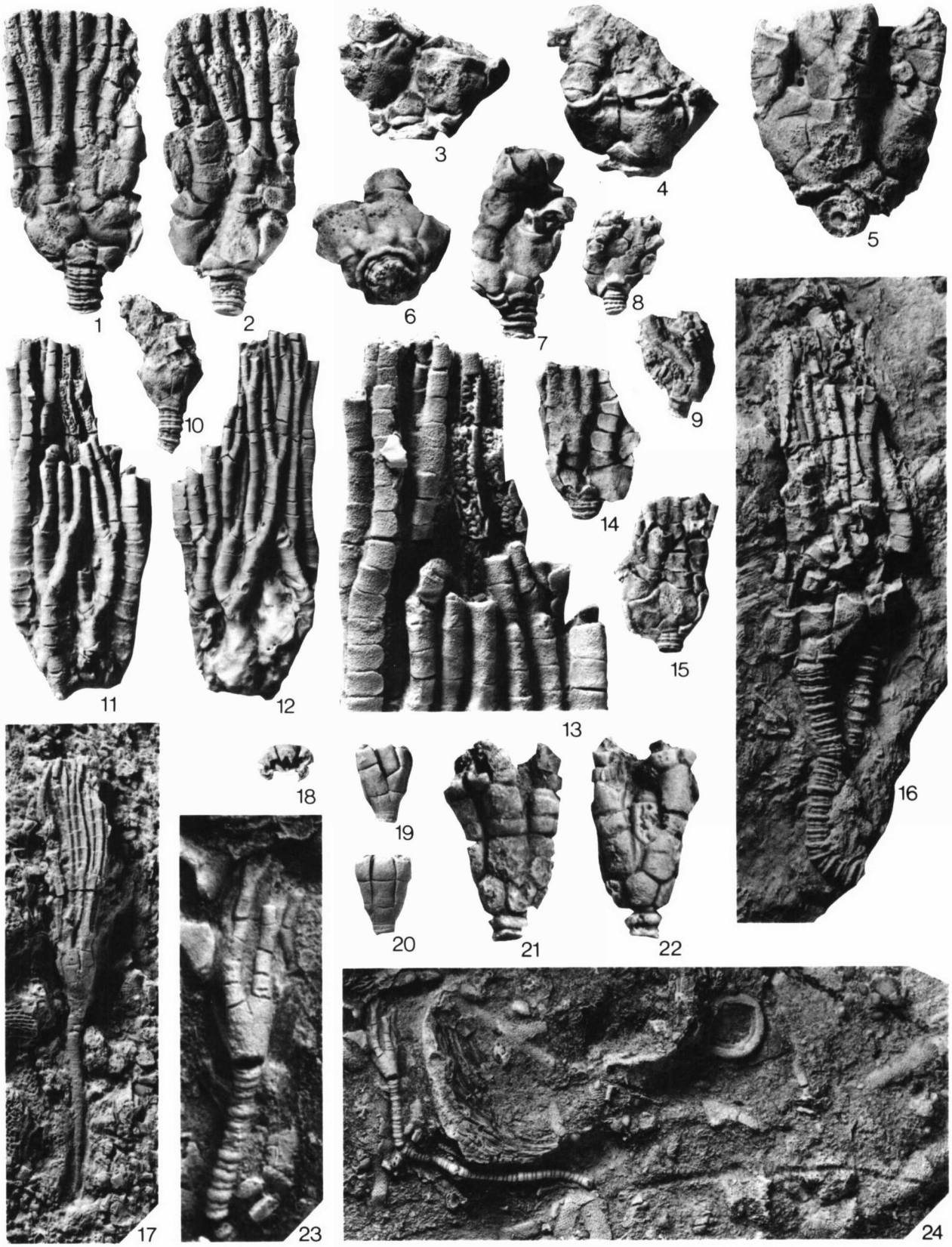
Plate 5, figures 17-20; Figure 21

Material.—Holotype OU 9054, paratype OU 9055, the only specimens known; both from the Pooleville Member of the Bromide Formation of south-central Oklahoma.

Diagnosis.—Because *Penicillicrinus* is monotypic at present, the specific diagnosis is the same as the generic diagnosis.

Etymology.—*Parvus* is Latin for small and refers to the small size of *P. parvus*.

Description.—Cup 3 to 4 times as broad as column, steeply conical (lekythosiform of Warn and Strimple, 1977, text-fig. 5), its sides diverging only slightly distally to tops of RR, then converging rapidly to tops of $IBrr_1$; cup widest near bases of $IBrr_1$; arms delicate and long, about 4 times as long as cup is tall; folded arm bundle only slightly broader than cup; cup heights (base of BB to top of $IBrr_1$) of known specimens 2.1 and 3.6 mm; cup plates relatively thin and fragile.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BB 5, about five-eighths the size of simple RR and three-fourths the size of sRR; 1 short symmetrically pentagonal B in the BC interray with 2 steeply sloping upper sides beneath the 2 adjacent compound RR; other BB taller, equal-sized, asymmetrically hexagonal with steeply sloping upper sides beneath compound RR and gently sloping upper sides (nearly horizontal) beneath simple RR, those 2 upper sides joined by a vertical side with the upper part of the B beneath simple RR inserted higher, in lateral junction with iRR (Fig. 21).

RR 5, 2 simple (in the A and D rays) and 3 compound (in the B, C, and E rays); tops of RR at about same level of cup, but bases of compound RR inserted far more deeply than simple RR into basal circlet of cup; iRR short, inverted, symmetrical pentagons about half as tall as overlying sRR; sRR rectangular, about one and one-fourth as tall as wide, and about seven-eighths as tall as simple RR; simple RR tall rectangles or obscurely pentagonal with 2 nearly horizontal lower sides, about one and one-third as tall as wide; $IBrr_1$ apparently functioning as part of dorsal cup.

Anal series unknown beyond X_1; X_1 a tall, quadrangular plate as tall as, or taller than, the subjacent sR and 2 to 3 times as tall as wide; X_1 resting on the steeply sloping truncated left shoulder of the C-ray sR; X_1 a thin, arcuate plate in cross section (viewed orally; Pl. 5, fig. 18).

IBrr 2 per ray; $IBrr_1$ equidimensional (height = width), distally tapering trapezoids with deep, flat-bottomed, V-shaped food grooves incised into their inner sides (Pl. 5, fig. 18); $IBrr_2$ distally expanding pentagonal axillaries similar in size to the underlying $IBrr_1$ (description of arms based only on D and E rays of single specimen, OU 9054, Pl. 5, fig. 17); IBr shapes causing a small constriction in the crown at the junction of the $IBrr_1$ and $IBrr_2$; each IBr_2 bearing 2 equal-sized isotomously branching arms with 4 IIBrr, 5 to at least 8 IIIBrr, and 4 or more IVBrr; first Br of each IIBr and higher series significantly shorter than rest of series; last Br (an axillary) of each

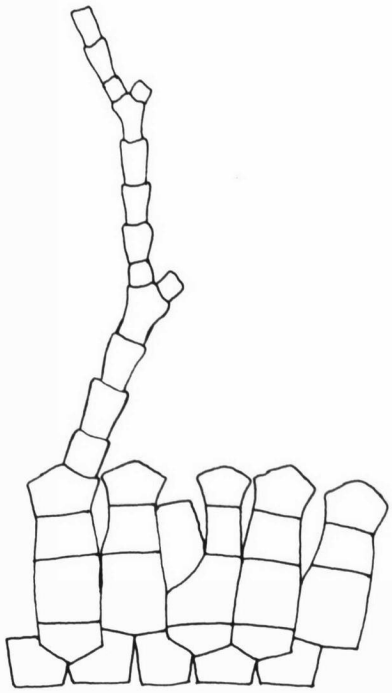

Fig. 21. Plate diagram of *Penicillicrinus parvus*. Only a portion of one arm (right branch of E ray) is shown, but complete arms have been observed and continue the pattern portrayed.

PLATE. 5.

Fig. 1-16. *Peltacrinus sculptatus* Warn, n. gen., n. sp.; upper part of Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 1-4, 6, 8-10, 14-16 from Zone 3 at Culley Creek; 5, 7 from float (probably from Zone 3) at Culley Creek; 11-13 from 2.2 m below the Viola Limestone at Dunn Quarry. 1, 2. DE-interray and B-ray views of flattened holotype OU 9057: X3. 3. Lateral view of flattened paratype OU 9061 showing sculptured RR; X3. 4. Lateral view of paratype OU 9062; X3. 5. C-ray view of flattened paratype 1405TX3 (Watkins Coll.) showing sculptured brachianal, sculptured X, and "hour-glass" sculpturing on Brr; X3. 6. Oblique aboral view of paratype 1122TX43 showing lobate character of column, lip around base of cup, and prominent sculpturing of cup plates; X3. 7. BC-interray view of crushed paratype 1405TX6 (Watkins Coll.); X3. 8, 9. CD-interray and A-ray views of tiny, crushed (and possibly abnormal) paratype OU 9063; X3. 10. Lateral view of small paratype OU 9060; X3. 11-13. A-ray and D-ray views of well-preserved but slightly abraded paratype OU 9058 plus enlargement of part of Figure 11 showing scalloped arm edges and cover plates; X2, X4. 14, 15. D-ray and AB-interray views of flattened paratype 1122TX42; X3. 16. Lateral view of crushed paratype OU 9059 showing heteromorphic column; X3.

Fig. 17-20. *Penicillicrinus parvus* Warn, n. gen., n. sp.; upper part of Pooleville Member, Bromide Formation, Zone 5 (17) and Zone 3 (18-20), Culley Creek, Criner Hills, southern Oklahoma. 17. DE-interray view of holotype OU 9054; X4. 18-20. Oral (with A ray at top), CD-interray, and A-ray views of paratype OU 9055; all X3.

Fig. 21, 22. *Praecursoricrinus sulphurensis* Frest, Strimple, and McGinnis, 1979; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation at Sulfur, southern Oklahoma; A-ray and CD-interray views of OU 9056; X3.

Fig. 23, 24. Unknown Cincinnaticrinidae 1276-TX13; float from Upper Mountain Lake Member, Bromide Formation at North-Central I-35, southern Oklahoma. 23. Enlarged EA-interray view of crown; X5. 24. Whole specimen including crown, preserved column, and impression of missing distal column in slab; X2.

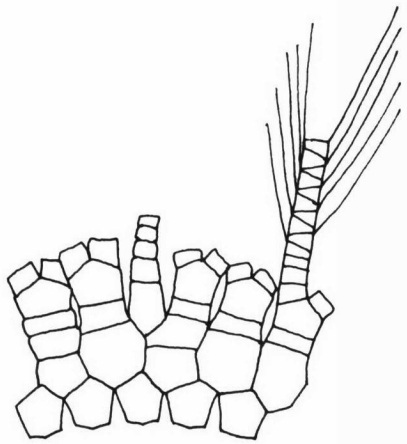

Fig. 22. Plate diagram of *Praecursoricrinus sulphurensis*. Only a portion of one arm (left branch of A ray) is shown, but nearly complete arms are known and continue as portrayed. Lines off Brr represent pinnules.

IIBr and higher series somewhat taller than adjacent Brr; proximal Brr about equidimensional, gradually increasing in relative height distally, distal Brr about 4 times as tall as wide; Brr expanding slightly distally with distal edges of subjacent Brr wider than proximal edges of superjacent Brr, producing appearance that Brr are inserted into one another like segments of a calamite fern (Fig. 21; Pl. 5, fig. 17).

Column incomplete, about 8 mm long in OU 9054 (Pl. 5, fig. 17), round, tapering slightly distally just below cup (for about 8 most proximal columnals); column composed of one series of shorter columnals intercalated between a series of taller columnals, with adjacent columnals of about equal width.

Occurrence.—Two specimens; from zones 3 and 5 of the Pooleville Member of the Bromide Formation at Culley Creek, Criner Hills, southern Oklahoma.

Discussion.—*P. parvus* appears to be closely related to members of *Ectenocrinus* and *Homocrinus*. All have similar dorsal cup shapes, similar cup-plate shapes and arrangements, and similar distally tapering round columns. However, the isotomous arms of *P. parvus* are unlike the 10 stout pinnulate arms of *Ectenocrinus* or the 5 atomous arms of *H. parvus*.

Superfamily CINCINNATICRINACEA
Warn and Strimple, 1977

Family CINCINNATICRINIDAE
Warn and Strimple, 1977

Subfamily CINCINNATICRININAE
Warn and Strimple, 1977

Genus PRAECURSORICRINUS
Frest, Strimple, and McGinnis, 1979

Type species.—*Praecursoricrinus sulphurensis* Frest, Strimple, and McGinnis, 1979, by original designation.

Diagnosis.—Cincinnaticrininae with 10 cuneate, uniserial, pinnulate arms; BB tall, taller than iRR, pentagonal to obscurely hexagonal; $IBrr_1$ short and wide; plate sutures deeply impressed.

PRAECURSORICRINUS SULPHURENSIS
Frest, Strimple, and McGinnis, 1979

Plate 5, figures 21,22; Figure 22

Praecursoricrinus sulphurensis Frest, Strimple, and McGinnis, 1979, p. 408-411, text-fig. 4, pl. 1, fig. 1-8.

Material.—Holotype SUI 44746; paratype SUI 44747. *P. sulphurensis* was originally described from two specimens from the Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation. One additional specimen (OU 9056) is known from the same zone.

Diagnosis.—Because *Praecursoricrinus* is monotypic, the specific diagnosis is the same as the generic diagnosis.

Description.—(Portions of the following description are based on the description given by Frest, Strimple, and McGinnis, 1979.) Cup about two and one-quarter times as broad as column, steeply conical (lekythosiform), its sides diverging only slightly distally; cup widest at tops of RR (at tops of RR in 2 of 3 known specimens; just below tops of RR in the third); 10 long stout arms each 4 or 5 times as long as cup is tall and about one-fourth cup diameter; cup heights (base of BB to top of RR of known specimens) ranging from 4.8 to 8.3 mm; plates relatively thick, separated by deeply impressed sutures.

BB 5, equal-sized, symmetrically pentagonal, or obscurely hexagonal with 2 nearly horizontal lower edges with steeply sloping upper sides (actually edges of BB beneath compound RR slope slightly more than edges beneath simple RR), taller than broad, nearly same height as simple RR; lateral sides of BB diverging noticeably distally (Pl. 5, fig. 21, 22).

RR 5, 3 simple (in the A, B, and D rays) and 2 compound (in the C and E rays); compound RR somewhat taller than simple RR, extending slightly farther both distally and proximally than simple RR; iRR equidimensional, inverted, symmetrical pentagons, with steeply sloping lower sides, slightly taller than overlying sRR; sRR low to equidimensional rectangles; simple RR equidimensional, inverted, symmetrical pentagons, or obscure hexagon and septagon to accommodate compound RR, with relatively steeply sloping lower sides.

Anal series composed of at least 5 plates; X_1 an inverted pentagon with apex inserted into fairly deep notch formed by steeply sloping truncated right shoulder of D-ray R and left shoulder of C-ray sR; X_1 taller than broad, tapering slightly distally; X_{2-5} trapezoids tapering slightly distally and diminishing in size distally (Pl. 5, fig. 22).

IBrr 2 per ray; $IBrr_1$ broad and short, tapering only slightly distally; $IBrr_2$ pentagonal axillaries taller than underlying $IBrr_1$ expanding slightly distally, that combination causing a small constriction in the crown at the junction of $IBrr_1$ and $IBrr_2$ (Pl. 5, fig. 21, 22); each IBr_2 bearing 2 equal-sized, long, stout arms tapering little over their observed length; arms cuneate beyond $IIBrr_{3-4}$ bearing long, narrow pinnules branching off every $IIBr_3$ or $IIBr_4$ and higher on alternate sides with the first given off away from ray axis; pinnulars cylindrical, about 4 times as long as wide.

Column pentagonal proximally with radially disposed angles, becoming round distally; 1 to a few thin (waferlike) internodals alternating with single, thick nodals; lumen small, pentalobate, probably with interradially disposed lobes.

Occurrence.—Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation at the Sulphur locality.

Discussion.—See Frest, Strimple, and McGinnis (1979).

Genus DOLIOCRINUS Warn, new

Type species.—*Doliocrinus pustulatus*, n. sp.

Diagnosis.—Cincinnaticrininae with cup scyphosiform (cup shape approaching a cup, rather than steeply conical as in other Cincinnaticrininae); tumid cup plates separated by moderately impressed sutures; 1 symmetrically pentagonal B (in the AB interray) and 4 slightly asymmetrically pentagonal BB; and highly pustulose plate surfaces.

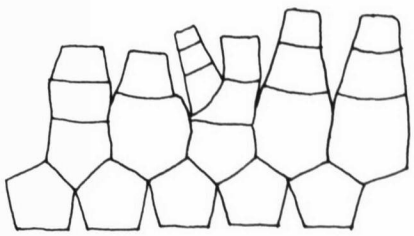

Fig. 23. Plate diagram of *Doliocrinus pustulatus*. Arms beyond $IBrr_2$ unknown.

Etymology.—The name is derived from *dolium*, Latin for large jar or cask, in reference to its cup shape. This generic name does not appear to be preoccupied by the similar names *Doliocrinites* proposed by Shumard in 1868 or by *Doliolocrinus* proposed by Wachsmuth and Springer (1881), both of which are now considered to be junior synonyms of the camerate genus *Talarocrinus*.

DOLIOCRINUS PUSTULATUS Warn, n. sp.

Plate 4, figures 1-12; Figures 23,24

Material.—Holotype 1391TX3; paratypes 1279TX-23, 1279TX176-177, and 1113TX51; these are the only known specimens.

Diagnosis.—Because *Doliocrinus* is monotypic, the specific diagnosis is the same as the generic diagnosis.

Etymology.—*Pustulatus* is Latin for pimpled or blistered and refers to the pustulose plate surfaces, a striking feature in this species.

Description.—Dorsal cup about one and three-quarter times as wide as column; cup shape apparently somewhat variable; cup sides diverging somewhat (flattened individuals appear to have more divergent cup sides, in two views, than they would have had during life); cup widest near tops of RR; cup heights (base of BB to tops of RR) of known specimens ranging from 4.9 to 7.0 mm; cup composed of thick plates, but coelomic cavity relatively large despite thickness (Pl. 4, fig. 4, 7, 9).

BB 5, equal-sized, equidimensional, about the same size as, or slightly taller than, iRR; 1 symmetrically pentagonal B in the AB interray having 2 equally steeply sloping upper sides beneath the 2 adjacent simple RR; other BB slightly asymmetrically pentagonal with steeply sloping upper sides beneath compound RR and slightly less steeply sloping upper sides beneath simple RR; lateral sides of BB diverging; widest part of B ranging from slightly wider than to almost twice as wide as base of B.

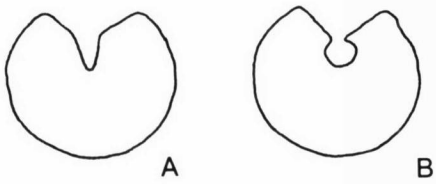

Fig. 24. Two types of food groove shapes in the arms of *Doliocrinus pustulatus*, greatly enlarged. A, IBr_1; B, IBr_2.

RR 5, 2 simple (in the A and D rays) and 3 compound (in the B, C, and E rays); compound RR significantly taller than simple RR, extending further both distally and proximally than simple RR; simple RR wider than compound RR, inverted pentagons with relatively steeply sloping lower sides in 3 individuals, taller than broad in 2 others; D-ray R an irregular, distally widening octagon with sides abutting against (beginning with IBr, and moving clockwise) D-ray IBr_1, 2 relatively large tegmenal plates, X_1 and C-ray sR (D-ray R has truncated right shoulder to accommodate X_1 but does not actually contact X_1), C-ray iR, CD-interray B, DE-interray B, E-ray iR, and E-ray sR (Pl. 4, fig. 3; Fig. 23); iRR slightly wider than tall, inverted, symmetrical, distally tapering pentagons, with steeply sloping lower sides, taller than overlying sRR; sRR low, distally expanding trapezoids.

Anal series composed of at least 3 brachial-like plates; X_1 an equidimensional, distally tapering, quadrangular plate (in side view; cylindrical in 3 dimensions), joining the C-ray sR with convex suture; X_1 resting on steeply sloping truncated left shoulder of C-ray sR; right shoulder of D-ray R also truncated to form notch in cup, but X_1 not abutting against D-ray R; succeeding XX equidimensional to short cylinders tapering distally; all XX with V-shaped grooves like food grooves incised into inner surfaces a distance about one-third plate diameter, covered by irregular series of small polygonal plates given off from tegmen (anal backing plates apparently extending distal to XX and forming tube).

Tegmen (Pl. 4, fig. 2, 3, 7) forming high, vaulted ceiling over dorsal cup; tegmen attached at top corners of RR (interradially), but vaulted to just above tops of $IBrr_1$ (radially); composed of single, large, central, flat-lying, oblong plate surrounded by numerous small irregularly polygonal plates arched to form large vaulted passageways to the B-ray IBr_1 and E-ray IBr_1 off which branch similar, but smaller, vaulted passageways to the A-, C-, and D-ray $IBrr_1$; 5 larger, hexagonal, peripheral, interradial plates between $IBrr_1$; 1 standing vertically in the AB interray making small, but sharp, notch in cup at junction of A- and B-ray RR (Pl. 4, fig. 1, 11); other larger interradial plates somewhat smaller, usually flat-lying, occupying a tegmenal rather than calyx position, as does the AB-interray peripheral tegmenal plate. (In one specimen, 1279TX176, two small peripheral tegmenal plates stand vertically in an interradial position on a flattened upper side of the D-ray R between the D-ray IBr_1 and X_1.)

IBrr at least 1 to 2 per ray, none observed to be axillary; distally tapering cylinders, taller than broad; with keyhole-shaped food grooves (Fig. 24) incised about one-third of way into inner surfaces; food grooves shallowing rapidly down RR and disappearing about one-third of the way down RR; food grooves covered over observed length by irregular series of small polygonal plates (apparently fixed and immobile) given off from tegmen; arms beyond $IBrr_2$ unknown.

Column (known over any length from 1 specimen; Pl. 4, fig. 6, 7) pentapartite and obscurely pentagonal adjacent to cup to round (distally) with radial pentameres and angles; lumen about one-sixth diameter of column, pentagonal with interradial angles (at least proximally), composed of larger nodals alternating with smaller internodals.

All plates, except tegmenal plates, covered with numerous pustules, fairly evenly disseminated, eroded on portions of some individuals; pustules ranging from short, fat, and rounded to fairly tall, thin, and sharp (almost spiny); single row of large downward projected pustules forming ring around base of BB, none to a few larger pustules per B; proximal columnal with similar ring of enlarged pustules directed slightly distally (but also with numerous smaller pustules); distal columnals highly pustulose, more so on nodals than on internodals, with scattered groups of 2 to 5 close-spaced pustules separated by areas with more evenly distributed pustules (Pl. 4, fig. 6-8).

Occurrence.—Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, from Fittstown Quarry (3 specimens) and McLish Ranch (1 specimen); shale band immediately below Lower Echinoderm Zone at Lick Creek Road (1 specimen).

Discussion.—The plate arrangement in the dorsal cup of *Doliocrinus pustulatus* places it in the Cincinnaticrininae. *D. pustulatus*, however, has a proportionally broader dorsal cup than other known cincinnaticrinids. The pustulose nature of the

plate surfaces is a unique feature among cincinnaticrinids. A complete or partial crown has not been found, and so the arm branching pattern is unknown.

Unknown Cincinnaticrinidae

Plate 5, figures 23, 24; Figure 25

A small, well-preserved cincinnaticrinid (1276-TX13) is briefly described, and its possible affinities are discussed.

Description.—Dorsal cup expanding distally, at widest plane (at tops of RR) about two and one-third times as broad as column; plate sutures hardly depressed; cup height (base of BB to top of RR) 2.0 mm; simple RR in A, B, and D rays, compound R in E ray, C ray not visible; BB probably 5, equal-sized, equidimensional, about same size as E-ray iR, expanding significantly distally, symmetrically pentagonal with steeply sloping upper sides; simple RR taller than broad, iR and sR broader than tall with sR somewhat larger than iR.

IBrr apparently 3 per ray, distally tapering cylinders; $IBrr_3$ axillaries, distally tapering to mid-height where they diverge rapidly distally; arm branching apparently isotomous, probably with 3 Brr per division series (Pl. 5, fig. 23).

Column at least 7 times as long as crown is tall, obscurely pentagonal proximally, with radial pentameres and angles, becoming round distally; taller and thicker nodals alternating with shorter, thinner internodals with every other nodal somewhat larger than intervening nodals (Pl. 5, fig. 24).

Occurrence.—From float, probably from between the *Carabocrinus* and *Bromidocystis* beds of the Mountain Lake Member at the North-Central I-35 locality.

Discussion.—This specimen could be a juvenile or adult *Isotomocrinus*, or an as yet undescribed genus, or a juvenile *Doliocrinus pustulatus*, *Praecursoricrinus sulphurensis*, or an undescribed species of *Doliocrinus* or *Praecursoricrinus*. It has a cup shape and cup and IBr plate shapes similar to *D. pustulatus* but lacks depressed sutures and pustulose plate surfaces. Lack of knowledge of arm branching in *D. pustulatus* and tegmen and food grooves in the specimen in question makes association difficult. Only *Isotomocrinus* Ulrich, 1925, among the Cincinnaticrinidae has isotomous arm branching, and what can be seen of 1276TX13 presents no significant divergences from what is known of *Isotomocrinus*. However, many peculiarities of *Isotomocrinus* involve insertion of X_1 and shape and length of the anal series (Warn and Strimple, 1977, p. 61-66), and placement of 1276-TX13 is suspended, at least until specimens exhibiting C-ray morphology are found.

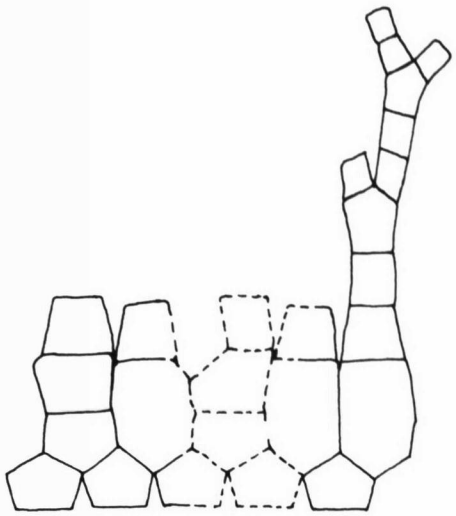

Fig. 25. Plate diagram of unknown Cincinnaticrinidae (1276TX13), hypothesized where dashed. Only a portion of one arm (right branch of the A ray) is shown; other arms are similar.

Superfamily MYELODACTYLACEA Miller, 1883

Family IOCRINIDAE Moore and Laudon, 1943

Genus PELTACRINUS Warn, new

Type species.—*Peltacrinus sculptatus* Warn, n. sp.

Diagnosis.—Iocrinidae with 5 roughly equal-sized, similarly shaped RR; with moderately to strongly sculptured plates; with pronounced lip around base of cup (at base of BB); and with broad anal series (significantly broader than arms) branching off brachianal.

Etymology.—The name *Peltacrinus* is derived from *pelta*, Latin for small shield, and refers to the shape of the RR.

PELTACRINUS SCULPTATUS Warn, n. sp.

Plate 5, figures 1-16; Figures 26-29

Material.—Holotype OU 9057; paratypes OU 9058-9063, 1122TX42-43, and 1405TX3 and 6; 7 additional

specimens (OU 9064, 1405TX7, and 1122TX44-47), making a total of 18, were used in this study.

Diagnosis.—Because *Peltacrinus* is monotypic, the specific diagnosis is the same as the generic diagnosis.

Etymology.—*Sculptatus* is Latin for carved or chiseled and describes the prominent plate sculpturing of this species.

Description.—Cup at widest point about two and one-half times as broad as column; cup sides diverging relatively rapidly distally to tops of RR; arms, when folded, not much wider than cup but at least 6 times longer than cup is tall; cup heights (base of BB to top of RR) ranging from 1.6 to 5.8 mm; cup composed of relatively thin, fairly fragile plates (which allowed flattening of numerous specimens).

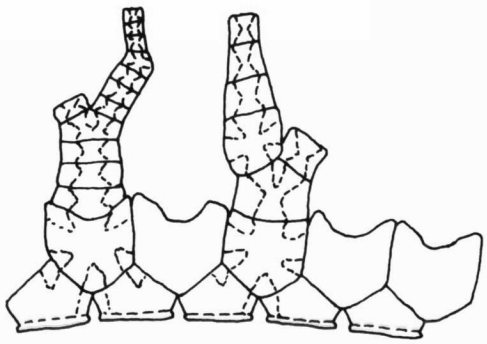

Fig. 26. Plate diagram of *Peltacrinus sculptatus*. Only a portion of one arm (right branch of E ray) is shown; that pattern continues distally; other arms are similar. Prominent plate sculpturing is portrayed in the C and E rays on the BB, RR, brachianal, XX, and primibrachs 1 to 3; sculpturing on other plates and other rays is similar.

BB 5, equidimensional, and of about equal size (except in a few abnormal specimens); low symmetrical pentagons with distally diverging sides; proximal edges of BB with prominent ridge making for out-flared lip around base of cup (Pl. 5, fig. 6).

RR 5, simple; thin, curved, shield or shovel-shaped, expanding distally to widest point at tops; C-ray R commonly slightly smaller than others (Pl. 5, fig. 5).

C-ray R supporting across its entire distal surface a large distally expanding pentagonal axillary (brachianal) bearing an arm on its right sloping upper side and a broad anal series on its left upper sloping side (Pl. 5, fig. 5); X_1 a large, quadrangular plate nearly as large as the underlying brachianal; succeeding XX (at least 4) distally tapering trapezoids, diminishing in size distally, extending at least halfway up crown; XX

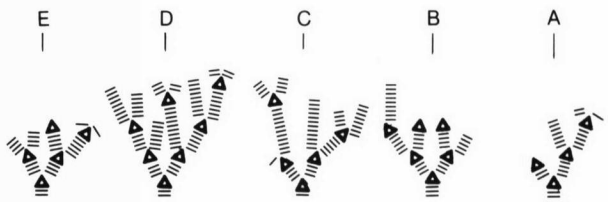

Fig. 27. Arm branching pattern of *Peltacrinus sculptatus* as typified by OU 9058. Each bar represents a nonaxillary Br beginning at the bottom with primibrach 1; each triangle is an axillary bearing 2 equal-sized arms. Rays are marked at top. Primibrach 1 of C ray rests on brachianal (not shown here) with anal series (also not shown here) as left branch into CD interray.

arcuate in cross section.

IBrr 2 to 4 per ray with variation observed both among and within individuals, most commonly 3 (occurrence of 2 IBrr may be confined to the C ray, although majority of specimens have 3 IBrr in C ray); $IBrr_1$ (except in C ray) appearing to occupy only middle two-thirds of subjacent distal R edge (actually they nearly join along that entire edge, but arcuate shape of plates hides their lateral edges); IBrr low, thin rectangles, arcuate in cross section, tapering only slightly, and distally diminishing in size only slightly; last IBr in each ray a pentagonal axillary bearing 2 isotomously branching arms; arms branching at least 3 times; IIBrr 3 to 6 per division series,

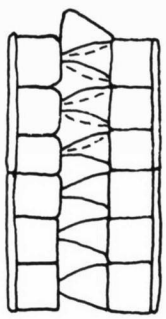

Fig. 28. Cover plate arrangement (double biseries) in the arms of *Peltacrinus sculptatus*. Two greatly enlarged Brr are shown, with 2 rows of nearly square cover plates just inside the edges of Brr and an imbricate biseries in the middle. Plates in the inner series are wedge-shaped with more proximal plates overlapping more distal plates. Dashed lines represent the hidden proximal edges of 5 plates.

the last an axillary; IIIBrr and higher 4 to 13 per division series (description of distal arms is based on OU 9058, Pl. 5, fig. 11, 12, whose branching pattern is illustrated in Fig. 27); Br edges convex so that arm edges, in side view, scalloped in appearance (Pl. 5, fig. 11-13); arm

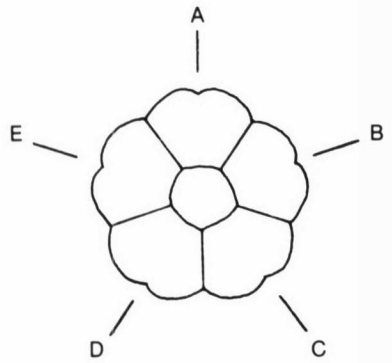

Fig. 29. Cross section of the column of *Peltacrinus sculptatus*, greatly enlarged, showing radial arrangement of pentameres and bilobes and interradial disposition of interpentameric sutures and lumen angles (letters denote the 5 rays).

food grooves covered by a double biseries of cover plates, an outer biseries of 3 tall rectangles per Br on each side of an inner biseries of 3 wedge-shaped plates per Br on each side; inner biseries of plates imbricate with distal edges overlapping proximal edges of superjacent plates (Pl. 5, fig. 13; Fig. 28); Brr with alternating biseries of wedge-shaped pits on their inner surfaces, one pit beneath each cover plate of the outer biseries (Pl. 5, fig. 13); all plates of crown highly sculptured (Pl. 5, fig. 3-6: Fig. 26).

Column pentapartite with radial pentameres; round to decalobate with each pentamere having a pair of closely spaced lobes separated from other pairs by shallow trough (Pl. 5, fig. 6; Fig. 29); lumen large, about one-third or more of diameter of column, round to obscurely pentagonal with interradial angles (Pl. 5, fig. 5; Fig. 29); column composed of 3 alternating sets of columnals proximally, perhaps grading into only 2 sets distally.

Occurrence.—*P. sculptatus* is known only from the upper part of the Pooleville Member of the Bromide Formation in south-central Oklahoma. All but one specimen are from Zone 3 at Culley Creek. A single specimen (OU 9058) is from 2.2 m below the Viola Limestone at Dunn Quarry.

Discussion.—*Peltacrinus* is much like *Iocrinus;* they have similar cup-plate shapes and arrangements. *Peltacrinus*, however, has a broader anal series, different plate sculpturing (perhaps related to differences in soft-part morphology), a more pronounced basal cup lip, and a strongly heteromorphic column. Also, *Peltacrinus* has a round to decalobate column, whereas *Iocrinus* has a strongly pentagonal column. These differences are judged sufficient to warrant erection of a genus for specimens placed here in *P. sculptatus*.

PHYLOGENY OF PRIMITIVE CALCEOCRINIDS

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Calceocrinids have fascinated paleontologists for many years because of their unique adaptation and mode of life (e.g., Moore, 1962a; Brower, 1966, 1977; Kesling and Sigler, 1969). Fortunately, calceocrinids comprise one of the more common elements of the Bromide fauna, and approximately 200 specimens placed in three species are available for study. This abundant material provides the data base necessary for statistical studies of growth and variation. Inasmuch as the Bromide calceocrinids represent some of the oldest known members of the Calceocrinidae, these crinoids are critical to understanding the origin and early evolution of the family. Detailed descriptions of the three Bromide species were published by Brower (1977). Brief annotations of the three taxa follow.

Paracremacrinus laticardinalis Brower (1977, p. 5, pl. 1, 2; see Fig. 31E-H, this paper) from the Lower Echinoderm Zone of the Mountain Lake Member. This species is characterized by four arm-bearing rays in which single radials occur in the B and C rays. The E-ray arm bifurcates once proximally; higher branches are heterotomous. The A-, D-, and B-ray arms bear many ramules arranged according to the usual cremacrinid pattern.

Cremacrinus ramifer (Brower) n. comb. (1977, p. 9, pl. 3, fig. 1, 4-9; pl. 4, fig. 9-11, text-fig. 2f-h; see Fig. 31A-D, this paper) from the Pooleville Member. The calyx is coarsely pitted and arms are present in four rays. The E-ray arm is either unbranched or has a single distal bifurcation. The A, D, and B rays exhibit few ramules and simple branching patterns, which retain some juvenile features.

Calceocrinus longifrons Brower, (1977, p. 13, pl. 3, fig. 2, 3; pl. 4, fig. 1-8; see Fig. 31I-L, this paper) from the Pooleville Member. Arms are present in three rays. The cup plates are pitted. The E-ray arm is unbranched whereas the A and D rays have simply branched arms.

The purpose of this paper is to reconstruct a line of ancestry and descent for primitive calceocrinids at the species level with the aid of numerical techniques. The reader who is interested in the functional morphology of these trends should consult Springer (1926), Moore (1962a), Brower (1966, 1977) and Kesling and Sigler (1969).

As discussed later, my phylogenetic studies indicate that *Anulocrinus* as defined at present (see Moore, 1962a, Brower, 1966, for diagnoses adopted by most workers) does not form a monophyletic genus. Accordingly, I reassign some species and emend the diagnoses of *Anulocrinus* and *Cremacrinus*. The following taxa are definitely transferred from *Anulocrinus* to *Cremacrinus: A. drummuckensis* Ramsbottom (1960), *A. forrestonensis* Kolata (1975), *A. ramifer* Brower (1977), and *Cremacrinus simplex* Springer (1926; this crinoid was placed in *Anulocrinus* by Moore, 1962a and Brower, 1966). These species are all small forms that are characterized by reduced and simple patterns of arm branching (see section on phylogeny). The poorly known *Anulocrinus latus* Brower and Veinus (1974) is questionably assigned to *Cremacrinus*.

Current diagnoses of the two genera follow.

Anulocrinus (Ramsbottom, 1961, p. 8). Type and only known species, *A. thraivensis* Ramsbottom, (1961, p. 8), by original designation. Diagnosis: Calceocrinidae with 4 arm-bearing rays; B and C rays showing both inferradials and superradials; inferradials of B and C rays not in lateral contact; inferradial and superradial of E rays in broad or narrow contact; number of basals unknown, presumably 4 as in *Cremacrinus*. E-ray arm branching at 2 or more levels. A and D rays with 4 or more axillary and 4 or more nonaxillary plates in main axil series; axil arm branches moderately numerous, separated by 3 or more brachials (average value equals 3.9 plates). B-ray arm reduced, with 1 or 2 axillary and nonaxillary plates in the main axil series.

Cremacrinus (Ulrich, 1886, p. 107). Type species, *C. punctatus* Ulrich (1886, p. 107), by original designation. Diagnosis: Calceocrinidae having 4 arm-bearing rays; B and C rays with both inferradials and superradials; inferradials of B and C rays widely separated; inferradial and superradial of E ray in broad contact; basals 4. E-ray arm variable, ranging from unbranched to ex-

tensively branched with 1 proximal bifurcation and numerous distal heterotomous branches. A and D rays with 2 (rarely 1) axillary and 2 (rarely 1 or 3) nonaxillary plates in main axil series; axil arm branches ranging from 1 to about 30 in number; axil arm branches separated by 2 to 3.5 plates. B-ray arm variable, ranging from identical to those in the A and D rays to reduced with smaller number of branches and fewer main axils.

Anulocrinus is easily separated from *Cremacrinus* by the more numerous plates in the main axils of the A and D rays. In addition, the ramules of the axil arms are more widely spaced in *Anulocrinus* than in *Cremacrinus*. As presently visualized, *Cremacrinus* is a moderately large and rather unwieldy genus with almost 20 species known from Ordovician and Silurian rocks (see Table 22 for list of species). Possibly the genus should be subdivided. If so, the most likely way would be based on the structure of the E ray, perhaps by resurrecting and redefining *Castrocrinus*, which was proposed by Ringueberg (1889, p. 396) with *Calceocrinus furcillatus* W. R. Billings as type species. However, this has not been done here because I have not examined all of the type specimens involved.

PREVIOUS WORK

Many authors have discussed various aspects of calceocrinid phylogeny, largely because of the unique hinge, cup structure, and adaptation of these animals. Jaekel (1918, p. 87-88) noted the fundamental difference between calceocrinids with three and four arm-bearing rays in erecting separate subfamilies for these two groups. He also realized that the Calceocrinidae was descended from monocyclic inadunates with compound radials in the B, C, and E rays. Springer (1926, p. 90-93) studied evolution in some detail and outlined evolutionary trends and stages. Springer's work provided a firm foundation for subsequent treatments of these forms. Moore (1962a) comprehensively reviewed the calceocrinids known at that time and also postulated evolutionary trends and a lineage based on qualitative considerations. Kesling and Sigler (1969) and Brower (1966) discussed the living habits of calceocrinids and the functional morphology of their evolutionary trends. Kesling and Sigler (1969) also applied numerical cladistic techniques in the form of rooted or directed Prim and Wagner trees. Their paper provided an excellent example of the computational techniques required for these methods. The Kesling and Sigler (1969) data include 7 characters and the 11 genera described by that time. Rowell (1969) restudied the Kesling and Sigler data with principal components. Kesling and Sigler (1969) and Rowell (1969) postulated similar lineages, which differ somewhat from those of Moore (1962a). In a monograph on Bohemian calceocrinids, Prokop (1970) reconstructed a phylogeny similar to that of Moore (1962a). Webster (1976) observed that calceocrinids had undergone mosaic evolution and sketched a lineage modified from that of Kesling and Sigler (1969).

Essentially this paper combines the numerical approaches of Kesling and Sigler (1969) and Rowell (1969). The principal components yield a purely phenetic view. Numerical cladistics are produced by the undirected Prim and Wagner networks. Previous authors presented phylogenies of the genera; however, evolution operates at the species or population level. Consequently, the present data involve the species of the four primitive genera. A later study will embrace the more advanced forms.

CHARACTERS AND SPECIES

Seventeen variables or characters were determined for 31 operational taxonomic units (OTU's), which consist of species assigned to the four primitive genera of calceocrinids, *Cremacrinus*, *Anulocrinus*, *Paracremacrinus*, and *Calceocrinus* (Tables 22, 23). The purpose of this paper is to study the evolution of the primitive genera that appeared during the Ordovician. Complete data sets were obtained for 21 OTU's and most later discussion deals with these sets. The 21 OTU's represent all of the genera and all stratigraphic levels from which primitive calceocrinids are known (Table 22). In addition, partial data sets are available for 10 forms; although incomplete, the information is sufficient to characterize the affinities of these forms (Table 22). Plate diagrams for the cups of the four primitive genera may be found in Figure 30. Line drawings of representative species are to be found in Figures 31 and 32.

The variables or characters listed in Table 23 fit into several categories. Parameters X1-X5 largely define the basic structure of the dorsal cup with respect to the number of arm-bearing radials, nature of the B and C rays, and contact between the super- and inferradials of the E ray. Parameters X6-X16 enumerate the branching patterns

Table 22. Calceocrinid species used in phylogeny study.

	Species	Age	Units, Locality
	Complete Data Sets		
1.	Paracremacrinus laticardinals Brower (1977, p. 5).	M. Ord. Blackriveran	Lower Echinoderm Zone of Mountain Lake Member, Bromide Formation, Oklahoma
2.	Cremacrinus ramifer (Brower, 1977, p. 9).	M. Ord. Blackriveran	Pooleville Member of Bromide Formation, Oklahoma
3.	Cr. arctus Sardeson (1928, p. 41; Kolata, 1975, p. 20).	M. Ord. Blackriveran	Platteville Limestone, Minnesota and Illinois
4.	Calceocrinus longifrons Brower (1977, p. 13).	M. Ord. Blackriveran	Pooleville Member of Bromide Formation, Oklahoma
5.	Cr. guttenbergensis Kolata (1975, p. 23).	M. Ord. Trentonian	Guttenberg Formation, Illinois
6.	Cr. articulosus (E. Billings) (Springer, 1926, p. 108).	M. Ord. Trentonian	Trenton Limestone, Kentucky and Ontario
7.	Cr. kentuckiensis (Miller and Gurley) (Springer, 1926, p. 109).	M. Ord. Trentonian	Trenton Limestone, Kentucky
8.	Cr. furcillatus (W. R. Billings) (1887, p. 51; Ringueberg, 1889, p. 393).	M. Ord. Trentonian	Trenton Limestone, Ottawa
9.	Ca. barrandii Walcott (1884, p. 212).	M. Ord. Trentonian	Trenton Limestone, New York
10.	Ca. multibifurcatus Brower (1966, p. 624).	M. Ord. Trentonian	Kirkfield crinoid beds, Ontario
11.	Cr. drummuckensis (Ramsbottom) (1961, p. 9; Moore, 1962a, p. 24).	U. Ord.	Drummuck Group, Scotland
12.	Anulocrinus thraivensis Ramsbottom (1961, p. 8; Moore, 1962a, p. 22).	U. Ord.	Drummuck Group, Scotland
13.	Ca. pustulosus Johnson (Brower, 1966, p. 627).	L. Sil.	Manitoulin Dolomite, Ontario
14.	Cr. tubuliferus Springer(1926, p. 106; Moore,1962a, p. 21).	M., U. Sil.	Beech River Formation, Tennessee
15.	Cr. decatur Springer (1926, p. 107).	M., U. Sil.	Decatur Limestone, Tennssee
16.	Cr. ulrichi Springer (1926, p. 105).	M., U. Sil.	Beech River Formation, Tennessee
17.	Cr. simplex Springer (1926, p. 107; Moore, 1962a, p. 24).	M., U. Sil.	Beech River Formation, Tennessee
18.	Ca. chrysalis (Hall) (Springer, 1926, p. 112; Moore, 1962a, p. 20).	M., U. Sil.	Rochester Shale, New York
19.	Ca. minor (Springer) (1926, p. 112; Moore, 1962a, p. 20).	M., U. Sil.	Beech River Formation, Tennessee
20.	Ca. anglicus (Springer) (1926, p. 112; Ramsbottom, 1952,p. 43; Moore, 1962a, p. 20).	M., U. Sil.	Dudley Limestone, England
21.	Ca. bohemicus Prokop (1970, p. 84).	M., U. Sil.	Kopanina Formation, Bohemia

Partial Data Sets			
22.	?Cr. latus (Brower and Veinus, 1974, p. 25).	M. Ord. Blackriveran	Benbolt Formation, Virginia
23.	Cr. forrestonensis Kolata (1975, p. 25).	M. Ord. Blackriveran	Platteville Limestone, Illinois
24.	Cr. billingsianus (Ringueberg) (1889, p. 394).	M. Ord. Trentonian	Trenton Formation, Ottawa
25.	Cr. inaequalis (E. Billings) (Wilson, 1946, p. 35).	M. Ord. Trentonian	Trenton Limestone, Canada
26.	Cr. lucifer Bolton (1970, p. 62).	M. Ord. Trentonian	Liskeard Group, Ontario
27.	Cr. punctatus Ulrich (Springer, 1926, p. 110; Moore, 1962a p. 21).	M. Ord. Trentonian	Decorah Shale, Minnesota
28.	Cr. rugosus (W. R. Billings) (1887, p. 53; Ringueberg, 1889, p. 393).	M. Ord. Trentonian	Trenton Limestone, Ottawa
29.	Ca. constrictus Brower (1966, p. 623; 1973, p. 451).	U. Ord.	Girardeau Limestone, Illinois
30.	Ca. ontario (Springer) (1919, p. 127; 1926, p. 112).	L. Sil.	Cataract Formation, Ontario
31.	Ca. humilis Strimple (1963, p. 58).	M., U. Sil.	Henryhouse Formation, Oklahoma

of the A, D, B, and E rays. The last character, X17, shows the degree of fusion of the brachials and ramulars in all rays.

STATISTICAL TECHNIQUES

Principal components analysis.—Two multivariate statistical techniques were used to study the phylogeny of the 21 species for which complete data sets are available. The first method, principal components analysis, is purely phenetic. Here, a correlation matrix was calculated for the 17 characters or variables. The correlation matrix was selected rather than a covariance matrix because the correlation matrix, in effect, standardizes all variables to have unit variance. This is necessary for the calceocrinids owing to the greatly different units of the various characters; for example, some are dichotomous whereas others are continuous (Table 23). The 17 by 17 matrix contains the correlation coefficients for all possible pairs of characters; these coefficients show all of the interrelationships between characters that existed during the evolution of primitive calceocrinids.

The principal components are given by the normalized eigenvectors and eigenvalues of the correlation matrix. The eigenvectors or principal components extract the main patterns of correlation among the variables or characters. The principal component scores were computed by multiplying the standardized data by the principal components. The data were standardized by Z-scores so that each character has a zero mean and unit variance. The principal component scores represent the orthogonal projections of the species onto the axes defined by the principal components. As such the scores serve two purposes. First, they aid in interpreting the principal components. Second, the scores ordinate the calceocrinid species in principal-component space so that evolutionary trends and groups of taxa can be seen relative to the patterns of correlation. Davis (1973, p. 152-168, 478-500) provided a clear outline of the computational details.

Network analysis.—Prim and Wagner networks represent the second class of techniques for the phylogeny study. In the first step, each character was standardized to range from 0.0 to 1.0 (Sneath and Sokal, 1973, p. 152-157). This ensures that each character has an equal total contribution to separating the species. The second step is to calculate a matrix of differences or distances between the species. The usual measure of distance for phyletic research is the Manhattan

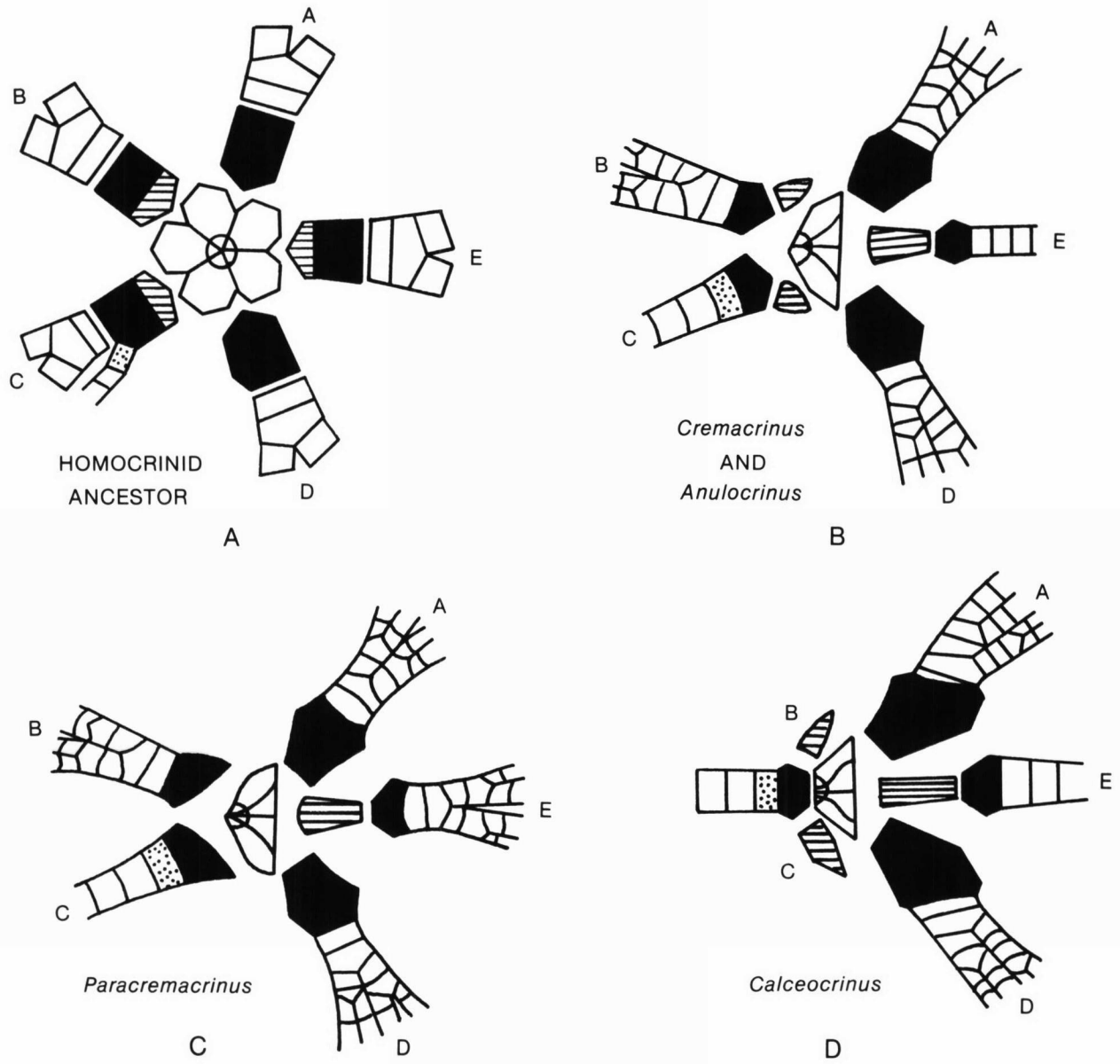

Fig. 30. Plate diagrams of primitive calceocrinid genera and homocrinid ancestor (modified from Moore, 1962a). Main radial elements are black; inferradials of B, C, and E rays ruled; anal X stippled.

distance, D_{jk}:

$$D_{jk} = \sum_{i=1}^{p} |X_{ij} - X_{ik}|$$

X_{ij} and X_{ik} are the standardized character values for species j and k with respect to character i; p gives the number of characters or variables. The Manhattan or City-block distance is simply the sum of the distances between the two species, measured parallel to the axes defined by the characters. In this study, several analyses have been done, based on different numbers of characters. Consequently the Manhattan distances have been converted to mean character distances (MCD) by dividing by the number of characters. The MCD gives the average distance between all characters so that the distances based on different numbers of characters can be compared. Hereafter the MCD's will be termed distances. Sneath and Sokal (1973, p. 121-128) reviewed the basic types of distance coefficients. The distance matrix has t rows and t columns where t is the number of species.

The third step is to calculate the Prim and Wagner networks. Prim networks connect or link up

the species that are separated by the smallest number of evolutionary steps or differences. The networks determined here are unrooted or undirected in that ancestors and primitive character states have not been specified. Because of the many evolutionary reversals for some of the characters, global primitive versus advanced character states cannot be defined for many variables. What constitutes primitive versus advanced or derived character states depends on which part of the evolutionary sequence is being considered. The networks of this paper have been extracted from the distance matrix with the strategy listed below. Farris (1970, 1972) and Sneath and Sokal (1973, p. 325-332) listed formal algorithms for the calculations of Wagner trees from distance matrices. As shown by Kluge and Farris (1969) and Farris (1970), Prim and Wagner networks can also be constructed directly from the data without having to form a distance matrix. However, the networks here were derived from the distance matrices because generally several networks were determined for any one distance matrix subject to different constraints.

A Prim network is a minimum spanning tree, that is, the shortest network that links up all of the species. The distance matrix is scanned and the distances are arranged from smallest (the most similar species) to largest (the least similar species). The Prim network is built from this list of distances; gradually increasing distances are selected until all forms are linked into the network. The necessary number of links equals the number of taxa less one. Two types of Prim network were prepared. The first is unconstrained and is the minimum spanning tree for that distance matrix. Also networks that are constrained to be consistent with the stratigraphy have been determined on an experimental basis. Stratigraphically consistent networks could be built in several ways. The philosophy adopted here is that a species is forced to join with the most closely related taxon that occurs at the same or an older stratigraphic level; links between the species and geologically younger forms are not accepted. The implicit assumption is that the ancestry of a species is found at the same or an older stratigraphic level. The total length of a Prim network is the sum of the distances along all of the links. Lengths can be compared for several different networks, for example, unconstrained versus stratigraphically consistent networks for the same set of data.

The length of a Prim network can often be shortened by inserting hypothetical taxonomic units (HTU's), which convert the Prim into a Wagner network. A Wagner network minimizes the total amount of evolutionary change over the entire network. The decrease in length takes place because the introduction of an HTU extends the line of ancestry closer to the descendants. Consider three species, A, B, and C, which on the Prim network are connected A to B and B to C. The distances $D(A,B)$ and $D(B,C)$ are in the distance matrix and can be added to get the length over the three forms. Inserting the HTU between the three species changes the links and the distances to $D(HTU,A)$, $D(HTU,B)$, and $D(HTU,C)$. If the sum of these distances is less than $D(A,B)$ plus $D(B,C)$, then the HTU has shortened the network. The distance between an HTU and a known species, say A, is equal to (see Farris, 1970): $D(HTU,A) = [D(A,B) + D(A,C) - D(B,C)]/2$. The character states for the HTU are given by the median of the values for A, B, and C. If the characters of the HTU are the same as those of one of the known species, then

Table 23. Characters used in phylogeny study; for characters that vary at the species level, the value used is the average for mature individuals.

X1.	Number of arm-bearing radials.
X2.	Height of B-ray arms/height of A- or D-ray arms.
X3.	Degree of separation of B- and C-ray interradials. 1 = widely separated, 2 = narrowly separated.
X4.	Interradials and superradials of B and C rays joined or not. 1 = not joined, 2 = joined.
X5.	Nature of contact between superradial and interradial of E ray. 1 = broad contact, 2 = narrow contact.
X6.	Number of ramules in E-ray arm.
X7.	Number of brachial bearing proximal branch in E ray.
X8.	Number of brachials separating adjacent distal branches in E ray.
X9.	Number of axillary plates in main axils of A and D rays.
X10.	Number of nonaxillary plates in main axils of A and D rays.
X11.	Number of ramules in A and D rays, excluding omega ramule.
X12.	Number of brachials separating adjacent ramules in the axil arms of the A and D rays.
X13.	Number of axillary plates in main axils of B ray.
X14.	Number of nonaxillary plates in main axils of B ray.
X15.	Number of ramules in B ray, excluding the omega ramule.
X16.	Number of brachials separating adjacent ramules in the axil arms of the B ray.
X17.	Amount of fused brachials in all arms. 1 = no fused plates, 2 = some plates fused in either E ray or A, D, and B rays, 3 = some plates fused in all rays.

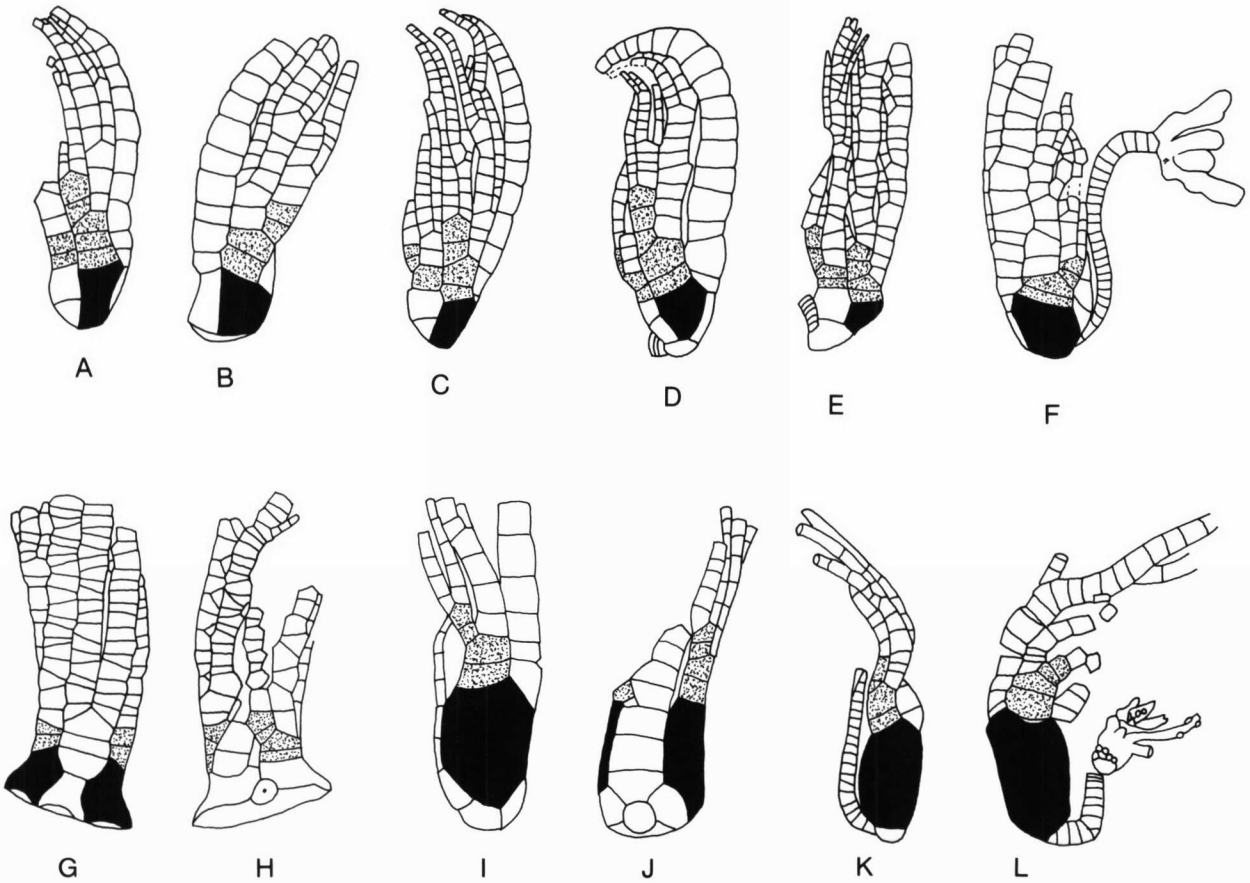

Fig. 31. Representative primitive calceocrinids from the Bromide Formation (Middle Ordovician, Blackriveran Stage) of Oklahoma; radials of A and D rays black; main axils stippled. A-D, *Cremacrinus ramifer* (Brower), Pooleville Member (after Brower, 1966, 1977). A, A and B rays of holotype USNM 156261, X1.8; B, D and E rays of paratype OU 8452, X1.6; C, A and B rays of paratype USNM 156262, X1.3; D, A and B rays of paratype OU 8450, X1.0. E-H, *Paracremacrinus laticardinalis* Brower, Mountain Lake Member (after Brower, 1977). E, A and B rays of paratype OU 8459, X0.7; F, D ray of paratype with complete stem and root OU 8461, X1.0; G, H, E-ray view and CD-interray view of holotype OU 8458, X0.6. I-L, *Calceocrinus longifrons* Brower, Pooleville Member (after Brower, 1966, 1977). I, J, A-ray view and CD-interray view of holotype USNM 221567, X2.4; K, A ray of paratype USNM 156267, X2.5; L, D ray of figured specimen USNM 156266, X1.6.

the HTU is not placed in the network because its length would not be shortened.

Many characters used in this study are continuous. Consequently, HTU's could be inserted almost anywhere into the network, although most of these HTU's would result in only minimal shortening of the network. To eliminate this problem, an HTU is placed on the network only if a reasonable amount of shortening occurs, namely 0.005 or 0.001 MCD units depending on the network.

After calculating a preliminary network from the original data, an improved network can be found based on weighted data (Farris, 1969). The consistency of a character, *C*, is defined in terms of the range of the character, *R*, and the length of change of the character over the entire network, *L*. For character *i*:

$$C_i = \frac{R_i}{L_i}$$

If C_i is 1.0, the character is perfectly consistent with the network and parallel evolution has not taken place. Low values of C_i denote characters than have undergone convergent evolution and are not consistent with the network. The character weights or consistencies can either be incorporated into the original data or into the calculation of the distance matrix. Either way, the end result is the same. For characters weighted by the consistencies, the previous distance formula becomes:

$$D_{jk} = \sum_{i=1}^{p} (|X_{ij} - X_{ik}|)\, C_i$$

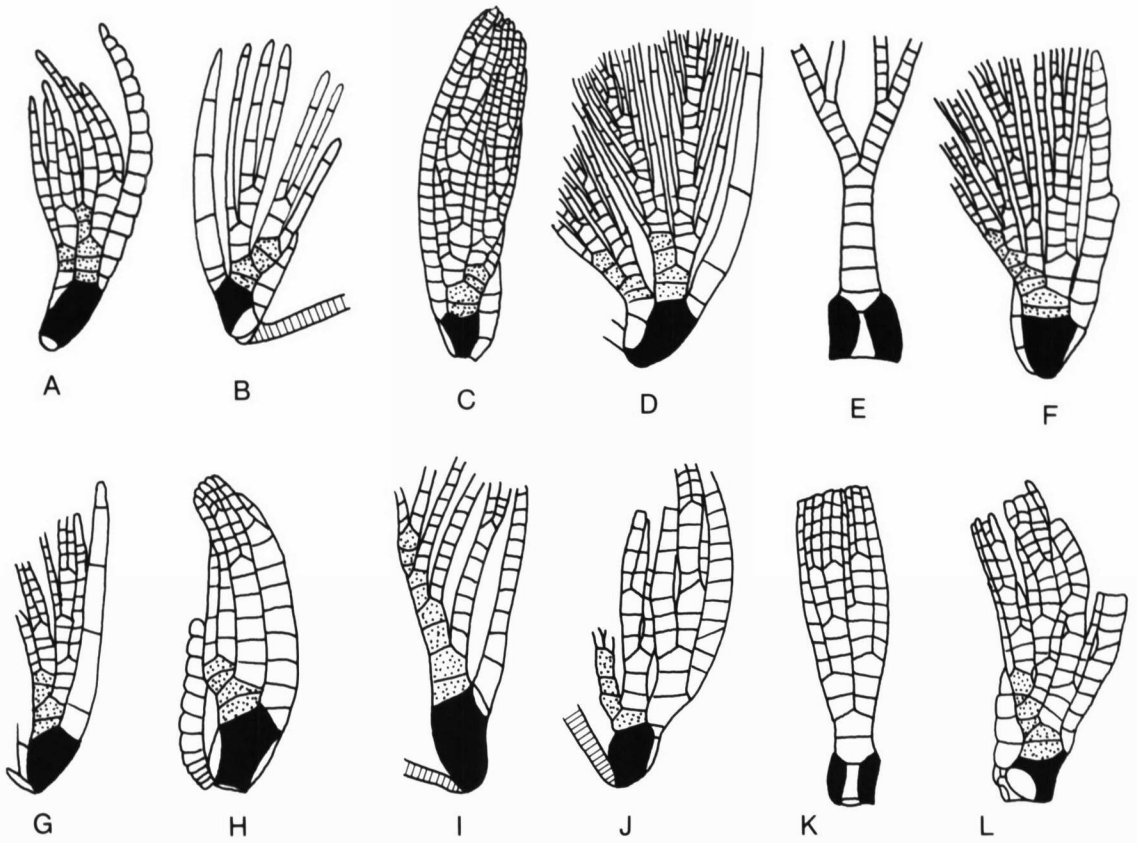

Fig. 32. Representative primitive calceocrinids from stratigraphic units other than the Bromide Formation; radials of A and D rays black; main axils stippled. A, *Cremacrinus drummuckensis* (Ramsbottom), A and B rays, X1.5; Upper Ordovician, Scotland (after Moore, 1962a, and Ramsbottom, 1961). B, *Cr. simplex* Springer, D ray, X1.0; Silurian, Beech River Formation, Tennessee (after Springer, 1926, and Moore, 1962a). C, *Cr. articulosus* (E. Billings), D ray, X0.8; Middle Ordovician, Trenton Limestone, Ontario (after Springer, 1926). D, *Cr. tubuliferus* Springer, A and B rays, X1.5; Silurian, Beech River Formation, Tennessee (after Springer, 1926, and Moore, 1962a). E, F, *Anulocrinus thraivensis* Ramsbottom, schematic restorations of E ray and A ray, X2.4; Upper Ordovician, Scotland (after Ramsbottom, 1961, and Moore, 1962a). G, *Calceocrinus minor* (Springer), A ray, X2.5; Silurian, Beech River Formation, Tennessee (after Springer, 1926, and Moore, 1962a). H, *Ca. chrysalis* (Hall), A ray, X1.8; Silurian, Rochester Shale, New York (after Springer, 1962, and Moore, 1962a). I, *Ca. barrandii* Walcott, A ray, X1.8; Middle Ordovician, Trenton Limestone, New York (after Walcott, 1884, and Moore, 1962a). J, K, *Ca. anglicus* (Springer), A ray and E ray, X2.3; Silurian, Dudley Limestone, England (after Springer, 1926, and Moore, 1962a). L, *Ca. pustulosus* Johnson, A ray, X1.8; Lower Silurian, Manitoulin Dolomite, Ontario (after Brower, 1966).

Because of the weighting, characters with high consistencies will contribute more to the distances than those with low consistencies. This seems reasonable; a highly consistent character should convey more meaningful evolutionary information than one with low consistency. Other weights can also be devised, such as weighting proportional to C_i^2 and so forth (Farris, 1969).

The Prim and Wagner networks can then be found for the weighted distance matrix. The entire weighting procedure can be iterated until a stable network has been reached (Farris, 1969). In this study, the inital weighted networks are almost the same as the original ones, and further iterations were not attempted.

Clear examples of a rooted Prim network and a Wagner tree are available in Kesling and Sigler (1969) for calceocrinids at the generic level; these outline the calculations beginning with the original data and continuing through a Wagner tree determined from weighted data. Farris (1972) and Sneath and Sokal (1973, p. 325-332) provided examples of Wagner networks derived from distance matrices.

According to Farris, Kluge, and Eckardt (1970), unrooted Wagner networks are consistent with the principles of phylogenetic systematics if no assumptions are made about the direction of evolu-

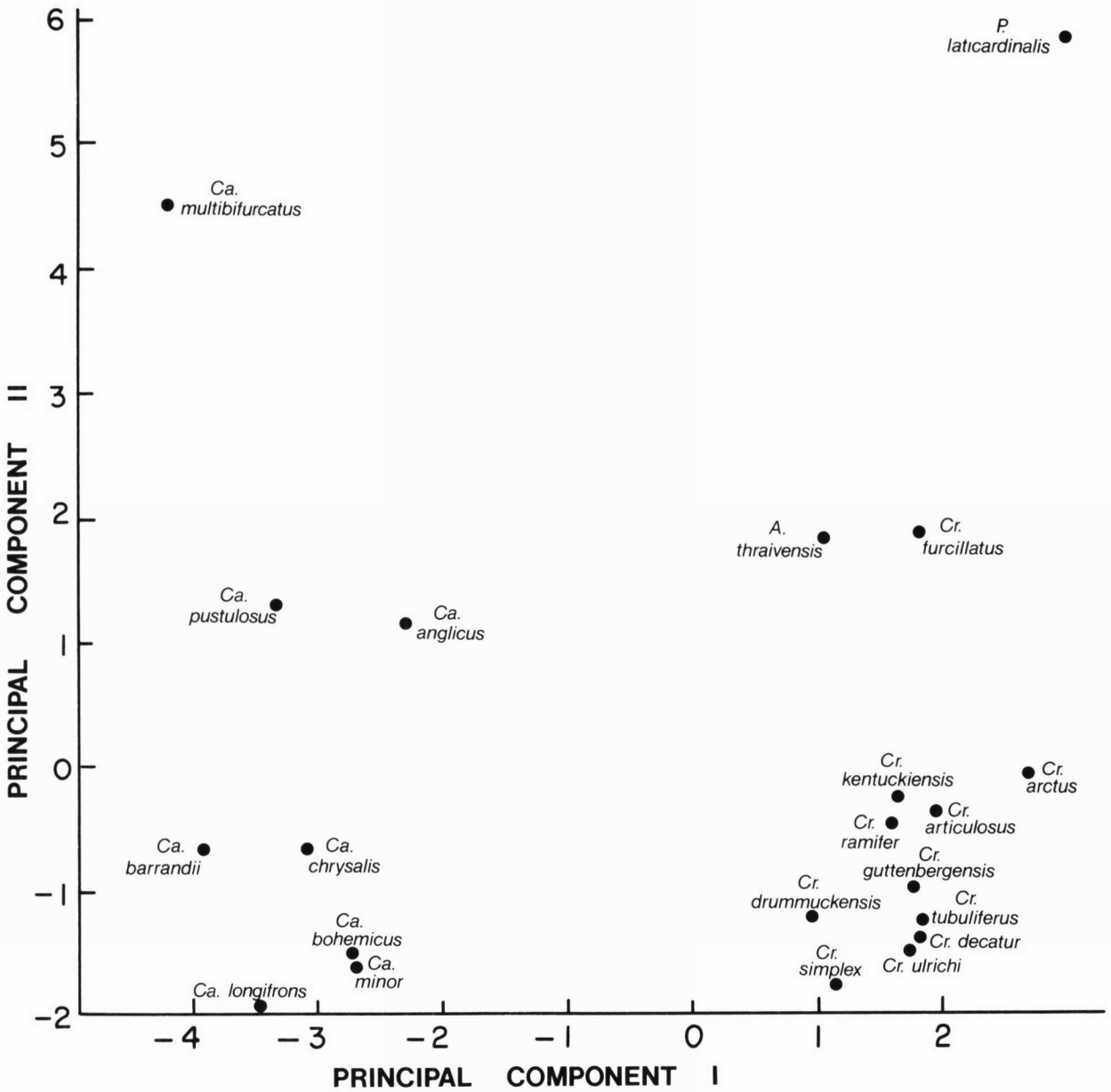

Fig. 33. Plot of scores of first two principal components for calceocrinid data.

tion of the characters. Consequently, the taxa grouped together on a Wagner network should be those that share the largest number of derived or advanced character states. The possession of common primitive or ancestral character states does not represent a valid similarity in phylogenetic systematics.

The reader should be aware of the basic assumption in the entire network procedure. This is that the most similar species with respect to the original or weighted data, whichever are used, are those considered to have common lines of ancestry and descent. In other words the evolutionary process works on parsimony or minimum evolutionary distance. This seems reasonable for the general case, if a statistically representative fossil record is assumed. However, because of the biased and unrepresentive nature of the fossil record for crinoids (doubtless all crinoid specialists will agree on this point) and many other organisms, a strict application of parsimony may not be valid for a given data set. At least as far as fossils

are concerned, the principle of evolutionary parsimony should be applied judiciously and with the proverbial grain of salt.

The monothetic cladogram algorithm of Camin and Sokal (1965; see Sneath and Sokal, 1973, p. 336-341) was also applied to the calceocrinid data. The Camin and Sokal method asssumes that evolution always proceded in one direction, and that no reversals took place. Because of the many reversals in calceocrinid evolution, the method produced poor results, which are not discussed in detail here. The Prim and Wagner networks make no such assumption.

RESULTS OF THE PRINCIPAL COMPONENTS ANALYSIS

Table 24 lists the first three principal components of the correlation matrix; a plot of the scores for the first two principal components is shown in Figure 33. The first three principal components explain over 73 percent of the correlation matrix variance and these reveal the main patterns of intercorrelation between the characters. The first principal component is associated with the most variance, namely 38.6 percent. The first principal component extracts positive correlations between the numbers of arm-bearing radials, X1; the ratio of heights of B-ray arms and A- or D-ray arms, X2; number of axillary and nonaxillary plates in main axils of B ray, X13 and X14; number of ramules in B ray, X15; and average number of axillary plates in the B-ray axil arms, X16. To a lesser extent, these variables are also inversely compared with the number of axillary and nonaxillary plates in the main axil series of the A and D rays, X9 and X10. A large negative principal component coefficient is observed for the nature of the contact between the E-ray inferradial and superradial, X5. Scrutiny of the principal component score plot in Figure 33 discloses the underlying relationships. Relative to the first principal component, species of *Calceocrinus* are discontinuously separated from those of *Anulocrinus*, *Cremacrinus*, and *Paracremacrinus*. Thus, the first principal component is linked to the characters that isolate *Calceocrinus*, with 3 arm-bearing rays, E, A, and D, from the other genera with arms in E, A, D, and B rays (see Fig. 30). Most of the distinguishing characters, X1, X2, X13-X16, are related to the loss of the arms in the B ray. This major dichotomy between calceocrinids with 3 and 4 arm-bearing rays is both important and striking. As far as X5 is concerned, the contact between the E-ray inferradial and superradial is typically narrow in *Calceocrinus* but wider in the other genera. Although most species are characterized by 2 axillary and 2 nonaxillary plates in the main axils of the A and D rays, three of the species with the most numerous plates are placed in *Calceocrinus;* hence the association of X9 and X10 with the first principal component.

Table 24. First three principal components for calceocrinids. (Explanation of characters, Table 23.)

Character	Principal component		
	I	II	III
X1	0.971	-0.027	0.111
X2	0.974	0.016	0.056
X3	-0.300	-0.210	-0.213
X4	0.263	0.646	-0.431
X5	-0.912	-0.028	-0.051
X6	-0.016	0.958	-0.166
X7	0.136	-0.793	-0.096
X8	0.165	-0.867	-0.047
X9	-0.474	0.474	0.497
X10	-0.463	0.522	0.421
X11	0.320	0.705	-0.372
X12	-0.263	-0.216	0.667
X13	0.958	0.045	0.123
X14	0.916	0.056	0.323
X15	0.589	0.353	-0.034
X16	0.926	0.002	0.332
X17	0.239	-0.434	-0.494
Percent of variance	38.6	24.2	10.4

Twenty-four percent of the correlation matrix variance is attributed to the second principal component (Table 24). The main variables contributing to this component are whether or not the inferradials and superradials of the B and C rays are fused together, X4; the branching pattern in the E ray, X6-X8; number of plates in the main axils of the A and D rays, X9 and X10; the number of ramules in the A and D rays, X11; and the amount of fusion of the arm plates, X17. Most of the parameters in this character suite relate to the arms of the E ray and the lateral or A and D rays. Taxa with extensively branched arms and numerous ramules in the E and lateral rays, including *Cremacrinus furcillatus*, *Anulocrinus thraivensis*, *Paracremacrinus laticardinalis*, *Calceocrinus multibifurcatus*, and *Ca. pustulosus*, are characterized by high scores on the second principal component. Forms with simple branching patterns in the lateral rays and unbranched E rays, such as *Cremacrinus simplex*, *Cr. drummuckensis*, *Ca. longifrons*, *Ca. minor* and *Ca. bohemicus*, tend to have low scores. The crinoids with fused brachials and

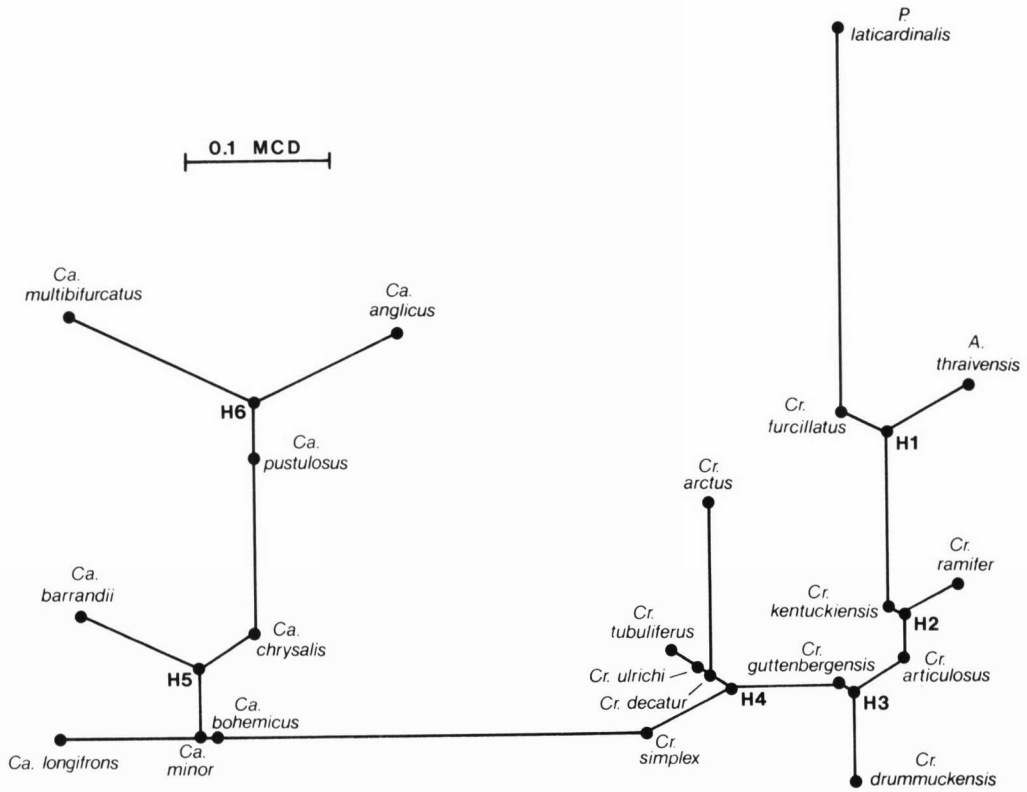

Fig. 34. Wagner network for calceocrinids based on 21 species and 17 characters. Length of network is 1.95 MCD units.

ramulars are also concentrated in the lower part of the score plot; examples are *Ca. minor*, *Ca. bohemicus* and *Cr. simplex*. It is notable that the distribution of the arm-branching patterns is independent of the number of arm-bearing rays, and parallel developments are seen in forms with arms in 3 and 4 rays. With one exception, all calceocrinids considered in this study possess separate inferradials and superradials in the B and C rays, but these plates are fused in *Paracremacrinus laticardinalis*. Because of the joining of these plates and the presence of numerous arm branches, this crinoid exhibits the highest score for the second principal component.

The third principal component accounts for slightly over 10 percent of the information in the correlation matrix. Three of the variables deal with the arms of the A and D rays, namely X9, X10, and X12. These characters are contrasted with the fusion of the inferradials and superradials of the B and C rays, X4; and the degree of fusion of the arm plates, X17. Crinoids with many close-spaced branches or numerous plates in the main axils of the lateral rays, or both, fall in the high score realm of this component. Some of these taxa are *Anulocrinus thraivensis*, *Calceocrinus barrandii* and *Ca. multibifurcatus*. *Paracremacrinus laticardinalis* and many forms having weakly branched lateral rays with a few wide-spaced ramules and more-or-less fused brachials lie in the low score area. As in the second principal component, similar sequences of arm structure can be seen in the genera with arms in 3 or 4 rays.

In summary of the principal components, the major source of variation resides in the first component, which discontinuously separates *Calceocrinus* with 3 arm-bearing rays from *Anulocrinus*, *Cremacrinus*, and *Paracremacrinus*, which have arms in 4 rays. The strength of the dichotomy is striking and supports the thesis of most workers that the reduction of the number of arm-bearing rays represented a major step in the evolution of the Calceocrinidae. Doubtless this change only happened once. The second and third principal components account for lesser amounts of variation. Most of the characters treat the branching patterns of the E ray and the lateral rays, the extent of fusion of the plates in the arms, and whether or not the radial elements are fused in the B and C rays. Parallel series of arm-branch-

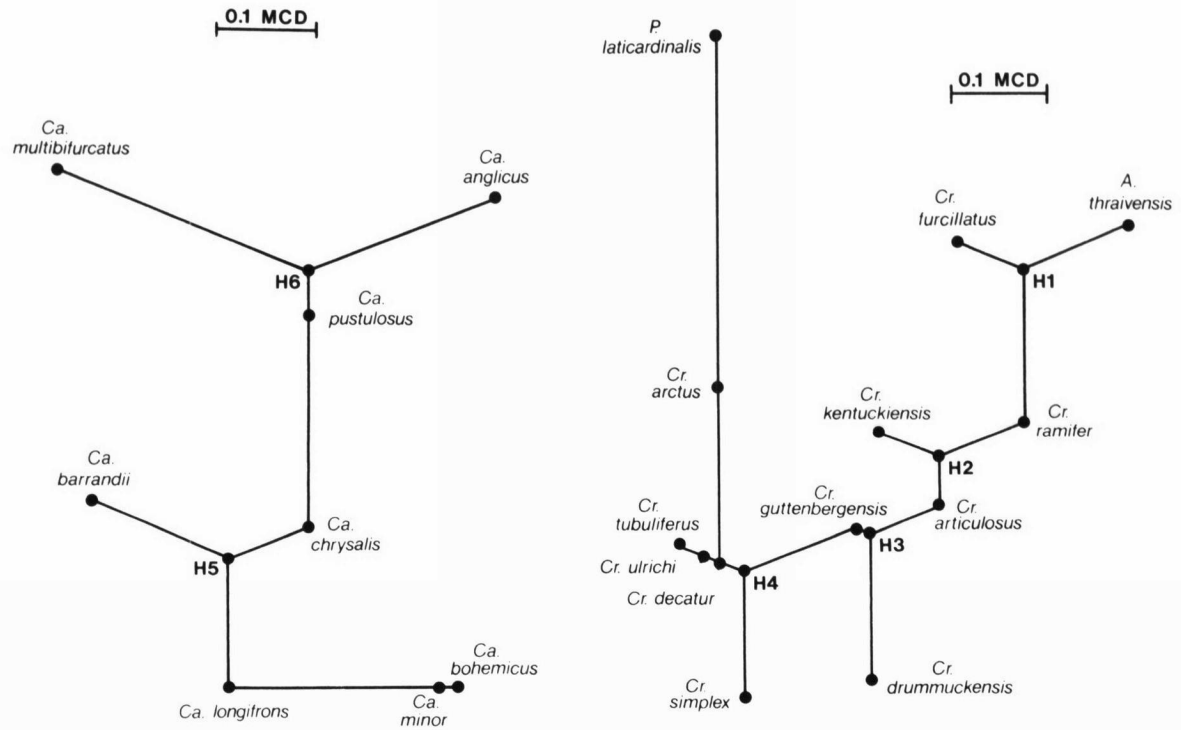

Fig. 35. Wagner networks for calceocrinids. One data set includes 13 species with 4 arm-bearing rays and 14 characters, the second 8 species of *Calceocrinus* and 10 characters. All characters are weighted equally. Lengths of the 2 networks equal 1.66 and 1.34 MCD units, respectively.

ing structure and fusion of brachials and ramulars are evident in genera with arms in 3 and 4 rays. The possession of many close-spaced arm branches in conjunction with fused inferradials and superradials in the B and C rays markedly separates *Paracremacrinus laticardinalis* from all other calceocrinids with 4 arm-bearing rays, suggesting that this form is far removed from the ancestry of the other genera.

DESCRIPTION OF THE NETWORKS

In determining the Prim and Wagner networks, several sets of data were tried in order to assess the consistency of the results. Three data sets follow. 1) All 21 species and 17 characters, the latter being standardized over the range of 0.0 to 1.0. 2) These data were broken into two subsets, one consisting of the *Calceocrinus* species and the other of the forms with 4 arm-bearing rays. 3) The 21 species based on the scores for the first three principal components. In addition, the first two data sets were analyzed twice, once using unweighted characters and again with the characters weighted proportional to the consistencies. Except for a few crinoids, the different analyses produced identical results. This indicates that the different data sets are consistent with each other.

Figure 34 illustrates the Wagner network for the 21 calceocrinids, calculated from all 17 characters standardized over the interval 0.0 to 1.0. The most striking feature is the marked separation of *Calceocrinus* with 3 arm-bearing rays from the genera with arms in 4 rays, *Cremacrinus*, *Paracremacrinus*, and *Anulocrinus*. This picture is the same as that derived from the principal components as previously mentioned. The data imply that the transition from 4 to 3 arm-bearing rays constitutes a fundamental change for evolution within the Calceocrinidae. The closest link between the 2 groups consists of *Cr. simplex* and *Ca. bohemicus*, these being separated by a distance of 0.305. Other close connections are *Ca. minor* and *Cr. simplex*, 0.306; *Ca. minor* and *Cr. drummuckensis*, 0.311; and *Ca. bohemicus* and *Cr. drummuckensis*, 0.315. The common denominator of the mature stages of these crinoids is that all are relatively small forms exhibiting juvenile arm features with small numbers of brachials. The E ray is unbranched whereas small numbers of branches are seen in the

Table 25. Character consistencies for calceocrinid data sets. (Explanation of characters, Table 23.)

Character	All characters for all species	14 characters for species with arms in 4 rays	10 characters for species of Calceocrinus
X1	1.000	---	---
X2	0.489	0.399	---
X3	1.000	---	0.500
X4	1.000	1.000	---
X5	0.500	---	1.000
X6	0.461	0.579	0.800
X7	0.343	0.479	0.571
X8	0.472	0.486	0.973
X9	0.375	1.000	0.500
X10	0.488	0.823	0.636
X11	0.233	0.528	0.694
X12	0.364	0.491	0.588
X13	0.667	0.500	---
X14	0.673	0.893	---
X15	0.419	0.514	---
X16	0.607	0.602	---
X17	0.333	0.500	0.500

other rays.

In order to gain increased resolution into the two groups, separate networks were determined for species with 3 and 4 arm-bearing rays (Fig. 35). Invariant characters within the groups were eliminated so the character subsets number 10 for *Calceocrinus* and 14 for *Cremacrinus*, *Paracremacrinus*, and *Anulocrinus*. As before, all characters were standardized. This network for *Cremacrinus* and allies will be discussed first. *Cr. guttenbergensis*, *Cr. articulosus*, *Cr. kentuckiensis*, and *Cr. ramifer* form a close group of species. All are characterized by E-ray arms that are unbranched or branch once at a distal level. As in most species with arms in the E, A, D, and B rays, 2 axillary and generally 2 nonaxillary plates are present in the main axils of the A-, D-, and B-ray arms. A moderate number of ramules is observed in the lateral rays with 7 to 13 and in the B ray with 5 to 11 branches. Variable spacing of the ramules exists where the axillary brachial ranges from 2.2 to 3.5. *Cr. drummuckensis* is connected to *Cr. guttenbergensis* and *Cr. articulosus* by an HTU. As discussed before, the former species is a small form that exhibits a juvenile arm-branching pattern in which the A, D, and B rays only bear 1 or 2 ramules; 1 or 2 axillary plates occur in the main axil series. *Cr. simplex* is attached to *Cr. decatur* and *Cr. guttenbergensis* by an HTU. *Cr. simplex* is similar to *Cr. drummuckensis* except that many of the brachials are fused to make elongate plates. *Cr. furcillatus* and *A. thraivensis* are linked to *Cr. ramifer* by an HTU. Extensively branched E-ray arms are found in both taxa, with 9 ramules in the former species and 4 in the latter. The A- and D-ray arms consist of a moderate number of ramules, 9 or 10, which are located on approximately every third brachial. Both forms show comparatively short B-ray arms, which are about 70 percent as long as those of the A and D rays. The branching pattern of the B ray is variable and from 3 to 9 ramules are observed with branching on every third plate. *Cr. decatur*, *Cr. ulrichi*, and *Cr. tubuliferus* are closely related and tied to *Cr. guttenbergensis* and *Cr. simplex* by an HTU. These species have extensively branched A- and D-ray arms with 10 to 16 ramules on alternate brachials. Reduced B-ray arms occur with only 2 or 3 ramules on every other brachial. The E-ray arms are unbranched. The brachials of all rays are elongate, presumably representing fused brachials. The line of *Cr. arctus* and *P. laticardinalis* is also joined to *Cr. decatur* on the network. These first two forms are united morphologically by some fused brachials and by extensively branched A, D, and B rays with 30 to 40 ramules, generally on alternate brachials. The length of the B-ray arm is the same as that of the lateral rays. In *Cr. arctus*, the E-ray arm is unbranched but that of *P. laticardinalis* bears over 20 ramules. In addition, the inferradials and superradials of the B and C rays are joined in *Paracremacrinus*.

The network pattern for *Calceocrinus* is simpler. *Ca. longifrons*, *Ca. minor*, and *Ca. bohemicus* are grouped together. All are small forms compared to other allied taxa and all exhibit simple arm-branching patterns. The main axils of the lateral rays equal 2 axillary and 2 nonaxillary plates with 2 to 5 ramules in the axil arms. Unbranched E-ray arms are in all species, with fused brachials being present in *Ca. minor* and *Ca. bohemicus*. Although separated by an HTU, *Ca. chrysalis* is similar to *Ca. longifrons* except that the E ray bears 2 distally located ramules. *Ca. barrandii* is linked to *Ca. longifrons* and *Ca. chrysalis* by an HTU. The main distinguishing feature of *Ca. barrandii* is the presence of numerous main axils with 4 axillary and 5 nonaxillary plates. As in *Ca. longifrons*, an unbranched E-ray arm is present. *Ca. pustulosus*, *Ca. multibifurcatus*, and *Ca. anglicus*, all taxa with extensively branched E rays having 4 to 16 ramules, are grouped together; in turn, *Ca. pustulosus* is attached to *Ca. chrysalis*. The A and D rays of these forms vary from extensively branched with many ramules in *Ca. multibifurcatus* to simple arms with a few main axils and ramules in *Ca. anglicus*.

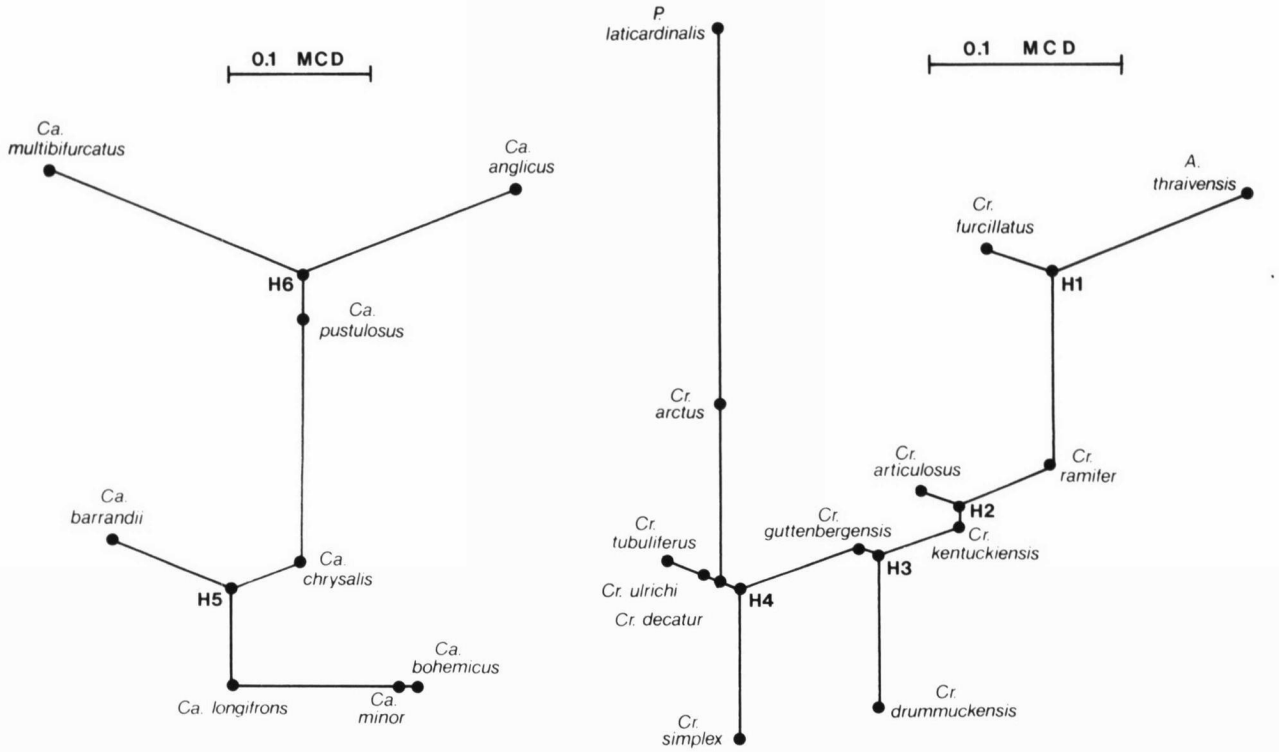

Fig. 36. Wagner networks for calceocrinids. The data sets are as in Figure 35 except that the characters are weighted proportional to the consistencies. Lengths of the networks for species with arms in 4 rays and *Calceocrinus* comprise 0.934 and 0.865 MCD units, respectively.

Figure 36 illustrates the Wagner networks for the two groups of crinoids where the characters were weighted according to the consistencies. Examination of Table 25 shows that the consistencies are highly variable with values ranging from 0.23 to 1.0. Despite the great range of consistencies, comparison of Figures 35 and 36 shows that the weighted and unweighted networks for *Calceocrinus* have exactly the same links although the distances change. For the 4-armed genera, two closely related taxa, *C. articulosus* and *C. kentuckiensis*, exchanged places on the network.

The Wagner networks are consistent with each other except for a few taxa (compare Fig. 34-36). For example, *P. laticardinalis* may be joined to *Cr. furcillatus* or *Cr. arctus* although the latter connection is most common. Study of the networks discloses some links that are not consistent with stratigraphic distribution of the crinoids, the main case consisting of the links between *Calceocrinus* and the other genera. In order to display more accurately the stratigraphic relations, a Prim network that is at least partially consistent with the stratigraphy was calculated (Fig. 37). This was done by allowing links to form only between the species under consideration and another species either at the same or an older stratigraphic level. At the higher levels (Upper Ordovician and above), most of the links on the stratigraphically constrained and unconstrained networks are the same (compare constrained Prim network of Fig. 37 with Wagner networks in Fig. 34-36); however, distortion appears at the lowest (Middle Ordovician) levels and the links are not the same. The changes in the links are caused by distortion due to forcing the taxa to cluster consistently with the stratigraphy. As outlined previously, this method assumes that the ancestral stock of a given species was present at the same or an earlier time and that this ancestral stock is represented in the fossil record. Because of this distortion, the stratigraphically constrained network is longer than the unconstrained one, in which the lengths are roughtly 4.1 and 3.5 MCD units.

As noted earlier, 10 species are known from partial data sets. Based on the statistics of these data, the most likely affinities of these crinoids are: *Cr. billingsianus*, *Cr. forrestonensis*, *Cr. inaequalis*, *Cr. punctatus*, and *Cr. rugosus* are a closely allied group of species that are

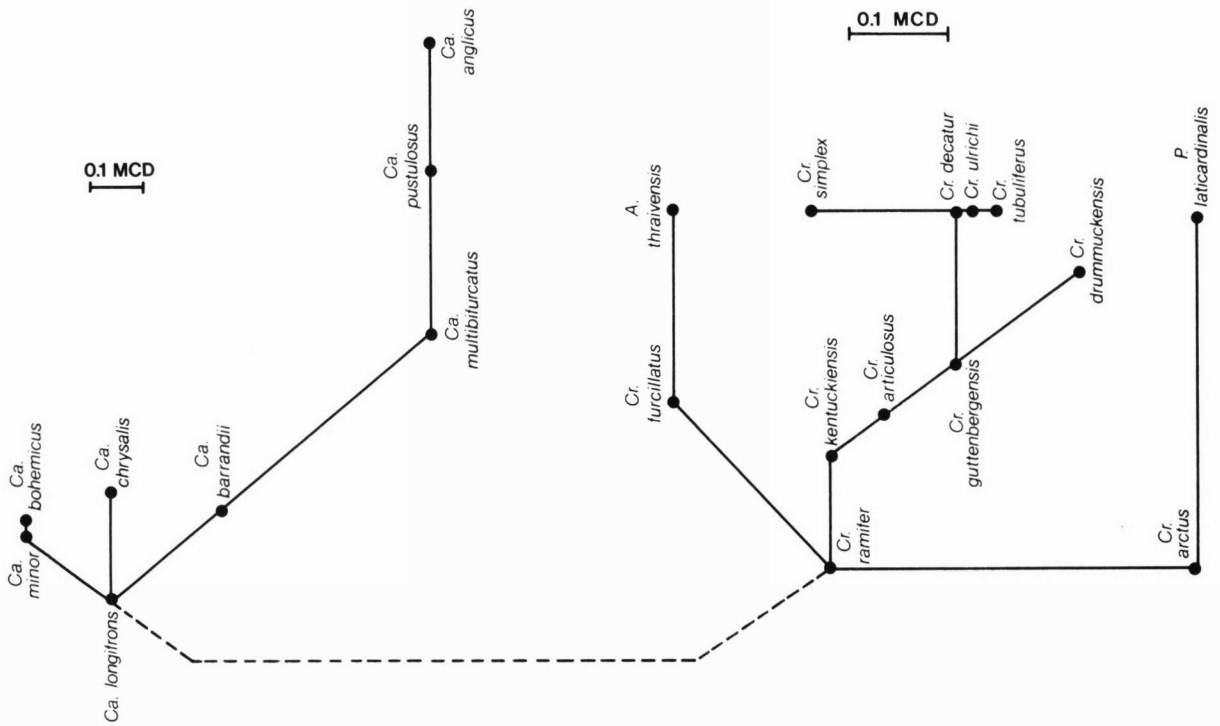

Fig. 37. Prim network in which the links are constrained to be consistent with the stratigraphy. The data sets used are as in Figure 35. Based on the data set for all 21 species, the closest Middle Ordovician (Blackriveran) link between species with arms in 3 and 4 rays is that of *Ca. longifrons* and *Cr. ramifer*. Lengths of the networks for crinoids with 3 and 4 arm-bearing rays represent 1.92 and 1.86 MCD units, respectively. The corresponding distances for unconstrained Prim networks constitute 1.73 and 1.47 MCD units, listed in the same order.

most similar to *Cr. guttenbergensis*. *Cr. lucifer* is most closely allied to *Cr. kentuckiensis*. *Cr. latus* has close relationships with *Cr. furcillatus* and *A. thraivensis*. *Ca. constrictus* and *Ca. humilis* are grouped with *Ca. minor* and *Ca. bohemicus*, whereas *Ca. ontario* and *Ca. anglicus* have strong affinities.

As discussed earlier, the Camin-Sokal method yields poor results for calceocrinids. The Camin-Sokal cladogram for the eight species of *Calceocrinus* is similar to the Wagner networks. After correcting the results for stratigraphic position, the resulting phylogeny is the same as that derived from the other techniques; however, major discrepancies are observed between the Camin-Sokal cladogram and the Wagner networks for the taxa with arms in 4 rays. The problem resides in the many evolutionary reversals in the arm-branching characters (see later discussion of phylogeny). The Camin-Sokal technique is monothetic and allows no reversals whereas the Wagner networks are not affected by reversals. Because of the reversals, the Camin-Sokal cladogram makes little sense with respect to the morphological groupings and stratigraphic relations of these species.

RECONSTRUCTION OF THE LINEAGE

Before outlining the phylogeny of calceocrinids, the ground rules under which I will operate are considered. Cracraft (1974) listed three points, which I annotate. First, taxa should be placed into lineages based on shared derived or advanced characters. Similarities in primitive characters do not provide meaningful evolutionary information. Second, I believe that ancestors can be recognized and identified with known or hypothetical taxa. Third, evolutionary patterns fall into two end-member categories, namely phyletic gradualism and punctuated equilibria. Thus, I agree with the phylogenetic systematic model on the first point and with the evolutionary systematic model on the other two points. Harper (1976) provided an excellent summary of the principles of phylogenetic systematics written from the paleontological viewpoint.

Turning to numerical techniques, Farris, Kluge, and Eckardt (1970) believed that Wagner networks are consistent with the principles of phylogenetic systematics. Where primitive versus derived character states are not completely known, as in this

study, unrooted or undirected networks should be used.

A few paleontologists believe that stratigraphic information should not be used in the study of phylogeny (e.g., Schaeffer, Hecht, and Eldredge, 1972). This view may be appropriate for rare fossil groups where the fossil record is strongly biased and perhaps misleading. On the other hand, the fossil record for many groups is abundant although certainly somewhat biased. Calceocrinids belong to this latter category. At least for common groups, many biologists and paleontologists including myself are convinced that stratigraphic information is important and useful in the search for phylogeny (e.g., Cheetham, 1968; Rowell, 1970; Kaesler, 1969; Sneath and Sokal, 1973, p. 37, 48, 50; Harper, 1976). Gingerich (1976) argued strongly for a stratophenetic approach. The consensus is that a phenetic or cladistic analysis is done first and then the stratigraphic data aid in defining the final phylogeny (Rowell, 1970, p. 269; probably Harper, 1976). Except for Harper (1976), exactly how the stratigraphic data are incorporated has generally not been specified. Here I have applied stratigraphic data in two ways, first in building stratigraphically consistent networks and second in converting relations seen on a Wagner network to a phylogeny.

All of the Prim and Wagner networks and the principal components show a consistent structure, which is reassuring. However, some features of the networks, especially the Prim and the Wagner to a lesser extent, are inconsistent with the stratigraphy. The prime example is the links between *Calceocrinus* and the other genera that involve Middle Silurian taxa. The fossil record shows that *Calceocrinus* had diverged from the other group prior to the Blackriveran Stage of the Middle Ordovician. Lesser inconsistencies can be found in some of the networks. Thus, at least some of the relationships in the networks must be adjusted to conform with the known stratigraphy of the taxa before the phylogeny emerges.

The reconstructed phylogeny is in Figure 38. Basically, this is taken from the Wagner networks of Figures 34-36 with slight elaborations from the principal components and the stratigraphically constrained Prim network (Fig. 33, 37). The connection between *Calceocrinus* and *Cremacrinus* has been moved back to the time interval denoted by the stratigraphy. Virtually all of the other relations can be taken directly from the Wagner networks. On the phylogeny, the HTU's are shown by H's. In drawing the phylogeny, I have followed a conservative procedure and not shown any species as directly ancestral to another form. Several points must be mentioned. The location of HTU2 is not consistent with the networks. On most networks, HTU2 lies between *Cr. ramifer*, *Cr. articulosus*, and *Cr. kentuckiensis*. In terms of the lineage, HTU2 must predate *Cr. ramifer*. *Cr. articulosus* and *Cr. kentuckiensis* are closely related species that interchange positions on several networks (e.g., Fig. 35, 36). The minimal distances between these two forms are also mutually exclusive. The change in this HTU seems most reasonable in view of the above relationships and stratigraphy. The *A. thraivensis* line must be extended back to Blackriveran time because *Cr. latus* lived at that time (see previous discussion of incomplete data sets). Generally, *P. laticardinalis* is linked with *Cr. arctus*, but in some networks *P. laticardinalis* is joined to *Cr. furcillatus*. The latter connection is shown on the phylogeny because it results in the simplest possible evolutionary trends for the E ray and lateral rays. However, it is also possible that *P. laticardinalis* should be grouped with *Cr. arctus*. Both *Cr. arctus* and *P. laticardinalis* are characterized by B-ray arms that are almost the same size as those of the lateral rays. On the networks (Fig. 34-36), HTU4 lies at the center of three links; however, the ancestor of HTU4 is not represented by any of these links. Consequently, the phylogeny was modified so that HTU4 has an ancestor. Because of this, HTU4 is at a four-fold junction in Figure 38. The rest of the phylogeny should be self-explanatory from previous discussion of the principal components and the networks.

Little doubt exists about the origin of the Calceocrinidae. All authors agree that the family was descended from homocrinids (e.g., Moore, 1962a; Brower, 1966). Calceocrinids and homocrinids share a common monocyclic cup structure with compound radials in the A, D, and E rays (see Moore, 1962b, for illustration and discussion of homocrinids). The changes required to convert a homocrinid cup into that of a calceocrinid are: 1) loss of BC-interray basal and change in orientation of the other basals; 2) reduction and migration of the inferradials of the B and C rays; and 3) development of the calceocrinid hinge between the 4 remaining basals and the radial elements of the A, E, and D rays. Moore (1962a, fig. 6) illustrated a series of plausible structural changes. Moore probably visualized these in terms of morphologically intermediate adults but the changes are more easily introduced into the early

ontogenetic states (see Brower, 1974, for discussion of crinoid ontogeny). The unique nature of the calceocrinid configuration indicates that it is an advanced or derived condition. The calceocrinid cup structure constitutes such a fundamental change that it was doubtless only derived once, and the Calceocrinidae form a monophyletic group.

As discussed earlier, the closest connections between *Calceocrinus* with 3 arm-bearing rays and the genera with arms in 4 rays are between *Cr. simplex* and *Cr. drummuckensis* versus *Ca. minor* and *Ca. bohemicus*. Obviously these do not represent the original line of ancestry and descent because these taxa range from Upper Ordovician to Upper Silurian in age. Inasmuch as all four primitive calceocrinid genera are present in Middle Ordovician (Blackriveran Stage), the divergence between *Calceocrinus* and the other genera must predate that time. However, it is important to note the nature of the above listed four species. All are smaller than average. The brachials of the arms may or may not be fused. The common denominator is the retention of immature arm characteristics into the adult stages. All arms consist of a relatively small number of plates; inasmuch as calceocrinids add new plates at the distal arm tips with progressive ontogeny, this is regarded as a juvenile characteristic. The E-ray arm is invariably unbranched. Because of the small number of plates, only a few main axils are present, and the axil arms are weakly branched with a total of 1 to 7 ramules per ray. Variable ramule spacing is observed. The reader should compare the illustrations of some of these taxa in Figures 31 and 32 with the juvenile individuals of *Halysiocrinus dactylus* and *H. tunicatus* pictured by Springer (1926, pl. 30, fig. 3, 3a, 20, 21). These considerations indicate that the similarities between juvenile individuals of *Calceocrinus* and juveniles of *Cremacrinus*, *Paracremacrinus*, and *Anulocrinus* are greater than are the similarities between the adults. In turn, this suggests that the derivation of *Calceocrinus* from the ancestral stock of *Cremacrinus* involved developmental divergences in the young crinoids. The retention of juvenile characters into the adult stages of the most similar species of *Calceocrinus* and *Cremacrinus* implies that the evolutionary pathway was paedomorphosis (Gould, 1977). The developmental divergences all relate to the loss of the B-ray superradial and associated arm. Two possible mechanisms exist, namely the fusion of the B-ray superradial with the adjacent superradial in the C ray, or the B-ray superradial and its arm may not have formed during ontogeny. Although I favor the latter possiblity based on the ontogeny of living crinoids, both alternatives are plausible. One abnormal specimen of *P. laticardinalis* denotes that such changes are feasible. Normal *Paracremacrinus* possess 4 arm-bearing rays, A, D, E, and B, but the abnormal specimen bears arms only in the A, D, and E rays as in *Calceocrinus*. This specimen is thought to be abnormal rather than a new taxon for several reasons. First, there is only one specimen with these characteristics out of more than 100 examples from the same zone. Secondly, the abnormal specimen is identical with normal individuals of *P. laticardinalis* except for the number of arm-bearing rays.

The occurrence of Middle Ordovician calceocrinids with arms in 3 and 4 rays raises the question as to which state is primitive and which derived. The three-armed configuration is derived on several grounds. First, the ancestry of the Calceocrinidae lies within the homocrinids, which have arms in all 5 rays. Thus, the four-armed condition is more similar to the ancestor than is the three-armed state. Second, this conclusion is supported by stratigraphic evidence. Although three- and four-armed forms both appear in the Middle Ordovician (Blackriveran), forms with arms in 3 rays are more diversified and presumably more successful than the genera with 4 arm-bearing rays. Geologically, calceocrinids with 3 arm-bearing rays outlived those with arms in 4 rays, the ranges being Middle Ordovician to Permian and Middle Ordovician to Middle Silurian, respectively.

Paracremacrinus diverges from all other calceocrinids in the structure of the B and C rays in that the inferradials and superradials are joined, whereas these plates are separate in all other genera.

The B- and C-ray inferradials are widely separated in primitive forms except for *Ca. longifrons* with relative large inferradials, which are close together.

All species of *Cremacrinus*, *Paracremacrinus*, and *Anulocrinus* possess wide contacts between the E-ray inferradial and superradial. Narrow contacts first appeared in *Calceocrinus*. Retrogressive evolution is shown by *Ca. anglicus* in the Silurian, which exhibits a wide contact between these two plates.

Subsequent discussion deals with the evolution of the arms. Inspection of Table 25 reveals that characters of the calyx have higher consistencies than those of the arms. Ranges of figures for the

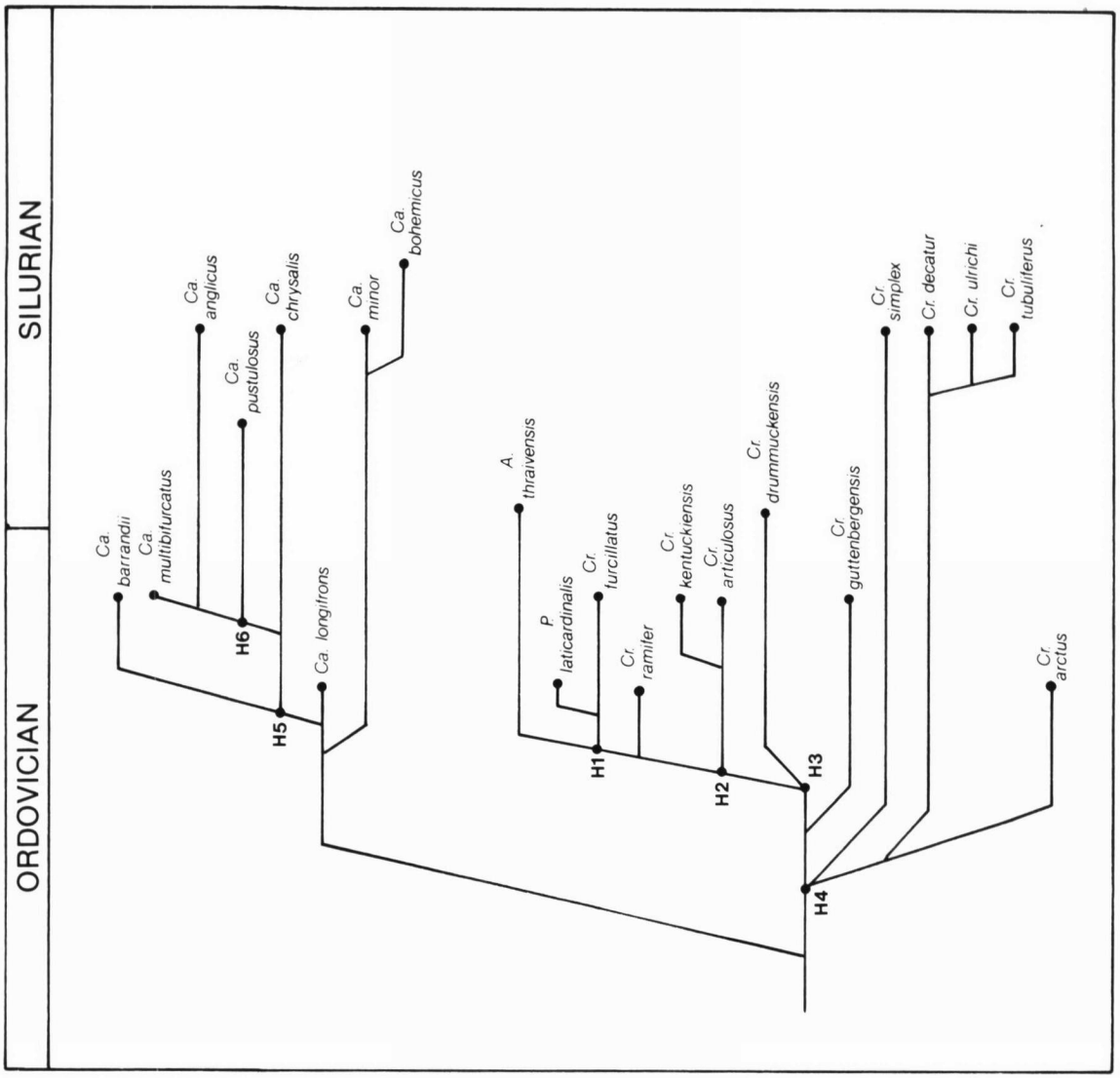

Fig. 38. Phylogeny for calceocrinids. The locations of the branching points in time are approximate.

two classes of characters equal 1.0 to 0.5 for the calyx and 0.97 to 0.23 for the arms. Thus, calyx features are more consistent with the networks than are the arm variables. This indicates that the arms were subject to more evolutionary parallelisms and reversals than the calyx. This pattern is general for the evolution of Paleozoic crinoids (Moore and Laudon, 1943).

All arms of the ancestral homocrinid stock are alike and undifferentiated. Such homocrinids as *Ectenocrinus* of the Middle and Upper Ordovician and *Drymocrinus* of the Upper Ordovician possess arms that branch isotomously on one of the proximal primibrachs; higher branches are heterotomous with unbranched ramules (e.g., Moore, 1962b, p. 12, fig. 3). There are 5 unbranched arms in the Silurian and Devonian genus *Homocrinus* (Moore, 1962b, p. 12, fig. 3). Either of these arm configurations could represent the ancestral stock. Relative to differentiation of the various rays, the most primitive arms within the Calceocrinidae are found in *P. laticardinalis* and *Cr. furcillatus* with the following characteristics. The E-ray arm exhibits the same branching pattern as in *Ectenocrinus* and *Drymocrinus*. The B-ray arm of *P. laticardinalis* is almost as large as those in the A and D rays, but that of *Cr. furcillatus* is reduced compared to the lateral rays. The typical calceocrinid pattern of heterotomy is weakly developed in the A, D, and B rays. Two axillary and 2 non-

axillary plates are present in the main axils; the axil arms bear numerous ramules that are generally located on close-spaced brachials. The homologies of the various arm branches between calceocrinids and homocrinids with numerous arm branches were discussed by Brower (1966); however, the extensively branched arms of *Cr. furcillatus* and *P. laticardinalis* are considered as derived or advanced characters. As pictured on the phylogeny, these two crinoids do not appear to constitute primitive forms. The arms of *Cr. arctus* are like those of *P. laticardinalis* except that the E-ray arm is unbranched, which differentiates it from the other arms.

The B-ray arm is absent in *Calceocrinus* but present in *Cremacrinus*, *Paracremacrinus* and *Anulocrinus*. Within the three latter genera, evolution of the B ray was erratic. The vague tendency is to reduce the height of the B-ray arms compared to those of the A and D rays. Relatively large B-ray arms with many ramules are found in *Cr. arctus* and *P. laticardinalis*. Reduced B-ray arms characterize the *Cr. furcillatus-A. thraivensis* line as well as the *Cr. decatur* group. Moderate-sized B-ray arms are found in other taxa. Many species exhibit 2 axillary and 2 nonaxillary plates in the main axils, but the small forms *Cr. drummuckensis* and *Cr. simplex* bear only 1 of each type of plate. Three nonaxillary plates occur in *A. thraivensis* and *Cr. furcillatus*. From 6 to 9 ramules are present in *Cr. guttenbergensis*, *Cr. articulosus*, *Cr. kentuckiensis*, and *Cr. ramifer*. The other crinoids show only 1 to 3 ramules.

Other aspects of the arms underwent parallel evolution in calceocrinids with 3 and 4 arm-bearing rays, which has not been recognized by other authors. The usual primitive condition of the E ray is unbranched, which can be seen in such Middle Ordovician taxa as *Cr. guttenbergensis* and *Ca. longifrons*. This configuration was retained by many later species, such as *Cr. drummuckensis*, *Cr. simplex*, *Cr. decatur* and allied forms, *Ca. minor*, and *Ca. bohemicus*. Slightly more advanced forms developed ramulate E-ray arms. The first few ramules formed distally as in *Cr. ramifer*, *Cr. kentuckiensis*, *Cr. articulosus*, and *Ca. chrysalis*, all with 1 isotomous branch in some or all specimens. The most advanced crinoids, including *A. thraivensis*, *Cr. furcillatus*, *P. laticardinalis*, *Ca. pustulosus*, *Ca. anglicus*, and *Ca. multibifurcatus*, acquired from 4 to 22 ramules. As new ramules were added, the old ones migrated proximally. The first or proximal branch is always isotomous but subsequent branches are invariably heterotomous.

The primitive number of axillary and nonaxillary plates in the main axils of the A and D rays equals 2; this condition is seen in over half of the species including *Cr. guttenbergensis* and *Ca. longifrons*, as well as most other Middle Ordovician species of *Cremacrinus* and *P. laticardinalis*. This configuration persisted into such later forms as *Cr. simplex*, *Cr. decatur* and allied crinoids, *Ca. chrysalis*, *Ca. minor*, *Ca. bohemicus*, and *Ca. anglicus*. From 2.5 to 3.0 nonaxillary plates and 2 axillary plates occur in *Cr. drummuckensis* and *Cr. furcillatus*. Among the four-armed taxa, the largest number of main axils, 4 axillary and 4 nonaxillary plates, is found in *A. thraivensis*. *Ca. pustulosus*, *Ca. barrandii*, and *Ca. multibifurcatus* developed numerous main axils with up to 5 axillary and 9 nonaxillary plates.

Most *Calceocrinus* species have a small number of ramules (1 to 5), and in general this state is probably primitive. Numerous ramules appeared in the A and D rays of *Ca. pustulosus* and *Ca. multibifurcatus* with 10 and 26 ramules, respectively, and this is thought to be the derived or advanced condition. Within the four-armed genera, consistent trends are not clear. *Cr. drummuckensis* and *Cr. simplex*, which are small forms with simple arms, usually have 2 ramules. *Cr. arctus* and *P. laticardinalis* show over 30 ramules, but 5 to 16 ramules are present in most taxa. Within a single lineage, the number of ramules can increase or decrease and the primitive versus derived states vary, although numerous ramules typically represent the derived state. As in the B ray, the ramule spacing was not subject to any consistent trends.

Most species have normal brachials and ramulars that show no trace of fusion. Elongate bladelike brachials and ramulars developed in all arms of *Cr. simplex*, *Cr. decatur*, and allied forms. The somewhat irregular length of these plates suggests that fusion is responsible. Fused brachials of this type also formed in the E-ray arm of *Ca. bohemicus* and *Ca. minor*. Scattered fused plates also appear in the various rays of *Cr. arctus* and *P. laticardinalis*.

One advantage of the unrooted Wagner method is that it allows predictions about ancestors. Based on this study, ancestral forms were extrapolated in two ways (Table 26). One set of values was obtained by taking the most primitive character states known for all species. Also the character states for HTU's 2, 4, and the stem for *Ca. longifrons* were determined by medians as in the Wagner

method. Both techniques produce almost identical ancestors except for the number of ramules in the A, D, and B rays for the four-armed crinoids; here, the Wagner method suggests larger numbers of ramules. The smaller number of ramules is preferred because of the apparent importance of paedomorphosis in the ancestry of the family. Note that all of the character states are present in at least one species. Thus, although the ancestors are hypothetical, the character states are not. The number of brachials separating the adjacent ramules of the A-, D-, and B-ray arms cannot be estimated owing to the numerous evolutionary reversals and parallelisms. The first form represents the ancestral stock with arms in 4 rays whereas the second one is the ancestor of *Calceocrinus* with 3 arm-bearing rays. The four-armed ancestor lies in the vicinity of HTU4 and HTU3 of the phylogeny; the most similar known species consist of *Cr. drummuckensis*, *Cr. guttenbergensis*, *Cr. ramifer*, *Cr. articulosus*, and *Cr. kentuckiensis*. The ancestor for *Calceocrinus* is found below the stem for *Ca. longifrons*. The species most similar to this ancestor include *Ca. longifrons*, *Ca. minor*, *Ca. bohemicus*, *Ca. chrysalis*, and *Ca. barrandii*. Again, because of reversals and parallelisms in many parts of the phylogeny, character states that are invariably primitive versus advanced or derived cannot be specified. Consequently no attempt has been made to calculate rooted Wagner trees.

Table 26. Primitive calceocrinid character states. (All states known from at least 1 species. Extrapolation of evolutionary trends and the Wagner method yield the same result in some; where results differ, that based on evolutionary trends is listed first. Explanation of characters, Table 23.)

Character	Most primitive calceocrinid with 4 arm-bearing rays	Most primitive species of Calceocrinus
X1	4	3
X2	1.0 to about 0.8	0.0
X3	1	1
X4	1	1
X5	1	1 or 2
X6	0	0
X7	25 (unbranched)	25 (unbranched)
X8	25 (unbranched)	25 (unbranched)
X9	2	2
X10	2	2
X11	2 or 7	1 or 2
X12	unknown	unknown
X13	2	0
X14	2	0
X15	2 or 7	0
X16	unknown	0
X17	1	1

SUMMARY

The evolution of primitive calceocrinids was studied statistically with Prim and Wagner networks and principal components. Both unconstrained networks and networks that are forced to be consistent with the observed stratigraphic occurrences were calculated. Except for a few species, all techniques, both phenetic and cladistic, reveal the same structure in the data. The networks do not directly yield phylogeny. Relationships in the networks have to be altered to be consistent with the stratigraphy to produce a line of ancestry and descent.

As suggested by most workers (e.g., Moore, 1962a; Brower, 1966), the Calceocrinidae evolved from a homocrinid. The calceocrinid cup with its hinge and modified plate structure represents a uniquely derived character among crinoids and the family is considered to be monophyletic. Geometrically, the changes are most easily visualized as affecting the development of juvenile crinoids.

Calceocrinids with 3 arm-bearing rays, such as *Calceocrinus*, diverged from the ancestral stock of *Cremacrinus* with arms in 4 rays and prior to Middle Ordovician (Blackriveran) time. The three-armed configuration is advanced or derived and probably developed once. In a comparison of members of the three-armed and four-armed groups, the most similar species are all small forms in which the adult exhibits juvenile arm structures. This fact indicates that the most likely evolutionary mechanism was paedomorphism and that the transition involved developmental changes in the growth of young crinoids.

The cup structure of *P. laticardinalis* with the joined inferradials and superradials of the B and C rays differs from that of all other calceocrinids. Generally, the contact between the E-ray inferradial and superradial becomes more narrow in advanced forms.

Low consistencies are seen in arm characters, indicating many evolutionary parallelisms and reversals. Parallel evolution in the arms occurred in forms with 3 and 4 arm-bearing rays. Main trends include a change in the E ray from unbranched in most forms to extensively ramulate. As new ramules formed, the old ones shifted proximally. New axillary and nonaxillary brachials were added to the main axil series of the A and D

rays. Generally, the number of ramules in the A and D rays increased in more advanced crinoids. Consistent evolutionary changes did not take place in the spacing of the ramules.

The B-ray arm is not present in *Calceocrinus*. Within the genera with arms in 4 rays, there is a vague tendency for the B-ray arm to become smaller compared to the A and D rays. Other consistent trends are not known in the B ray. Several species evolved fused brachials in some or all parts of the arms.

This study has allowed the prediction of hypothetical ancestors for calceocrinids with arms in 3 and 4 rays. Both ancestors are characterized by simple patterns of arm branching, which indicate the paedomorphic origins of calceocrinids. Study of the ontogeny of camerate and living crinoids indicates that these changes are easily introduced into the growing arms as new plates form at the distal tips of arms (Brower, 1974).

ACOLOCRINUS

James Sprinkle

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Two new species and several extra plates of *Acolocrinus*, an unusual disparid inadunate, have now been found in the Bromide Formation of southern Oklahoma. The first Bromide specimen, the holotype of *A. crinerensis*, n. sp., was found by Allen Graffham about 1963, four years before the first complete specimens of members of this genus were collected from the Appalachians (later described as *A. hydraulicus* Kesling and Paul, 1971). At present, *Acolocrinus* is also known from plates collected from the Tulip Creek or McLish formations on Denmark Creek in the southern Arbuckle Mountains of Oklahoma, from numerous plates collected from the Upper Ordovician of Sweden (C. R. C. Paul, pers. commun. 1977), and a related genus has recently been discovered in the Upper Silurian Rochester Shale of western New York State (Brett, 1980). One new Bromide species of *Acolocrinus* (*A. crinerensis*) is a highly ornamented form with elaborate respiratory structures; it occurs in the Pooleville Member in the Criner Hills and is represented in the present collections by the well-preserved holotype specimen and three separate plates. A second new Bromide species (*A. arbucklensis*) has nearly smooth plates and more subdued respiratory structures; it has been found in the Lower Echinoderm Zone as well as the *Carabocrinus* and *Bromidocystis* beds of the Mountain Lake Member in the Arbuckle Mountains and is represented by three partial calyces and seven separate plates. A third form (*Acolocrinus?* sp.) is represented by two very large basal plates that lack respiratory structures; it occurs with *A. arbucklensis* in the *Bromidocystis* Bed of the Mountain Lake Member in the Arbuckle Mountains.

Of particular interest is the holotype of *A. crinerensis*, which definitely shows that no anal opening is present on the calyx summit near the mouth. Kesling and Paul (1971, p. 231) also noted the possible absence of the anal opening on their specimens. This "missing" anus in *Acolocrinus* and the unusual "anal X," which is a rounded-triangular, inset, flat-bottomed plate with subdued ornament and no sutural respiratory structures, leads me to propose that the "anal X" is in fact a hinged operculum covering the actual anal opening on the side of the calyx. This type of opercular covering for the anus is not known in any other described crinoid, where the anus is usually covered by a pyramid of small plates on the domed tegmen or near the tip of an elongate anal tube. However, an anal operculum has been described in several other early echinoderms, primarily homalozoans (see Ubaghs, 1968b, p. S573).

Superfamily Indeterminate

Family ACOLOCRINIDAE Brett, 1980

Discussion.—The recent assignment of *Acolocrinus* to the superfamily Allagecrinacea and family Catillocrinidae by Moore and Strimple (1978) is probably not correct. However, because Carlton Brett, University of Rochester, is now working on the classification of acolocrinids based on the occurrence of a new genus in the Upper Silurian of western New York State, this subject will not be discussed further here (see Brett, 1980).

Genus ACOLOCRINUS Kesling and Paul, 1971

Type species.—*Acolocrinus hydraulicus* Kesling and Paul, 1971.

Diagnosis.—Disparid inadunate crinoids with large goblet-shaped cup composed of 3 unequal BB (small one in BC interray), 5 iRR directly overlain by 5 sRR, and a rounded-triangular "anal X" on the posterior side surrounded by 2 iRR and 2 sRR; sRR with prominent crests on their upper right edges and a flat shelf bearing ambulacral grooves extending to the central mouth; arms absent, row of small armlets (possibly pinnules) mounted on upper edge of sRR, armlets folding between crests, ambulacral grooves from mouth

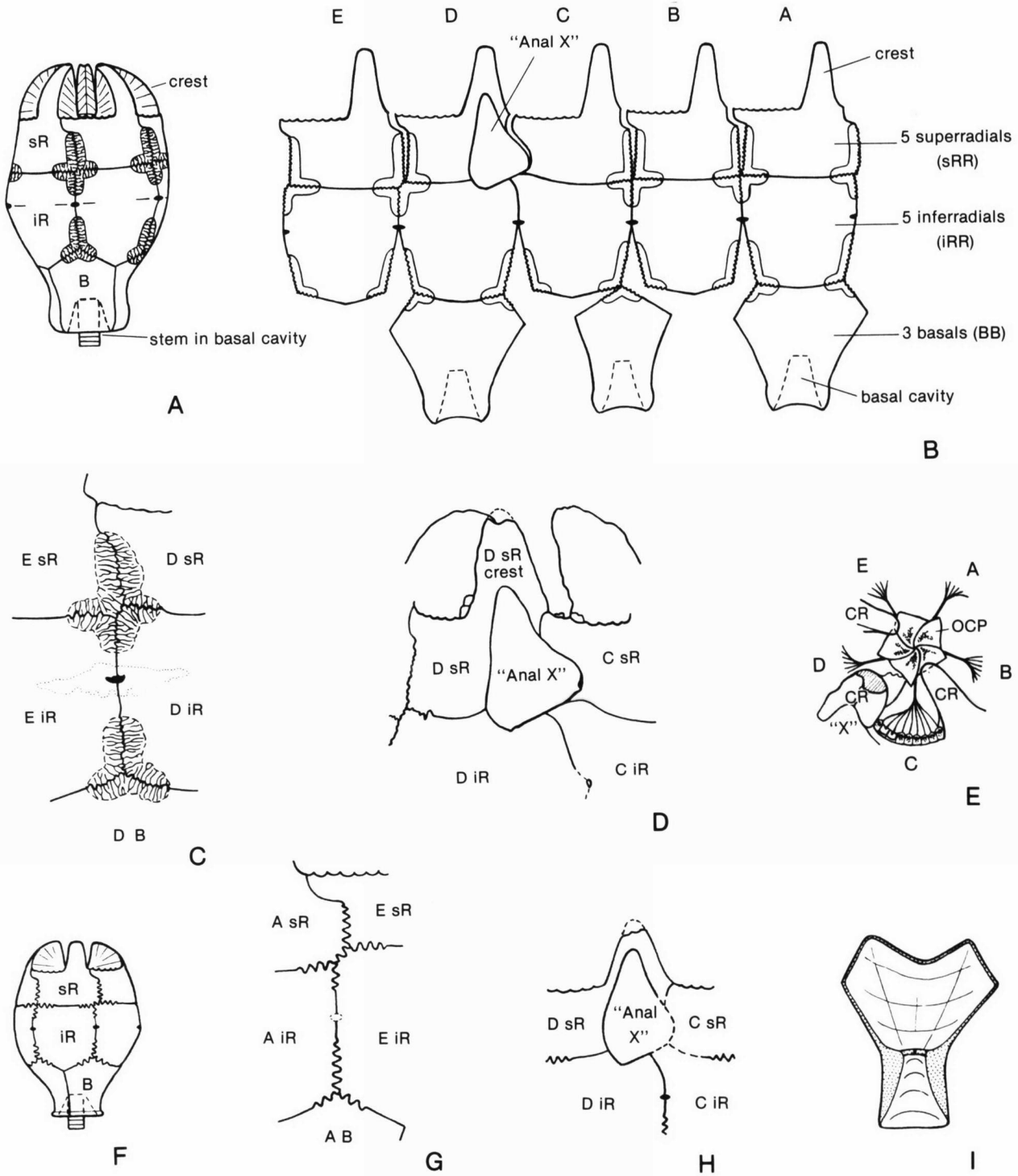

Fig. 39. Morphology of Bromide specimens of *Acolocrinus*. A-E, *Acolocrinus crinerensis* Sprinkle, n. sp. A, Side view based on nearly complete holotype; B, Side-layout plating diagram with plate circlets and other features labeled; C, One set of respiratory structures in holotype showing upper and lower zigzag inlet areas with surrounding drainage fields and central outlet pore, X4; D, Posterior side of holotype showing unusual triangular "anal X" which apparently represents a hinged anal operculum over the hidden anus, X4; E, Summit of holotype with complete C-ray ambulacrum leading to armlet facets at edge of summit between crests (CR) and 5 curved oral cover plates (OCP)

exotomously branched, central mouth covered by 5 spiraled oral cover plates, no anal opening on summit; sutural respiratory structures developed on margins of most cup plates except "anal X," consisting of zigzag inlet slits on B-iR, iR-iR, iR-sR, and sR-sR sutures and a larger outlet pore near center of each iR-iR suture; "anal X" apparently a hinged operculum with anal opening beneath; most calyx plates with distinctive pitted ornament; small stem mounted in large and fairly deep basal cavity.

Occurrence.—Middle Ordovician, Virginia, Tennessee, and Oklahoma; Late Ordovician?, Sweden.

Discussion.—The above diagnosis is similar to that given by Kesling and Paul (1971), except that the distinctive respiratory structures are included and the unusual "anal X" is considered to be an operculum covering the "missing" anus.

ACOLOCRINUS CRINERENSIS Sprinkle, n. sp.

Plate 6, figures 1-16; Figure 39A-E

Diagnosis.—A species of *Acolocrinus* with elongate krater-shaped calyx (L:W = 1.6) with very long and bulbous BB, long iRR, and large crests on the sRR; "anal X" elongate triangular, inset; 8 to 9 armlets per ambulacral area; respiratory slits with numerous short zigzags surrounded by elliptical trellislike "drainage fields," outlet pores elongate across sutures; ornament consisting of large pits sometimes connected together to produce a labyrinthine pattern, some plate sutures depressed.

Description.—Calyx krater- or goblet-shaped, elongate, with high blade-shaped crests. Holotype 20.5 mm long, 12.5 mm wide, calyx L:W = 1.6; maximum width near midheight, base elongate and somewhat bulbous, summit slightly constricted (Pl. 6, fig. 1-6).

Plating consisting of 3 unequal basals (BB) forming a protruding base with a fairly deep basal cavity, 5 large inferradials (iRR), 5 crest-bearing superradials (sRR), a triangular "anal X" on the CD side, and 5 small triangular oral cover plates on the summit (Fig. 39B). All plates relatively thick (1.0 to 1.5 mm on separate B and sR plates), most plates highly ornamented.

Basals 3, unequal-sized, elongate, 2 medium sized, 1 (in BC interray) fairly small, more than half as wide as others, A- and D-ray BB hexagonal externally, about 6.7 mm long and 7.4 mm wide in holotype, giving basal L:W = 0.91. Small BC basal pentagonal, about 5.6 mm wide. All BB recurved to form relatively deep basal cavity for stem attachment; in holotype, BB circlet 6.0 mm wide aborally, basal cavity 3.5 mm wide and at least 2 mm deep, and preserved stem circular, 1.5 mm in diameter, with a very small (about 0.1 mm) circular lumen. Aboral end of basals bulbous and nearly smooth (Pl. 6, fig. 4, 5), probably because of secondary deposits of calcite.

Inferradials 5, nearly equal-sized, apparently largest plates in calyx; rectangular-pentagonal (modified near "anal X"); 6.7 mm long and 7.3 mm wide in E ray of holotype, giving iR L:W = 0.92. Maximum calyx diameter about two-thirds distance up iRR.

Superradials 5, directly above iRR (forming near-junctions of 4 plates with iRR), nearly equal-sized, each bearing a large, erect, blade-like crest on the upper right corner and a shelf-like platform extending inward to form the calyx summit (Fig. 39B). Body of sR modified rectangular, about 3.9 mm long and 6.3 mm wide, giving sR body L:W = 0.62. sR crest 4.3 mm long, 2.0 to 2.5 mm wide at base, and 3.5 mm deep at base, sR-crest-L:sR-body-L = 1.1. Each crest tapering to a ragged edge adorally and a rounded upper tip (Pl. 6, fig. 1, 9). Each sR with small extension at upper left corner, and C and D sR shape modified by "anal X" in CD interray.

"Anal X" an unusual, elongate, rounded-triangular, tilted, and inset plate on CD side of calyx (Fig. 39D). Surrounded by C and D iRR (about 7 and 19 percent of margin) and C and D sRR (about 23 and 51 percent of margin). Tip of "anal X" extending up into D sR crest, crest slightly wider than other crests. "Anal X" nearly flat, unornamented, and somewhat inset (about 0.75 mm) below level of adjacent iRR and sRR. Rounded triangular "anal X" has a nearly straight lower edge 3.1 mm long with a depressed suture tilted about 30° from

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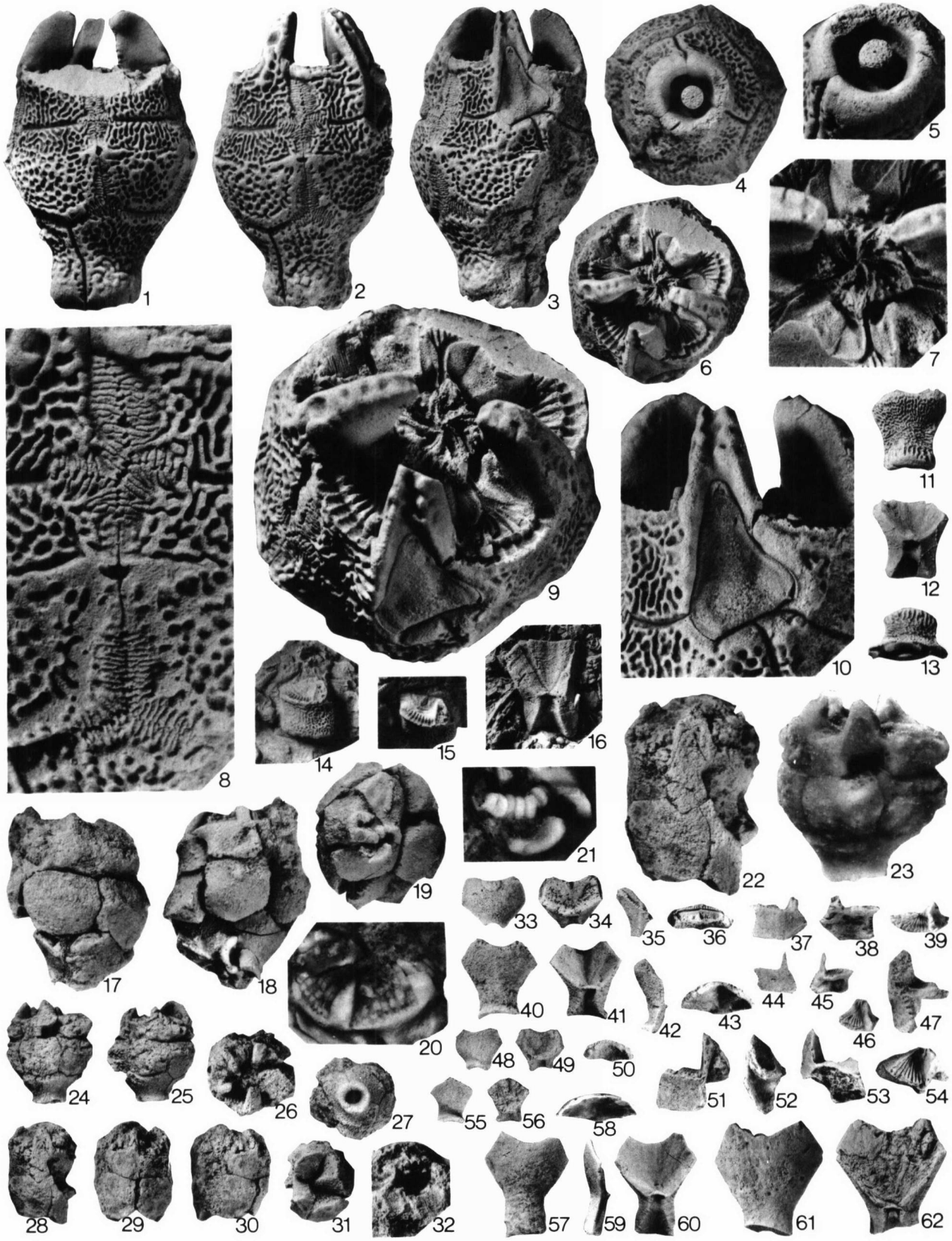
over the central mouth, X3. F-H, *Acolocrinus arbucklensis* Sprinkle, n. sp. F, Reconstructed composite side view based on 3 nearly complete specimens; note smaller size, less elongate shape, lower crests, and somewhat different respiratory structures than in Figure 39A; G, Respiratory structures in EA interray of holotype showing no drainage fields around zigzag inlet areas, X4; H, Posterior side of paratype showing triangular anal X projecting into D-ray superradial crest; note slight differences in shape from structure in Figure 39D, X6. I, Interior of large reconstructed basal of *Acolocrinus?* sp.; note absence of respiratory zigzags on inferradial sutures, deep basal cavity for stem, and thinness of upper part of plate, X1.9.



horizontal summit, a nearly straight left side, and a slightly concave right side. Length 4.9 mm, maximum width 3.7 mm; "anal X" L:W = 1.3. No respiratory structures present around "anal X" on iR and sR sutures as in other interrays (Fig. 39B).

Summit perpendicular to calyx axis, slightly concave, 10.5 mm in diameter in holotype; made up of shelves from sRR supporting armlets mounted around edge of summit, ambulacral grooves leading from armlets, and central mouth covered by 5 oral cover plates (Pl. 6, fig. 6, 7, 9). Nine armlets per ambulacrum on each sR in holotype, 10 to 11 in separate sR, mounted in row between adjacent crests. Armlets small, uniserial, 2 lowest segments of rightmost armlet on D sR (plus few other fragments) preserved in holotype (Pl. 6, fig. 9), each segment about 0.5 mm long and 0.4 mm wide and deep with a U-shaped adoral food groove probably protected by tiny cover plates. Shelf behind armlet facets with shallow grooves (probably implying that armlets fold out perpendicular to side of calyx for feeding and fold in between crests for protection). Leftmost armlets (at sR-sR suture) probably newest ones. Food grooves from mouth small, slightly raised, branching exotomously (Fig. 39E); most branches to left, few to right. Central mouth covered by small pyramid of 5 raised, spiraling-triangular, oral cover plates (Pl. 6, fig. 6, 7, 9; Fig. 39E). Each triangular cover plate 1.6 mm long and wide, interradial in position, and raised above surrounding shelf. Adoral tip curving counterclockwise though about 60°; food groove from each ambulacrum entering beneath pyramid at lower left corner of each cover plate. No other openings observed on summit.

Respiratory structures strongly developed on side of calyx on most B-iR, iR-iR, iR-sR, and sR-sR sutures. Structures consist of zigzag sutures and surrounding trellislike "drainage fields" on these sutures (apparently inlet areas) and a large

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PLATE 6.

Fig. 1-16. *Acolocrinus crinerensis* Sprinkle, n. sp.; upper Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 1-10, 16 from float about 9 m below the Viola Limestone at Dunn Quarry; 11-15 from an unknown zone at Culley Creek. 1-10. AB, DE, and CD side views, base, summit, and various enlargements of holotype OU 9050 (Graffham Coll.) showing elongate cup shape, high crests, coarse ornament, small stem in basal cavity (4, 5), summit with armlet facets, 5 curved cover plates over central mouth and no anal opening visible here (6, 7, 9), trellislike groups of respiratory slits and central outlet pore (8), and triangular, inset, anal operculum plate ("anal X") on outside of posterior crest (3, 9, 10); X2.6 (1-4, 6), X3.9 (5), X5.3 (7, 9), X6.5 (8), X5.1 (10). 11-13. Outside, inside, and top edge of paratype basal 1405TX4 (Watkins Coll.); note deep basal cavity, thickness of plate, and respiratory slits on top edge; X1.5. 14, 15. Outside and top edge of paratype superradial 1405TX5 (Watkins Coll.) with armlet facets and broken crest; X1.5. 16. Inside of nearly complete paratype basal 1119TX3 on slab; note thickness of plate; X1.5.

Fig. 17-56. *Acolocrinus arbucklensis* Sprinkle, n. sp.; middle and upper Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 17-21 apparently from the *Carabocrinus* Beds at North-Central I-35; 22, 28-39 from the *Bromidocystis* Bed at Daube Ranch; 23-27, 44-50, 55-56 from the *Carabocrinus* Beds at Lick Creek; 40-43 from the Lower Echinoderm Zone at Fittstown Quarry; 51-54 from the *Bromidocystis* Bed at North-Central I-35. 17-21. Two side views, basal view, oblique enlarged summit view (immersed), and enlargement of basal cavity (immersed) of holotype OU 9051 showing slightly crushed cup partly covered with silty matrix (17), armlets still attached around edge of summit (20), and several columnals still attached in basal cavity (19, 21); X2.1, X3, X3.4. 22, 28-32. Enlarged side view (CD interray), 3 side views, basal view, and oblique enlarged side view of paratype 1397TX53; note slightly damaged, triangular, anal operculum plate ("anal X") (22, compare with 10 above), abnormally large iR underlying 2 sRR (30) with only 4 indentations for BB (31), and U-shaped cross sections of pinnules on damaged side of cup (32); X4, X2, X4. 23-27. Enlarged side view (CD interray, immersed), 2 side views, summit view, and basal view of paratype 1390TX1 showing top half of anal operculum plate (23) preserved above broken-through anal opening (23, 24), cup plates overgrown with diagenetic calcite (increasing diameter), trace of summit structures (26), and unornamented lip around basal cavity (27); X4, X2. 33-36. Outside, inside, right side, and top edge views of paratype basal 1397TX55; note extensive respiratory zigzags (35, 36) and thick diagenetic calcite on inside; X1.5. 37-39. Outside, inside, and top views of paratype superradial 1397TX54 with broken crest; X1.5. 40-43. Outside, inside, right edge, and top edge views of large paratype basal 1297TX317; note elongate shape and deep basal cavity (41) with lip around lower edge (40, 42); X1.5. 44-47. Outside, inside, top, and enlarged right edge views of paratype superradial 1390TX2 showing complete crest and respiratory zigzags on edge; X1.5, X3. 48-50. Outside, inside, and top edge views of small paratype basal 1390TX3; X1.5. 51-54. Outside, right edge, inside, and top views of large paratype D-ray superradial 1393TX16; note edge of anus on lower right margin of plate (51, 52) and groove in wide crest (51, 54) where anal operculum plate fits; X1.5. 55, 56. Outside and inside views of paratype azygous basal 1390TX4 showing different shape from 48, 49 above; X1.5.

Fig. 57-62. *Acolocrinus?* sp.; *Bromidocystis* Bed, upper Mountain Lake Member, Arbuckle Mountains, southern Oklahoma; 57-60 from North-Central I-35; 61, 62 from Daube Ranch. 57-60. Outside, top edge, right edge, and inside views of complete basal 1393TX17 showing very deep basal cavity (60), lack of respiratory zigzags (58), and thinness of plate; X1.5. 61, 62. Outside and inside views of very large but broken basal 1397TX56; this plate as preserved is nearly as large as the holotype specimen of *A. arbucklensis* (see 17, 18 above); X1.5.

raised pore about two-thirds the distance up each iR-iR suture (an apparent outlet). Lower calyx with 5 three-sided inlet areas, each between a B and 2 iRR's (Fig. 39C). Upper calyx with 4 four-sided inlet areas, each between two iRR's and 2 sRR's (none present in CD interray where "anal X" located) (Fig. 39D). Zigzag inlet sutures extending about 1.2 to 1.6 mm on each B-iR suture with 6 to 10 "zigs," 2.0-2.2 mm on each lower iR-iR suture with 11 to 13 "zigs," 1.0 mm on each upper iR-iR suture with 4 to 5 "zigs," 1.0 to 1.5 mm on each iR-sR suture with 6 to 8 "zigs," and 2.8 to 3.0 mm on each sR-sR suture (about three-fourths of suture length on side of calyx) with 12 to 14 "zigs." Drainage fields consisting of shallow parallel to anastomosing slits extending out from zigzag sutures about 0.75 mm, usually one slit per "zig." Drainage fields slightly depressed below surrounding plate surface. Outlet pores on iR-iR sutures, between upper and lower inlet areas. Each pore in a raised ridge crossing this suture, apparently nearly circular or elongate across suture, 0.5 to 0.9 mm wide and 0.5 to 0.8 mm long in different interrays. Canals on plate sutures apparently connecting inlet zigzag areas with outlet pore for each interray.

Ornament coarse, consisting of either large single pits 0.4 to 0.5 mm in diameter excavated in plate surface or rows of connected pits forming a labyrinthine pattern oriented nearly perpendicular to some plate sutures (Pl. 6, fig. 1-3). Plate sutures between sR-iR, iR-B, and B-B depressed below ornamented surfaces. Ornament best developed on upper part of iRR and bodies of sRR below edge of summit. Slight ridges lacking ornament extending laterally from iR centers to outlet pores on iR-iR sutures (Pl. 6, fig. 8). Lower part of BB bulbous and nearly smooth; outside of sRR crests with subdued ornament; and ornament almost completely lacking from inset "anal X" and adjacent iR and sR edges (Pl. 6, fig. 10).

Name.—This species is named for the Criner Hills where all described specimens were found.

Studied specimens.—Holotype OU 9050 (Graffham Coll.), paratype plates 1119TX3 and 1405TX4-5 (Watkins Coll.).

Occurrence.—Known only from the upper Pooleville Member, Bromide Formation, at Dunn Quarry in the float about 9 m below the top and at Culley Creek from an unknown zone, both in the Criner Hills, southern Oklahoma.

Discussion.—*Acolocrinus crinerensis* has coarser ornament and more highly developed respiratory structures with unusual drainage fields than any other species of *Acolocrinus*. It also has a somewhat more elongate calyx shape, more elongate and bulbous BB, larger sRR crests, a differently shaped "anal X," more zigzags in its inlet respiratory areas, differently shaped outlet respiratory pores, and perhaps fewer armlets per ambulacral area than other species.

ACOLOCRINUS ARBUCKLENSIS Sprinkle, n. sp.

Plate 6, figures 17-56; Figure 39F-H

Diagnosis.—A species of *Acolocrinus* with a cup-shaped calyx (L:W = 1.2), BB rather long and protruding, crests on sRR relatively high; "anal X" elongate, slightly inset; 7 to 10 armlets per ambulacral area, respiratory slits very elongate and with numerous short zigzags, outlet pores probably elongate across sutures; ornament consisting of fine pits.

Description.—Calyx cup- to goblet-shaped, moderately elongate, with fairly high blade-shaped crests. Holotype OU 9051 about 16 mm long, about 11 mm wide (slightly crushed and disarticulated); in 3 nearly complete specimens, calyx L:W = 1.19+ to 1.45+. Maximum width near midheight in iRR circlet, base rapidly tapering, summit slightly constricted (Pl. 6, fig. 17, 18, 24, 25; Fig. 39F).

Basals 3, unequal-sized, fairly elongate, 2 medium-sized, 1 (in BC interray) fairly small, over half as wide as others. A- and D-ray BB hexagonal externally, about 5.0 mm long and 6.5 mm wide in holotype; B L:W = 0.66 to 0.97 based on measurements in 2 specimens and 3 separate BB. Small BC basal pentagonal, about 5.0 mm wide in holotype. All BB recurved to form relatively deep basal cavity for stem attachment; basal cavity ranging from 1.7 mm deep in a small B to 3.5 mm deep in a large one (Pl. 6, fig. 33, 34, 40, 41). In paratype 1390TX1 (Pl. 6, fig. 27), BB circlet 2.9 mm wide aborally, basal cavity 2.0 mm wide and at least 1.0 mm deep, preserved stem circular, about 0.7 mm in diameter, with a 0.1 mm central lumen. Larger holotype with 7 or more columnals preserved in side view; columnals circular in end view, 1.0 mm wide and 0.5 mm long with a slightly rounded exterior, with a trace of crenulae on their ends. Most BB with a prominent outflared lip at edge of basal cavity (Pl. 6, fig. 55, 56).

Inferradials 5, nearly equal-sized, largest

plates in calyx; iRR rectangular-pentagonal (modified near "anal X"), 6.0 mm long by 6.5 mm wide in holotype; iR L:W = 0.92 to 1.0 in 3 nearly complete specimens. Maximum calyx diameter apparently about two-thirds the distance up iRR.

Superradials 5, directly above iRR, nearly equal-sized, each bearing a fairly large, erect, bladelike crest on the upper right corner, and a shelflike platform extending inward to form the calyx summit (Pl. 6, fig. 20, 23). Body of sR modified rectagular, about 3.0 mm long and 6.5 mm wide in holotype; sR body L:W = 0.46 to 0.79 in 3 fairly complete specimens and 3 separate plates. sR crest 2.5 mm long, 1.3 mm wide at base, and about 2.6 mm deep at base in holotype; sR-crest-L:sR-body-L = 0.60 to 0.83 in regular sRR (4 specimens), but a 1.07 figure was recorded for a large modified D sR (see Pl. 6, fig. 51). Crests curving inward over summit rapidly and with a slightly curved adoral edge and a rounded distal tip. Each sR with a small lateral extension at upper left corner, and C and D sR shape modified by "anal X" in CD interray.

"Anal X" exposed in paratype 1397TX53, slightly broken but otherwise fairly well preserved (Pl. 6, fig. 22), partly exposed in paratype 1390TX1, with less than half plate present (Pl. 6, fig. 23). "Anal X" plate elongate, triangular, tilted, and somewhat inset on CD side of calyx, surrounded by C and D iRR (about 7 and 19 percent of margin) and by C and D sRR (about 14 and 60 percent of margin). "Anal X" tilted about 30° from horizontal summit, in paratype 1390TX1 nearly flat, 3.0 mm long, about 2.1 mm wide (estimated), and with a flat base 1.6+ mm wide; estimated "anal X" L:W = 1.43 for this specimen. Elongate tip extending up into D sR crest; slightly convex left side of "anal X" nearly flush with calyx surface, concave right side slightly inset below adjacent plates (Pl. 6, fig. 22). "Anal X" surface apparently unornamented, no respiratory structures present on adjacent iR and sR sutures as in other interrays. Paratype 1390TX1 missing bottom half of "anal X," instead having medium-sized hole about 1.3 mm in diameter at this four-plate junction (see Pl. 6, fig. 23, 24), the anal opening. Separate D sR 1393TX16 (Pl. 6, fig. 51-54) with edge extending almost 4.0 mm deep into calyx interior on left-hand side of apparent anal opening.

Summit not well exposed in complete specimens because of covering matrix and armlets but apparently perpendicular to calyx axis, slightly concave, and about 9.5 mm in diameter in holotype; 6 to 11 armlets per sR mounted around rim of summit between crests. Armlets small, uniserial, at least 2.5 mm long with 5 to 7 segments. Segments 0.5 mm long, 0.4 mm wide, and 0.3 mm "deep" in paratype 1397TX53, with a large, deep, U-shaped groove adorally (Pl. 6, fig. 32), probably protected by tiny cover plates (now absent). Food grooves from armlets to mouth small, slightly raised, and probably branching exotomously only to left (Pl. 6, fig. 39, 46, 54), implying leftmost armlets (at sR-sR suture) probably newest ones. Oral cover plates not well exposed in any complete paratype, but one sR plate with a blunt adoral edge on summit shelf that may be edge of mouth (Pl. 6, fig. 46).

Respiratory structures well developed on side of calyx on most B-iR, iR-iR, iR-sR, and sR-sR sutures. Structures consist of zigzag sutures on these plates (apparent inlet ares) and a prominent pore about two-thirds way up each iR-iR suture (an apparent outlet). Respiratory structures not well exposed on complete specimens because of covering matrix and overgrowths of secondary calcite. Zigzag inlet slits small and relatively few; 2 to 4 "zigs" on each B-iR suture extending 1.2 to 1.8 mm, 4+ "zigs" on each lower iR-iR suture extending 1.7 mm, 2 to 3 "zigs" on each upper iR-iR suture extending 1.0 mm, 1 to 3 "zigs" on each iR-sR suture extending about 0.6 mm, and 6 to 7 "zigs" on each sR-sR suture extending 2.0 mm. (However, separate basal 1397TX56 has 9 to 12 "zigs" extending the whole length of each B-iR suture, about 3.0 mm; see Pl. 6, fig. 36.) Drainage fields mostly absent around sutural zigzags, but one sR plate with slight trellislike drainage extending 0.3 mm outside "zigs." Each outlet pore in raised ridge on iR-iR suture, about 0.3 mm wide and 0.2 mm long, having a strengthening bar crossing plate suture below pore (Pl. 6, fig. 29, 30). Canals on plate sutures apparently connecting inlet zigzag areas with outlet pore for each interray.

Ornament subdued, plates of most specimens nearly smooth with slight granules or covered with tiny pits about 0.07 to 0.1 mm in diameter (Pl. 6, fig. 33). Pits perhaps surface expression of stromal canals in plate. Some specimens and plates from *Carabocrinus* Beds overgrown with diagenetic calcite so that sutures now inset (Pl. 6, fig. 24, 25), but this apparently secondary. Lip of basal cavity and sR crests appearing almost smooth and unornamented.

Paratype 1397TX53 apparently abnormal; 1 large iR (instead of 2 smaller ones) underlying 2 sRR in D and E rays (Pl. 6, fig. 29, 30), ?no respiratory slits or pore in DE interray, and BB (missing)

possibly abnormal also because only 4 basal indentations present (perhaps implying 2 small and 1 large BB). Other structures in this specimen (sRR, "anal X," armlets on summit) apparently normal.

Name.—This species is named for the Arbuckle Mountains where all the known specimens were collected.

Studied specimens.—Holotype OU 9051 (Graffham Coll.), complete paratypes 1390TX1 and 1397TX53, paratype plates 1390TX2-4, 1397TX54-55, 1393TX16, and 1279TX317.

Occurrence.—Found in the Lower Echinoderm Zone (1 plate) at Fittstown Quarry, in the *Carabocrinus* Beds at Lick Creek (1 specimen, 3 plates) and at North-Central I-35 (holotype specimen), and in the *Bromidocystis* Bed at Daube Ranch (1 specimen, 2 plates) and at North-Central I-35 (1 plate), all in the middle or upper Mountain Lake Member, Bromide Formation, in the Arbuckle Mountains, southern Oklahoma.

Discussion.—*Acolocrinus arbucklensis* has finer ornament than any other species of *Acolocrinus*. It also differs from *A. crinerensis* by having less highly developed respiratory slits, smaller sR crests, a somewhat less elongate calyx shape, a less constricted summit, and less bulbous BB. *A. arbucklensis* also differs from *A. hydraulicus* by having a more elongate calyx, a more elongate anal X extending higher into the D sR crest, an outlet pore elongate across each iR-iR suture, a more pronounced lip around the basal cavity, and perhaps fewer armlets in larger calyces.

The holotype specimen was collected by Graffham from the A cut at North-Central I-35 just after the Interstate opened in the late 1960's, and was subsequently labeled by Fay as apparently coming from the Lower Echinoderm Zone. However, this specimen almost certainly came from the *Carabocrinus* Beds at this locality because of its preservation with slight overgrowths, its gray matrix, and the apparent absence (by faulting) of the Lower Echinoderm Zone in this particular cut.

ACOLOCRINUS? sp.

Plate 6, figures 57-62; Figure 39I

Two very large basal plates from the *Bromidocystis* Bed belong to an acolocrinid different from the two named species now known from the Bromide. One broken basal is 13.5+ mm long by 13.0 mm wide (almost as large as the holotype calyx of *A. arbucklensis*) with a broken basal cavity at least 3.0 mm deep; the other is 12.4 mm long by 10.0 mm wide with a complete basal cavity 5.2 mm deep; B L:W = 1.0+ to 1.24, a much higher value than other species of *Acolocrinus*. Both BB are only 0.4 to 0.5 mm thick (several times thicker at top of basal cavity), and have a deeply indented B-iR suture at top center (Pl. 6, fig. 57-62).

The B-iR sutures do not have any of the zigzag respiratory slits that usually characterize this genus. The plate surfaces are almost smooth without pitted ornament, and the elongate basal cavity lacks a lip at the lower edge (Pl. 6, fig. 57, 59, 60).

Discussion.—These two acolocrinid BB do not belong to either of the described Bromide species of *Acolocrinus*, and because they appear to lack respiratory slits, may not even belong in *Acolocrinus*. In general morphology they are similar to, and occur with, *A. arbucklensis*, but differ in being much larger but thinner, having a higher length to width ratio, a more angular B-iR suture, no lip on the basal cavity, no porous ornament, and apparently no zigzag sutural respiratory slits. These two BB may possibly belong to *Paracolocrinus* (see Brett, 1980), now known from the Upper Silurian Rochester Shale in western New York.

Studied specimens and occurrence.—Figured plates 1397TX56 from the *Bromidocystis* Bed at Daube Ranch and 1393TX17 from the *Bromidocystis* Bed at North-Central I-35, both from the upper Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma.

HYBOCRINUS

James Sprinkle

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Hybocrinus is the most abundant crinoid (and perhaps the single most abundant echinoderm) found as complete specimens in the Bromide Formation of Oklahoma. It is known from all of the echinoderm zones and beds and apparently is represented by two species, *Hybocrinus nitidus* and *H. crinerensis*. *Hybocrinus nitidus* occurs throughout the Mountain Lake Member: it is the dominant form in the Lower Echinoderm Zone (where it makes up about 51 percent of the echinoderm fauna) throughout the Arbuckles, is fairly common in the overlying *Carabocrinus* Beds, is known only from plates in the *Bromidocystis* Bed, and is relatively common in the Upper Echinoderm Zone at the top of the Mountain Lake. *Hybocrinus crinerensis* is fairly common in the upper Pooleville Member at the top of the Bromide in the Criner Hills, and may also occur with *H. nitidus* in the underlying Upper Echinoderm Zone in the Arbuckle Mountains. Because of their small, compact, somewhat conical cups with few plates, *Hybocrinus* specimens hold together better and are more often found complete than most other echinoderms in the Mountain Lake Member. Thus, *Hybocrinus* is probably overrepresented as complete specimens in the Lower Echinoderm Zone compared to its true original abundance.

Each Bromide species of *Hybocrinus* apparently had a short stem not much longer than the cup length and was attached to objects on the substrate (bryozoans, brachiopods) by a small, discoidal or radicular, type 2 holdfast (see chapter by Lewis). Two contrasting ways of life have recently been proposed for hybocrinids. Strimple (1975b, fig. 1) and Frest and Strimple (1978) have reconstructed Bromide and Curdsville *Hybocrinus* as lying upright on the substrate with a short recumbent or slightly buried stem that was probably unattached. In contrast, Brett and Liddell (1978) have reconstructed Kirkfield Quarry *Hybocystites* as a low-level suspension feeder held off the bottom on a short erect stem attached by a discoidal holdfast to a hardground surface. I believe that Bromide *Hybocrinus* with their very short stems and holdfasts attached to other objects more likely lived in a position such as that proposed by Brett and Liddell, up in the water column tethered just above the sea floor.

Order HYBOCRINIDA Jaekel, 1918

Family HYBOCRINIDAE Zittel, 1879

Genus HYBOCRINUS Billings, 1857

Type species.—*Hybocrinus conicus* Billings, 1857.

Diagnosis.—Cup slightly to moderately asymmetric, apparently pseudomonocyclic; BB nearly equal to unequal in size, medium-sized C radial and anal X beside each other on side of cup above RA, several small accessory anals may be present above anal X alongside low periproct with wide membrane; arms atomous, uniserial, relatively short, may show some difference in diameter; stem probably short, round, with rounded star-shaped lumen and cryptic pentameres, small holdfast distally.

Occurrence.—Middle Ordovician; southern Canada, eastern, central, and western United States.

Discussion.—*Hybocrinus* is distinguished from other five-armed hybocrinids (*Hoplocrinus*, *Revalocrinus*) by having the anal X entirely on the side of the cup alongside the raised C-ray radial and nearly as large as this adjacent plate. The asymmetric cup, unequal-sized basals, raised porelike hydropore in the posterior oral, and wide periproctal membrane around the low anal pyramid are also distinctive features that may not be present or so well developed in these other genera. *Hybocrinus* appears to range from the Whiterockian to the Wildernessian in the Middle Ordovician.

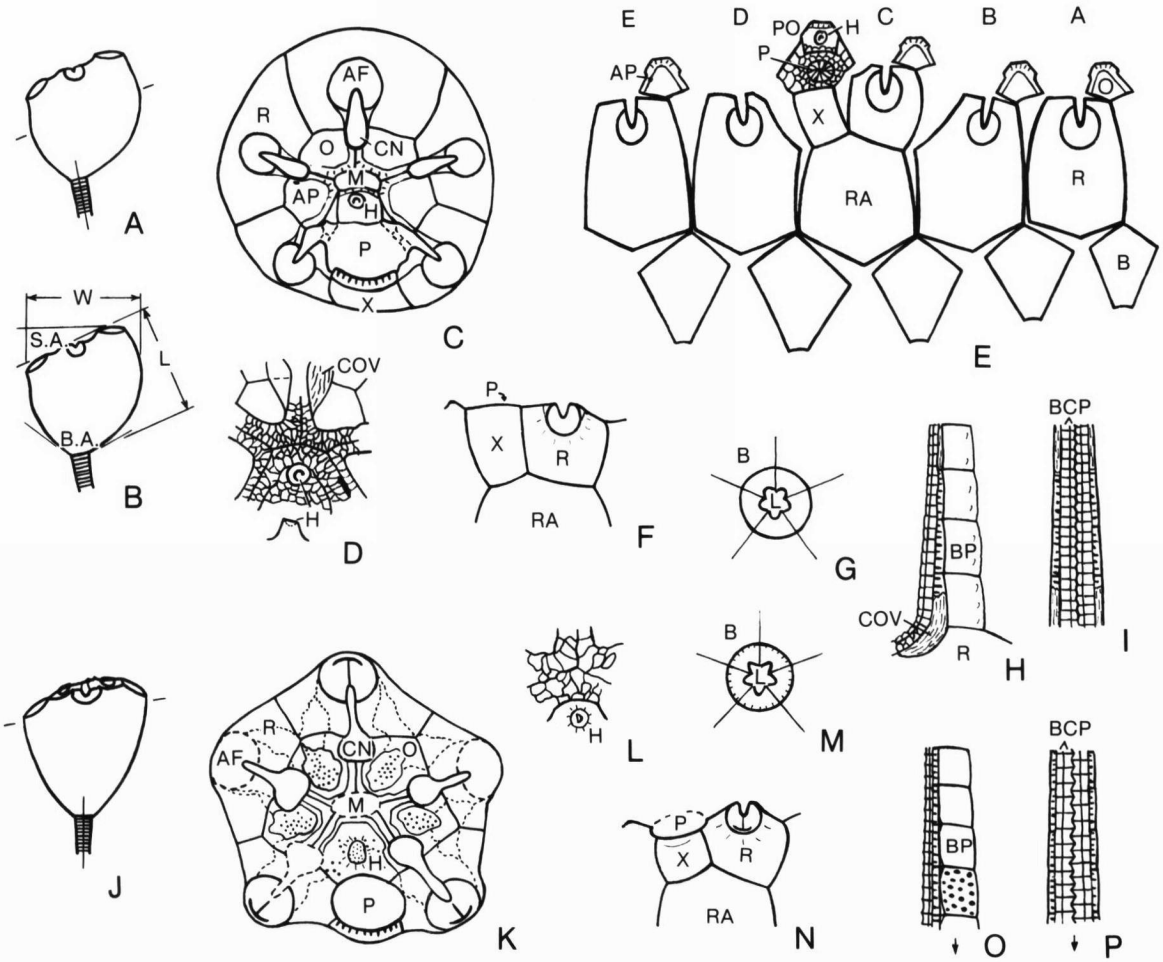


Fig. 40. Morphology of specimens of *Hybocrinus*, Mountain Lake and Pooleville members, Bromide Formation, Arbuckle Mountains and Criner Hills, southern Oklahoma. A-I, *Hybocrinus nitidus* Sinclair. A,B, Outline of calyx showing asymmetrical bulged shape, slightly tilted stem attachment, flat but tilted summit, location of maximum diameter (short lines), and where measurements were taken for cup length (L), cup width (W), basal angle (B.A.), and summit tilt angle (S.A.). C, Summit view mostly drawn from OU 9173, note nearly circular profile, arm facets (AF) that differ slightly in size, wide elliptical coelomic notches (CN), orals (O) surrounding elliptical central mouth (M), posterior oral bearing small slitlike hydropore (H) in raised tubercle but not reaching C or D radials (R), and fairly large periproct (P) also bordered by anal X (X), X3. D, Closeup of central summit in OU 9174 showing cover plates over mouth and ambulacra, small area of covers (COV) from A-ray arm, and curved slitlike hydropore (H) surrounded by cover and periproctal plates and in side view (below) in its raised tubercle, X3. E, Side-layout plating diagram showing unequal-sized basals (B), radials (R) with different-sized arm facets, radianal (RA) equally supporting C radial and anal X, 4 small regular orals (O), with the DE oral bearing a small accessory pore (AP) in some specimens, and the posterior oral (PO) with its raised hydropore (H) on the adoral side of the periproct (P). F, Posterior cup plating; note that anal X is longer than wide with the periproct (P) tucked in behind, and that the C radial (R) has a smooth, only slightly raised facet, much enlarged. G, Stem facet showing size and shape of lumen (L); pentamere sutures match those of basals (B) indicating cup is pseudomonocyclic, much enlarged. H, Side and I, adoral views of proximal arm showing brachial plates (BP) with few pustules, 2 sets of biserial brachial cover plates (BCP), and lateral ridges alongside food groove that are protected by elongate covers (COV) that extend down onto radial (R), much enlarged. J-P, *Hybocrinus crinerensis* Strimple and Watkins. J, Outline of calyx showing more symmetrical cup and stem attachment, location of maximum diameter (short lines), and slightly tilted and domed summit. K, Summit view mostly drawn from OU 9558, note pentagonal profile, arm facets (AF) that are nearly the same size and have medial and curved aboral grooves, unusual T-shaped coelomic notches (CN), orals (O) that have raised and pustular centers that are not overlain by ambulacral cover plates (dotted lines), the central elliptical mouth (M), and the posterior oral, which bears a bowl-shaped pitted hydropore (H), reaches the C and D radials (R), and forms the margin of the smaller elliptical periproct (P), X2.3. L, Oral cover plates, drawn from USNM 172035, compare this second type of hydropore developed as a slit in a raised tubercle with that in Figure 40K, X3. M, Stem facet showing size and shape of lumen and

HYBOCRINUS NITIDUS Sinclair, 1945

Plate 7, figures 1-18, 21-39; Plate 8, figures 1-4; Figure 40A-I

Diagnosis.—Cup moderately asymmetric, nearly circular in top view, L:W averaging 1.01, summit tilted to cup axis, tilt angle averaging 26°; BB differing greatly in size because stem facet offset toward A ray, RR differing slightly, anal X elongate, about two-thirds width of small adjacent C-ray radial; PO small with horseshoe-shaped hydropore in raised tubercle, PO not reaching RR but no large accessory OO or anals observed, wide periproctal membrane around anal pyramid, few small ambulacral flooring plates present; plates with fine pustular ornament; arms relatively short, one to one and a half times cup length, differing slightly in diameter with A-ray arm largest; stem short, approximately equal to cup length, round with rounded star-shaped lumen, divided into pentameres centered directly below BB, terminating in small type 2 holdfast distally.

Description.—Cup small to relatively large (smallest 4.7 mm long, largest 20.5 mm long), slightly to moderately asymmetric, rounded conical to skewed and squat cup-shaped in side view, nearly circular in top view, base widely conical with stem facet displaced toward A-ray, summit flat but tilted from cup axis, maximum diameter variable but usually near midheight (Fig. 40A). (As preserved, many cups lack PO; others lack regular OO as well as the anal X and C radial.) L:W varying from 0.71 to 1.27, averaging 1.01 in 25 measured specimens; basal angle varying from 85 to 125° and averaging 106°; summit tilt angle ranging from 20 to 35° and averaging 26° in same specimens. Cup asymmetry expressed in several ways: 1) stem facet considerably displaced toward A ray, 2) posterior BB much longer than anterior ones, 3) posterior RR (plus RA) slightly longer than anterior ones, 4) anal X and C radial considerably raised over rest of summit, producing summit tilt, and 5) arms differing somewhat in size with A-ray arm largest. Cup plates relatively thin to very thin (0.25 to 0.8 mm thick normally, up to 1.0 mm thick beneath arms), only slightly ornamented with low pustules.

BB 5, medium in size, in closed circlet around stem facets, but unequal, each pentagonal with a fairly small stem facet, flat to slightly convex on exterior. Because stem facet displaced toward A ray, CD basal largest, and EA or AB basal smallest (Fig. 40E). In one large cup, CD basal 8.2 mm long by 6.0 mm wide, leaning slightly left; BC basal 7.3 mm long by 6.1 mm wide and nearly symmetrical; DE basal 7.2 mm long by 5.5 mm wide, leaning right; AB basal 6.2 mm long by 4.7 mm wide, leaning left; and EA basal 5.3 mm long by 4.3 mm wide, leaning slightly right. Each basal forming about 20 percent of stem facet, facet nearly perpendicular to cup axis although sometimes almost parallel to surface of CD basal.

RR 5, relatively small to large, in open circlet around upper half of cup, circlet interrupted by RA and anal X, length greater than width for all except C radial. C radial smallest, hexagonal, raised above others; A radial medium, hexagonal; B radial relatively large, septagonal; E radial relatively large, hexagonal; D radial large, septagonal. Adoral tips of RR folded in to form edge of summit except in CD interray where C and D RR form 15 and 10 percent of curved periproct margin. Arm facet on adoral edge of each radial fairly large (33 to 55 percent of width), elliptical to horseshoe-shaped; facets in A, C, and D rays slightly larger and more elevated, facets in B and E rays slightly smaller, only slightly elevated. Relatively wide coelomic notch in base of food groove just adoral of arm facet (Fig. 40C).

RA large, usually equaling D radial as largest in cup, hexagonal, slightly to very convex, in middle of cup. Equally supporting C radial diagonally above on right and anal X diagonally above on left. Anal X small, rectangular, nearly flat, longer than wide, about two-thirds as wide as C radial. Upper sloping edge supporting aboral edge of periproct (about 25 percent), ornamented with shallow, vertical grooves adorally for membrane attachment (Fig. 40C).

OO 5, small, in closed circlet around mouth; 4 regular OO all nearly symmetrical and pentagonal, slightly concave on exterior, nearly smooth; PO smaller, rounded-rectangular, not connected to RR in posterior interray. No major accessory orals or anals apparently present aboral to PO; PO bearing highly raised (up to 0.8 mm) tubercle with sunken U-shaped or circular hydropore in center (Pl. 8,

small crenulae on edge of basals (B), much enlarged. N, Posterior cup plating, note that anal X is nearly equidimensional, bowed outward at the top, and does not reach the summit so that the periproct (P) is visible here, and that the adjacent C radial has a raised and grooved arm facet, much enlarged. O, Side and P, adoral views of proximal arm showing heavily pitted brachial plates (BP), 2 sets of biserial brachial cover plates (BCP) with an unusual medial suture, and a thin ridged area alongside the food groove perhaps protected by small covers, much enlarged.

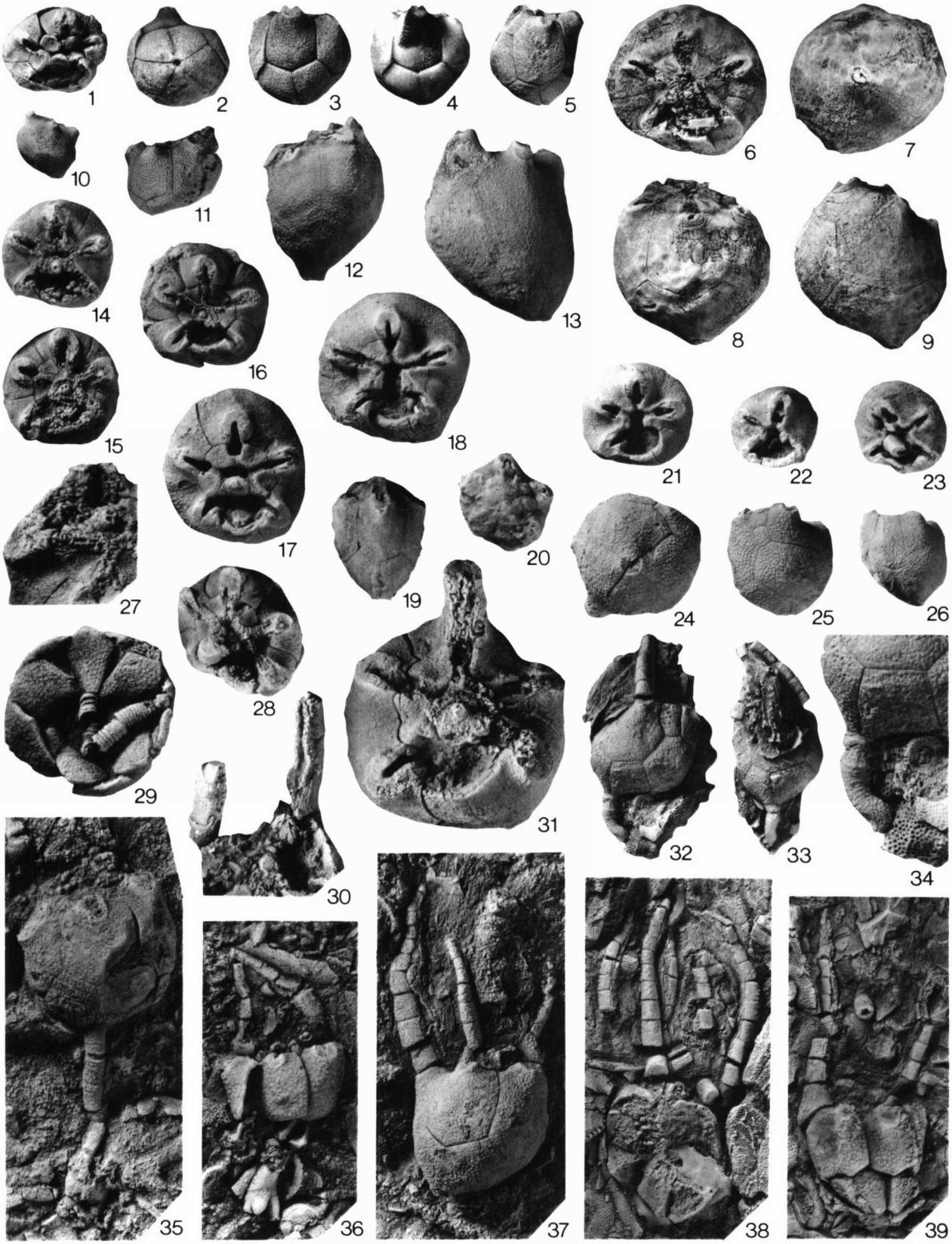


fig. 2, 3). In about 20 percent of specimens, tiny accessory pore present in DE oral near adoral edge of E-ray coelomic notch (Pl. 7, fig. 17, 18, 21).

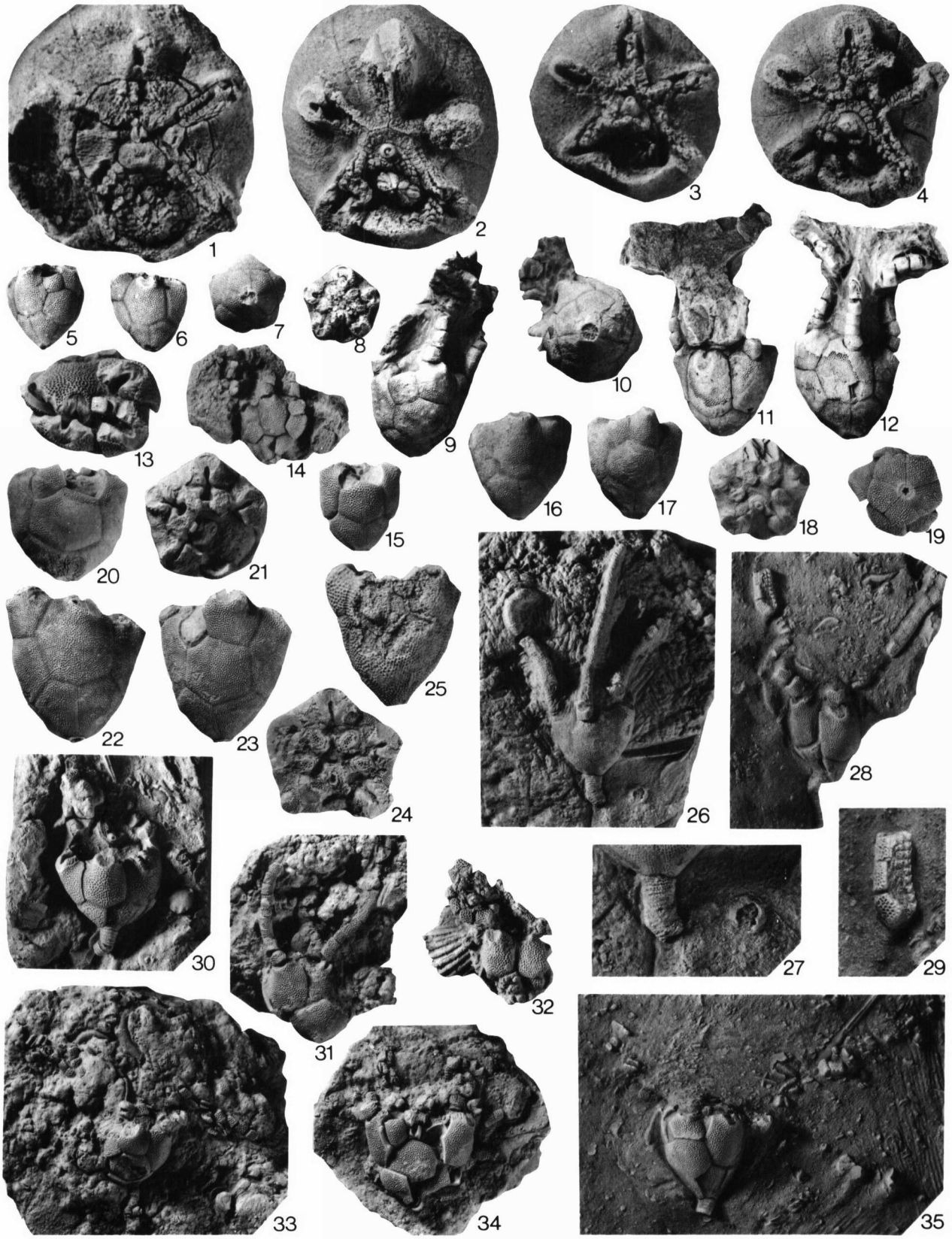
Mouth nearly central on summit, elliptical, fairly small. Shallow food grooves from arms entering mouth with characteristic "2-1-2" symmetry pattern (Sprinkle, 1973); D and E ambulacra entering left end, A entering upper center, B and C entering right end (Pl. 7, fig. 15, 17). No flooring plates observed in ambulacral grooves where edges of OO underlie groove, but biserial set of small plates present in bottom of elongate elliptical (not pinched) coelomic notches near arm facets (Pl. 8, fig. 1). Mouth and ambulacral grooves protected by 2 sets of tiny biserial cover plates, a larger, outer, rectangular set about 0.5 mm long and a smaller, inner, triangular set about 0.2 mm long intermeshing in center (Pl. 8, fig. 2, 4; Fig. 40D).

Periproct large, elliptical, surrounded by PO adorally (20 percent), C and D ambulacra laterally (about 15 percent each), and C radial (15 percent), anal X (about 25 percent), and D radial (10 percent) aborally. Wide periproctal membrane with small plates covering aboral edge of PO and beveled adoral edge of anal X and adjacent RR (Pl. 7, fig. 15). Small, domal, anal pyramid in center or closer to right edge about 2.1 mm in diameter and 1.5 mm high, consisting of about 14 long and short triangular plates (Pl. 8, fig. 1,2). Small, only slightly exposed flooring plates appearing to separate periproctal area from adjacent C- and D-ray ambulacra (Pl. 8, fig. 1).

PLATE 7.

Fig. 1-18, 21-39. *Hybocrinus nitidus* Sinclair; Lower Echinoderm Zone (except Fig. 11), Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1-9, 17, 22, 23, 35-39 from Daube Ranch; 10, 12, 13, 15, 18, 21, 25, 27, 28, 32-34 from Lick Creek; 11 from Upper Echinoderm Zone at Buckhorn Ranch; 14 from Fittstown Quarry; 16, 24, 26, 29-31 from Amis Ranch. 1-5. Summit, basal, A-ray side, immersed A-ray side, and B-ray side views of Sinclair's small holotype USNM 112074 of *H. nitidus;* note abraded CD interray on summit, accessory pore in DE oral (1), bowl-shaped cup, pustular ornament, and unusually large "black spot" on A-ray radial (4); X1.5. 6-9. Summit, basal, A-ray side, and B-ray side views of Sinclair's large holotype USNM 112073 of *H. pyxidatus (= H. nitidus)* showing some cover plates preserved on summit, abraded cup plates, and highly bulged posterior side (9); X1.5. 10. B-ray side view of small cup OU 9175; note asymmetry and tilted summit at this size; X1.5. 11. DE-interray side view of cup OU 9176 showing great asymmetry, stem facet almost in plane of posterior BB, and pitted ornament resembling that of *H. crinerensis;* X1.5. 12. DE-interray side view of fairly large cup OU 9174; note elongate shape, flat but tilted summit, and fine pustular ornament; X1.5. 13, 18. BC-interray side and summit views of very large cup OU 9177 showing asymmetrical "bulged" cup shape, arm facets and narrow coelomic notches, and missing PO below mouth on summit; X1.5. 14. Summit view of cup 1279TX331; note some cover plates and periproctal plates; X1.5. 15, 27. Summit and oblique posterior summit views of cup OU 9178 showing cover plates, poorly preserved anal pyramid, unusual double hydropore in PO, and elongate covers just adoral of C-ray arm facet (27); X1.5, X3. 16, 29. Summit and basal views of crushed cup OU 9179 showing slightly disarticulated cup plates, ambulacral and oral cover plates, and short incomplete stem attached to BB and folded back on itself; X1.5, X2. 17. Summit view of cup OU 9173; note rounded profile, summit plating, slightly concave OO with accessory pore in edge of DE oral, elliptical coelomic notches, slightly different-sized arm facets, and small PO that does not reach posterior RR; X1.5. 21. Summit view of abnormal cup OU 9564 showing missing C-ray arm facet and enlarged periproct; X1.5. 22. Summit view of abnormal cup OU 9565 in which B-ray arm facet and groove failed to develop; X1.5. 23. Summit view of abnormal cup OU 9566 showing only 4 RR with 2 arm facets on the same radial; X1.5. 24. Basal view of abnormal cup OU 9567 with 2 BB (at top) fused together; X1.5. 25. C-ray side view of abnormal cup OU 9568 showing anal X divided into 2 parts by horizontal suture; X1.5. 26. C-ray side view of abnormal cup OU 9569 lacking RA; note unusually long C radial, anal X, and posterior BB to compensate; X1.5. 28. Summit view of slightly crushed small cup OU 9570 showing cover plates and slightly open anal pyramid in periproct; X3. 30. Oblique summit view of calyx OU 9571; note 2 arms with cover plates over food groove, some lateral covers on C-ray arm (right), possibly regenerated distal tip of B-ray arm (left), and displaced anal pyramid at edge of periproct; X3. 31. Summit of cup OU 9572 showing some oral and brachial cover plates and lateral covers over ridged area on A-ray arm; X3. 32-34. C-ray side, D-ray side, and enlarged stem views of calyx OU 9573; note posterior cup asymmetry and plating (32), several partly complete arms, and short possibly complete stem (34) with the distal end made up of tiny platelets and abutting a small bryozoan; X1.5, X3. 35. E-ray side view of specimen 1121TX110 (Graffham Coll.) showing complete stem slightly longer than cup attached to a small round object with a badly weathered holdfast; X2. 36. E-ray side view of calyx USNM 172043 (Graffham Coll.); note several poorly preserved arms, disarticulated cup and short stem, and fairly large digitate holdfast not typical of type 2; X2. 37. E-ray side view of specimen OU 9574 showing cup asymmetry, pustular ornament, and much larger complete A-ray arm (left) than possibly regenerated E-ray arm (center); X2. 38. Side view of specimen USNM 172044 (Graffham Coll.); note badly damaged cup filled with epitaxial calcite and several nearly complete, similar-sized, atomous arms bearing a few pustules aborally; X2. 39. BC-interray side view of specimen USNM 172045 (Graffham Coll.) showing nearly complete D-ray arm about one and a half times cup length and bearing cover plates; X2.

Fig. 19, 20. *Hybocrinus crinerensis?* Strimple and Watkins; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Buckhorn Ranch, Arbuckle Mountains, southern Oklahoma; A-ray side and summit views of elongate, nearly symmetrical cup with a domed summit and pitted ornament that may belong to this species (compare with 11 above); X1.5.



Arms 5, uniserial, atomous; longest complete arm 17 mm long with 11 brachials (Brr) in a cup 12 mm long (Pl. 7, fig. 37), implying arm length ranging up to about one and one-half times cup length. Arms canted outward 30 to 45° at elliptical to horseshoe-shaped radial facets but usually curving inward in first few Brr to extend vertically over summit; most preserved arm segments unattached at radial facet. Arms varying somewhat in size, A-ray arm largest (especially at base), perhaps longest, C- and D-ray arms intermediate, B- and E-ray arms smallest, perhaps only two-thirds width of A-ray arm (Pl. 7, fig. 37). Brr in A-ray arm 2.3 mm long, 2.2 mm wide, and 2.7 deep at base, decreasing slowly in size to 0.9 mm long, 0.8 mm wide, and 0.8 deep near distal tip. Brr hemielliptical in cross section with a deep food groove protected by 2 sets of slightly domed cover plates (BrCP), about 0.1 to 0.2 mm long and wide; BrCP:Br about 4.0 to 5.0; Brr nearly smooth externally except for row of short ridges on each side of food groove in proximal Brr (Pl. 7, fig. 37). Few well-preserved proximal Brr show tiny, elongate, domed covers running across ridges and down onto area on RR alongside arm facets (Pl. 7, fig. 30, 31; Fig. 40H, I).

Stem relatively short, small, terminating in small type 2 holdfast. Longest complete stem only 14 mm long with about 50 columnals attached to cup 11.5 mm long (Pl. 7, fig. 35), tapering slowly from 1.8 mm in diameter proximally to 1.2 mm distally; most other stems shorter than cup and tapering very slowly. Proximal columnals circular, thin, apparently homeomorphic, divided into cryptic pentameres with sutures matching those of BB (implying cup pseudomonocyclic), lumen rather large (approximately one-half stem diameter), pentagonal to rounded star-shaped (Fig. 40G). Distal stem divided up into numerous tiny platelets about 0.1 to 0.15 mm in size (Pl. 7, fig. 39). Stem terminating distally in small, lobate to slightly radicular, type 2 holdfast about 3.0 mm in diame-

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PLATE 8.

Fig. 1-4. *Hybocrinus nitidus* Sinclair; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1 from Cedar Village, 2-4 from Lick Creek. 1. Summit view of small cup 1278TX14, a badly abraded and weathered specimen, which preserves the anal pyramid and surrounding periproctal plates and ambulacral flooring plates in the B-ray coelomic notch and in the C- and D-ray ambulacral grooves; X5. 2. Summit view of cup OU 9174 showing well-preserved tiny oral and ambulacral cover plates, slightly distorted anal pyramid with some surrounding periproctal plates, and slitlike hydropore in raised tubercle on mostly covered PO; X3. 3. Summit view of very small cup OU 9175; note some oral cover plates and raised hydropore on PO; X5. 4. Summit view of cup OU 9575 showing larger but fewer oral and ambulacra cover plates than in 2 and difference in arm facet size; X3.

Fig. 5-35. *Hybocrinus crinerensis* Strimple and Watkins; Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 5-12, 15-18, 22-24, 28, 29, 35 from Rock Crossing, most from 6 m below the Viola Limestone but also from 0.3-1.0 m below and undesignated; 13, 14, 19-21, 25-27, 30-34 from Culley Creek, either from Zone 3 or an undesignated zone. 5-8. CD-interray side, B-ray side, basal, and summit views of small paratype cup USNM S4752 (Watkins Coll.) showing plating, summit features, and pitted ornament; X1.5. 9-12. CD-interray side, basal, DE-interray side, and B-ray side views of holotype USNM S4751 (Watkins Coll.); note atomous arms, plating, cup asymmetry, and stem facet; X1.5. 13, 19. Summit and basal views of crushed cup 1122TX105 (Graffham Coll.) showing arm facets with grooves, pitted ornament on plates, and BB nearly all the same size and shape with a central stem facet and pentagonal lumen; X3, X2. 14. D-ray side view of small specimen 1122TX106 (Graffham Coll.); note cup plating and proximal brachials; X2. 15. C-ray side view of cup OU 9559 showing inset sutures, missing C radial and anal X, and pitted ornament; X1.5. 16, 18. E-ray side and summit views of cup OU 9560; note slightly tilted summit, lining up of ornamental pits on plate sutures, and raised OO plus PO with hydropore on summit; X1.5. 17. C-ray side view of cup OU 9561 showing plating and ornament; X1.5. 20, 21. C-ray side and summit views of large cup USNM 172036 (Graffham Coll.); note wide cup shape, missing C radial, and T-shaped coelomic notches on summit with smooth areas for cover plates alongside on adoral RR and OO; X1.5. 22-24. B-ray side, C-ray side, and summit views of large cup OU 9558 showing pitted ornament, depressed plate sutures, missing anal X, raised and pitted centers of OO on summit, bowl-shaped pitted hydropore on PO, and abnormal D-ray arm facet (24); X1.5. 25. E-ray side view of abnormal cup USNM 172037 (Graffham Coll.); note extra set of plates inserted between BB and RR in all rays; X3. 26, 27. A-ray side view and enlargement of stem of calyx 1405TX9 (Watkins Coll.) showing long, atomous, uniserial arms with at least 19 Brr and short incomplete stem with possible holdfast attached nearby to a brachiopod; X1.5, X3. 28, 29. EA- or AB-interray view plus enlargement of arm segment in crushed calyx OU 9562; note short stem segment and partly disarticulated arm segments with well-preserved cover plates on 1 segment (29); X2, X5. 30. A-ray side view of calyx 1405TX10 (Watkins Coll.) showing short incomplete stem, arm facets with ridged area alongside (left), scattered brachials, and PO with slitlike hydropore in highly elevated tubercle (vs 24); X2. 31. Side view of calyx USNM 172038 (Graffham Coll.); note arm segments with pitted ornament; X1.5. 32. Side view of small calyx USNM 172039 (Graffham Coll.) showing disarticulated arm segments, stem, and cup plates; X2. 33. C-ray side view of calyx USNM 172040 (Graffham Coll.); note short incomplete stem (bottom) and many disarticulated arm segments; X1.5. 34. C-ray side view of calyx USNM 172041 (Graffham Coll.); note disarticulated cup plates and arms plus bryozoan fragments with similar ornament (lower right); X1.5. 35. BC-interray side view of calyx OU 9563 showing pitted cup plates, proximal stem segment, and mostly disarticulated arm segments; X2.

ter and 1.5 mm high (Pl. 7, fig. 34-36). Holdfasts commonly attached to small bryozoan debris.

Cup plates usually showing slight to moderate pustular ornament with rather widely spaced, low pustules (Pl. 7, fig. 12). (However, some specimens in the Upper Echinoderm Zone have more closely spaced pustules grading into pitted ornament; Pl. 7, fig. 11.) Widely spaced pustules randomly scattered over plate surface, not aligned. Most OO, Brr, and columnals in proximal stem nearly smooth and unornamented.

Nineteen abnormal specimens discovered in cursory examination of about 2,400 total; proportion of abnormal specimens roughly 0.79 percent. Most abnormalities consisting of either horizontally-divided plates (B radial, anal X) or missing or fused plates: E radial, RA(2), 2 BB(3). Several different four-sided specimens present in this material either because radial failed to develop (Pl. 7, fig. 23) and 2 arm facets occur together, or because arm facet failed to develop on otherwise normal radial (Pl. 7, fig. 21). One specimen with short stem segment bearing 6 lumen lobes, and another specimen with rounded capping columnal lacking a distal suture on stem facet. One additional specimen, not counted above, with repaired and regenerated small arm fragment (see Pl. 7, fig. 30).

Occurrence.—Known from the Lower Echinoderm Zone at Lick Creek (871 specimens plus about 500 retained by Graffham), Daube Ranch (622 specimens plus about 500 retained by Graffham), Amis Ranch (523 specimens), Cornell Ranch (315 specimens), Fittstown Quarry (21 specimens), Johnston Ranch (16 specimens), Bromide (4 specimens), and Fittstown Roadcut, McLish, Nebo, Cedar Village, and Rhynes Ranch (2 specimens each). Two specimens are known from the *Carabocrinus* Beds, 1 from North-Central I-35 and 1 from North I-35; only plates are known from the *Bromidocystis* Bed. Fairly common in the Upper Echinoderm Zone at Buckhorn Ranch (25 specimens), Sulphur (11 specimens), Lick Creek (6 specimens), Nebo (2 specimens), and Rock Crossing, North I-35, and Bromide (1 specimen each).

Studied specimens.—Holotypes of *H. nitidus*, USNM 112074, and *H. pyxidatus*, USNM 112073, figured specimens OU 9173-9179; OU 9564-9575, 1121-TX110, 1279TX331, 1278TX14, and USNM 172043-172045; many unfigured specimens in OU, TX, SUI, USNM, and other museum and private collections.

Discussion.—Over 2,400 complete specimens were available for study, and at least 1,000 more are known to have been collected by Graffham (and retained by him) during excavation work at Daube Ranch and Lick Creek. The holotype specimens of Sinclair's *Hybocrinus nitidus* and *H. pyxidatus* are conspecific (they are from the same zone and locality); *H. nitidus* is here accepted as the name of this species and *H. pyxidatus* is synonymized, in agreement with the name used by Frest and Strimple (1978). The holotype of *H. nitidus* (USNM 112074) is a small, nearly complete, and only slightly asymmetric cup (Pl. 7, fig. 1-4). Although it is abraded on the summit in the C and D rays and slightly crushed, it shows the general cup shape, plating, including the abraded orals, and ornament. The holotype of the conspecific *H. pyxidatus* (Pl. 7, fig. 6-9) is a large, asymmetric cup slightly abraded all over. The orals, hydropore, and some ambulacral cover plates are preserved in this specimen.

Hybocrinus nitidus is a fairly distinctive species most common in the Lower Echinoderm Zone. It has moderate cup asymmetry with unequal basals, a tilted summit, length to width ratio near 1.0, slight asymmetry in the arms, a short stem with type 2 holdfast, and pustular ornament (except for some specimens in the Upper Echinoderm Zone). Several specimens show pentameres in the proximal stem and indicate that the cup in this species (and probably the entire genus) is pseudomonocyclic (pentamere sutures in proximal stem match overlying basal sutures). Based on Warn (1975), this is not the expected pattern for a true monocyclic crinoid, but an unusual one that might have been derived from a large-calyx dicyclic ancestor that had lost one circlet of lower cup plates (probably the infrabasals). *Hybocrinus* does resemble most of the large-calyx dicyclic inadunates in the Bromide faunas in a variety of features (1 divided radial, fairly large anal X, well-developed orals, presence of a hydropore, type of cup asymmetry, relatively simple arms, stem with pentameres), and an origin from this source seems quite reasonable. However, this discovery does question the taxonomic importance of dicyclic vs. monocyclic plating as a basic way of subdividing inadunate crinoids.

The appearance of pitted ornament in specimens of *H. nitidus* from the Upper Echinoderm Zone is a puzzling feature. In most specimens, cup shape, asymmetry, and other cup features are the same as in other specimens of *H. nitidus* from lower in the Mountain Lake Member, but a few specimens from this zone with this pitted ornament are different and appear to belong to *H. crinerensis*, which occurs more commonly in the overlying Pooleville. Pustular and pitted ornament may be closely re-

lated; one is a low planar surface with spaced hemispherical pustules, the other is a high planar surface bearing spaced hemispherical depressions. A simple transition between these two ornament types may have occurred below the Upper Echinoderm Zone.

HYBOCRINUS CRINERENSIS Strimple and Watkins, 1949
Plate 7, figures 19, 20; Plate 8, figures 5-35; Figure 40J-P

Diagnosis.—Cup rounded conical, pentagonal in top view, slightly asymmetrical, L:W averaging 1.04, summit tilt angle averaging 15°; BB nearly same size, stem facet nearly central; anal X nearly square, OO with ornamented centers, PO with raised tubercle usually with bowl-shaped madreporite, PO reaching RR and periproctal membrane medium-sized, coelomic notches constricted and T-shaped; pitted ornament on cup plates, pitting aligned near slightly depressed sutures; arms nearly same size, pitted like cup plates, medium length; stem apparently short, slightly rugose on exterior, may terminate in small type 2 holdfast distally.

Description.—Cup small to medium sized (smallest 8.4 mm long, largest 17.0 mm long), slightly asymmetrical, rounded conical in side view, pentagonal in top view; base conical with stem facet only slightly displaced toward A ray, summit slightly domed and tilted, maximum diameter above midheight (Fig. 40J). L:W ratio ranging from 0.92 to 1.20, averaging 1.04 in 10 measured specimens; basal angle varying from 80 to 115°, averaging 92°, summit tilt angle ranging from 10 to 20°, averaging 15° in same specimens. Cup plates relatively thin (0.5 to 0.7 mm thick normally), ornamented with numerous small circular pits (Pl. 8, fig. 5-7, 22, 23).

BB 5, medium in size, in closed circlet around stem facet, nearly equal in size (CD basal slightly longer in some specimens), longer than wide, all pentagonal and nearly symmetrical (Pl. 8, fig. 19), slightly convex on exterior. Stem facet relatively small, displaced slightly toward A ray, nearly perpendicular to thecal axis and often parallel to summit; each B forming about 20 percent of facet (Fig. 40M).

RR 5, relatively small to large, in open circlet around upper half of cup, circlet interrupted by RA and anal X. C radial smallest, hexagonal, raised above others on summit, other RR hexagonal or septagonal, relatively large. Adoral tips of RR folded in to form edge of summit; C and D radials also forming small lateral edge of periproct. Arm facet on adoral edge of each radial, facet slightly elliptical with length slightly greater than width, with a deep adoral coelomic notch, occupying about 30 to 50 percent of radial width, with a distinctive longitudinal groove and small aboral arc-shaped groove (Pl. 8, fig. 13). Facets elevated above radial surface, nearly same size in all rays (Fig. 40K).

RA large, hexagonal, either equilateral or wider than long, slightly to moderately convex, in middle of cup. Equally supporting C radial diagonally above on right and anal X diagonally above on left. Anal X small, rectangular to square, usually tilted slightly, margins slightly curved, bulged outward at top, about as long as wide, tip slightly below summit, about two-thirds as wide as C radial width (Fig. 40N). Adoral edge of anal X forming curved lower margin (about 30 percent) of periproct; this edge slightly grooved (Fig. 40K).

OO 5, small, in closed circlet around central mouth; 4 regular OO all nearly symmetrical, pentagonal, flat to slightly convex on exterior with elliptical central area (not overlapped by cover plates) strongly pitted (Pl. 8, fig. 24). PO differently shaped, parabolic with long lateral limbs reaching C and D RR. No accessory OO or anals present aboral to PO around periproct (Pl. 8, fig. 18, 24). Slightly to moderately raised tubercle in center of PO bearing either shallow, bowl-shaped, porous madreporite or more highly raised, curved, slitlike hydropore (Fig. 40K, L). No other accessory pores observed on summit.

Mouth central on summit, elliptical, fairly small, shallow ambulacral grooves from arms entering edges of mouth; no flooring plates observed anywhere in ambulacra. Coelomic notches elongate, T-shaped (sides constricted, adoral end much wider) (Fig. 40K); ambulacral grooves and mouth protected by tiny cover plates in two biserial series, a larger rectangular series about 0.6 mm long and 0.4 mm wide laterally and a very small triangular series about 0.1 to 0.2 mm long meshing together medially (Pl. 8, fig. 8; Fig. 40K).

Periproct medium-sized, elliptical, slightly wider than long, sloping off edge of summit, surrounded by PO adorally (30 percent), C and D RR laterally (20 percent each), raised edge of anal X aborally (30 percent); in a large specimen, periproct 3.4 mm long and 3.5 mm wide. Anal pyramid not preserved in any studied specimens but apparently surrounded by a narrow periproctal membrane

with at least 2 plate circlets of small periproctal plates about 0.4 mm long.

Arms 5, unbranched, uniserial, medium length, all about same size. No complete arms preserved; longest incomplete one 23 mm long with 19 Brr in a cup 10 mm long (Pl. 8, fig. 26). Arms probably twice to two and one-half times cup length. Brr hemielliptical in cross section, usually about 1.3 mm long, 0.9 mm wide, and 1.2 mm deep, with a relatively deep, U-shaped food groove adorally about 0.5 mm wide and deep. Brr (and even some BrCP) pitted like cup plates, showing strong ridges alongside food groove proximally (Pl. 8, fig. 28, 34). Two sets of domed, biserial BrCP present over food groove, an outer rectangular set about 0.3 mm long and wide and an inner interdigitating set with concave centers 0.2 mm long and 0.3 mm wide (Fig. 40P); outer BrCp:Br about 3.0. Ridged area on proximal Brr and smooth area alongside radial facets apparently covered by low, elongate, covers (Pl. 8, fig. 24).

Stem apparently relatively short; none complete, but one incomplete stem 5.6 mm long with 25 columnals. Another cup 10 mm long with short 3.6 mm stem segment having its distal end 2.2 mm away from small holdfast on a brachiopod shell, to which it may have been attached (Pl. 8, fig. 27). Proximal columnals circular, heteromorphic (alternating thicker and thinner), ornamented with small pustules; stem tapering slowly in diameter. Proximal stem may be divided into pentameres. Lumen star-shaped, about half columnal diameter, points of lumen interradial (Fig. 40M). Possible holdfast a low disc about 2.5 mm in diameter and 0.3 mm high; apparently a type 2 or 3.

All cup plates, Brr, and some BrCP ornamented with moderate-strength, partly aligned pits about 0.1 to 0.15 mm in diameter (Pl. 8, fig. 22, 23). Pits strongly aligned at (and sometimes connected across) plate sutures, plate sutures slightly depressed.

Two abnormal specimens found in studied material (about 5 percent). One with 4 RR (all except C) divided horizontally into lower and upper halves (inferradial and superradial plates) (Pl. 8, fig. 25). The other with an abandoned brachial facet with a rounded capping Br on the D radial with a new facet added just adorally (Pl. 8, fig. 24).

Occurrence.—Known from the upper Pooleville Member, Bromide Formation, at Culley Creek (27 specimens), Rock Crossing (12 specimens, including the holotype and paratype), and Dunn Quarry (1 specimen). Two specimens from the Upper Echinoderm Zone at Sulphur and 1 from the same zone at Rock Crossing also appear to belong to this species.

Studied specimens.—Holotype USNM S4751, paratype USNM S4752, figured specimens USNM 172035-172041, 1122TX106-107, 1405TX9-10, OU 9180, and OU 9558-9563; other specimens in USNM, TX, and OU collections.

A total of 43 specimens were available for study. Strimple and Watkins' holotype (USNM S4751) is a medium-sized calyx showing cup plating, 3 partial arms plus a single Br attached to a fourth radial, but no summit features; their figured paratype (USNM S4752) is a small, well-preserved cup showing the plating, ornament, and summit structures, including a few cover plates.

Discussion.—*Hybocrinus crinerensis* differs from *H. nitidus*, which occurs lower in the Bromide, and from other species in several ways. It has only a slightly asymmetric cup with a pentagonal cross section, a lower average basal angle (92°), a slightly domed and less tilted summit (15°), basals nearly all the same size, a nearly equilateral and convex anal X not quite reaching the plane of the summit, a bowl-shaped porous madreporite in the posterior oral in many cups, a slightly pustular stem, and medium-strength pitted ornament on the cup plates, brachials, and some brachial cover plates.

Hybocrinus crinerensis resembles *H. punctatus* (Miller and Gurley) (see Brower and Veinus, 1974, p. 32 and pl. 4, pl. 5, fig. 1-3), especially in its pitted ornament, but *H. punctatus* has a more asymmetric cup with greater summit tilt and a larger anal X. The only other *Hybocrinus* species with strong pitted ornament is *H. perperamnominatus* Brower and Veinus (1974, pl. 3, fig. 2-4), but this species has a larger and much more elongate cup.

If the unattached small holdfast in Plate 8, figure 27 does in fact belong to the adjacent specimen of *H. crinerensis*, then this species most likely would also be a short-stemmed form similar to *H. nitidus* in the Mountain Lake Member. Both species would have been short-stemmed, low-level, suspension feeders tilted over in the water column by bottom currents and tethered in place by a small cemented holdfast usually attached to other fossils. Because *H. crinerensis* has a nearly symmetrical cup, it is unlikely that it was recumbent on the sea floor, as proposed for some other *Hybocrinus* species (see Strimple, 1975b).

LONG-ARMED CLADID INADUNATES

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Long-armed dicyclic inadunates (order Cladida) constitute a subordinate element of the Bromide fauna in which about 30 specimens are assigned to five species. Despite the rarity of these crinoids, several forms provide important information about evolution. *Eopinnacrinus pinnulatus*, n. gen., n. sp., is the oldest known pinnulate dicyclic inadunate crinoid. *Quinquecaudex glabellus*, n. gen., n. sp. lies close to the ancestral stock of the Dendrocrinidae. *Dendrocrinus villosus*, n. sp., *D.? bibrachialis*, n. sp., and *Merocrinus impressus*, n. sp. are either the oldest or nearly the oldest members of these two genera.

Order CLADIDA Moore and Laudon, 1943

Suborder DENDROCRININA Bather, 1899

Family MEROCRINIDAE S. A. Miller, 1889

Genus MEROCRINUS Walcott, 1884

Type species.—*Merocrinus typus* Walcott, 1884.

Diagnosis.—A genus of dicyclic inadunate crinoids characterized by superradial in C ray bearing anal X and C-ray arm; radial facets wide; dorsal cup low and flat with large round stem; anal tube long, slender, coiled in 1 species; arms nonpinnulate, branching isotomously several times.

MEROCRINUS IMPRESSUS Brower and Veinus, n. sp.

Plate 9, figures 2, 6; Figure 41

Diagnosis.—A species of *Merocrinus* with smooth dorsal cup plates with impressed or depressed sutures; dorsal cup low, moderately wide, with straight sides; 7 primibrachs present; proximal part of stem straight, not tapering.

Description.—Dorsal cup wide and low, height: width 0.59, cup walls straight and expanding slightly, distal width of cup only slightly larger than proximal width. Dorsal cup plates smooth with depressed or impressed sutures.

Infrabasals 5, pentagonal, height:width 0.6. Basals 5, hexagonal, height:width about 0.6. Radials 5, pentagonal, height:width 0.59; radial facet occupying entire width of radial plate. Superradianal located above C-ray radial; judging from facet, superradial bearing small anal X on left and larger C-ray arm on right (Fig. 41A). Anal X and anal tube not preserved.

Arms represented only by primibrachs; nonaxillary primibrachs rectangular, nonpinnulate, height:width ranging from 0.34 to 0.48; primibrach 7 axillary, pentagonal. Articular surfaces unknown.

Only proximal part of stem known, round. Columnals thin and flat with crenulate articular surfaces, only 1 order of columnals present.

Discussion.—*Merocrinus impressus* is known only from a single, poorly preserved specimen that consists of a partial crown with a portion of the column. Despite poor preservation, the specimen can clearly be assigned to *Merocrinus* and distinguished from other species of the genus.

The Bromide taxon is most similar to *M. britonensis* Kolata (1975, p. 36, pl. 5, fig. 6, text-fig. 10) from the Platteville of Illinois, which possesses a more narrow cup with plates and primibrachs that are higher relative to their widths. The three species from the Trenton of New York, *M. typus* Walcott (1884, p. 209, pl. 17, fig. 5), *M. corroboratus* Walcott (1884, p. 210, pl. 17, fig. 6), and *M. retractilis* (Walcott) (1884, p. 211, pl. 17, fig. 4), have smooth dorsal cup plates that lack depressed or impressed sutures, in contrast to the sunken sutures of the Bromide species. In addition, the cup of *M. typus* has a rounded base unlike the straight-walled cup of *M. impressus*. *M. corroboratus* exhibits more slender primibrachs and a tapering proximal column. The stem of *M. curtus* (Ulrich) (1879, p. 18, pl. 7,

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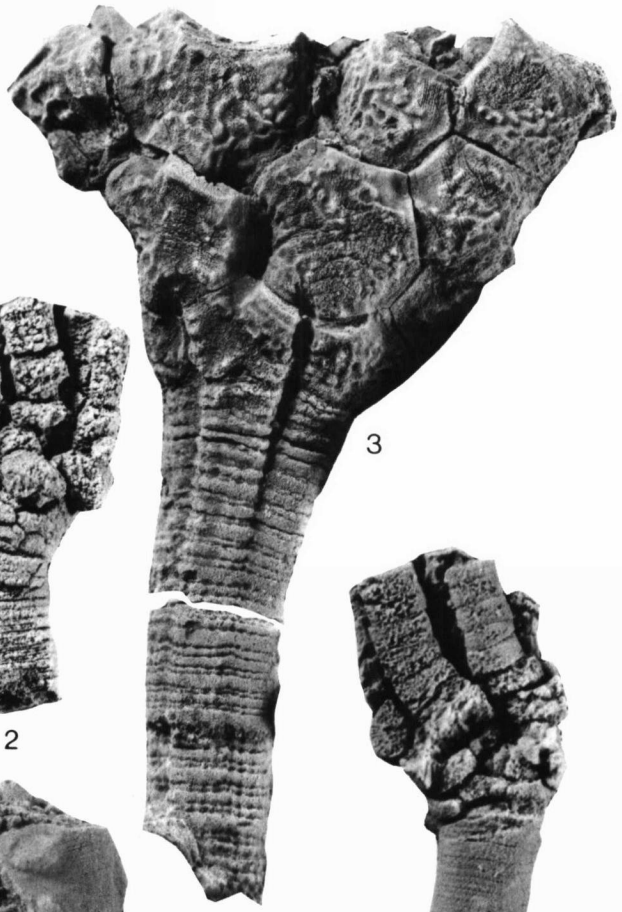

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fig. 14) from the Ordovician of the Cincinnati area is probably divided into pentameres, whereas that of the Bromide form is solid; only seven primibrachs are found in the lateral rays of *M. impressus*, but 10 plates are seen in *M. curtus*. The English crinoid *M. salopiae* Bather (see Ramsbottom, 1961, p. 11, pl. 3, fig. 6) has a lower, wider dorsal cup that expands more rapidly than does that of the new species, and four or five primibrachs in contrast to the seven plates of *M. impressus*.

Specific name.—*Impressus*, in allusion to the sunken, depressed or impressed sutures of the dorsal cup.

Holotype.—OU 9001.

Occurrence.—Pooleville Member of the Bromide Formation, Zone 3, 9 to 10 m below the Viola Limestone, Culley Creek, Criner Hills, southern Oklahoma.

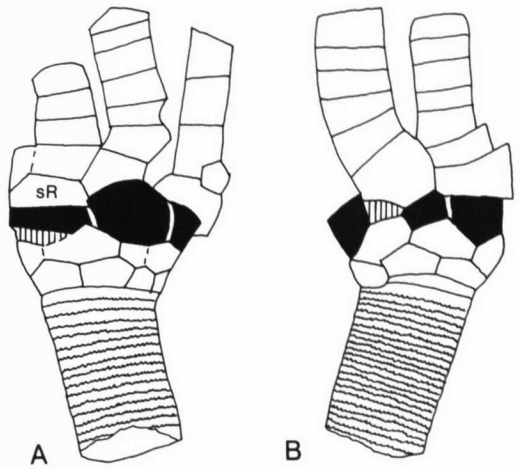


Fig. 41. *Merocrinus impressus* Brower and Veinus, n. sp., holotype OU 9001, Pooleville Member, Zone 3, 9 to 10 m below Viola Limestone, Culley Creek; radials black, broken portions with vertical rule, sR = C-ray superradial. Note low dorsal cup with straight sides and presence of 7 primibrachs. A, B-ray view; B, DE-interray view; X6.

Family DENDROCRINIDAE Bather, 1890

Genus DENDROCRINUS Hall, 1852

Type species.—*Dendrocrinus longidactylus* Hall, 1852.

Diagnosis.—A genus of Dendrocrinidae with radianal located in primitive position below C-ray radial; anal X in dorsal cup between C- and D-ray radials; radial facets typically narrow; column round or pentagonal, not divided into pentameres.

DENDROCRINUS VILLOSUS Brower and Veinus, n. sp.

Plate 9, figure 3; Figure 42A

Diagnosis.—A species of *Dendrocrinus* with rugose or wrinkled ridges on the dorsal cup plates; proximal portion of stem pentalobate, becoming pentagonal distally.

Description.—Dorsal cup large, conical, with straight walls, height:width about 0.6; dorsal cup plates covered by strong rugose markings, plate sutures depressed.

Infrabasals pentagonal, smallest plates in cup, height:width 0.78; infrabasal circlet representing less than one-third cup height. Lateral interray basals hexagonal, CD-interray basal with 7 sides, height:width 0.94; basals largest circlet of plates in dorsal cup; basal circlet forming about 50 percent of cup height. Radials basically pentagonal, height:width equaling 0.79; radial circlet occupying roughly one-third of cup height. Radial facets narrow, facet width:width of radial

PLATE 9.

Fig. 1, 4, 5. *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, southern Oklahoma; 1, 4 from Daube Ranch; 5 from Lick Creek. 1. Lateral view of crushed paratype 1121TX64; note round stem and somewhat nodose cup plates; X2.5. 4. A-ray view of paratype dorsal cup 1404TX3 (Watkins Coll.) with nearly smooth cup plates; X4. 5. Lateral view of paratype dorsal cup OU 9006 with low nodes on some plates; note round columnals with crenulate sutures; X4.

Fig. 2, 6. *Merocrinus impressus* Brower and Veinus, n. sp.; 9-10 m below the Viola Limestone, Pooleville Member, Bromide Formation, Culley Creek; views of B-ray and DE-interray sides of holotype OU 9001; note low and wide dorsal cup composed of smooth plates with impressed sutures; X5.

Fig. 3. *Dendrocrinus villosus* Brower and Veinus, n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Daube Ranch; CD-interray view of holotype cup 1221TX19 with partial stem; note rugose marking on cup plates and pentalobate stem that lacks pentameres; X2.

Fig. 7, 8. *D? bibrachialis* Brower and Veinus, n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Daube Ranch; views of CD and AE interrays of holotype 1221TX9; note pentalobate stem lacking pentameres, stellate ridges on dorsal cup plates, presence of 2 primibrachs in all rays except the D ray, and numerous branches in proximal arms; X3.

0.48; facets horseshoe-shaped with concave surface and faint marginal rim, facets sloping outward slightly; ambulacral groove wide and deep, with rounded base. Radianal pentagonal, found in primitive position below C-ray radial. Anal X located above truncated CD-interray basal, height:width 1.04 (Fig. 42A). Articular surfaces partially preserved on some plates, either smooth or slightly concave with very small crenulate rims on outer margin.

Proximal portion of column preserved, pentalobate but not divided into pentameres, proximal part of column tapering slightly. Columnals faintly nodose with crenulate sutures; proximal part of stem with only 1 order of columnals; in central part of stem, 2 orders of columnals present, one order thicker than the other; distalmost known part of stem probably with 3 orders of columnals; structure of stem suggesting that most columnals originated by intercalation. Axial canal large, pentalobate, points in line with rays.

Discussion.—*Dendrocrinus villosus* is based on one specimen (embedded in matrix), which consists of the posterior part of the dorsal cup with an attached stem section. Numerous arm fragments are located immediately above the dorsal cup, most of which probably belong to a disarticulated carabocrinid lying to the right of the dendrocrinid. A small arm segment situated 32 mm above the dendrocrinid cup and composed of a multibranched series of angular-backed uniserial and cuneiform brachials that bear pinnules is not believed to be part of the dendrocrinid; they are probably the distal arm tips of a crinoid buried at a slightly lower level than the dendrocrinid.

Although known only from the dorsal cup and part of the stem, *D. villosus* can easily be separated from all other known species of *Dendrocrinus* by the nature of the ornamentation. No other dendrocrinid exhibits dorsal cup plates covered by irregular rugose or wrinkled ridges. In addition, the pentalobate and pentagonal column differs from that of most dendrocrinids, which possess round columns. Species of *Dendrocrinus* with dominantly round stems include: from the Silurian, *D. longidactylus* Hall (1852, p. 193, pl. 42, fig. 7a, b; pl. 43, fig. 1a-k), *D. celsus* Ringueberg (1888, p. 132, pl. 7, fig. 3); from the Upper Ordovician, *D.? constrictus* Brower (1973, p. 459, pl. 79, fig. 1), *D.? oswegoensis* Meek and Worthen (1868, p. 333, pl. 4, fig. 4, unnumbered fig. on p. 333); from the Middle Ordovician, *D. acutidactylus* E. Billings (see 1859, p. 37, pl. 3, fig. 2a, b), *D. alternatus* (Hall) (1847, p. 83, pl. 28, fig. 1a-f), *D. gregarius* E. Billings (see 1859, p. 36, pl. 3, fig. 1a-c), *D. dyeri* Meek (see 1873, p. 24, pl. 3bis, fig. 3a, b). Dendrocrinids other than *D. villosus* are also characterized by pentalobate and/or pentagonal stems. They include: from the Upper Ordovician, *D. caduceus* (Hall) (see 1872, p. 208, pl. 5, fig. 7, 8), *D. casei* Meek (1873, p. 28, pl. 3bis, fig. 2a-c; Brower, 1973, p. 455, pl. 77, fig. 1, 2, 4), *D.? navigiolum* S. A. Miller (1880, p. 253, pl. 7, fig. 6, 6a; see Brower, 1973, p. 457, pl. 78, fig. 1), *D. granditubus* Ramsbottom (1961, p. 15, pl. 4, fig. 1-7), *D. rugocyathus* Ramsbottom (1961, p. 16, pl. 3, fig. 1-5), *D. curvijunctus* Brower (1973, p. 456, pl. 77, fig. 3); from the Middle Ordovician, *D. proboscidiatus* E. Billings (see 1859, p. 38, pl. 3, fig. 3a-c), *D. rusticus* (E. Billings) (see 1859, p. 41, pl. 3, fig. 7a, b).

Specific name.—*Villosus* in allusion to the rough appearance of the doral cup plates, which is caused by the rugose ridges.

Holotype.—1221TX19.

Occurrence.—Lower Echinoderm Zone, Mountain Lake Member of Bromide Formation; shale dump beside dig at Daube Ranch, Arbuckle Mountains, southern Oklahoma.

DENDROCRINUS? BIBRACHIALIS
Brower and Veinus, n. sp.

Plate 9, figures 7, 8; Figures 42B, C

Diagnosis.—A species questionably assigned to *Dendrocrinus;* dorsal cup wide; cup plate ornament of stellate ridges; 2 or rarely 3 primibrachs present; number of secundibrachs, tertibrachs, and quartibrachs 2; all arms apparently branching isotomously; proximal column pentalobate.

Description.—Dorsal cup conical with straight and rapidly expanding sides, height:width 0.64. Dorsal cup plates swollen, bearing heavy stellate ridges, ridges single or multiple. Some brachials with rugose markings roughly paralleling axis of arms, brachials slightly nodose.

Infrabasals 5, pentagonal, height:width 0.66, smallest plates in dorsal cup; infrabasal circlet occupying about 17 percent of cup height. Basals 5; lateral interray basals hexagonal, height:width ranging from 0.91 to 1.04; CD interray basal with 7 sides, distally truncated for anal X; basal circlet height 38 percent of cup height. Radials 5,

basically pentagonal, height:width roughly 0.77, largest plates in dorsal cup; radial circlet height 44 percent of cup height. Radial facets horseshoe-shaped with smooth articular surfaces and narrow rim on outer margins, facets sloping outward, facet width:width of radial 0.75. Radianal pentagonal, in primitive position below C-ray radial, height:width 0.83. Anal X large, not completely preserved, located above truncated CD-interray basal (Fig. 42C).

Only proximal portion of arms known; arms branching several times close to calyx; primibrachs branching isotomously, higher branches probably isotomous. Two primibrachs present in all rays except for D ray, D ray with 3 plates. All known branched series of secundibrachs, tertibrachs, and quartibrachs with 2 plates. Nonaxillary brachials rectangular, height to width ratio for primibrachs 0.5, secundibrachs 0.52, tertibrachs 0.44, quartibrachs 0.42. Axillary brachials pentagonal, height to width ratio for primibrachs 0.7, secundibrachs 0.55, tertibrachs 0.8, quartibrachs 0.76. Food grooves small with rounded base; for nonaxillary brachials food groove depth:brachial depth 0.41, brachial depth roughly equal to brachial width. Articular surfaces slightly concave with small raised rim on dorsal and lateral margins.

Only proximal part of column preserved, pentalobate with lobes in radial position.

Discussion.—Only one specimen, a dorsal cup with a short stem segment and the proximal parts of the arms, can be placed in this species. The posterior area of the cup is partly covered by a large, twiglike bryozoan, but enough plate sutures can be seen to suggest the outlines of an anal X and a radianal underlying the C-ray radial. The arm-branching structure constitutes the unique feature of this species. Two primibrachs are observed in each of the rays except the D ray, which bears three plates. The number of secundibrachs, tertibrachs, and quartibrachs is two in all brachial series in which these plates can be counted. Each primibrachial branch is isotomous as far as can be ascertained. The higher branches are probably also isotomous. All previously described species of *Dendrocrinus* have averaged more than two primibrachs, typically with more than four plates being present. *D.? bibrachialis* is the single form that exhibits only two plates in the secundibrachial, tertibrachial, and quartibrachial series. Generally more than six plates occur in these brachial series in other dendrocrinids.

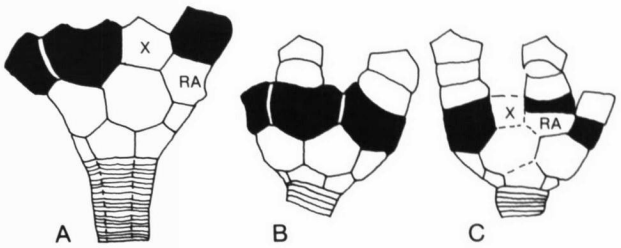


Fig. 42. New species of dendrocrinids from the Lower Echinoderm Zone of the Mountain Lake Member, Daube Ranch; radials black, RA = radianal plate, X = anal X plate. A, *Dendrocrinus villosus* Brower and Veinus, n. sp., note conical cup and pentalobate stem; holotype 1221TX19; CD-interray view, X1. B, C, *Dendrocrinus? bibrachialis* Brower and Veinus, n. sp., note wide dorsal cup, presence of 2 primibrachs in all rays except D, which has 3 plates, and pentalobate stem; holotype 1221TX9; AE-interray amd CD-interray views; X1.5.

Because of the unusual nature of the arms, the Bromide form is assigned to *Dendrocrinus* with reservation.

The stellate-ridge ornamentation and the pentalobate column are partly diagnostic of *D.? bibrachialis*. These characters are shared only by three other forms, namely *D. casei* Meek (see 1873, p. 28, pl. 3bis, fig. 2a-c; Brower, 1973, p. 455, pl. 77, fig. 1, 2, 4), *D. granditubus* Ramsbottom (1961, p. 15, pl. 4, fig. 1-7), and *D. rugocyathus* Ramsbottom (1961, p. 16, pl. 3, fig. 1-5), all Upper Ordovician. The stellate ridges of the Bromide taxon are finer than those of *D. casei* and *D. rugocyathus*, but the ridges of the new species and *D. granditubus* are similar. However, the brachials of *D. granditubus* possess sharp backs with angular margins but those of *D.? bibrachialis* show round backs with normal margins. All other species of *Dendrocrinus* are characterized by smooth or slightly swollen dorsal cup plates that lack sharp stellate ridges.

D.? bibrachialis is easily separated from *D. villosus* by the presence of stellate ridges rather than rugose or wrinkled ridges on the dorsal cup plates.

Specific name.—*Bibrachialis* in allusion to the almost invariable presence of two plates in each brachial series in the proximal parts of the arms.

Holotype.—1221TX9.

Occurrence.—Lower Echinoderm Zone, Mountain Lake Member of Bromide Formation; Daube Ranch, Arbuckle Mountains, southern Oklahoma.

Genus QUINQUECAUDEX Brower and Veinus, new

Type species.—*Quinquecaudex glabellus* Brower and Veinus, n. sp.

Diagnosis.—A genus of Dendrocrinidae with stem divided into pentameres, column pentagonal or pentalobate; dorsal cup plates smooth or nearly so; radianal below C-ray radial; anal sac plates plicate; arms branching isotomously, brachials with round dorsal sides.

Description.—Dorsal cup conical, composed of smooth or nearly smooth plates. Infrabasals, basals, and radials with 5 plates each. Radianal in primitive position below C-ray radial. Anal X in cup, resting on top of truncated CD-interray basal. Radial facets horseshoe-shaped, smooth; width of radial facet less than width of entire radial.

Anal sac erect, high and narrow, with a relatively small number of regular plates; all plates in an anal sac circlet of equal size; anal sac plates typically hexagonal, proximal plates smooth, becoming plicate distally, height to width ratios of anal sac plates decreasing distally; anal sac with 6 to 8 plates in each circlet.

Arms uniserial, nonpinnulate; arms branching isotomously several times; arm branches moderately wide spaced; 4 or more primibrachs present. Articular surfaces of brachials essentially smooth, articulations of ligamental type.

Proximal part of column either pentagonal or pentalobate; columnals divided into pentameres with sutures in radial position. Axial canal known only in type species, pentalobate with points oriented radially.

Occurrence.—Middle and Upper Ordovician, North America.

Derivation of name.—*Quinquecaudex*, in allusion to the pentagonal or pentalobate stem constructed of pentameres.

Discussion.—Several species are assigned to the new genus *Quinquecaudex*. These include the type species *Q. glabellus*, n. sp., from the Pooleville Member of the Bromide Formation; *Q. springeri* (Kolata) (1975, p. 31, pl. 5, fig. 8, 9; pl. 6, fig. 1-3, 5, 6) from the Trenton Limestone of Canada and Platteville Group of the Upper Mississippi Valley; and *Q. cincinnatiensis* (Meek) (1871, p. 312; see 1873, p. 20, pl. 3bis, fig. 5a, b) from the Maysville of Ohio; and the crinoid described as *Dendrocrinus* sp. A by Kolata from the Platteville Group of northern Illinois.

As mentioned by Brower (1973, p. 452) and Kolata (1975, p. 31), *Dendrocrinus* constitutes a heterogeneous genus which is in dire need of revision. *Quinquecaudex* is most closely allied to *Dendrocrinus* (Hall, 1852, p. 193), and the two taxa share many common features of the cup and arms, including: 1) similar conical dorsal cups with the radianal in the primitive position under the C-ray radial; 2) anal X in the dorsal cup, resting on the truncated CD-interray basal; 3) anal sac elongate, consisting of a small number of regular plates; 4) width of radial facets less than width of radials; 5) numerous primibrachs present, generally with four or more plates; and 6) arms typically branching isotomously, rarely heterotomously, at widely spaced intervals. The nature of the stem provides the only complete contrast between the two genera. The *Dendrocrinus* column can be round, pentagonal, or pentalobate, but it is composed of solid columnals that lack pentameres. The proximal part of the stem of *Quinquecaudex* is divided into pentameres and has a pentagonal or pentalobate outline. Several comments about the stem of dendrocrinids are necessary. Some species of *Dendrocrinus* possess pentagonal axial canals in conjunction with pentagonal or round stems. Examples are *D. caduceus* (Hall) (1866, p. 4; see 1872, p. 208, pl. 5, fig. 7, 8; Meek, 1873, p. 26, 27, pl. 3bis, fig. 1a-d), *D. dyeri* (Meek) (see 1873, p. 24; pl. 3bis, fig. 3a, b), and *D. posticus* (Hall) (1872, p. 209, pl. 5, fig. 5, 6; see Meek, 1873, p. 22, pl. 3bis, fig. 4a-c) of the Upper Ordovician and *D. acutidactylus* E. Billings (see 1859, p. 37, pl. 3, fig. 2a, b) of the Middle Ordovician. When crushed, the stem commonly breaks along the angles of the axial canal so that part or all of the column appears to have pentameres. Also, weathered stems may seem to exhibit pentameres if the weathering is deep enough to expose the angles of the axial canal. Such "pseudo-pentameres" are not visible in fresh or uncrushed columns. This feature is especially pronounced in *D. caduceus*. These "pseudo-pentameres" are not considered as true pentameres although they probably indicate that the ancestor of *Dendrocrinus* was characterized by a stem with pentameres. At least one species of *Dendrocrinus* is somewhat transitional between the two genera. In the Silurian crinoid *D. celsus* Ringueberg (1888, p. 132, pl. 7, fig. 3), the proximal stem is round and lacks pentameres; however, pentameres are developed in the middle and distal regions of the stem. It is possible that *D. celsus* evolved from a member of *Quinquecaudex* by partial fusion of the pentameres and proliferation of ra-

dicular cirri (C. E. Brett, pers. commun.).

Three other genera of Ordovician dicyclic inadunates also possess stems consisting of pentameres. *Grenprisia* (Moore, 1962b, p. 38) is the most similar, and shows the same type of dorsal cup as *Quinquecaudex*. *Grenprisia* is characterized by a balloon-shaped anal sac made up of many irregular plates, but that of *Quinquecaudex* is erect and composed of a small number of regular plates. Above the primibrachs, the arms of *Grenprisia* branch heterotomously, but those of the new genus are isotomous. The axial canal of *Grenprisia* is large and pentagonal with the points oriented interradially, an unusual characteristic. This feature is probably related to the development of a large axial canal occupying most of the column, a character shared by *Aethocrinus moorei* Ubaghs (see later discussion). In *Quinquecaudex* the axial canal is also pentagonal or pentalobate but with points facing the radials, at least in the type species *Q. glabellus*, n. sp; this is the typical orientation found in most crinoids.

As in *Quinquecaudex*, a pentameric column with a pentagonal axial canal having radially oriented points is found in *Ottawacrinus* (W. R. Billings, 1887, p. 49; amended by Moore, 1962b, p. 35, 36). However, *Ottawacrinus* has straight radial facets that occupy the entire width of the radials, in contrast to the narrow, horseshoe-shaped radial facets seen in *Quinquecaudex*. *Ottawacrinus* either bears compound radials in which both the inferand superradials are fixed into the cup as interpreted by Moore (1962b, p. 35, 36) or the primibrachs 1 are incorporated into the cup. Regardless of which possibility is correct, the arms of *Quinquecaudex* are free above the first plate in the radial circlet.

The peculiar *Aethocrinus moorei* Ubaghs (1969; see discussion of plate structure in Philip and Strimple, 1971; Ubaghs, 1972) has the distinction of being the oldest known dicyclic inadunate crinoid; for the present discussion, we accept the plate designations of Philip and Strimple (1971). Both *Aethocrinus* and *Quinquecaudex* are characterized by columns made up of pentameres, nonpinnulate arms that branch isotomously several times, and a posterior interray with a radianal under the C-ray radial and an anal X resting above a truncated CD-interray basal. *Aethocrinus* differs from *Quinquecaudex* in the presence of strong stellate ridges and in having several interradials in the radial circlet as well as some fixed proximal primibrachs. The cup plates of the new genus are smooth; aside from the anal X, large interradial elements are lacking and the arms are free above the radials.

The dorsal cup plate and arm-branching formulae of the Ordovician *Cupulocrinus* (d'Orbigny) (see Springer, 1911, p. 28-37; Brower, 1973, p. 453, 454) and the new genus are essentially the same. The radial facets of most cupulocrinids are wider than those of *Quinquecaudex;* in addition, many cupulocrinids have flexible crinoid-type articulations in the arms, which are absent in the new genus. The anal sacs of the two genera are quite distinctive. That of *Quinquecaudex* consists of a small number of equal-sized plates. In *Cupulocrinus*, the large median row of anal sac plates is flanked by many small and irregular plates. The poorly known Ordovician form *Esthonocrinus* (Jaekel, 1918, p. 52) also possesses a cupulocrinid-like anal sac, which separates it from *Quinquecaudex;* the arms and stem of esthonocrinids are not known.

It is easy to differentiate the Devonian dendrocrinid *Bactrocrinites* (Schnur) (see Schmidt, 1934, p. 56) from the new genus by its small quadrangular radianal and its round stem of solid columnals.

Quinquecaudex is most similar and closely related to the contemporary *Dendrocrinus*, and both genera were probably derived from the same ancestral stock. The presence of pentameres is clearly a more primitive character than solid columnals; pentameric columnals are largely found in primitive and archaic lineages of crinoids and other stalked echinoderms (e.g., Moore and Jeffords, 1968; Moore and Laudon, 1943). Accordingly, *Quinquecaudex* is judged to be closer to the ancestry of the two genera. As mentioned earlier, *D. celsus* is transitional between *Dendrocrinus* and *Quinquecaudex*, and it is regarded as a primitive *Dendrocrinus*.

The pentameric column together with the same basic construction of the dorsal cup suggests phyletic linkages between the Ordovician taxa *Aethocrinus*, *Ottawacrinus*, *Quinquecaudex*, and *Grenprisia*. Certainly the morphology of *Quinquecaudex* is consistent with a single ancestral stock for these widely different genera. *Cupulocrinus* and *Esthonocrinus* were probably descended from the same ancestral stock.

QUINQUECAUDEX GLABELLUS Brower and Veinus, n. sp.

Plate 10; Figure 43

Diagnosis.—A species of *Quinquecaudex* characterized by steeply conical dorsal cup with expanding sides. Sutures between dorsal cup plates not strongly depressed; proximal column pentalobate but not markedly so; margins of stem rounded, not angular.

Description.—Crown high and narrow with arms in closed position; crown height about equal to preserved stem length. Dorsal cup conical with smooth plates in most specimens (1 specimen has fine, multiple, longitudinal ridges on the basals and infrabasals); shape of cup widely variable; height to width ratio varying from 0.77 to 1.39 with mean and coefficient of variation equal to 0.98 and 24.4 percent, respectively.

Infrabasals 5, pentagonal, height:width from 0.89 to 1.06; infrabasal circlet height less than 33 percent of cup height. Basals 5, hexagonal; height:width from 1.2 to 1.53, largest plates in dorsal cup; basal circlet height over 33 percent of cup height. Radials 5, basically pentagonal, height:width from 0.83 to 1.0; radial circlet height about 33 percent of cup height. Radial facets wide for dendrocrinids; radial facet width: width of radial plate from about 0.6 to almost 1.0; radial facets horseshoe-shaped, smooth, inclined slightly outward. Radianal pentagonal, located in primitive position below C-ray radial and to right of anal X, height:width from 0.92 to 1.02. Anal X large, resting on truncated CD-interray basal; height:width from 0.98 to 1.18. Radianal supporting C-ray radial, C-ray radial slightly smaller than other radial plates.

Several ranges of interbrachials present between primibrachs 1 of lateral interrays; proximal range consisting of 1 large polygonal plate; 2 or 3 smaller, less regular plates in second range; third range, if present, with about 4 small, irregular plates.

Anal X "axillary," giving rise to 2 large plates, plates merging into anal sac; proximal anal sac plates smooth, large, almost equidimensional; height to width ratios decreasing distally, plates becoming plicate in fourth or fifth range; proximal part of anal sac with 5 or perhaps 6 plates in each circlet. Distal part of anal sac known only from isolated fragments, with 8 plates in each circlet; individual plates hexagonal, average height:width 0.52; each plate with a strong median-ray ridge with finer stellate ridges on sides; anal sac plates relatively thick at stellate and median ridges but much thinner between ridges; at least some plates with pores on lateral margins in depressed areas between stellate ridges. (These pores could represent primary structures or they could be caused by weathering.)

Arms uniserial, nonpinnulate, slender, with round dorsal margins, branching isotomously at 4 or 5 levels, composed of smooth brachials. Number of brachials variable: 3 to 5 primibrachs present with mean and coefficient of variation equal to 4.3 and 15 percent, respectively. Secundibrachs ranging from 5 to 7 plates, averaging 6, coefficient of variation 11 percent. (The number of tertibrachs, quartibrachs, and quintibrachs is 8 or 9 in the few known examples.) Primibrach 1 tapering distally; height:width from 0.63 to 0.74. Higher nonaxillary brachials quadrangular; height: width of primibrachs 0.5 to 0.78, secundibrachs 0.53 to 0.92, higher brachials about 1.4. Axillary brachials pentagonal, height:width of primibrachs from 0.63 to 0.78. Brachials deep; width: depth roughly 0.8; food grooves deep, V-shaped, food groove depth:brachial depth from 0.4 to 0.7. Ventral side of each brachial bearing 4 rows of interlocking plates (Pl. 10, fig. 2; Fig. 43J); outer 2 rows covering plates, innermost 2 rows lappets; each brachial with 3.5 to 4.5 covering plates and lappets in each row; one plate row typically shared by two adjacent brachials. Articular surfaces essentially smooth, slightly concave with faint marginal rim.

Column pentalobate, divided into pentameres, tapering slightly. (The column length is about the same as that of the crown in the only known nearly complete specimen, paratype OU 9019; see Fig. 43G, H.) Adjacent pentameres commonly alternate, at least to some extent. Columns heteromorphic (isomorphic in 1 specimen), consisting of 2 orders of columnals; proximal pentameres with up-turned areas for articulation with infrabasals, more distal pentameres flat; thickness of individual pentameres increasing distally. Some specimens with a single or double row of pores located at junctions between adjacent pentameres (Pl. 10, fig. 4, 11); pores of some columns filled with a brown substance presumably representing original organic material, brown substance may include some pyrite; pores of other columns apparently covered with small plates (Pl 10, fig. 4); some specimens appear to lack pores (Pl. 10, fig. 3). Articular surfaces of columnals not completely known; axial canal pentalobate with points oriented radially;

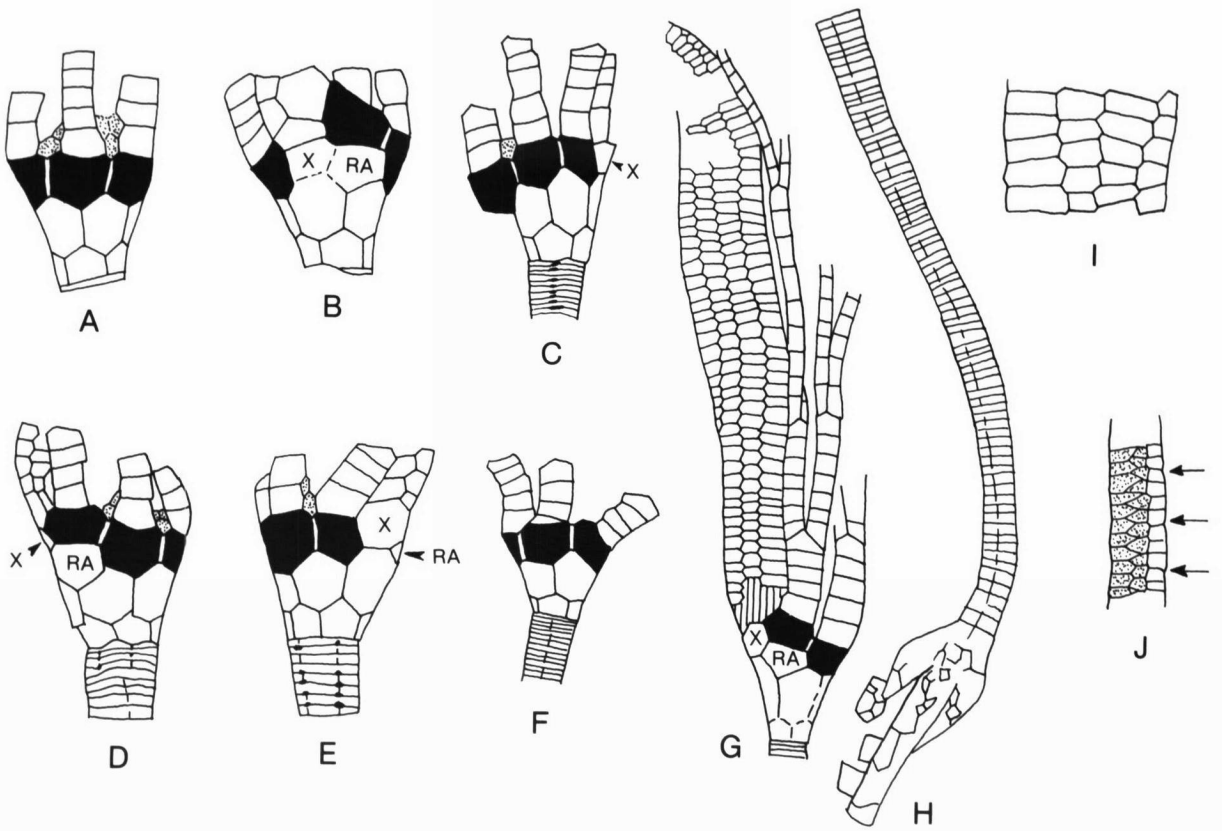


Fig. 43. *Quinquecaudex glabellus* Brower and Veinus, n. gen., n. sp.; note conical dorsal cup with radianal (RA) under C-ray radial and stem divided into pentameres; radial black, X = anal X plate; Pooleville Member, Zones 3 and 5. A, B, Paratype OU 9011, A ray and CD interray, Rudd Quarry, X3.8. C, Paratype OU 9010, E-ray view, Rudd Quarry, X3.2. D, E, Paratype 1123TX7, views of C and D rays, Rudd Quarry, X3.2. F, Holotype OU 9009, lateral view, Culley Creek, X2.5. G, H, Paratype OU 9019, CD interray view of nearly complete crown and column; broken parts with vertical rule. The structure of the anal sac is somewhat conjectual; parts of the rooting device appear to show irregular plate structure which is drawn as accurately as possible; Culley Creek, X3.8. I, Paratype OU 9015, view of portion of anal sac, Rudd Quarry, X6.3. J, Paratype OU 9013, ventral view of arm fragment, lappets strippled, arrows at sutures between brachials, Rudd Quarry, X6.3.

in side view, articular surface margins of some columnals crenulate, of others, smooth. Attachment device poorly known, apparently a lumplike area lacking pentameres, lumplike area giving rise to several unbranched and irregularly plated appendages (probably representing cirri that were rooted into the substrate); although poorly preserved, cirri apparently in line with pentameres of stem (Fig. 43H).

Discussion.—*Quinquecaudex glabellus* is represented by one well-preserved partial crown (holotype) and numerous paratypes: a poorly preserved complete individual in matrix, about six dorsal cups, a large part of an anal sac, several stem segments, and an arm fragment. Despite the fact that the crinoids were obtained from several localities, almost all cups are about the same size, roughly 4.0 to 5.0 mm high. Perhaps most of the crinoids were about the same age at the time of their death and burial. Although all specimens exhibit conical cups, the shape of the cup varies and the height to width ratio ranges from about 0.8 to 1.4. The arm segment shows roughly eight covering plates and lappets on each brachial. Assuming that the arms of *Q. glabellus* had the same arrangement of tube feet as does the recent *Antedon* (Nichols, 1960), each brachial of the Bromide form would have had about 24 tube feet available for food catching. The poorly preserved complete specimen is about 50 mm high; the crown occupies about half of the height (Fig. 43G, H). The attachment device is obscure, but it seems to involve cirri radiating from a central lumplike area.

Quinquecaudex glabellus is easily separated from the Trenton form *Q. springeri* (Kolata) (1975,

p. 31, pl. 5, fig. 8, 9; pl. 6, fig. 1-3, 5, 6) by its much smaller size and differences in the cup shapes. The cup of the new species is steeply concial, but that of *Q. springeri* is wider relative to its height with steeper sides. Also the margins of the proximal part of the stem in *Q. springeri* are sharp and angular whereas those of *Q. glabellus* are rounded. Although the proximal stem of *Q. springeri* is pentagonal, distally it becomes round and the sutures between adjacent pentameres are fused together in the vicinity of the massive cirrus root. *Quinquecaudex* sp. A (Kolata) (1975, p. 32, pl. 5, fig. 4) is characterized by much lower infrabasals and a more widely expanding cup than *Q. glabellus*.

The Upper Ordovician *Q. cincinnatiensis* (Meek) (see 1873, p. 20, pl. 3bis, fig. 5a, b) is closely related to the Bromide species. However, the cup of *Q. cincinnatiensis* is wider relative to its height, the cup plate sutures are more strongly impressed, and the pentalobate outline of the stem is more pronounced than in *Q. glabellus*.

In contrast to *Q. glabellus*, *Dendrocrinus caduceus* (Hall) (1866, p. 3; see Hall, 1872, p. 208, pl. 5, fig. 7, 8; Meek, 1873, p. 26, pl. 3bis, fig. 1a-d) exhibits median-ray ridges on the dorsal cup plates, a relatively narrow stem facet, and a stem which is only slightly pentagonal.

Specific name.—*Glabellus* in allusion to the smooth plates and outline of the dorsal cup as well as the smooth brachials of the arms.

Type specimens.—Holotype OU 9009; paratypes OU 9010-9019 and 1123TX7-8.

Occurrence.—Pooleville Member of Bromide Formation; Zone 5 (11 to 14 m below the Viola Limestone) and Zone 3 (9 to 10 m below the Viola Limestone) at Culley Creek; also 2 and 2.5 m below the Viola Limestone at Rudd Quarry, Criner Hills, southern Oklahoma.

Family BOTRYOCRINIDAE Bather, 1899

Genus EOPINNACRINUS Brower and Veinus, new

Type species.—*Eopinnacrinus pinnulatus* Brower and Veinus, n. sp.

Diagnosis.—A genus of dicyclic inadunates with primitive type radianal underneath the C-ray radial; anal X in cup, located on truncated CD interray basal; radial facet width less than width of entire plate. Primibrach 1 axillary in all rays. Two heavy, uniserial, pinnulate arms present in each ray; pinnule facets lacking transverse ridge. Column round, made up of solid columnals.

Description.—Crown stout with 10 heavy arms. Dorsal cup widely conical with 5 low infrabasals; radial facet width less than total width of plates, radial facet horseshoe-shaped, lacking transverse ridge; radianal large, pentagonal, lying in primitive position under C-ray radial; anal X large, resting on truncated CD-interray basal. Tegmen poorly known, apparently consisting of small irregular plates; only proximal part of anal sac or tube preserved, composed of large regular plates.

Primibrach 1 large, pentagonal, always axillary. Arms 2 in each ray, heavy, consisting of uniserial pinnulate brachials. Brachials uniserial and slightly wedge-shaped. Articular surfaces of brachials with ligamental articulations; pinnule facets lacking transverse ridges.

Only proximal part of column known, composed of round columnals lacking pentameres; column tapering distally; at least 2 orders of columnals present; shape of axial canal not seen.

Occurrence.—Middle Ordovician, Blackriveran; Bromide Formation, Oklahoma.

Derivation of name.—*Eopinnacrinus* was selected as follows: *pinna* refers to the presence of pin-

PLATE 10.

Fig. 1-11. *Quinquecaudex glabellus* Brower and Veinus, n. gen., n. sp.; Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 1-10 from Rudd Quarry, 11 from Culley Creek. Note smooth cup plates, radianal in primitive position below C-ray radial, high anal sac with plicate plates, pentagonal stem divided into pentameres, and isotomous arms with round dorsal margins. 1, 10. Views of D ray and BC interray of slender paratype 1123TX7; note proximal part of anal sac, which is composed of smooth plates that become plicate distally; X5, X6. 2. View of paratype arm fragment OU 9013 showing covering plates and lappets; X5. 3. Paratype stem segment OU 9018 with poorly developed sutures between pentameres; X6. 4. Paratype stem segment OU 9017 with pentameres, pores, and attached infrabasals; X5.5. 5. Distal portion of paratype anal sac OU 9015 with stellate ridges on the plates; some of the plates in the upper left part of the anal sac may have marginal pores; X5.5. 6. AB-interray view of crushed paratype cup OU 9012 with crenulate sutures in the stem; X6. 7, 8. Views of CD interray and A ray of paratype OU 9011 with relatively wide cup; note location of radianal and smooth plates in proximal part of anal sac; X6. 9. DE-interray view of slender paratype OU 9010; X6. 11. Lateral view of partial holotype crown OU 9009; note isotomous arms and long stem segment with pentameres; X4.

1 2 3 4 5 6

7 8 9 10 11

nules; *eo* points out the early stratigraphic occurrence of this crinoid with its evolutionarily advanced arms; and *crinus* indicates the echinoderm class to which the genus is assigned.

Discussion.—This genus is founded on a single species from the Mountain Lake Member of the Bromide Formation. The family assignment is somewhat uncertain because *Eopinnacrinus* shows a mixture of primitive and advanced characters. Primitive features include the moderately conical and high dorsal cup, the positions of the radianal under the C-ray radial and the anal X in the cup and resting on the truncated CD-interray basal, and the radial facets that are less wide than the radials. These features are found in various Ordovician Dendrocrinidae and Silurian Botryocrinidae. Advanced aspects of morphology are the presence of an axillary primibrach 1, which is very rare in other Lower Paleozoic dicyclic inadunates, and of two pinnulate and unbranched arms in each ray, a feature observed in several Silurian and Devonian botryocrinid genera. [We follow Moore (1952) in our definition of pinnules, which are unbranched ramules normally present on all nonaxillary brachials. The pinnule facets on the brachials may or may not have transverse ridges. The latter is the case in *Eopinnacrinus*.] The round stem is not divided into pentameres. Although the cup of the Bromide genus is similar to that of certain forms in both the Botryocrinidae and the Dendrocrinidae, the new genus is placed in the Botryocrinidae because the arm morphology is more allied to that of many botryocrinids (see later discussion). Unfortunately, such critical characters as the nature of the anal sac are unknown in *Eopinnacrinus*, and the family placement is with some reservations. The definition of the Botryocrinidae adopted here is broad and follows that of Moore and Laudon (1943, p. 43, 54). At present, botryocrinids are under study by G. C. McIntosh and C. E. Brett (pers. commun.) and these crinoids will probably eventually be assigned to several families of Cyathocrinina and Dendrocrinina.

Eopinnacrinus can be separated from all members of the Dendrocrinidae and Cupulocrinidae by the presence of pinnulate arms. The dorsal cup construction of *Eopinnacrinus* is essentially the same as in *Dendrocrinus* (Hall, 1852, p. 193), *Grenprisia* (Moore, 1962b, p. 38), and some species of *Cupulocrinus* (d'Orbigny) (see Springer, 1911, p. 38), but all of these crinoids possess nonpinnulate arms that branch either isotomously or heterotomously.

The Silurian genus *Gothocrinus* (Bather, 1893, p. 115) is the most closely related taxon. Other similar forms include *Cyliocrinus* (Jaekel, 1918, p. 60) and *Dictenocrinus* (Jaekel, 1918, p. 59) of the Silurian, the Devonian species of *Bathericrinus* (Jaekel, 1918, p. 58; see Schmidt, 1934, p. 92, listed as a subgenus of *Botryocrinus*), and the Devonian genus *Imitatocrinus* (Schmidt, 1934, p. 104). The radianals of both *Gothocrinus* and *Eopinnacrinus* lie in the primitive position below the C-ray radial. Unfortunately, the 10 unbranched arms (two in each ray) of *Gothocrinus* are poorly known, but either pinnules or closely spaced ramules are present. The primibrachs of *Gothocrinus* number four or five versus the invariable single plate of the Bromide genus. Quadrangular radianals are found in *Cyliocrinus*, *Dictenocrinus*, and *Bathericrinus*, but this plate is lacking in *Imitatocrinus*. All these contrast with the pentagonal radianal of *Eopinnacrinus*, which is located in the primitive position. Two pinnulate arms are seen in each ray of *Cyliocrinus*, *Imitatocrinus*, and the genotype of *Dictenocrinus*, *D. decadactylus* (Bather) (1891, p. 395, pl. 13, fig. 5-15); the arms of *D. decadactylus* and *Cyliocrinus* are stout as in *Eopinnacrinus*, but those of *Imitatocrinus* are long and slender. Two to four primibrachs can be counted in *Cyliocrinus*, *Imitatocrinus*, and *Dictenocrinus decadactylus*. The arms of *D. pinnulatus* (Bather) (1891, p. 402, pl. 13, fig. 16) are also pinnulate; but the arms branch isotomously several times. Except for *Cyliocrinus*, each uniserial brachial bears a single pinnule. However, *Cyliocrinus* shows compound brachials with two pinnules on each plate. The arm branching pattern of *Bathericrinus* is variable. *Bathericrinus spaciosus* Schmidt (1934, p. 96, text-fig. 20d, pl. 3, fig. 4) possesses two pinnulate arms per ray, as in *Eopinnacrinus*. About three primibrachs are known in *Bathericrinus spaciosus*. However, the other species of *Bathericrinus* generally exhibit ramules on alternate brachials (see Schmidt, 1934, p. 92-94 and cited figures). *Eopinnacrinus* can be separated from all other botryocrinid genera by the pinnulate arms and nature of the radianal.

The Bromide genus also resembles certain Devonian and Mississippian genera of Glossocrinidae with uniserial pinnulate arms, such as *Maragnicrinus* (Whitfield, 1905, p. 17; see Goldring, 1923, p. 384), *Glossocrinus* (Goldring, 1923, p. 389), *Catactocrinus* (Goldring, 1923, p. 405), and *Lophocrinus* (von Meyer, see Schmidt, 1930, p. 31). All of these glossocrinids possess either a quadrangular radianal or a pentagonal plate to the left of the C-ray radial; the radianal of *Eopinnacrinus* is

pentagonal but placed below the C-ray radial. Also most glossocrinids are characterized by wider radial facets than is the new genus. The arms of *Maragnicrinus* are most like those of *Eopinnacrinus;* two arms are found in each ray of both crinoids with three primibrachs in the former but only one in the latter genus. Only one arm is present in each ray of *Lophocrinus* and *Catactocrinus,* but the arms of *Glossocrinus* branch isotomously two times.

All members of the Devonian and Carboniferous family Poteriocrinitidae show uniserial pinnulate arms that branch several times above the primibrachs. Distinct transverse ridges occur on the radial facets of poteriocrinitids, but these are lacking in *Eopinnacrinus.* The radianal of most poteriocrinitids is pentagonal and inserted to the left of the C-ray radial. The primitive type of radianal, a large pentagonal plate underneath the C-ray radial, is characteristic of *Eopinnacrinus* and one Devonian species of *Propoteriocrinus,* namely *P. scopae* Schmidt (1934, p. 109, 110, pl. 5, fig. 3).

The origin of *Eopinnacrinus* is subject to some conjecture. The conical cup, primitive radianal and anal X, and narrow radial facets suggest that the new genus shares common ancestry with *Dendrocrinus* and *Grenprisia,* which is consistent with the Ordovician stratigraphic occurrence of these genera. *Eopinnacrinus* is probably not ancestral to any other crinoid, as demonstrated by the specialized nature of the arms; the single large axillary primibrach constitutes a character unique among dicyclic inadunate crinoids of the early Paleozoic. In addition, the two heavy pinnulate arms in each ray are far removed from those of most dicyclic inadunates. Essentially, *Eopinnacrinus* is considered as an element in an early dicyclic inadunate lineage with advanced and specialized arms, which died out without leaving any known descendants.

EOPINNACRINUS PINNULATUS Brower and Veinus, n. sp.
Plate 9, figures 1, 4, 5; Plate 11; Figure 44;
Table 27

Diagnosis.—As for genus, inasmuch as there is only one species known.

Description.—Crown stout with 10 heavy arms. Dorsal cup wide, conical, with narrow base and rapidly expanding sides, walls slightly rounded,

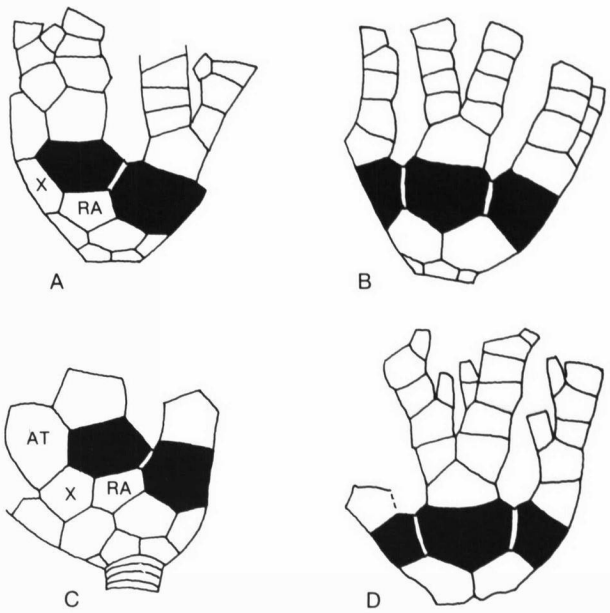


Fig. 44. *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp.; note primitive location of radianal (RA) under C-ray radial and presence of 1 large primibrach in each ray; Lower Echinoderm Zone of Mountain Lake Member, Daube Ranch; radials black, X = anal X plate. A, B, Holotype 1121TX66, C-ray and E-ray views, X1.8. C, Paratype 1121TX67, C-ray view of smallest specimen, AT = anal tube, X3.3. D, Paratype 1404TX2 (Watkins Coll.), lateral view of partial crown which lacks infrabasals, X2.

height:width 0.57. Dorsal cup plates with depressed sutures; plates may be slightly swollen or with raised rims along margins.

Infrabasals 5, smallest plates in dorsal cup, pentagonal, height:width from 0.55 to 0.58; infrabasal circlet low, occupying only 14 percent of cup height. Basals 5; lateral interray basals hexagonal, height:width 0.94 to 1.09; CD-interray basal with 7 sides, distal margin truncated for reception of anal X; basal circlet including 43 percent of cup height. Radials 5, basically pentagonal, largest plates in dorsal cup, height:width 0.76 to 0.78; radial circlet occupying 43 percent of cup height. Radial facets narrow; radial facet width:radial width from 0.62 to 0.73; radial facets horseshoe-shaped, concave, with faint marginal rim along outside of plate, facet directed upward; axial canal moderately wide and deep with rounded base. Radianal pentagonal, in primitive position below C-ray radial, height:width 0.72. Anal X large, pentagonal, reaching to mid-level of adjacent C- and D-ray radials. Anal X supporting large, hexagonal plate, plate forming base of anal tube, height:width 1.03. Proximal part of anal sac or tube visible in smallest spec-

Table 27. Data on the food-gathering system of *Eopinnacrinus pinnulatus*, n. gen., n. sp.

	Small specimen Paratype 1121TX67	Large specimen Holotype 1121TX66
Height of cup	7.7 mm	12.1 mm
Number of brachials in each arm	14	30
Length of arm	13.7 mm	35 mm
Length of average pinnule	4.2 mm	13 mm
Number of plates in average pinnule	5.38	13
Total length of entire food-gathering system	794 mm	4250 mm
Total number of plates in entire food-gathering system	990	4200

imen (1121TX67; Pl. 11, fig. 1; Fig. 44C); distal portion of anal tube not known; observed plates large and regular. Tegmen poorly preserved, apparently composed of small irregular plates. Articular surfaces known for several cup plates, either smooth, slightly concave, or deeply concave with a marginal rim on all sides.

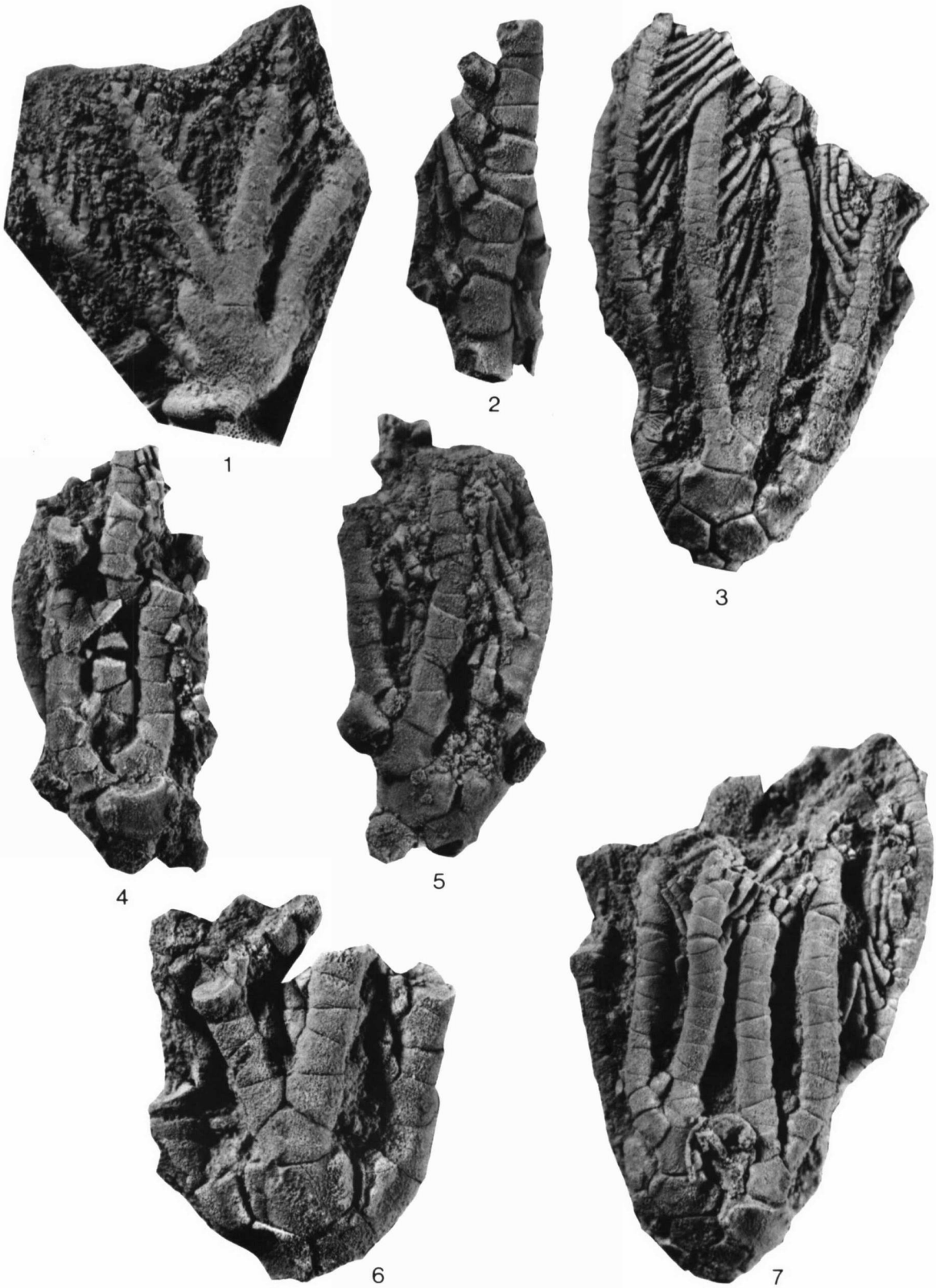
Arms 10, each ray bearing 2 arms, pinnulate, composed of uniserial brachials, brachials slightly wedge-shaped or cuneiform. (In all 24 known rays, primibrach 1 is axillary; the first and second pinnules are located on the interray side of secundibrach 1 and the intraray side of secundibrach 2; except for the terminal brachials at the distal tips of the arms, all brachials bear pinnules.) Primibrach 1 axillary, large, pentagonal, sides commonly slightly constricted, height:width 0.76 to 0.87. Secundibrachs uniserial, pinnulate, wedge-shaped or cuneiform with converging proximal and distal margins; average height:width 0.32 to 0.65 (maximum height:minimum height varies from 1.67 to 2.33); brachials slightly deeper than wide, depth to width ratio about 1.02; food groove small with rounded base, food groove depth:brachial depth 0.39; pinnule facets not strongly protuberant, directed upward at about a 45° angle. Articular surfaces of brachials poorly known, either smooth or concave, possibly with marginal rim on dorsal and lateral sides. Articular surfaces of pinnule facets not well preserved, concave, definitely lacking transverse ridge. Pinnules heavy, not completely known, at least 12 mm long in mature crinoid, composed of elongate plates. Pinnulars uniserial, elongate; length or height to width ratio ranging from 1.1 to 2.4; depth to width ratio from 0.90 to 1.15.

Only proximal part of column preserved, round, tapering distally. Column of 2 orders of columnals, one order slightly higher and more nodose, sutures slightly crenulate; articular sufaces and orientation of axial canal unknown.

Discussion.—This form is known from two complete or nearly complete crowns, about eight partial crowns, two dorsal cups and two arm fragments. The reasonably abundant material allows some insights about growth and variation. The dorsal cup plates are either smooth or have slightly upraised marginal rims and depressed sutures. Several specimens exhibit slightly nodose or swollen plates with sunken sutures. Scattered nodes occur on some of the plates. The arm branching formula is invariable. Primibrach 1 is axillary in all 24 rays where this can be determined. Each ray has two stout and unbranched pinnulate arms. Each brachial bears a single pinnule and the pinnules alternate from side to side of the arm. The proximal pinnule is located on the interray side of secundibrach 1. This arm branching pattern is unique for Ordovician dicyclic inadunates. Among other dicyclic inadunates, it does not become common until the Devonian and Mississippian, where it is found in such families as the

PLATE 11.

Fig. 1-7. *Eopinnacrinus pinnulatus* Brower and Veinus, n. gen., n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1, 3, 6, 7 from Daube Ranch; 2, 4, 5 from Lick Creek. Note location of radianal in primitive position under C-ray radial, narrow radial facets, axillary primibrach 1, and presence of 2 pinnulate arms in each ray. 1. C-ray view of smallest paratype 1121TX67; note short arms, presence of base of anal tube, smooth cup plates, and round stem; X3. 2. View of pinnulate paratype arm fragment OU 9004; the pinnule facets are partly visible and there is no trace of transverse ridges; X5. 3, 7. Views of E ray and CB interray of holotype 1121TX66; note location of radianal, long and heavy arms composed of many brachials, and cup plates with marginal rims and depressed sutures; X2. 4, 5. Lateral views of small paratype crown OU 9007 with smooth cup plates; the infrabasals are broken from the crown; X3. 6. Lateral view of paratype 1404TX2 (Watkins Coll.); note infrabasals not preserved, dorsal cup plates with marginal rims and depressed sutures, and clear view of proximal pinnules; X3.



Scytalocrinidae, Erisocrinidae, Cromyocrinidae, and Eupachycrinidae.

The anal tube and tegmen are partially preserved in two specimens. The smallest crinoid, paratype 1121TX67 (Pl. 11, fig. 1), exhibits the base of the anal tube. The small and irregular plates of the tegmen are preserved in a crushed paratype 1297TX318, which unfortunately lacks the anal tube.

Two complete crowns are available, which have dorsal cup heights of 7.7 and 12.1 mm (height is measured from the base of the cup to the distal margin of primibrach 1). Although the size range is not great, the two crinoids illustrate some aspects of ontogeny of the arms (see data in Table 27). During ontogeny new plates form at the distal tips of both the arms and pinnules. The length of the arms and pinnules is augmented by two processes: namely, the addition of new plates and the accretion of calcite on previously developed plates. Some of the data were analyzed statistically by fitting allometric equations, using the reduced major axis method, to the data on the two specimens (see Brower, 1974, for methods and similar studies on camerate crinoids). Although we interpret the equations with somewhat more than the proverbial grain of salt, the equations do generate some interesting data. The two pertinent equations are: (Total length of food-gathering system in mm) = 0.407 (Cup height in mm)$^{3.71}$, and (Total number of plates in food-gathering system) = 1.45 (Cup height in mm)$^{3.20}$.

The cup height and the length and number of plates in the food-gathering system are linear dimensions so that the expected exponents based on geometrical similarity for size of food-gathering system versus cup height should be 1.0. The observed exponents are 3.7 and 3.2, both much larger than 1.0. Evidently the length and number of plates in the food-gathering system increase more rapidly during ontogeny than one would predict based on the geometry of the parameters concerned. The growth pattern of the arms produces a multiplicative rate of growth of the food-gathering system. Similar results are obtained for camerate crinoids with pinnulate arms (Brower, 1974, p. 33-40). We assume that the volume of tissue which must be supplied with food is proportional to the cube of calyx height, an assumption which is probably reasonable for camerate and other crinoids (Brower, 1974, p. 33-40). If so, then the following relationships should be approximately correct for *E. pinnulatus:* (Length of food-gathering system) (Tissue volume)$^{1.24}$, and (Number of plates in food-gathering system) (Tissue volume)$^{1.07}$. It then follows that the food-gathering capacity of *E. pinnulatus* as measured by these relationships probably remains roughly constant or increases slightly during ontogeny.

Specific name.—*Pinnulatus* in allusion to the presence of pinnules.

Type specimens.—Holotype 1121TX66 (Graffham Coll.); paratypes 1121TX64-65, 67, 69 (Graffham Coll.), 1279TX318, OU 9002-9008, and 1404TX2-3 (Watkins Coll.).

Occurrence.—Lower Echinoderm Zone, Mountain Lake Member of Bromide Formation; Daube Ranch, Lick Creek, and Fittstown Quarry, Arbuckle Mountains, southern Oklahoma.

LARGE-CALYX CLADID INADUNATES

James Sprinkle

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Three genera of large-calyx cladid inadunate crinoids are known from the Bromide Formation of southern Oklahoma. These include *Palaeocrinus* (apparently three species) based on about 520 specimens and *Carabocrinus* (apparently two species) based on about 205 specimens, both from the Lower Echinoderm Zone through the Upper Echinoderm Zone of the Mountain Lake Member, and *Porocrinus* (one new species) based on 21 specimens from echinoderm zones in the upper Pooleville Member. These three crinoids have been assigned to different families in the superfamily Gasterocomacea by Lane and Moore (1978), an assignment which is followed here with some minor reservations. Although closely related, these three genera differ from each other in cup shape, size and number of radianals, nature of the arms, proximal stem morphology, and especially in their development of three different types of calyx respiratory structures. If these genera lacked respiratory structures or had all developed the same type, they would probably have been assigned to the same family because the remaining differences do not appear important enough to warrant placement in three separate families.

Calyx respiratory structures are not common in crinoids (Sprinkle, 1973, p. 34), but are not unexpected in these Ordovician large-calyx cladid inadunates. All of these genera have medium to large, conical to ovoid cups bearing short to medium-length arms (unbranched in *Porocrinus*) which lack pinnules. Thus, they probably had relatively fewer tube feet on the arms than most other crinoids and a low ratio of cup surface area to volume, so that the tube feet plus epidermis may not have been extensive enough to keep the coelomic tissue in the large cup oxygenated under some conditions. During deposition of the Bromide, Oklahoma was located in the Southern Hemisphere Tropics about 20 to 25° south of the equator (Ziegler and others, 1979, p. 485-486), and Paul (1976, p. 565-571) has argued that echinoderms living in the Ordovician Tropics may have needed specialized calyx respiratory structures because of low concentrations of oxygen in moderate-depth shelf environments.

The biggest unanswered question is why three different types of calyx respiratory structures were developed. All three consist of slits or folds crossing plate sutures, but these structures are exothecal in two genera (*Carabocrinus* and *Palaeocrinus*) and endothecal in the third, they are three-cornered in two genera (*Porocrinus* and *Carabocrinus*) and linear in the third, and they cover most of the cup in two genera (*Palaeocrinus* and *Porocrinus*) and are present only around the summit in the third. These differences indicate that the three types of respiratory structure did not have a common origin in an earlier structure, but apparently evolved independently. Perhaps the common ancestor of these three crinoids originated in an environment, such as the Ordovician temperate latitudes, where oxygen concentrations were higher and calyx respiratory structures unnecessary. Descendants of this "rhomb-less" common ancestor developed differences in their calyx, arm, and stem morphology, but continued to lack respiratory structures until they migrated into the tropics in the Early or Middle Ordovician. Then each lineage independently developed specialized calyx respiratory structures of a different nature, resulting in the occurrence pattern observed in the Bromide. Unfortunately, neither the hypothesized common ancestor nor any of the "rhomb-less" descendants are known at present; these three Bromide crinoid genera are among the earliest representatives of their respective families. Thus, the above evolutionary scenario must remain only a hypothesis until older representatives of these families are found in the fossil record.

Suborder CYATHOCRININA Bather, 1899

Superfamily GASTEROCOMACEA Roemer, 1854

Family CARABOCRINIDAE Bather, 1899

Genus CARABOCRINUS Billings, 1857

Type species.—*Carabocrinus radiatus* Billings, 1857.

Diagnosis.—Cup ovoid to cup-shaped, IBB elongate, iRA and sRA present, obliquely supporting medium-sized anal X; three-cornered, exothecal, covered "rhombs" present around summit on RR, OO, anal X, and plates surrounding periproct; arms medium length, showing bilateral heterotomous branching with up to 13 branches; stem ?short to relatively long, divided into pentameres, apparently attached to substrate by large discoidal holdfast.

Occurrence.—Middle to Late Ordovician, eastern, north-central, and south-central United States, eastern Canada, and western USSR (Estonia).

Discussion.—*Carabocrinus* is now the only genus assigned to the family Carabocrinidae. It differs from related genera in the families Sphaerocrinidae and Porocrinidae most notably by having a split radianal (iRA + sRA), distinctive exothecal respiratory "rhombs" around the summit, and heterotomously branched arms. Without the characteristic "rhombs," *Carabocrinus* probably would not warrant a family of its own. It seems to be represented by two species in the Bromide Formation: *C. treadwelli* (known from over 200 specimens) ranges through the middle and upper Mountain Lake Member, although commonest in the Lower Echinoderm Zone and *Carabocrinus* Beds; *Carabocrinus* sp. is known from a single partly complete specimen from the Upper Echinoderm Zone.

CARABOCRINUS TREADWELLI Sinclair, 1945

Plate 12, figures 1-18, 20-23; Plate 13, figures 1-5, 7, 8; Figure 45

Diagnosis.—Cup rounded conical to cup-shaped, slightly asymmetrical, calyx L:W averaging 1.02; 4 to 11 low radiating ridges per plate suture, spacing averaging 0.94 mm/ridge; respiratory "rhombs" large, 18 to 21 grooves per plate; arms 1½ to 2 times cup length, showing bilateral heterotomous branching; stem at least 3 times cup length, probably with type 1A holdfast distally.

Description.—Specimens ranging from small (cup 5.5 mm long) to large (cup 32 mm long). Cup rounded conical to cup-shaped in side view, rounded pentagonal in top and bottom views, slightly asymmetrical (C radial projecting laterally and vertically more than other RR); stem facet narrow, cup sides slightly rounded, summit wide and either flat or slightly domed. Maximum diameter above midheight at centers of BB or RR in different side views. Calyx L to W ratio ranging from 0.9 to 1.2 and averaging 1.02 for 20 measured specimens.

Infrabasals (IBB) 5, relatively small, visible in side view, in closed conical circlet around small stem facet at base of cup; IBB expansion angle 90 to 110°. Three IBB relatively small, elongate pentagonal, either symmetrical or leaning slightly to left; C infrabasal smaller, elongate pentagonal, leaning to right; D infrabasal slightly larger, hexagonal and wider because of 3 overlying plates, leaning to left (Fig. 45B). IBB making up nearly equal parts of small stem facet.

Basals (BB) 5, large (largest plates in cup), in an open circlet (interrupted by iRA and sRA) around center of cup. Four BB hexagonal, longer than wide; BC basal septagonal, longer than wide. Most BB moderately convex with raised growth centers where radiating ridges join.

Radials (RR) 5, large, in an open circlet (interrupted by anal X on posterior side) around top of cup; each radial convex with projecting growth center at aboral edge of arm facet. E, A, and B RR hexagonal, slightly wider than long; C and D RR modified hexagonal with short extra sutures for outer periproctal plates. C radial slightly smaller than others, length and width nearly equal, set higher in cup, and projecting more. Central hemielliptical arm facet longer than wide, occupying about 40 percent of radial width, raised above radial surface, and directed outward between 20 to 45° from horizontal. RR sharing respiratory "rhomb" with each adjacent oral, anal X, accessory oral, or outer periproctal plate. Each radial with narrow coelomic notch in base of food groove just adoral to arm facet.

Two medium-sized radianals, an inferradianal (iRA) below and a superradianal (sRA) above, plus a medium-sized anal X on posterior side of cup interrupting BB and RR circlets (Fig. 45B). The iRA pentagonal, slightly longer than wide; sRA pentagonal, wider than long, located above and slightly to right of iRA, equally supporting C radial and anal X obliquely above. Anal X modified pentagonal, bounded by 5 to 6 sutures (1 to 2 very short) and curved lower margin of periproct (about 25 to 30 percent of periproct circumference), wider than long, with 2 fairly small respiratory structures on upper corners. Several circlets of periproctal plates and anal pyramid between anal X and poste-

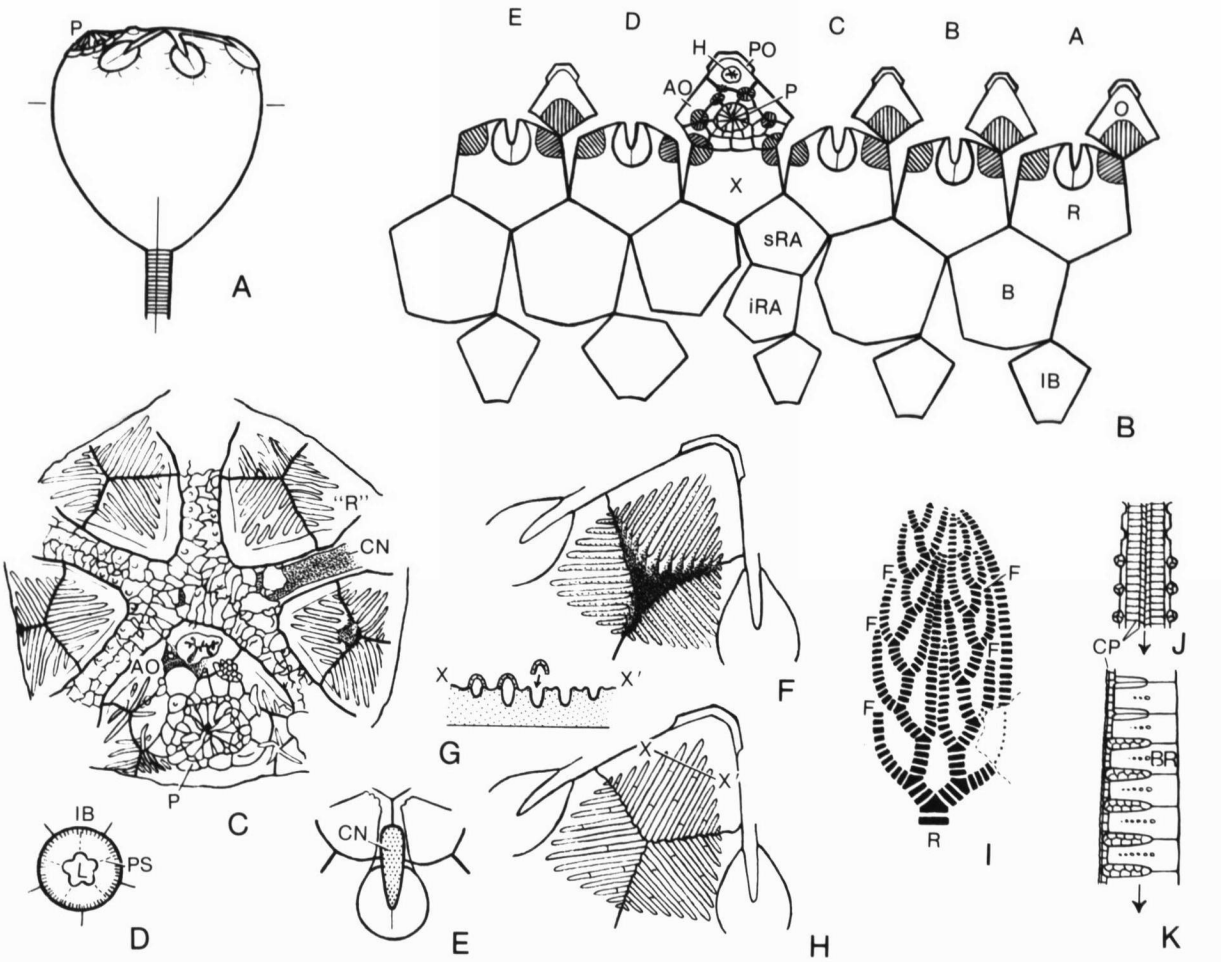
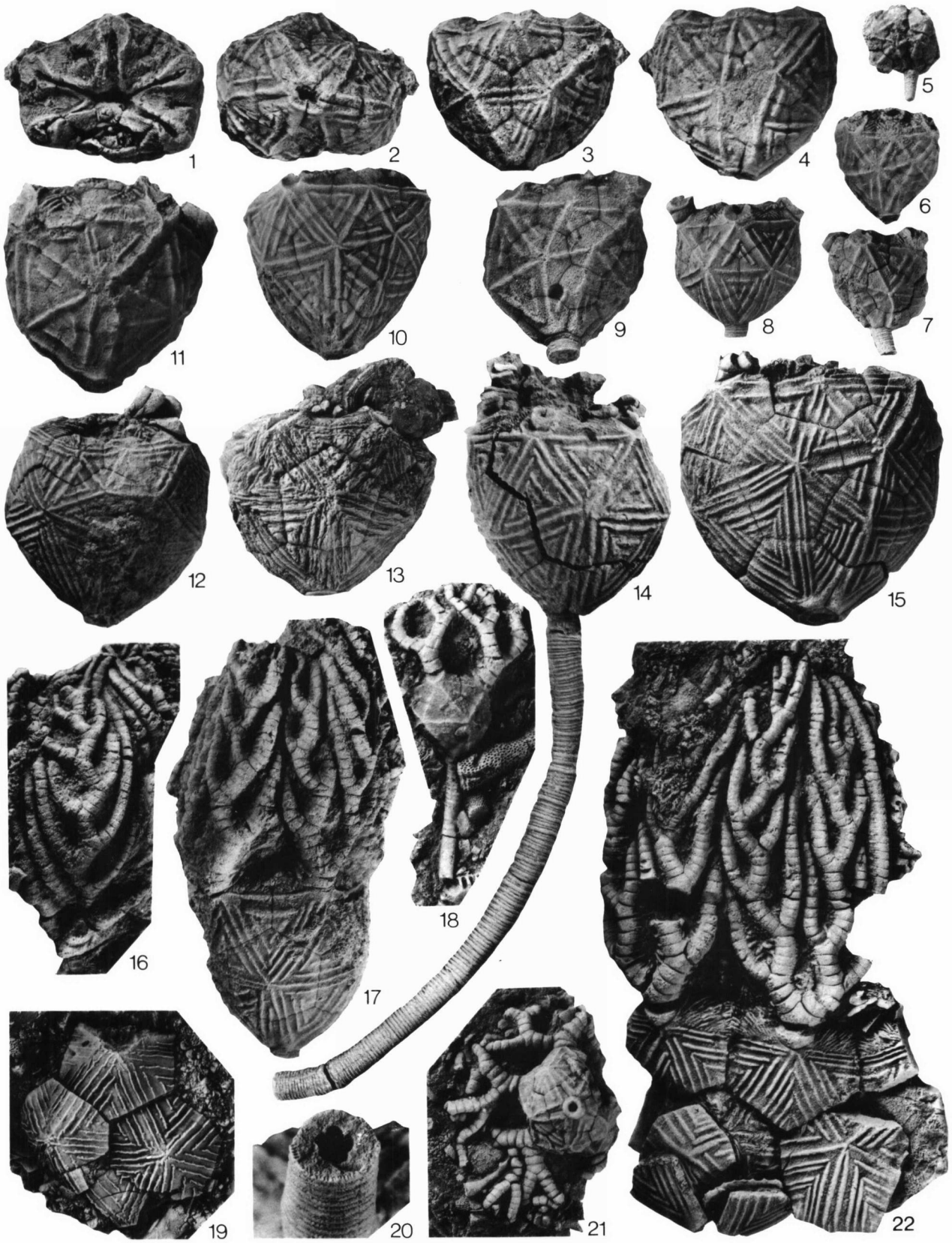


Fig. 45. *Carabocrinus treadwelli* Sinclair, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. A, Outline of a large calyx showing cup-shaped profile, maximum diameter (short lines), slightly domed periproct (P) on summit, and proximal stem size and attachment. B, Side-layout plating diagram of a large cup showing unequal-sized infrabasals (IB), basals (B) in an interrupted circlet, radials (R) with equal-sized arm facets, orals (O) on summit, split radianal (iRA + sRA) below fairly large anal X (X), and posterior oral (PO) with hydropore (H), 2 accessory orals (AO), and other small periproctals around periproct (P); note "rhombs" at R-R-O corners and especially around periproct. C, Summit of small cup OU 9127 showing cover plates over central mouth and ambulacra (note small pustules on some), coelomic notch (CN) and lack of floor plates in B-ray ambulacrum, slitlike branching hydropore just below mouth and sunken area (possible pore) just aboral to this, accessory orals (AO), periproct (P) with toothlike anal pyramid plates, and "rhombs" ("R") between radials and orals with smaller ones around periproct, X4.5. D, Proximal stem near infrabasal (IB) attachment; note rounded star-shaped lumen (L) and cryptic pentamere sutures (PS), much enlarged. E, A-ray arm facet and coelomic notch (CN) on summit; note that adjacent orals are symmetrical, enlarged. F, "Rhomb" with covers removed, showing triangular pore to coelomic cavity and grooves radiating out on adjacent plates. G, Section X-X' across "rhomb" showing how covers fit over grooves, much enlarged. H, "Rhomb" with covers (perhaps segmented) sutured in place. I, Diagram of large, nearly complete, B-ray arm in I121TX108; note branching pattern above radial (R), number of branches, and places (F) where lateral branches folded in behind higher branches, X0.9. J, Adoral, and K, side views of a proximal arm (lateral branch) showing shape of brachial plates (BR), 2 sets of cover plates (CP) over wide food groove, and elongate lateral "covers" over interbrachial sutures, much enlarged.

rior oral.

Orals (OO) at least 5 and probably 7, small, in closed circlet around central mouth; 4 regular OO, much smaller and differently shaped CD or posterior oral (PO), and 2 apparent accessory OO below PO. Regular OO medium-sized, modified pentagonal, slightly wider than long, slightly overlapping RR along suture, surface nearly flat, depressed, with central and aboral parts occupied by single large respiratory "rhomb" shared with 2 adjacent RR (Fig. 45F). Lateral edges of regular OO raised along narrow coelomic notches and food grooves;



adoral edge bordering mouth with 2 small vertical ridges alternating with shallow grooves (Pl. 13, fig. 7). PO smaller, irregularly polygonal to elliptical with at least 3 aboral sutures and a curved adoral edge with 4 small vertical ridges alternating with shallow grooves; bearing elevated hydropore near center (Fig. 45B).

Two small but elongate plates present diagonally below PO bordering coelomic notches of C and D ambulacra; these plates bearing respiratory "rhombs," bordering a radial and other periproctal plates, and probably representing accessory orals (to PO). PO plus accessory OO extending about same distance aborally as regular OO (Fig. 45C).

Mouth central, elongate pentagonal, surrounded by adoral ridged edges of OO and PO. Mouth protected by ?2 sets of small, nearly flat, cover plates, an elongate set about 1 mm long by 0.25 to 0.3 mm wide and a smaller triangular set about 0.3 mm long filling in gaps (Pl. 13, fig. 1; Fig. 45C). Food grooves covered by 2 sets of tiny cover plates becoming more highly arched aborally; larger set at edge of food groove with polygonal plates 0.6 to 0.7 mm long often bearing tiny central spine; tiny set of triangular plates about 0.2 to 0.3 mm long over center of food groove between larger cover plates (Pl. 13, fig. 1, 2). Hydropore a relatively small raised tubercle with branched pore or slit near center of PO; in relatively small specimen OU 9127, tubercle 1.2 mm in diameter, 0.5 mm high, center depressed, with 8 to 10 short radiating slits covering a diameter of 0.8 mm (Pl. 13, fig. 2; Fig. 45C).

Periproct a nearly circular to slightly elliptical area inside ring formed by PO and the 2 accessory OO, C and D radials, and anal X (Fig. 45B). Best-preserved periproct 2.5 mm in diameter in OU 9127 (cup 13 mm in diameter) and containing 2 concentric circlets of periproctal plates and a nearly central anal pyramid (Pl. 2, fig. 2). Outer circlet with 8 to 9 rather small polygonal plates bearing respiratory "rhombs" with surrounding plates; 2 to 3 plates bordering central part of anal X smaller than others (Fig. 45C). Inner circlet with about 16 very small polygonal plates, many bearing a tiny spine (Pl. 13, fig. 2). Anal pyramid inside inner circlet, 1.7 mm in diameter and slightly domed in OU 9127, and containing 14 to 15 long and short triangular plates arranged in circlet (Fig. 45C). Pyramid larger and projecting as much as 2 mm in some larger cups (Pl. 13, fig. 4).

Respiratory "rhombs" three-cornered, groove and cover-bearing, exothecal structures located around summit at corners of RR and regular OO (4 large "rhombs") and around periproct at corners of C and D RR, anal X, outer periproctals, accessory OO, and PO (6 to 8 small to medium-sized "rhombs").

PLATE 12.

Fig. 1-18, 20-22. *Carabocrinus treadwelli* Sinclair; Mountain Lake Member, Lower Echinoderm Zone (except 7, 13), Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1-4 from Nebo; 5, 9, 10, 12, 15-18, 20, 22 from Daube Ranch; 6 from Cedar Village; 7 from Upper Echinoderm Zone at Sulphur; 8, 11, 21 from Lick Creek; 13 from *Carabocrinus* Beds at North-Central I-35; 14 from Amis ranch. 1-4. Summit, basal, A-ray, and CD-interray views of holotype USNM 112082, a moderately crushed medium-sized specimen; note "rhombs," hydropore in PO, and accessory orals on summit; X1.5. 5. CD side view of very small cup USNM 172031 (Graffham Coll.) with short attached proximal stem and single radiating ridges on cup plates; X2. 6. CD side view of small cup 1278TX13; note "rhombs" and ring of periproctal plates around missing anal pyramid on summit; X2. 7. BC side view of small cup OU 9123 with relatively few ridges; X1.5. 8. A-ray side view of medium-sized specimen OU 9124 showing proximal Brr and short stem segment; X1.5. 9. Oblique CD side view of medium-sized cup OU 9125 (about same size as specimen in 8); note hole drilled into coelomic cavity at lower center and fewer ridges on plates; X2. 10. CD side view of fairly large cup OU 9126 showing normal cup plating and triangular ridge pattern; X1.5. 11. Enlarged CD side view of slightly abnormal small cup OU 9127; note that CD basal and sR appear fused (compare with 10, 12); X3. 12. CD side view of abnormal cup OU 3422 showing 2 small anal X's overlying two Sr's overlying an enlarged (but poorly exposed) iR; this is the same "abnormality" reported by Sardeson for a Minnesota specimen; X1.5. 13. EA side view of large cup 1276TX15; note coarsening of plate ornament and inset sutures caused by diagenetic overgrowths of calcite (characteristic of this zone); X1.5. 14. B-ray view of large cup OU 9128 with attached 74-mm stem segment (broken and recemented in 5 places); X1.5. 15. CD side view of very large, slightly crushed cup OU 9129 showing plating and characteristic ridgelike ornament; X1.5. 16. D-ray arm in large crushed and weathered calyx OU 9130; note at least 11 branches and tipped Brr at top; X1.5 17. BC side view of large calyx OU 9131 showing branching pattern in B and C arms; X1.5. 18. Side view of small calyx 1121TX109 with simple arms and proximal stem; X2. 20. Distal tip of proximal stem 9 mm from base of cup OU 9132; note large rounded-pentagonal lumen, barely visible pentameres, and crenulae; X4. 21. Basal view of medium-sized calyx OU 9133 showing incomplete short arms; X1.5. 22. B-ray side view of extremely large calyx 1121TX108; note B- and C-ray arm branching pattern with at least 10 branches, "rhombs" at edge of summit, and much larger plates than 15 above; X1.5.

Fig. 19. *Carabocrinus* sp.; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Sulphur, northern Arbuckle Mountains, southern Oklahoma; partial specimen OU 9108 showing very thin plates, numerous sharp ridges, and smaller area for "rhombs" on radial (compare with 22); X2.

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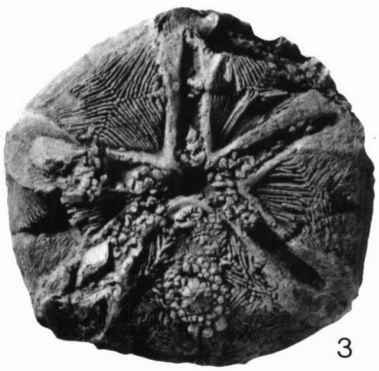

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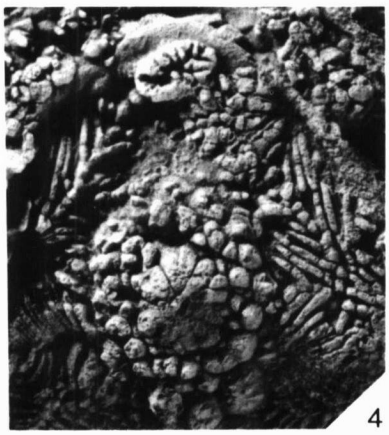

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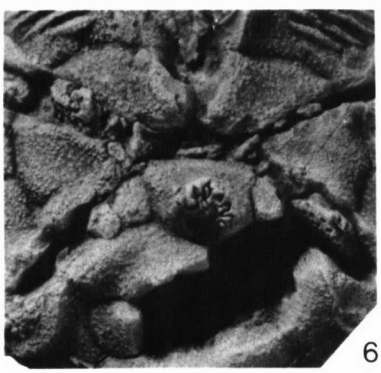

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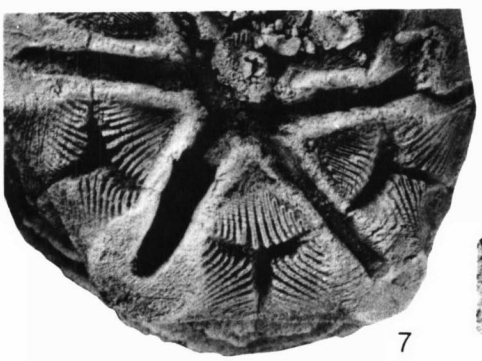

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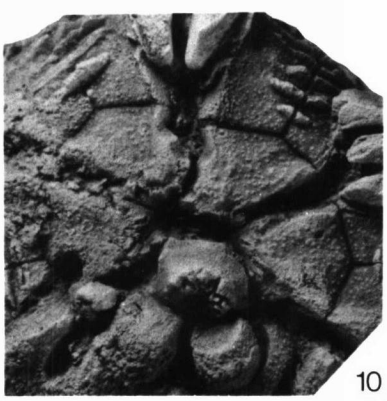

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Large "rhomb" located at each R-R-O corner (4 total); each "rhomb" rounded-triangular, up to 6.5 mm long by 9.0 mm wide, in a large cup containing 18 to 21 closely spaced (0.25 to 0.3 mm/fold), parallel, covered grooves per plate. Longest grooves central, extending from near plate growth center to corner; grooves becoming shorter (and younger) away from center. Eroded "rhombs" showing plate sutures not quite extending to corner, leaving triangular hole to calyx interior (Pl. 13, fig. 7). Shallow grooves on eroded "rhomb" surface extending away from this hole at corner (Pl. 13, fig. 7). Surface of grooves smooth, implying that foldlike covers suturing here and not just broken off. Well-preserved specimens showing grooves protected by elongate foldlike covers of thin calcite about 0.4 to 0.5 mm high, covers appearing tightly sutured together where they meet covers from adjacent plates at sutures (Pl. 13, fig. 3). Most covers smooth and one-piece, a few showing evidence of multiplating. "Rhombs" around periproct smaller with fewer and shorter grooves; "rhombs" at corner of anal X largest in this interray with about 14 folds in large specimen, other "rhombs" much smaller with only few folds. Small depressed area just aboral and to left of raised hydropore (Fig. 45C) either "rhomb" lacking most grooves and covers or accessory calyx opening (?gonopore). Smallest specimen (USNM 172031; Pl. 12, fig. 5) may lack all "rhombs."

Cup plates relatively thin, usually 0.6 to 1.1 mm thick in large specimens, but locally as much as 2.0 to 2.2 mm thick beneath arm facet and adjacent to respiratory "rhombs." Many plate sutures showing very fine labyrinthine or wavy vertical ridging. Ornamental ridges well developed, radiating from plate growth centers to edges, ridges rounded to low triangular in cross section, usually about 0.2 to 0.3 mm high, solid; 1 to 2 ridges crossing each suture in small specimens, 4 to 11 ridges in large specimens; ridge spacing ranging from 0.80 to 1.14 mm/ridge and averaging 0.94 mm/ridge based on 27 measurements in 12 medium-large specimens and separate plates. Earliest-formed central ridge most prominent, adjacent ridges slightly smaller, shorter, forming nested triangles around plate corners (Pl. 12, fig. 10).

Arms 5, relatively long, uniserial, repeatedly branched. Longest preserved arm at least 52 mm long, attached to crushed cup approximately 30 mm long (Pl. 12, fig. 22); arms probably 1½ to 2 times cup length in most specimens. Arm branching bilateral heterotomous to produce 10 main branches or rami (2 per ray), rami bifurcating 2 to 3 times in small specimens and 10 to 13 times in large specimens; large side branches (ramuli) appearing to extend unbranched to arm tips (Fig. 45I). Primibrachs (IBrr) 1 to 2, appearing equal-sized in all rays, rectangular or pentagonal looking adorally; in large specimen, nonaxillary IBrr 1.1 mm long, 4.2 mm wide, and 6.1 mm deep with a 4.0 mm deep, adoral, narrowly U-shaped groove; highest primibrach axillary with equally developed branches. Secundibrachs (IIBrr) 3 to 4 (rarely 2), slightly longer but not so wide or deep as IBrr, top one axillary with equal-sized multibrached

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PLATE 13.

Fig. 1-5, 7-8. *Carabocrinus treadwelli* Sinclair; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1, 2, 8 from Lick Creek, 3, 4 from Amis Ranch, 5, 7 from Daube Ranch. 1, 2. Oblique summit and enlarged CD summit of small cup OU 9127; note excellently preserved ambulacral and oral cover plates, apparent absence of ambulacral flooring plates, small "rhombs" with relatively few slits mostly protected by covers, raised hydropore with branched slit, accessory OO diagonally below PO with very small "rhombs," and low anal pyramid surrounded by 2 circlets of periproctal plates; X4, X7. 3, 4. Summit and enlarged CD summit of relatively large cup OU 9134 showing "rhombs" with many more slits than in 1, some slit covers stripped from AB "rhomb" exposing grooves below, raised elliptical hydropore with branched slit, anal pyramid with surrounding periproctal plates, and medium-sized rhombs with numerous slits on PO, accessory OO, periproctals, anal X, and C and D RR; X2, X6. 5. Adoral view of arms on a slab from broken-up specimen USNM 172032 (Graffham Coll.); note very wide food grooves, 2 sets of arm cover plates, lateral covers between Brr, and branching pattern of arms; X4. 7. Summit view of cup OU 9135 showing 3 "rhombs" with covers missing so that triangular hole into coelomic cavity is visible; also note elongate coelomic notch for A ambulacrum; X4. 8. Enlarged view of well-preserved proximal arms in specimen OU 9136; note segmented covers between Brr, branching pattern, and abnormal branch with extra Brr at lower center; X4.

Fig. 6, 9-11. *Palaeocrinus hudsoni* Sinclair; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 6, 10 from Lick Creek, 9, 11 from Amis Ranch. 6. Enlarged summit of cup OU 9137 showing zigzag curved hydropore on PO, asymmetrical EA and AB OO, and symmetrical BC and DE OO; X5. 9. Summit of cup OU 9138; note hydropore in PO, accessory OO and damaged anal cone below PO, ambulacral flooring plates plus some cover plates, and elongate pore on suture of DE oral and D radial; X3. 10. Enlarged summit of specimen OU 9139 showing hydropore in PO and ornamented adoral edges of OO for articulating oral cover plates; note deep pore at edge of DE oral (left) enlarged by weathering; X5. 11. Enlarged summit of cup OU 9140; note flooring plates with pores in several ambulacra (especially B and E) and wide coelomic notch for A arm; X5.

ramus branching inward (adradial) and unbranched ramulus branching outward (abradial). Tertibrachs (IIIBrr) 3 to 4 (rarely 2, 5, or 6) in ramus, as many as 40 in one nearly complete ramulus apparently extending to top of arms (Pl. 12, fig. 22), IIIBrr not so wide or deep as IIBrr but otherwise similar. Quartibrachs (IVBrr) 3 to 5 in ramus, 14+ in ramulus, slightly smaller than preceding series. Higher series continuing gradual decrease in size; VBrr usually 4 to 5 in ramus, 19+ in ramulus; VIBrr usually 4 to 5 in ramus, 19 in one complete ramulus; VIIBrr 4 to 5 in ramus, 14+ in ramulus; VIIIBrr 4 to 6 in ramus, 23 in one complete ramulus; IXBrr 3 to 5 in ramus; XBrr 3 to 6 in ramus, 13 in one complete ramulus; XIBrr 3 to 5 in ramus; XIIBrr 3 in ramus, 7 in relatively short ramulus; and XIIIBrr 4 in largest arm. Preserved tips of arms rather stubby, tapering rapidly to tip in 2 to 3 Brr (Pl. 12, fig. 16). Two to three sets of brachial cover plates present over fairly wide adoral food groove (Pl. 13, fig. 5); 2 rows of small elongate rectangular outer plates about 0.45 mm long and 0.2 mm wide forming domed cover over most of food groove and attached to inner edge of Brr, about 4 cover plates/Br (Pl. 13, fig. 5). Tiny set of inner cover plates intermeshing over center of food groove in highly domed pattern; inner cover plates appearing to be aligned with outer cover plates (Fig. 45J). Additional set of tiny cover plates may possibly be present outside others at edge of Brr. Lateral sutures between Brr depressed (especially proximally), shallow groove covered by elliptical domed covers (Pl. 13, fig. 8), covers appearing to be multiplated (see Ubaghs, 1978, p. T188-T190) (Fig. 45K). In OU 9136, covers on IIBrr about 2.2 to 2.5 mm long, 0.4 to 0.5 mm wide, and 0.5 to 0.6 mm high in a medium-sized specimen (Pl. 13, fig. 8); covers gradually becoming much smaller distally, on VBrr in this specimen, covers only 0.7 to 0.8 mm long, 0.3 to 0.4 mm wide, and 0.2 to 0.3 mm high. Covers not seen on higher Brr.

Stem moderately long; proximal region preserved in several specimens, middle region and distal region present in only one specimen (Pl. 12, fig. 14), in this specimen stem about 74 mm long, attached to cup 25 mm long. Proximal stem nearly cylindrical (only slightly enlarged at cup attachment), slightly heteromorphic with alternating thicker and thinner columnals, in best specimen about 24 mm long by 4.5 mm in diameter proximally and 3.9 mm, distally. Columnals disc-shaped, circular, smooth and slightly rounded externally, with symplectial articulations; columnals divided into pentameres with cryptic radial sutures and a small rounded star-shaped lumen (Pl. 12, fig. 20). Medial stem about 35 mm long in best specimen, about 3.5 to 3.9 mm in diameter, most columnals 0.4 to 0.5 mm thick, smooth, pentamere sutures nearly invisible. Preserved distal stem about 14 mm long (total length unknown), becoming more heteromorphic distally with gradual introduction of thin node-bearing columnals between smooth ones (Pl. 12, fig. 14), pentameres becoming more prominant externally because longitudinal sutures gradually become depressed. Large type 1A holdfasts suspected of belonging with this species (see chapter by Lewis).

(Several abnormalities were noted in studied material; the most unusual involves a single large specimen having 2 anal X plates overlying 2 sRA plates; see Pl. 12, fig. 12. The anal X plates in this specimen lie beside each other, are somewhat smaller than the normal anal X, and together form the curved lower margin of the periproct, which is especially wide. The sRA plates are below and to the right, beside each other, and both are pentagonal and normal or slightly larger in size. The iRA plate below is not well preserved, and appears much larger than usual although otherwise normal; adjacent RR, BB, and IBB plates are slightly displaced and have modified sutures because of extra plates. Another small specimen, OU 9127, apparently has the CD basal fused with the sRA; see Pl. 12, fig. 11. Two other specimens, Pl. 13, fig. 8, have extra brachial plates inserted in a "V" above lower arm axil; one is rounded triangular in shape and modifies the adjacent Br.)

Studied specimens.—Holotype USNM 112082, other figured specimens USNM 172031, 172032; 1278TX13, 1276TX15, and 1121TX108, 109; and OU 3422, OU 9123-9136; unfigured specimens in OU, TX, USNM, and other collections.

A total of 205 specimens were available for study. Sinclair's holotype is a medium-sized, moderately crushed, but fairly well-preserved cup from Nebo, probably from the Lower Echinoderm Zone. It has most of the cup plates exposed and still articulated (Pl. 12, fig. 1-4) and some of the respiratory "rhombs," accessory OO, and PO with hydropore well preserved on the summit.

Occurrence.—Found in the Lower Echinoderm Zone at Daube Ranch (100 specimens), Amis Ranch (42 specimens), Lick Creek (32 specimens), Cornell Ranch (Tulip Creek) (15 specimens), Fittstown Quarry (3 specimens), Nebo (1 specimen, holotype), and Cedar Village (1 specimen); in the *Carabocrinus* Beds at North-Central I-35 (9 specimens and

many plates) and North I-35 (1 specimen and plates); and in the Upper Echinoderm Zone at Sulphur (1 specimen), all Mountain Lake Member, Bromide Formation, southern Oklahoma.

Discussion.—*Carabocrinus treadwelli* is a fairly distinctive species based on cup shape, plate sizes, ornamental ridges, and respiratory "rhombs," as pointed out originally by Sinclair (1945, p. 715-716). The respiratory "rhombs" are especially large and well developed in this Bromide species; in several other *Carabocrinus* species, these structures are either small or poorly preserved in the available material (for example, see Brower and Veinus, 1974). As pointed out by Ubaghs (1978, p. T208 and fig. 174,9,10) and also by C. R. C. Paul (pers. commun., August, 1977), these respiratory "rhombs" in *Carabocrinus* are not the same as goniospires in *Porocrinus*, although this idea has been implied or actually stated by several authors (Sinclair, 1945, p. 716; Kolata, 1975, p. 29-30; Brower and Veinus, 1978, p. 447-451, 495). The "rhombs" in *Carabocrinus* were exothecal structures in which, I believe, coelomic fluid flowed out through a large pore at the plate corner and circulated in radiating grooves protected by thin calcite covers through which gas exchange took place with the overlying sea water. Although they are also three-cornered, goniospires are endothecal structures with sea water circulating down into thin folds of plate material to exchange gases with the coelomic cavity; in addition to the difference in circulation, goniospires also lack the underlying pore, the grooves in the plate surface, and the sutured covers. The "rhombs" in *Carabocrinus* probably functioned in much the same way as the slitlike plate ridges of *Palaeocrinus* (which were also exothecal respiratory structures), but these plate ridges are linear and run directly across plate sutures, do not have separate covers, and probably had different circulation of coelomic fluid through the slits. Finally, the "rhombs" in *Carabocrinus* are located only around the summit on the radials, orals, and anals, instead of over most of the cup as in *Porocrinus* and *Palaeocrinus*. The posterior interray seems especially well covered, with six to eight small to medium-sized "rhombs" around the anal pyramid; perhaps respiratory ability was needed here for the hindgut, a possible gonad, or other summit structures. The small porelike opening just to the left and aboral to the raised hydropore may possibly have been a gonopore, although this seems less likely because of the extensive arms which, based on living crinoids, should have housed the gonads.

Carabocrinus has relatively long arms that show a bilateral heterotomous branching pattern, partly described by Brower and Veinus (1978, p. 448). This pattern is like that found on each axil arm in the A and D rays of calceocrinids (Ubaghs, 1978, p. T147 and fig. 121). The branching above the primibrachs is toward the middle of each half-ray to form a repeatedly branched central ramus and long unbranched outside ramuli, which appear to extend to the top of the arm series. At each axil, the ramus and ramulus are equal-sized, and both slowly taper in size distally; however, many of the lower ramuli are folded in and hidden beneath higher ramuli. In very large specimens, the arms may reach twice the calyx length and branch 13 times. The elongate lateral covers between Brr on the lower arms had an unknown function. They probably restricted bending movement of the arm and protected the Brr sutures; however, because *Carabocrinus* lacks pinnules, another possibility is that they housed the gonads as do the genital pinnules in the proximal arms of living crinoids (Ubaghs, 1978, p. T204-T205).

At least one specimen of *Carabocrinus treadwelli* has a preserved stem which, though incomplete distally, is 74 mm long, about three times the cup length. This contrasts greatly with the very short stem proposed by Brower and Veinus (1978, p. 401-403) for the relatively similar *C. dicyclicus;* it has only a few columnals (three shown in their reconstruction) directly attached to a large discoidal holdfast. Many Bromide specimens of *C. treadwelli* also have two to three columnals of the proximal stem still attached to the cup, similar to the preserved *C. dicyclicus*, but the stem is now known to have been much longer. Brower and Veinus' studied specimens of *C. dicyclicus* are larger and have a smaller proximal stem diameter than *C. treadwelli;* thus a very short stem in this Decorah species cannot be ruled out, although it may now be less likely. Based on distal stem morphology, stem and holdfast size, and abundance in the various Mountain Lake echinoderm faunas, specimens of *C. treadwelli* appear to have been attached to the substrate with a type 1A holdfast. Brower and Veinus (1978, p. 399) believe, as Sardeson did, that *C. dicyclicus* was attached to the substrate with a *Podolithus* or *Disconia*-type holdfast. These are also present in the Bromide (type 1C) but are much less common.

One Bromide specimen of *C. treadwelli* has the same abnormality in cup plating (doubling of sRA and anal X) that was used by Sardeson (1899) as

the basis for his new genus *Strophocrinus*, also based on a single specimen. Brower and Veinus (1978, p. 395) concluded that Sardeson's specimen was in fact an abnormal individual of *Carabocrinus dicyclicus* and synonymized Sardeson's genus; based on the appearance of a single specimen with the same unusual features (but no other differences) in the Bromide species, I would agree with their analysis. Abnormalities of this type should be expected in other *Carabocrinus* populations.

CARABOCRINUS sp.

Plate 12, figure 19

A single partly complete specimen (OU 9108) that differs from *C. treadwelli* has been found in the Upper Echinoderm Zone at Sulphur. This specimen has an infrabasal, two basals, and a radial plate attached together on a slab (Pl. 12, fig. 19); as preserved in a flattened state, the specimen is 17.5 mm long and 19 mm wide.

Infrabasal relatively small, pentagonal, longer than wide, leaning left; 2 basals relatively large and hexagonal, 1 longer than wide, the other wider than long (crushed differently?); radial large (perhaps larger than BB), incomplete (adoral tips broken off), originally hexagonal with adoral coelomic notch and central arm facet making up about 35 percent of width, wider than long as preserved, lateral sutures nearly parallel. No "rhombs" preserved on broken radial; apparently small if present. All plates very thin, about 0.2 mm thick. Thin sharp solid ridges crossing most plate sutures (Pl. 12, fig. 19), 5 to 8 ridges per suture, ridge spacing about 0.7 mm/ridge, each ridge about 0.2 mm high and 0.1 to 0.15 mm wide; few nodes present between ridges on lower infrabasal.

Discussion.—This single specimen differs significantly from other specimens of *C. treadwelli*, including one that occurs at the same locality and zone (Pl. 12, fig. 7). *Carabocrinus* sp. has much thinner plates, sharper and more closely spaced ornamental ridges, large radials with nearly parallel sides, and smaller (or no) "rhombs." This specimen does resemble specimens of *Palaeocrinus* sp., which also occurs at this locality, but it lacks the hollow slit-bearing ridges and has even thinner plates. *Carabocrinus* sp. is most similar to *C. micropunctatus* Brower and Veinus (1974, p. 64-65) from the Benbolt Formation of Virginia and Tennessee, but has fewer ornamental plate ridges and no surface pitting. It also shows some resemblance to *Carabocrinus* sp. (Kolata, 1975, p. 30-31) from the Platteville Group of northern Illinois and to some specimens of *C. dicyclicus* (Brower and Veinus, 1978, p. 446-449) from the Decorah Shale of Minnesota. More complete specimens will be necessary before this Bromide form can be assigned to a definite species.

Family SPHAEROCRINIDAE Jaekel, 1895

Genus PALAEOCRINUS Billings, 1859

Type species.—*Palaeocrinus striatus* Billings, 1859.

Diagnosis.—Cup conical to bowl-shaped with slight to moderate asymmetry, IBB elongate, tetragonal RA supporting larger anal X, several accessory anals and orals present; exothecal covered slits on most plate sutures (except OO); arms fairly short to medium length, ?unbranched or showing relatively few isotomous branches; proximal stem small, heteromorphic, of unknown length.

Occurrence.—Middle Ordovician, eastern, north-central, south-central, and perhaps western United States and eastern Canada.

Discussion.—*Palaeocrinus* and the later genera *Sphaerocrinus* and *Thalamocrinus*, both of which apparently lack the sutural covered slits (but see Lane and Moore, 1978, fig. 378, 1d), are grouped now in the family Sphaerocrinidae. *Palaeocrinus* further differs from *Sphaerocrinus* by having a smaller RA, anus on the summit directed upward, OO more nearly the same size, and possible accessory OO on the posterior summit. *Palaeocrinus* differs from *Thalamocrinus* by having a less elongate cup without the constricted summit, smaller IBB and BB, and much larger RR; *Thalamocrinus* also lacks the sutural slits covered by radiating ridges. *Palaeocrinus* differs from related genera in the families Carabocrinidae and Porocrinidae by having a different type of respiratory slits, only one RA, accessory orals and anals, more asymmetry in the cup and arms, different arm branching, and a small proximal stem with a star-shaped lumen. *Palaeocrinus* appears to be represented in the Bromide Formation by two to three species; *P. hudsoni* (known from over 500 specimens) is most common in the Lower Echinoderm Zone and *Carabocrinus* Beds but is replaced by a closely related species with wider slit spacing in the *Bromidocystis* Bed and Upper Echinoderm Zone at the top of the Mountain Lake Member; *P.* sp. cf. *P. planobasalis* is based on a few distinctive plates from the *Bromidocystis* Bed.

PALAEOCRINUS HUDSONI Sinclair, 1945

Plate 13, figures 6, 9-11; Plate 14, figures 1-35; Figures 46A-E,H-L, 47

Diagnosis.—Cup subglobose to cup-shaped, slightly to moderately asymmetric, widest across B-E rays, calyx L:W averaging 0.93; 4 to 12 exothecally covered slits crossing most plate sutures, spacing averaging 0.48 mm/slit; anus at top of small anal cone, arms three-quarters to one and one-half times cup length, showing apparent isotomous branching with up to 5 branches, A-ray arm one and one-half times as large as others; proximal stem small, heteromorphic, with cryptic pentameres and a rounded star-shaped lumen.

Description.—Specimens ranging from small (cup around 5 mm long) to medium sized (cup 20.5 mm long). Cup subglobose to cup-shaped in side view, usually slightly wider than long, ovoid in top and bottom views; base bowl-shaped with small stem facet, sides rounded, summit slightly domed. Maximum diameter above midheight between BB and RR. Cup slightly to moderately asymmetric in several ways: 1) C-ray radial and arm facet slightly raised, 2) cup wider across B-E rays than across A-CD, 3) stem facet displaced slightly toward A ray, and 4) flattened area with reduced ornamental ridges usually located on C or CD side of lower cup (Pl. 14, fig. 6, 7, 10). Calyx L to W ratio (using maximum diameter and without anal cone) ranging from 0.79 to 1.10 and averaging 0.93 for 21 measured specimens.

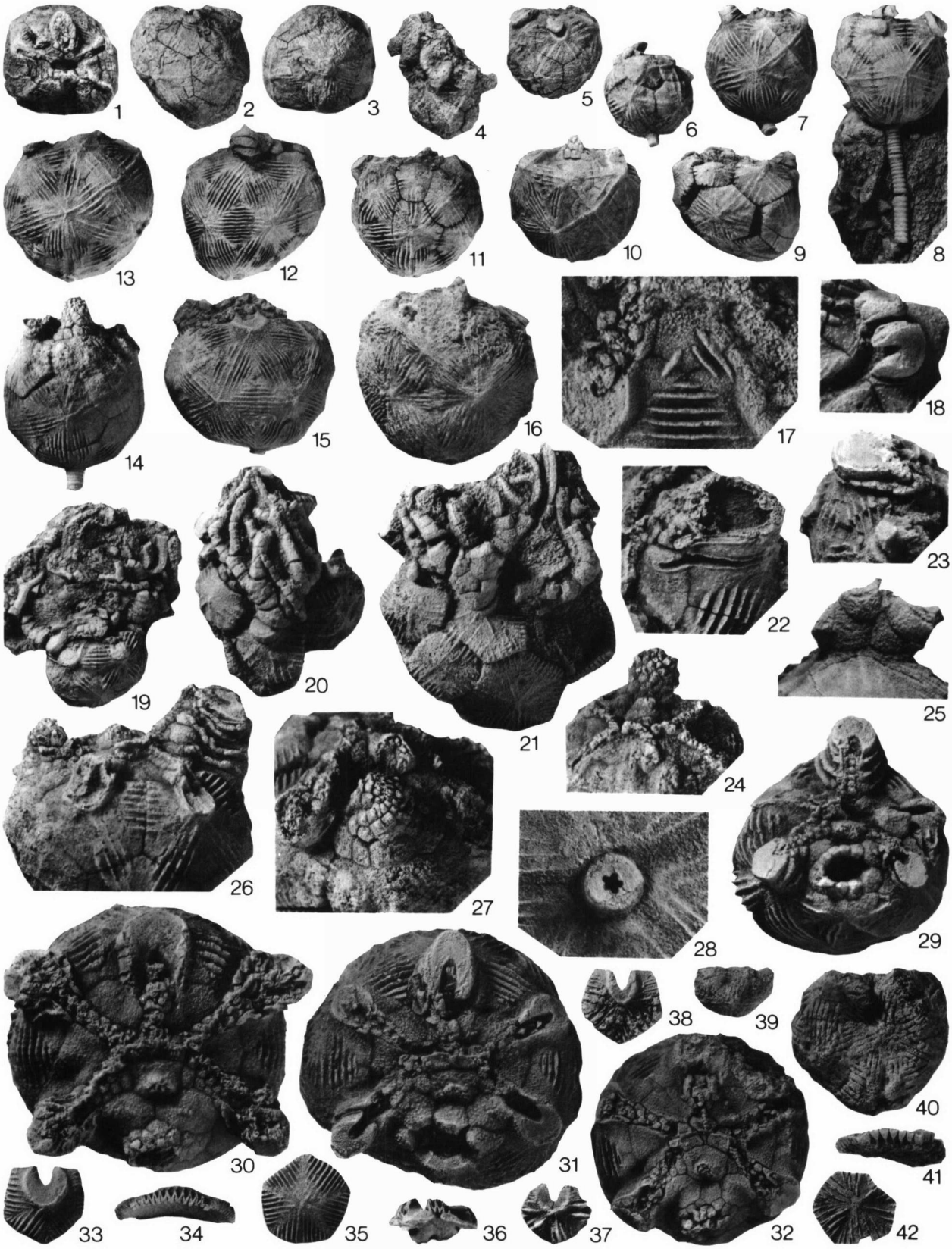
Infrabasals (IBB) 5, nearly equal in size, relatively small, visible in side view; in closed, widely conical circlet around central stem facet at base of cup with IBB expansion angle 130 to 170°. All IBB pentagonal, nearly symmetrical, with hollow ridges to overlying BB, making up nearly equal parts of small round stem facet, stem facet ranging up to 3.2 mm in diameter (Pl. 14, fig. 28).

Basals (BB) 5, probably largest plates in cup, forming a closed circlet around center of cup. Three BB hexagonal, BC and CD basals septagonal because of overlying RA; all BB slightly wider than long with a slightly convex surface. BB with hollow ridges radiating to all adjacent plates (Pl. 14, fig. 12).

Radials (RR) 5, fairly large, in an open circlet (interruped by anal X on posterior side) around top of cup, moderately convex with projecting arm facets, folding over to form edge of summit. E, A, and B RR hexagonal; C and D RR modified hexagonal with short extra suture to an outer periproctal, slightly smaller than other RR, C radial set slightly higher in cup. All RR slightly longer than wide (including summit projections), with slightly converging lateral edges and hollow ridges radiating to adjacent RR and BB. Central hemielliptical arm facet longer than wide, occupying between one-third (B and E rays) and two-thirds (A ray) of radial width, flush or slightly raised, directed outward between 20 to 45° from horizontal. Arm facets in B and E rays slightly lower on RR and directed outward more (Pl. 14, fig. 5). Each radial with narrow to wide coelomic notch just adoral of central arm facet.

Medium-sized radianal (RA) obliquely supporting medium-sized anal X on posterior side of cup; these plates interrupting RR circlet. RA tetragonal with slightly convex edges, obliquely above BC and CD basals, width equal to or slightly greater than length. Anal X modified pentagonal, wider than long, upper edge supporting curved lower margin of periproct (about 30 percent of periproct circumference) with 3 to 5 small periproctals. One circlet of periproctals, conical anal pyramid, and 2 possible accessory OO between anal X and posterior oral.

Orals (OO) at least 5 and probably 7, in closed circlet around central mouth; 4 regular OO, of these 2 (BC and DE) symmetrical and 2 (EA and AB) slightly to strongly asymmetrical, a differently shaped CD or posterior oral (PO), and 2 possible accessory OO below PO (Fig. 46C). BC and DE orals moderately small, modified pentagonal and symmetrical, slightly wider than long, surfaces nearly flat with no ornamental ridges. EA and AB orals similar to above in size and shape but slightly to strongly asymmetrical (skewed) and mirror images of each other across A-ray ambulacral groove. Viewed from anterior, AB oral leaning right, EA oral leaning left (Fig. 46C). Lateral edges of regular OO slightly raised along coelomic notches and food grooves; adoral edge bordering mouth slightly convex, nearly smooth, with small lip at top where oral cover plates attached. PO smaller, irregularly rectangular with 4 to 6 sutures aborally and laterally and a wide slightly convex edge adorally; bearing raised parabolic-shaped hydropore on aboral half and depressed possible pore on aboral suture (Pl. 13, fig. 6, 9-11; Fig. 46D). Two slightly larger plates diagonally below PO bordering coelomic notches of C and D ambulacra; these plates modified hexagonal, bordering a radial and either periproctal plates or the anal pyramid, probably representing accessory orals (to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PO). PO plus accessory OO extending slightly further aborally than adjacent regular OO (Fig. 46C).

Mouth central, elongate pentagonal, surrounded by nearly smooth adoral edges of regular OO and PO. Mouth protected by one set of fairly small rectangular cover plates usually numbering 6 to 8 (Fig. 46D), 2 wide ones abutting wide PO and 2 or more small ones from each anterior oral. Oral cover plates with raised central edges; larger cover plates about 0.8 mm long by 1.4 mm wide, smaller plates 0.7 mm long by 0.8 mm wide. Food grooves protected by 2 sets of cover plates, may have thin alternating biserial plates flooring at least 2 and perhaps all 5 grooves between OO (Fig. 46C). Flooring plates most obvious in C- and D-ray ambulacra, becoming larger and exposed laterally at contact between PO and each accessory oral; flooring plates here about 1.0 to 1.3 mm long and 0.8 to 1.2 mm wide (Pl. 13, fig. 6, 9; Fig. 46C). Flooring plates also present aborally in long B- and E-ray ambulacra, appearing to cover elongate coelomic notches (Pl. 13, fig. 9, 11); uncertain whether they continue to mouth or whether similar plates present in short A-ray ambulacrum. Coelomic notches elongate openings through base of ambulacral groove into cup interior be-

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PLATE 14.

Fig. 1-35. *Palaeocrinus hudsoni* Sinclair; Lower Echinoderm Zone (except 16), Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1-5, 14, 22-28, 32 from Daube Ranch; 6-8, 10, 12, 15, 17-21, 29, 30, 33-35 from Lick Creek; 9, 11, 13, 31 from Amis Ranch; 16 from *Carabocrinus* Beds at North I-35. 1-3. Summit, B-ray side, and basal views of holotype USNM 112072 showing highly abraded asymmetric cup with only a trace of slits; X1.5. 4. B-ray side view of very small specimen OU 9141; note few slits and short arm branching once; X2. 5. E-ray side view of small cup OU 9142 showing some slits and larger diameter A-ray vs. E-ray arm; X2. 6. CD-interray side view of abnormal cup OU 9143, which lacks RA; note anal X reaches BC basal; X1.5. 7, 29. CD-interray side view and oblique summit view of medium-sized cup OU 9144 showing decrease in slit development on RA and anal X (7), very large but rapidly tapering A-ray arm with complete lateral covers between Brr (29), and ring of periproctal plates around missing anal cone (29); X1.5, X3. 8, 18. B-ray side view and enlarged summit view of B-ray Brr in slightly abnormal specimen OU 9139; note proximal stem 13.4 mm long and abnormal (perhaps regenerated) B-ray arm which has a conical plug covering the aboral end of the facet and a small divided IBr1 adorally (18); X1.5, X5. 9. CD-interray side view of abnormal cup OU 9145 lacking RA and having C-ray radial reaching CD basal; X1.5. 10. CD-interray side view of medium-sized cup OU 9146; note fairly low anal cone on edge of summit; X1.5. 11. CD-interray side view of slightly abnormal cup OU 9147 showing RA extending up between anal X and C radial to edge of periproct; X1.5. 12, 17. D-ray side view and oblique EA summit view of medium-sized cup OU 9148; note asymmetric cup with well-developed ornamental folds (some stained black) and 1 to 2 folds (very unusual) across R-O suture (17); X1.5, X5. 13, 31. CD-interray side view and enlarged summit of moderately large cup OU 9149 showing well-developed folds and summit (31) with some large oral cover plates, E-ray ambulacral floor plates, and different-sized arm facets; X1.5, X3. 14, 26, 27. CD-interray side view, enlarged BC-interray view of summit, and oblique enlarged view of CD summit of moderately large cup OU 9150; note large anal cone on summit, short proximal stem segment (14), hydropore in low hump (26, 27), very large size difference between arms in different rays (26), and accessory plates and lateral covers on large A-ray arms (26); X1.5, X2.5, X3. 15, 28. A-ray side view and enlarged proximal stem of large cup OU 9151 showing asymmetrical cup shape with numerous ridges and canted stem attachment bearing a rounded pentagonal lumen (28); X1.5, X5. 16. C-ray side view of largest known cup 1280TX2; surface is heavily recrystallized and partly covered with caliche; X1.5. 19. EA-interray side view of specimen OU 9152; note several branched arms slightly longer than cup; X1.5. 20. C-ray arm on badly crushed specimen OU 9153 showing 3 to 4 nearly isotomous arm branches; X2. 21. B- and C-ray arms on crushed specimen OU 9154; note 5 branches and slight abnormality in lower Brr in C-ray arm; X2. 22. Enlarged side view of A-ray arm in broken cup OU 9155 showing slot for cover extending from lowest Br to oral; X4. 23. Enlarged side view of A-ray arm in crushed cup OU 9156 with segmented lowest Br cover still attached; X3. 24. Oblique summit (from A ray) of cup OU 9157 showing large anal cone behind ridged hydropore and covered food grooves; X3. 25. Enlarged view of abnormal B-ray arm in cup OU 9158; note divided ?IBr1 on facet; X4. 30. Enlarged summit view of cup OU 9159 showing ambulacral and oral cover plates, basal Br covers around arm facets, raised hydropore, and damaged anal cone; X3.5. 32. Enlarged summit view of cup OU 9160; note large oral cover plates, some ambulacral cover plates and flooring plates, hydropore in PO with depressed pore immediately behind, similar pore on aboral edge of DE oral, and anal cone; X3. 33. Separate A-ray radial OU 9161 showing large arm facet, ornament, and slightly converging lateral margins; X1.7. 34, 35. Separate basal OU 9162 in edge and outside views; note spacing of covered slits and thinness of plate; X2.3, X1.7.

Fig. 36, 37. *Palaeocrinus* sp. cf. *P. planobasalis* Brower and Veinus; *Bromidocystis* Bed, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 36 from Daube Ranch, 37 from North-Central I-35. 36. Edge view of basal 1397TX59 showing "bundled" slits with a single opening into the interior; X2.3 37. Probable A-ray radial 1393TX18; note small size, raised "bundles" of covered slits, large arm facet, and converging lateral margins; X1.7.

Fig. 38-42. *Palaeocrinus* sp.; Upper Echinoderm Zone (39-40) and *Bromidocystis* Bed, (38, 41, 42), Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 38 from North-Central I-35; 39, 40 from Sulphur; 41, 42 from Daube Ranch. 38. Separate radial 1393TX19 showing shape, slit spacing, and converging lateral margins; X1.7. 39. Small vertically crushed cup OU 9120; X1.5. 40. Larger crushed cup OU 9121 showing slit spacing and plating; X1.5. 41, 42. Separate basal 1397TX60 in edge and outside views; note greater thickness and wider spacing of covered slits compared to 34; X2.3, X1.7.

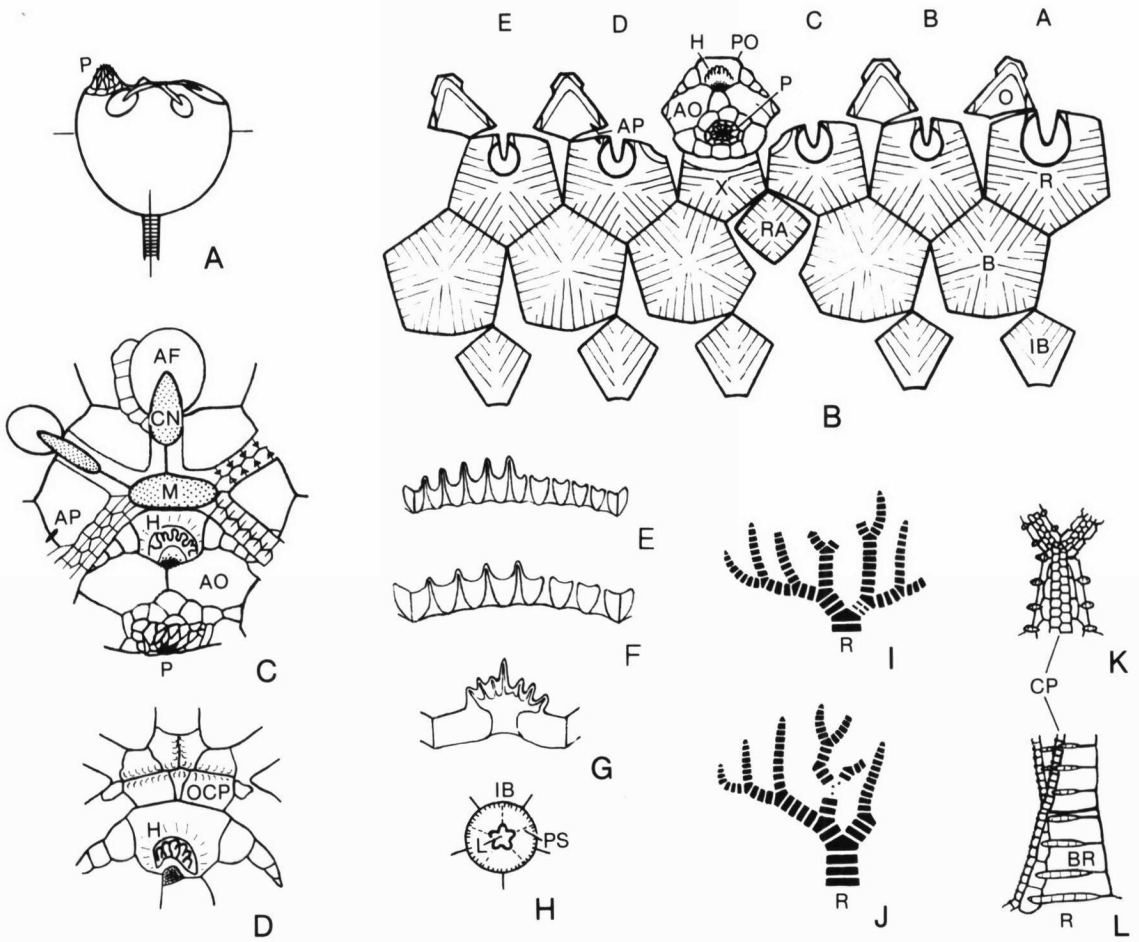


Fig. 46. *Palaeocrinus hudsoni* Sinclair with *Palaeocrinus* sp. in F and *Palaeocrinus* sp. cf. *P. planobasalis* in G, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. A, Outline of large calyx showing bowl-shaped profile, maximum diameter (short lines), projecting periproct (P) on summit developed as anal cone, and proximal stem size and attachment. B, Side-layout plating diagram of a large cup showing equal-sized infrabasals (IB), basals (B) in a complete circlet, radials (R) with unequal-sized arm facets, orals (O) on summit (note asymmetry in AB and EA ones), radianal (RA) below anal X (X), and posterior oral (PO) with hydropore (H), 2 accessory orals (AO), and other small periproctals around periproct (P); also note small accessory pore (AP) between D radial and DE oral and radiating covered slits between most cup plates (except orals). C, Composite summit from several specimens showing central mouth (M), ambulacra leading to coelomic notches (CN) and arm facets (AF) (note that A-ray ones much larger than E-ray ones), or having ambulacral flooring plates present (B-ray, showing tiny sockets or pores, and D-ray), or with ambulacral cover plates in place (C-ray), posterior oral with zigzag slitlike hydropore (H) and depressed pore on aboral suture, 2 accessory orals (AO) extending slightly farther aborally than regular orals, crushed periproct (P), accessory pore (AP) at left, and lowest segmented cover on left side of A-ray arm, much enlarged. D, Summit of OU 9160 showing oral cover plates (OCP) in place over mouth plus curved and branched hydropore (H) in posterior oral, X5.5. E, Plate edge showing covered slits in *P. hudsoni*; note thin heart-shaped partitions between slits and high ridges covering slits (left), much enlarged. F, Plate edge showing covered slits in *P.* sp. (compare with Figure 46E); note wider slit spacing, larger partitions, and smaller ridges (left), much enlarged. G, Plate edge showing bundled covered slits in *P.* sp. cf. *P. planobasalis*; note small size of plate, closely spaced slits in raised bundle, and single opening to interior, much enlarged. H, Proximal stem near infrabasal (IB) attachment; note rounded star-shaped lumen (L) and cryptic pentamere sutures (PS), much enlarged. I, J, Relatively complete arms in OU 9153 and USNM 172034, respectively, showing somewhat irregular isotomous branching pattern, both approximately X1.3. K, L, Adoral and side views of proximal A-ray arm attached to radial (R) showing brachials (BR), 1 set of cover plates (CP) over fairly narrow food groove, large decrease in size before first branch, accessory plates in lower arm between brachials and cover plates, and segmented "covers" over interbrachial sutures, much enlarged.

tween arm facet and midpoint of OO. Notches elongate and elliptical (3.0 to 3.2 mm long and 0.5 to 0.6 mm wide) in rays B to E of a medium-sized specimen; much wider and elliptical to club-shaped (3.1 mm long and 1.4 mm wide) in short A-ray ambulacrum (Pl. 13, fig. 31; Fig. 46C). Ambulacral cover plates in 2 biserial series: a domed set of small alternating rectangular or pentagonal plates about 0.7 mm long and 0.6 mm wide, and a central set of tiny triangular plates about 0.3 mm long and wide interfingering above outer plates (Pl. 14, fig. 30-32; Fig. 46C). Hydropore a curved to parabolic-shaped, zigzagged or branching slit with apex adorally on aboral side of raised area near center of PO; hydropore usually about 1.0 mm long by 0.9 to 1.3 mm wide and with 5 to 7 zigzags or aboral branches (Pl. 13, fig. 9-11). Depressed elliptical area just aboral of hydropore may house porelike opening on PO-periproctal suture; a few specimens showing 4 to 5 tiny round or triangular cover plates over this pore (Pl. 13, fig. 6, 9). Another depressed pore or short groove on suture between DE oral and D radial near D-ray ambulacrum in nearly all examined specimens (Pl. 13, fig. 9-11; Fig. 46C); suture sometimes deflected at this pore.

Periproct an elliptical area inside ring formed by PO and 2 possible accessory OO, C and D radials, and anal X (Fig. 46B). Periproct made up of outer elliptical circlet of periproctal plates and central, nearly circular, anal cone made up of several circlets of elongate pyramid plates (Pl. 14, fig. 27, 32). Periproct 3.6 mm long by 5.2 mm wide in a cup 14.2 mm in diameter (Pl. 14, fig. 14). Outer circlet usually containing 7 to 11 small, polygonal, periproctal plates, 0 to 2 of these directly below PO between accessory OO (Fig. 46C, D). Outer circlet either complete or interrupted by edges of accessory OO. Anal pyramid developed as medium to high cone containing 3 to 5 rows of alternating, polygonal to tooth-shaped, anal pyramid plates; as many as 52 plates in a large cone 3.8 mm in diameter and extending 3.2 mm above summit (Pl. 14, fig. 26, 27). Pyramid plates becoming smaller up the cone, more elongate, with each distal tip projecting as small spine, perhaps imbricate at top; anus opening at top of cone (Pl. 14, fig. 24, 27).

Respiratory structures developed as exothecal slits appearing externally as raised ornamental ridges radiating from plate origins across most plate sutures. Respiratory slits developed across all major cup plate sutures except for IB-IB and usually R-O or other summit plates; normal specimen with 35 sets of covered slits. A few specimens showing 1 to 2 short covered slits across R-O sutures (Pl. 14, fig. 17). Usually 4 to 12 covered slits crossing each suture in large cup, fewer across IB-B suture than across B-B or B-R sutures. Only 3 to 4 covered slits present across sutures of smallest specimens (Pl. 14, fig. 4). Ridges usually separate but sometimes in slightly raised rhomb-shaped bundles crossing each suture (Pl. 14, fig. 7); central ridge (except on IBB) longest, almost reaching growth centers of both plates; lateral ridges on both sides sequentially shorter, centered on suture. Longest ridges lateral on each IB, ridges becoming shorter toward adoral tip of plate, essentially 2 half bundles per IB. Ridges usually reduced in number and size or sometimes even absent on posterior side of cup above IBB; greatest reduction on RA and adjacent parts of 4 surrounding plates (Pl. 14, fig. 6, 7). External ridges hollow, opening extending from sutural slit about two-thirds of ridge length toward plate center; sutural slits short, usually about 0.2 to 0.6 mm long on each plate, narrow, separated by heart-shaped segments of plate material (Fig. 46E). Ridge and slit spacing ranging from 0.40 to 0.58 mm/slit and averaging 0.47 mm/slit based on 28 measurements in 21 medium to large specimens and plates from the Lower Echinoderm Zone; in specimens from the *Carabocrinus* Beds, spacing ranging from 0.38 to 0.58 mm/slit and averaging 0.52 mm/slit based on 7 measurements in 3 specimens.

Cup plates relatively thin, usually 0.6 to 0.8 mm thick (not counting hollow ridges) in medium to large specimens, RR up to 1.6 mm thick beneath aboral end of arm facet. Sutures appearing smooth. Almost no other plate ornament beside hollow radiating ridges described above; where hollow ridges absent, single low ridge (perhaps solid) radiating from center of each plate to suture (Pl. 14, fig. 7).

Arms 5, relatively short, uniserial, branched several times, unequal in size. Longest preserved arm at least 15.6 mm long in badly crushed cup approximately 16 mm wide (Pl. 14, fig. 20); this C-ray arm branching 4 times (Fig. 46J); several other nearly complete arms also branching 4 times, but slightly smaller, somewhat abnormal arm showing 5 branches (Pl. 14, fig. 21). Arms probably three-quarters to one and one-half times cup length in most specimens. Arm branching apparently isotomous with some irregularity; branches at each bifurcation equal-sized. Primibrachs (IBrr) 1 to 4 (most commonly 2 to 3), rounded, unequal in size in different rays. A-ray IBrr usually about

one and one-half times as large as C- and D-ray IBrr, C- and D-ray IBrr slightly larger than B- and E-ray IBrr (Pl. 14, fig. 31). Large A-ray IBrr tapering very rapidly (Pl. 14, fig. 29), IBrr in other rays tapering slowly, size of all nearly equal at top of IBrr. In medium-sized specimen, A-ray IBr1 1.0 mm long by 3.0 mm wide by 3.6 mm deep with a 1.6 mm deep, narrowly U-shaped, adoral groove; C-ray IBr1 0.8 mm long by 2.3 mm wide by 3.0 mm deep; B-ray IBr1 0.7 mm long by 2.1 mm wide by 2.9 mm deep. Nonaxillary IBrr rectangular aborally, axillary IBr pentagonal and highly domed, lowest IIBr in each branch usually in contact medially (Pl. 14, fig. 20). Secundibrachs (IIBrr) 2 to 4 (most commonly 3), much smaller in width and depth than IBrr, but about as long, top one axillary with equal-sized branches not in contact. Tertibrachs (IIIBrr) 2 to 5 (rarely 1 or 8), about as long but only about two-thirds as wide and deep; may be terminal series in small specimens. Quartibrachs (IVBrr) ranging from 1 to 9, but 2 to 5 most common, smaller than preceding series; if branching further, axillary larger than Brr below (Pl. 14, fig. 21). Higher series only slightly smaller than preceding ones; VBrr 3 to 4 or 9 to 10 (tipped) in 2 specimens where complete (Fig. 46J); VIBrr 4 to 5 in 1 specimen. Terminal Brr relatively small and equidimensional, tapering over 2 to 4 Brr to a fairly blunt distal tip. Food groove relatively narrow, protected by 2 biserial sets (inner and outer) of tiny, domed, triangular, slightly imbricate, cover plates, with about 3/Br in each series. A large specimen (OU 9150) with 2 sets of accessory plates at base of very large A-ray arm (and perhaps C- and D-ray arms also), located between adoral edges of IBrr and cover plates (Pl. 14, fig. 26). Larger plates between each Br up to 1.3 mm long by 1.8 mm deep (decreasing distally); bearing adoral edge of Br cover. Smaller set at edge of cover plates, 0.7 mm long by 0.8 mm deep, disappearing distally before IIBrr; may continue flooring plates from ambulacrum on summit (Pl. 14, fig. 26). Lateral sutures between lower Brr depressed and shallow groove covered by highly elliptical domed covers (Pl. 14, fig. 23, 26, 29; Fig. 46K, L). Covers at base of large A-ray arm as much as 4.2 mm long, 0.4 mm wide, and 0.7 mm high; smaller in other arms and decreasing distally (absent above IIIBrr). Covers segmented along length into pieces 0.6 to 0.8 mm long; 6 to 8 segments in longest cover (Pl. 14, fig. 26; Fig. 46L).

Stem of unknown length, fairly small proximally, round in cross section. Longest preserved stem segment 13.4 mm long attached to cup 12.8 mm long (OU 9139; Pl. 14, fig. 8); diameter tapering slowly from 2.0 mm proximally to 1.7 mm distally. Proximal stem about 5.2 mm long in this specimen, composed of alternating rounded thicker and thinner columnals; medial stem at least 8.2 mm long, composed of equal-sized, thicker, slightly rounded columnals. Many other specimens have 1 to 4 proximal columnals still attached (Pl. 14, fig. 6, 7, 14, 28); these showing very cryptic pentameres and rounded star-shaped central lumen with radial projections about 0.6 to 0.7 mm across. Several cups showing proximal stem strongly curved, usually toward E or EA side (Pl. 14, fig. 7, 13). Type of attachment structure present distally unknown.

(Several abnormalities were noted in studied material. Two cups lack the RA; in one of these, the CD basal is large and supports the anal X; in the other, the anal X is larger and supported by normal CD and BC basals; Pl. 14, fig. 6, 9. Other specimens have abnormal IBrr, with split brachials—especially IBr1, see Pl. 14, fig. 18, 25—and additional plates added in the "V" above the IBr axil. One cup has the C and D IBB fused, but size and arrangement is otherwise nearly normal.)

Studied specimens.—Holotype USNM 112072, other figured specimens OU 9137-9161, 1280TX2, and USNM 172034; many unfigured specimens in OU, TX, USNM, and other collections. A total of 514 specimens were available for study. Sinclair's holotype is a medium-sized, slightly crushed, abraded, and rather poorly preserved cup from the Lower Echinoderm Zone at Daube Ranch. It shows general cup shape, plating, some covered slits, and one primibrach, but few summit structures are preserved because of severe abrasion of the left-posterior summit (Pl. 14, fig. 1-3).

Occurrence.—Found in the Lower Echinoderm Zone at Daube Ranch (178 specimens including the holotype), Amis Ranch (175 specimens), Lick Creek (144 specimens), Cornell Ranch (Tulip Creek) (13 specimens), Johnston Ranch (2 specimens), and Fittstown Quarry (1 specimen), and in the *Carabocrinus* Beds at North I-35 (3 specimens).

Discussion.—*Palaeocrinus hudsoni* is a fairly distinctive species that is now based on the largest sample for any species of this genus. As mentioned by Brower and Veinus (1974, p. 38), several groups of *Palaeocrinus* species are known; *P. hudsoni* belongs to a group characterized by an anal cone on the summit and separate covered ridges not grouped into bundles. Known members of this group include *Palaeocrinus angulatus*, *P. puchellus*, and perhaps *P. rhombiferous* and *P. avondalensis*. *Pa-*

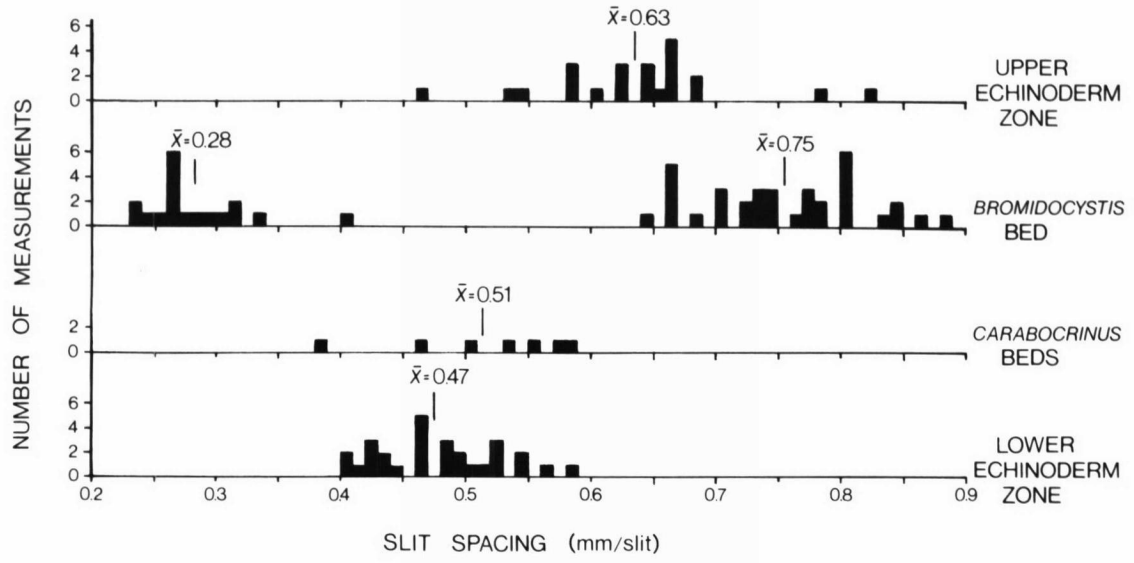


Fig. 47. Slit spacing in Bromide species of *Palaeocrinus*. Lower two plots, *P. hudsoni* in the Lower Echinoderm Zone and *Carabocrinus* Beds; note almost complete overlap in slit spacing values and similar means. Third plot from bottom, measurements for *P.* sp. cf. *P. planobasalis* (left) with tightly bunched slits and *P.* sp. (right) with wide slits from the *Bromidocystis* Bed. Upper plot, measurements for *P.* sp. from the Upper Echinoderm Zone where only this species has been found; despite only partial overlap in values and somewhat different means, *P.* sp. in these upper 2 zones is thought to be the same.

laeocrinus hudsoni differs from the first three of these by having many more covered slits crossing the plate sutures and from *P. avondalensis* by having shorter covered slits and a somewhat different cup shape. However, the anal structure is poorly known in many *Palaeocrinus* species and comparisons are difficult. *P. hudsoni* seems to show more asymmetry in its cup and arms than any other described species, but this observation may result from the large sample of well-preserved specimens studied here. The flattened area on the CD side of the cup and the reduction of covered slits in this area, seen in many specimens, may argue for a recumbent, tethered way of life, with this side resting on the muddy substrate (see similar arguments for *Hybocrinus* in Strimple, 1975b). Other asymmetrical features of the cup and the unequal arms in *P. hudsoni* would agree with this way of life.

Based on the spacing of covered slits, two closely related species of *Palaeocrinus* with unbundled slits appear to be present in the Mountain Lake Member of the Bromide, *P. hudsoni* in the Lower Echinoderm Zone (av. 0.47 mm/slit) and *Carabocrinus* Beds (av. 0.52 mm/slit) and *Palaeocrinus* sp. in the *Bromidocystis* Bed (av. 0.75 mm/slit) and Upper Echinoderm Zone (av. 0.64 mm/slit) (Fig. 47). Only the Lower Echinoderm Zone has a large number of complete *Palaeocrinus* specimens; all other beds and zones have only two to three complete specimens and/or plates. Specimens of *Palaeocrinus* from the Lower Echinoderm Zone and *Carabocrinus* Beds are very similar overall, the ranges in slit spacing are almost identical, and the averages for slit spacing are close enough that these specimens almost certainly belong to the same species, *P. hudsoni*. However, although similar in cup and covered slit morphology, specimens of *Palaeocrinus* from the *Bromidocystis* Bed and Upper Echinoderm Zone have much higher ranges and averages for slit spacing, probably implying they belong to a different species, here termed *Palaeocrinus* sp. There is little overlap of ranges in slit spacing between these two species. A third species, *P.* sp. cf. *P. planobasalis*, with distinctive bundled slits on the plates, is also present in the *Bromidocystis* Bed with *Palaeocrinus* sp.

The arms and ambulacra of *Palaeocrinus hudsoni* show several unusual features. This is the only species of *Palaeocrinus* known to have flooring plates in the ambulacral grooves on the summit, accessory plates extending up into the lower arms, arms of a single specimen differing greatly in size, and elliptical covers on the lateral sutures of the lower Brr. Some previously figured specimens of other species, such as the *P. planobasalis* figured by Brower and Veinus (1974, pl. 6, fig. 7), also show possible inequality of the arms based on the size of arm facets. Ubaghs (1978, p.

T179) noted the unusual presence of flooring plates in the ambulacra of *Hybocrinus conicus;* these appear very similar to those described here in *Palaeocrinus hudsoni.* Also, the elliptical covers in the lower arms of *P. hudsoni* are almost identical to the structures on the brachials of *Palaeocrinus angulatus* termed "spiny shelf-like lateral margins" by Brower and Veinus (1978, p. 452, pl. 16, fig. 3 and explanation). These covers are similar to the well-developed brachial covers in *Carabocrinus treadwelli,* which occurs with *Palaeocrinus hudsoni* in the Bromide. However, the brachial covers in *P. hudsoni* are smaller, more highly domed, and definitely segmented.

The unusual small summit pore between the DE oral and the D radial in *P. hudsoni* has not previously been reported in *Palaeocrinus,* although it may be present in the specimen of *P. planobasalis* figured by Brower and Veinus (1974, pl. 6, fig. 7). This same figured specimen also shows a curved hydropore in the middle of PO and a large accessory pore just aboral to it (misidentified as the hydropore by Brower and Veinus), similar to the arrangement in *P. hudsoni* described here. Finally, many specimens of *P. hudsoni* have a small, dark, stained area (a "black spot") on one side of the cup. This is probably a result of decaying organic matter accumulating in the bottom of the cup after death and before complete burial, but is not so strikingly developed as in the Bromide rhombiferans, where the "black spot" is usually much larger and darker.

PALAEOCRINUS sp.

Plate 14, figures 38-42; Figure 46F

Two complete but poorly preserved *Palaeocrinus* specimens (OU 9120, 21) and several plates from the Upper Echinoderm Zone as well as about 20 *Palaeocrinus* plates from the *Bromidocystis* Bed have an appreciably larger slit spacing than *P. hudsoni* from lower in the Mountain Lake Member. These apparently represent a separate species (or perhaps more than one), and are here grouped as *Palaeocrinus* sp. because of the limited material and poor preservation.

The two complete cups range from small, incomplete adorally, and slightly crushed to medium-sized and moderately crushed. The larger cup was originally about 13 mm long and 17 mm in diameter across the B and E rays, had moderate asymmetry, and was cup-shaped with a nearly flat summit (Pl. 14, fig. 39, 40). Plating arrangement and shapes are nearly identical to those in *P. hudsoni.* In the two complete cups, 3 to 8 separate covered slits are present across each plate suture; in separate plates, 4 to 13 slits are present. Slit spacing ranges from 0.64 to 0.88 mm/slit and averages 0.75 mm/slit, based on 35 measurements on 21 plates from the *Bromidocystis* Bed, and ranges from 0.46 to 0.82 mm/slit and averages 0.63 mm/slit, based on 23 measurements on two cups and eight plates from the Upper Echinoderm Zone (see Fig. 47).

Other cup similarities to *P. hudsoni* include the similar-sized stem facet with its rounded star-shaped lumen and the presence of a pore on the right aboral edge of the DE oral. Observed differences include: the lateral edges of the RR that converge adorally, the slightly narrower arm facets with longer and narrower coelomic notches, somewhat thicker plates (especially BB) with more robust edges between slits (Pl. 14, fig. 41; Fig. 46F), more elevated centers of many of the plates, and perhaps longer covered slits extending almost to the plate centers. Arms and stem of this species are unknown. The smaller cup has the C and D infrabasals fused, but otherwise in their normal position.

Discussion.—The rare specimens and more numerous plates of *Palaeocrinus* sp. from the *Bromidocystis* Bed and Upper Echinoderm Zone differ from *P. hudsoni* found lower in the Mountain Lake Member by having a much wider spacing of covered slits; other more minor differences are somewhat thicker plates, longer slits, and narrower arm facets. The slit spacing of specimens from the Upper Echinoderm Zone overlaps that of *P. hudsoni* somewhat, but the mean values are quite different (0.63 mm/slit and 0.48 mm/slit; see Fig. 47). Plates from the *Bromidocystis* Bed have an even higher mean value for slit spacing (0.75 mm/slit) and show no overlap at all with *P. hudsoni.* Specimens of *Palaeocrinus* sp. from these two beds show many morphological similarities and considerable overlap in their slit spacing although their means differ (0.63 mm/slit and 0.75 mm/slit). These two populations are here grouped as one unnamed species. *Palaeocrinus* sp. occurs in the *Bromidocystis* Bed with another species of *Palaeocrinus* (*P.* sp. cf. *P. planobasalis)* which has closely spaced, bunched slits; perhaps the unusually large slit spacing of *Palaeocrinus* sp. in this bed represents an example of character displacement to decrease morphologic

similarity between closely related competing species.

PALAEOCRINUS sp. cf. P. PLANOBASALIS
Brower and Veinus, 1974

Plate 14, figures 36, 37; Figure 46G

Nine small separate plates from the *Bromidocystis* Bed (1393TX18 from North-Central I-35 and 1397TX59-66 from Daube Ranch) belong to a *Palaeocrinus* species closely resembling *P. planobasalis* from the Benbolt and associated formations in Virginia and Tennessee. These plates include several BB ranging up to 7.5 mm long by 8.0 mm wide, several RA, and a radial 6.0 mm long by 7.0 mm wide. They are similar in shape to those of other Bromide species of *Palaeocrinus* except that they are relatively small, the lateral edges of the radial appreciably converge adorally, and the plate (although overgrown internally with epitaxial calcite) appears thicker than those of *P. hudsoni* (but similar to those of *Palaeocrinus* sp.). The covered slits crossing the center of each plate suture are grouped into raised bundles extending one-half to two-thirds of the distance in toward the plate center (Pl. 14, fig. 36, 37). Between 3 and 12 slits cross each suture, and slit spacing ranges from 0.23 to 0.40 mm/slit and averages 0.28 mm/slit (see Fig. 47) based on 19 measurements from all 9 plates. The sutural opening to the coelomic cavity ranges from 0.5 to 1.2 mm wide. Slit spacing is more difficult to interpret in this species because in some bundles the lateral slits are almost horizontal, thus increasing the apparent spacing. A few plates have low ridges beside the raised bundles that lack slits.

Discussion.—This distinctive species with its bundled slits is quite unlike other Bromide species of *Palaeocrinus*, but similar to *P. planobasalis* described by Brower and Veinus (1974) from the Benbolt Formation of Virginia and Tennessee. Unfortunately, cup shape, tegmen features, and arm and stem morphology are all unknown in the Bromide species. *Palaeocrinus planobasalis* from the Benbolt has somewhat larger cup plates, more covered slits (up to 22 per suture) in large individuals, and a more angular arm facet on the radials. However, slit spacing and morphology are very similar in these two forms; based on measurement of 6 figures in Brower and Veinus (1974), slit spacing in *P. planobasalis* ranges from 0.24 to 0.38 mm/slit and averages 0.32 mm/slit, values that are very close to those measured in Bromide plates. The small size of the Bromide specimens compared to *P. planobasalis* from the Benbolt might have resulted from either environmental factors or competition with specimens of *Palaeocrinus* sp., which also occurs in the *Bromidocystis* Bed and has much larger plates.

Family POROCRINIDAE Miller and Gurly, 1894

Genus POROCRINUS Billings, 1857

Type species.—*Porocrinus conicus* Billings, 1857.

Diagnosis.—Cup conical to ovoid; IBB wide, small tetragonal RA supporting larger anal X, no accessory anals or orals present; circular to triangular goniospires bearing numerous three-cornered endothecal folds present at most plate corners; proximal stem greatly enlarged; arms atomous, fairly long.

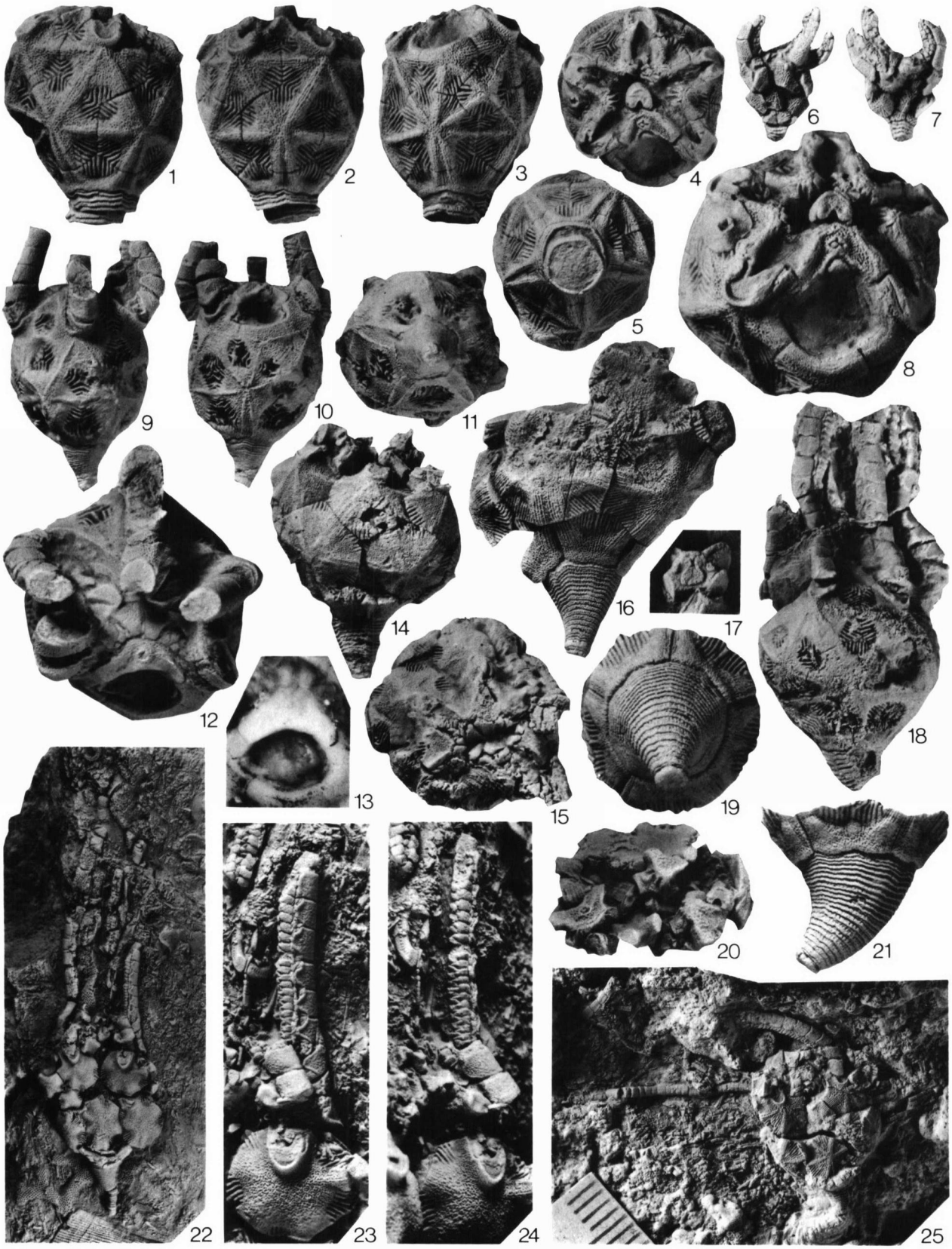
Occurrence.—Middle to Late Ordovician, northern Canada, eastern, north-central, and south-central United States, and Scotland.

Discussion.—*Porocrinus* (many folds in goniospires) and *Triboloporus* (2 folds in goniospires) are the only genera now assigned to the family Porocrinidae. They are nearly identical in calyx and proximal stem morphology except for the differently developed goniospires. *Porocrinus* differs from other genera in the families Sphaerocrinidae and Carabocrinidae by having a single radianal and no accessory anal or oral plates, wide infrabasals plus an enlarged proximal stem, atomous arms, and endothecal three-cornered goniospires over most of the calyx. A new species of *Porocrinus* is present in the Pooleville Member of the Bromide Formation.

POROCRINUS BROMIDENSIS Sprinkle, n. sp.

Plate 15; Figure 48

Diagnosis.—Cup rounded conical to ovoid with slight to moderate asymmetry, calyx L:W averaging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1.1; plates weakly to moderately ridged with slightly domed centers; goniospires fairly large, slightly depressed, almost circular, and usually with 6 to 11 folds per plate; IBB two-thirds as high as wide; arm facets fairly small, slightly longer than wide; proximal stem short, rapidly expanding, nearly round; distal stem small.

Description.—About 20 partly or nearly complete specimens and a few additional separate plates available for study; many specimens with the proximal stem, some with arms. Specimens ranging from very small to medium in size; cup in smallest specimen 2.9 mm long, in largest specimen about 15 mm long (both crushed). Cup rounded conical to ovoid in shape with length slightly greater than width; calyx L:W ratio in 5 well-preserved specimens ranging from 1.0 to 1.2 and averaging 1.1; stem attachment at base wide and flat, summit broadly rounded. Maximum width just above mid-height near top of BB circlet or base of RR circlet. Cup slightly to moderately asymmetric with centers of RA and anal X raised (Pl. 15, fig. 3-5). Specimens showing fair amount of variation in cup shape and asymmetry, goniospire size, plate shape, and ornament, but complete gradation between end members present and only one species thought to be present in this material.

Infrabasals (IBB) 5, small, in closed circlet around wide stem facet. In holotype, each infrabasal 1.7 mm long and 2.8 mm wide; IBB L:W 0.61. IBB all pentagonal in shape externally, with hidden triangular projection to center of stem facet. Edge of stem facet on IBB slightly sinuous externally with a small overhang. Each IB sharing a single goniospire with 2 overlying BB.

Basals (BB) 5, large (equal to or slightly larger than RR), in a closed circlet in middle of calyx. In holotype, BB averaging 4.6 mm long and 4.2 mm wide; BB L:W 1.1. Most BB hexagonal, but BC and CD BB septagonal because of small RA diagonally above (Fig. 48B). Each BB with a goniospire at each of the 5 to 6 plate corners (all except B-IB-IB).

Radials (RR) 5, large, in an open circlet (interrupted by anal X) at top of cup. In holotype, RR averaging 4.2 mm long by 4.4 mm wide; RR L:W 0.97. Most RR hexagonal with a central coelomic notch just adoral of the arm facet (Fig. 48C), but C and D RR septagonal with 20 to 25 percent of periproctal margin; C radial slightly raised above level of others. RR with 4 to 5 medium-sized goniospires at all corners except adjacent to periproct (Fig. 48B). Arm facets fairly small, hemielliptical, raised above RR surface; in holotype each facet 1.6 mm long by 1.5 mm wide, with arm facet L:W 1.1. Each facet only about 36 percent of RR width, facets directed outward at about 45° (Pl. 15, fig. 9, 10).

Radianal (RA) a small diamond-shaped (tetragonal) plate above and between BC and CD basals; RA equally supporting C radial and anal X above. In holotype, RA 2.9 mm long and wide, the most highly bulged plate in cup, with fairly small goniospires at all 4 corners. Anal X a medium-sized pentagonal plate interrupting RR circlet in CD interray (Fig. 48B). In holotype, anal X 2.5 mm long by 3.0 mm wide, with a considerable bulge (Pl. 15, fig. 4). Anal X forming lower central 25 to 30 percent of periproct (Pl. 15, fig. 8), usually with 3 goniospires on lower corners.

PLATE 15.

Fig. 1-25. *Porocrinus bromidensis*, n. sp., upper Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 1-5, 8 from 5.5 to 7.0 m below the Viola Limestone at Rock Crossing; 6, 7, 14, 16-18, 20, 25 from Zone 3 at Culley Creek; 9-13, 15, 19, 21-24 from 4.5 m below the Viola Limestone at Rudd Quarry. 1-5, 8. B, EA, CD, summit, basal, and oblique summit views of holotype OU 9091 showing slightly asymmetrical cup shape, goniospires, enlarged proximal stem with small lumen and large depressed areola (5), and circular groovelike hydropore and periproct surrounded by only 4 plates on posterior summit (8); all X3.5, but 8, X5. 6, 7. A and CD side views of tiny paratype OU 9104; note typical plating and tapering proximal stem, absence of goniospires, and only 3 short but complete arms; X4.2. 9-13. A, CD, enlarged basal, enlarged summit, and immersed periproctal views of paratype OU 9094 showing ovoid cup shape, proximal arms, small ambulacral and larger paired oral cover plates (12), and poorly preserved anal pyramid crushed into periproct (13); X3 (9-11), X3.5 (12), X5 (13). 14, 17. Side view plus greatly enlarged view of adoral edge of oral on summit of paratype OU 9092; note cup shape and tongue-shaped attachment area for oral cover plates at edge of mouth; X3, X6. 15. Summit view of paratype OU 9095 showing ambulacral and paired oral cover plates between orals; X3. 16. Side view of paratype 1122TX103; note well-preserved proximal stem attached to IBB and aligned porelike ornament on plate ridges; X3. 18. Side view of paratype 1122TX102 showing circular goniospires and attached atomous arms; X3. 19, 21. Basal and side views of proximal stem and IBB on crushed and mostly disarticulated paratype OU 9099; note tight sutures, rapid taper and curvature of proximal stem, and small size of distal stem; X5. 20. Summit of mostly disarticulated paratype OU 9100 showing PO with hydropore at left and adoral edge of other orals, which differ somewhat from 17; X5. 22-24. BC side view plus enlarged side and adoral views of well-preserved arm in paratype OU 9105; note crushed cup, part of distal stem (22), brachials, biserial cover plates, and hemielliptical areas with accessory plates ("?covers") on proximal arms (23, 24); X1.5 (22), X4 (23, 24). 25. CD side view of paratype 1405TX8 (Watkins Coll.) showing part of distal stem and 2 partial arms (top and upper left); X2.

Orals (OO) 5, small, in closed circlet around central mouth; regular OO plus differently shaped posterior oral (PO). Regular OO modified pentagonal with a concave surface; in holotype, each oral 2.3 mm long by 2.1 mm wide and with 1 goniospire on aboral corner shared with 2 RR, coelomic notches and food grooves laterally, mouth at adoral edge (Fig. 48C). PO boomerang-shaped to triangular, with 6 sutures; in holotype, PO 2.2 mm long by 3.0 mm wide, with concave margin aborally for periproct (25 to 30 percent), 2 small sutures with C and D RR (but no goniospires), coelomic notches and food grooves laterally, mouth adorally (Fig. 48B; Pl. 15, fig. 8). Small curved or V-shaped depression in center of aboral side of PO (Pl. 15, fig. 8, 10), probably attachment point for plates of periproctal membrane. Coelomic notches rounded triangular openings about 2.0 mm long by 0.9 mm wide adorally through bottom of food groove into coelomic interior. Food grooves covered by ?2 sets of tiny, biserial, arched, cover plates (Pl. 15, fig. 15).

Central mouth an elongate pentagonal opening 1.6 mm long by 2.3 mm wide surrounded by adoral ridged edges of OO. Three vertical grooves surround 2 shallow depressions on adoral edge of each OO (Pl. 15, fig. 17, 20); these probably supporting large, tongue-shaped, paired oral cover plates (Fig. 48D; Pl. 15, fig. 12, 15) similar to those shown for *Triboloporus xystrotus* (Kesling and Paul, 1968, p. 18), but not previously illustrated in *Porocrinus*. Ten oral cover plates apparently present over mouth, 2 attached to each oral, averaging about 1.3 mm long. Hydropore a small (0.2 to 0.4 mm) raised area in center of PO about 1.0 mm from edge of mouth (Pl. 15, fig. 8, 12), consisting of an inverted U-shaped or circular groove around a tiny central boss (Fig. 48C).

Periproct a roughly elliptical, medium-sized opening at edge of summit (Fig. 48A); surrounded by anal X below, C and D RR laterally, and PO above, each making up roughly equal parts of margin (Fig. 48C). No accessory OO or anals present around periproct. In holotype, periproct 3.0 mm long by 3.4 mm wide; anal pyramid preserved in only one paratype (OU 9094), crushed into interior. This specimen showing single row of small rectangular periproctal plates surrounding central anal pyramid about 1.6 mm in diameter and composed of 9 to 10 spear-shaped plates (Pl. 15, fig. 12, 13).

Goniospires three-cornered, fold-bearing, endothecal structures on corners of most cup plates; 22 goniospires present in a normal specimen (Fig. 48B). Most goniospires fairly large, nearly circular, and slightly to moderately depressed below plate centers; in holotype, goniospires in lower and middle of calyx about 2.0 mm in diameter, but goniospires smaller (1.5 to 1.8 mm in diameter) around RA and on edge of regular OO (Pl. 15, fig. 9). Number of folds per plate in a normal goniospire ranging from 2 to 14, but most medium-large specimens with 6 to 11 folds. Folds apparently extending directly downward into coelomic cavity about 0.7 mm and bending about 60° at each plate suture (Fig. 48F); downward-projecting folds and upward-projecting ridges apparently equally developed. Triangular central ridge and long adjacent folds in goniospire apparently first-formed; newest-formed folds and ridges shortest lateral ones on plate sutures. Smallest specimen (Pl. 15, fig. 6, 7) lacking goniospires, small goniospires in other small calyces with only 2 to 4 folds. A few specimens with goniospires stained black by ?organic material.

Most cup plates (except regular OO) convex in cross section with much variation in ridging. Some specimens with fairly large goniospires separated by thin raised ridges (about 1.0 mm thick) between relatively small plate centers and around stem facet and periproct (Pl. 15, fig. 1-3, 16). Others with large strongly domed centers about 1.2 mm thick with smaller goniospires (Pl. 15, fig. 9, 10, 14, 18); distinct ridges not so well developed in these specimens. Domed plate centers and radiating ridges usually ornamented with fine to medium pits (probably external expression of internal stromal canals); pits often arranged in rows along ridges and adjacent to where goniospire slits begin (Pl. 15, fig. 1, 16). Brachials and proximal stem also showing slight rugose ornament.

Arms 5 (except in smallest specimen); fairly long, atomous, uniserial. Arms extending at least 28 mm from top of large cup, although not continuously exposed or preserved (Pl. 15, fig. 22). Brachials (Brr) small, hemielliptical in cross section, about 1.3 mm long by 1.4 mm deep (from ambulacral groove to back) by 1.2 mm wide (across food groove face) (Pl. 14, fig. 23). Food groove adoral, deeply V-shaped proximally (apparently becoming shallower distally), about 0.7 mm deep by 0.5 mm wide, protected by a ?single biserial set of highly domed cover plates with projections (or a tiny central set of accessory plates) intermeshing and possibly slightly imbricate (Pl. 15, fig. 23, 24); about 4 cover plates per Br. Interbrachial sutures slightly curved and oblique, proximal Brr with small wedge-shaped gaps on ad-

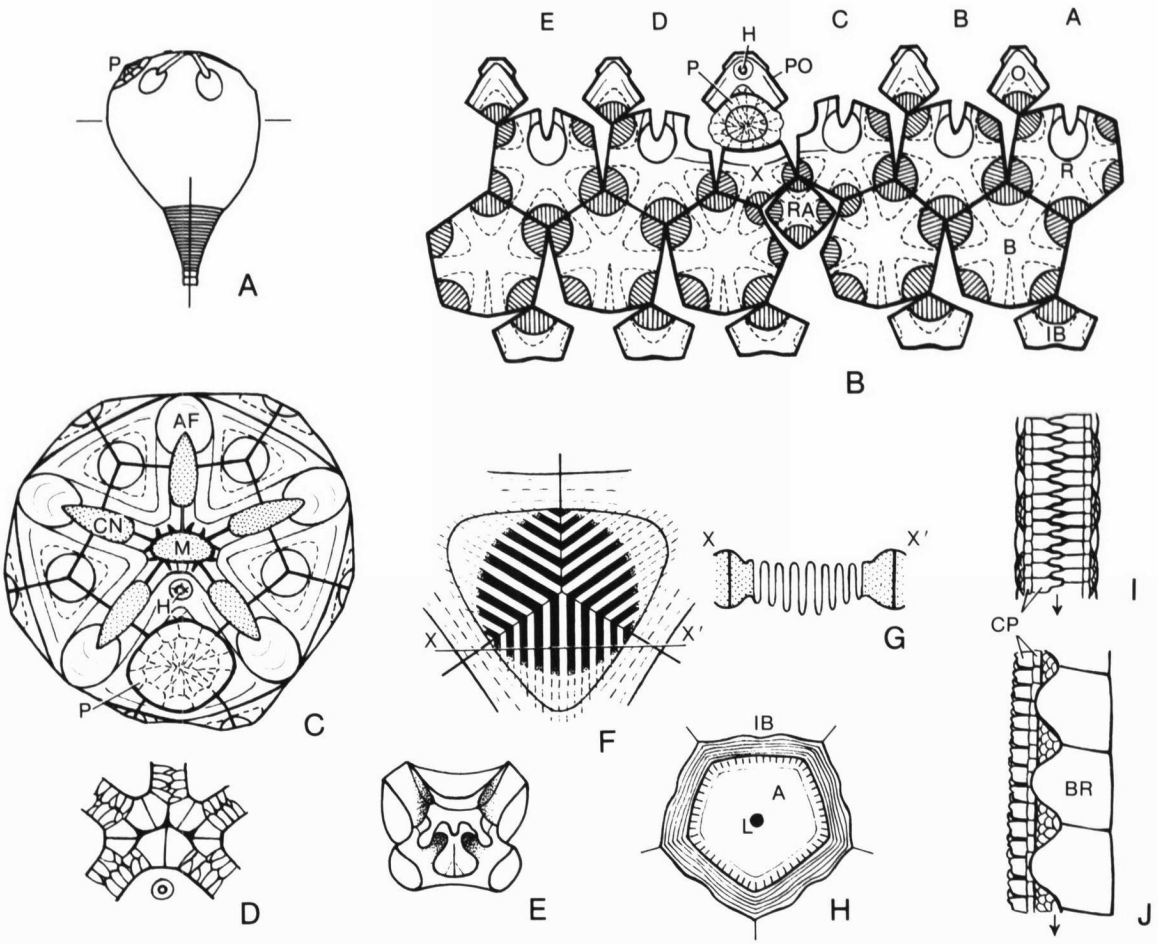

Fig. 48. *Porocrinus bromidensis* Sprinkle, n. sp., Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma. A, Outline of calyx showing ovoid shape, bulging of posterior side below periproct (P), maximum diameter (short lines), and greatly enlarged proximal stem grading rapidly into small distal stem. B, Side-layout plating diagram showing short infrabasals (IB) with large stem facet, 5 basals (B) in complete circlet, 5 radials (R) with equal-sized arm facets, symmetrical orals (O) around mouth, relatively small radianal (RA) supporting anal X (X) on posterior side, and posterior oral (PO) with raised hydropore (H) forming adoral edge of periproct (P) with no accessory orals; note distribution of goniospires at plate corners (nearly everywhere except around periproct) and strengthening ridges on cup plates (dashed lines). C, Summit view based mostly on holotype OU 9091 showing central mouth (M), equal-sized coelomic notches (CN) just adoral to arm facets (AF), hydropore (H) in posterior oral developed as circular slit with small extensions, and only 4 plates around periproct (P), much enlarged. D, Composite reconstruction of oral region showing small ambulacral and larger, lappet-shaped oral cover plates in place, much enlarged. E, Adoral edge of BC oral in paratype OU 9092 showing attachment facets for oral cover plates; orals in other specimens show different morphology, X9.1. F, Outside, and G, cross section of goniospire at plate corner showing folds, shape, and ornament and ridges on adjacent plates, much enlarged. H, Stem facet short distance down proximal stem from infrabasal (IB) attachment; note shape, small lumen (L), and large flat areola (A). I, Adoral and J, side views of proximal arm showing brachials (BR), 2 sets of cover plates (CP) over wide food groove, and flat, tiny-plated areas (possible "covers") between brachials, much enlarged.

oral lateral edges covered with tiny plates similar to covers found in *Carabocrinus* (Fig. 48J). Smallest specimen (OU 9104; Pl. 15, fig. 6, 7) with only 3 short arms (each with 4 Brr); no arms or facets present on B and E RR.

Stem strongly differentiated into short, greatly enlarged, proximal region directly beneath calyx and longer, small-diameter, distal (or medial) region of unknown length. Proximal stem conical in shape, usually slightly to moderately curved, composed of numerous, very thin, nearly circular to rounded pentagonal columnals (Pl. 15, fig. 21); proximal stem continuing taper of lower cup. In largest complete paratype (Pl. 15, fig. 16), proximal stem 3.3 mm long with 17 columnals and tapering from 3.5 mm in diameter at stem facet to 1.1

mm at distal tip. For all 9 specimens with complete proximal stems, proximal stem L:W ranging from 0.81 to 1.19 and averaging 1.04. Proximal columnals circular to rounded pentagonal in different specimens, with slight granular ornament and straight to slightly wavy sutures matching any undulations at stem facet on IBB. Proximal columnals nearly solid in cross section with a small central lumen (0.2 mm in diameter in a 3.0 mm columnal); no evidence of pentameres in proximal stem (Fig. 48H). Three specimens showing incomplete distal stems ranging up to 5.4 mm long (Pl. 15, fig. 22, 25) and having differently shaped and thicker columnals. Distal stem 3.2 mm long in best specimen and tapering slowly from 1.2 mm proximally to 1.0 mm at preserved tip; 14 to 15 convex columnals present showing irregular alternation between thicker and thinner columnals (Pl. 15, fig. 22). Distal stem also appearing to have one-piece columnals with a small lumen.

Etymology.—Named for the Bromide Formation in southern Oklahoma, the only place where this species has been found.

Studied specimens.—Holotype OU 9091, paratypes OU 9092-9105 (mostly Graffham Coll.), 1122TX102-104 (Graffham Coll.), 1281TX12, 1405TX8 (Watkins Coll.), and USNM 172033 (Graffham Coll.).

Occurrence.—Found in the upper Pooleville Member, Bromide Formation, at Culley Creek (10 specimens, mostly from Zone 3, 9 to 10 m below the Viola), at Rudd Quarry (7 specimens from 4.5 m below the Viola), at Rock Crossing (3 specimens and a plate from 5.5 to 7 m below the Viola), and at Dunn Quarry (1 specimen from 3 m below the Viola), all in the Criner Hills, southern Oklahoma.

Discussion.—At least 10 species of *Porocrinus* have already been described and are considered valid (see Kesling and Paul, 1968). Although *P. bromidensis* is known to be a variable species in some features because of the fairly large sample size, it can be separated from other described species using calyx shape, plate morphology and ornament, IBB shape, goniospire development, and proximal stem length. *P. bromidensis* has a rounded-conical to ovoid calyx shape with calyx L:W above 1; this is shared by *P. conicus*, *P. elegans*, *P. smithi*, *P. shawi*, *P. pyramidatus*, *P. petersenae*, and *P. scoticus*. In plate morphology and ornament, *P. bromidensis* has either low ridges or domed plate centers, both with small pores or granules. Several species are similar, including *P. pentagonius*, *P. elegans*, *P. fayettensis*, *P. pyramidatus*, and *P. scoticus;* other forms have plates that are either smooth and nearly flat or highly ridged. *P. bromidensis* has fairly large, nearly round goniospires with 6 to 11 slits on each plate corner; many other *Porocrinus* species have about the same slit number, but only *P. pentagonius*, *P. elegans*, and *P. fayettensis* have goniospires with a similar shape. The short IBB in *P. bromidensis* are shared by most other *Porocrinus* species except *P. conicus* and *P. scoticus*. The short proximal stem in *P. bromidensis* differs from that of most other species in which the stem is known except *P. elegans* and perhaps *P. crassus*.

Based on the above review, *P. bromidensis* is probably most closely related to the somewhat younger *P. elegans* Kesling and Paul (1968), which has similar calyx shape, plate ornament, goniospires, IBB shape, and proximal stem. However, the goniospires in *P. bromidensis* remain more nearly the same size instead of becoming considerably smaller toward the calyx summit, and *P. bromidensis* has a hydropore on PO instead of a more complex madreporite. *P. bromidensis* does not seem very closely related to any other *Porocrinus* species. It is also one of the oldest species of *Porocrinus* now known, either slightly older or about the same age as *P. pentagonius* from the Platteville and Galena groups in northern Illinois (Kolata, 1975) and in southern Minnesota (Brower and Veinus, 1978).

Several recent authors have commented on the unusual proximal stem morphology of *Porocrinus*, and have compared it with the enlarged, imbricate, proximal stem found in many rhombiferan cystoids. Kesling and Paul (1968, p. 1) stated that the proximal stem in *Porocrinus* "appears to have been highly flexible with a large lumen," and Kolata (1975, p. 28) stated "proximal stem . . . [has] large central lumen, columnals telescopically imbricating . . .." However, figures in both of these papers show that the stem facet or proximal columnal has a very small lumen (Kesling and Paul, 1968, pl. 4, fig. 4, 9, pl. 8, fig. 4, 8; Kolata, 1975, pl. 4, fig. 3). *P. bromidensis* also shows a small central lumen in the proximal stem, surrounded by a slightly depressed areola (Pl. 15, fig. 5), which in life was probably occupied by a thin pad of muscular or ligamental tissue. *Porocrinus* also lacks the alternation of larger and smaller columnal types and the paired hinges for flexibility found in the proximal stems of most rhombiferans.

These differences probably imply that the superficially similar enlarged proximal stems of *Porocrinus* and many rhombiferans functioned in different ways. A large percentage of the complete

cups of *P. bromidensis* have part or all of the proximal stem still attached (60 percent), in comparison to cups lacking the stem (25 percent) or cups having both the proximal and distal stem attached (15 percent). Also many of these short attached proximal stems are curved through an angle of 30 to 90° to the calyx axis (Pl. 15, fig. 18, 21). These morphologic and preservational features imply that the enlarged proximal stem in *Porocrinus* was not capable of active or rapid flexing movements and was probably quite stiff and curved through a considerable angle most of the time. It is still not certain whether *Porocrinus* was a normal, rheophilic, low- or medium-level suspension feeder tilted over in the water column or whether it sat on the bottom with the calyx held upright by the curved proximal stem and with the distal stem recumbent.

CAMERATES

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The Bromide Formation of southern Oklahoma contains one of the most abundant, diverse, and well-preserved Ordovician camerate crinoid faunas known. Nineteen species representing ten genera and five families are described herein. One unusual species representing a new family is described by Sprinkle and Kolata in a separate chapter. Except for one monocyclic camerate species, all of the crinoids are dicyclic. Thirteen of the species belong to the family Rhodocrinitidae. The rest are distributed among the Cleiocrinidae, Reteocrinidae, Anthracocrinidae, and Glyptocrinidae. All species and four of the genera are restricted to the Bromide of southern Oklahoma.

This fauna provides much information on the early evolution of the camerate crinoids. In addition, the unusual abundance of specimens makes possible a better understanding of the variation and ontogeny of many species.

Occurrence.—The camerate crinoids occur primarily in three thin stratigraphic units in the Bromide Formation: the Upper and Lower Echinoderm Zones of the Mountain Lake Member and Echinoderm Zones 1 through 5 in the upper part of the overlying Pooleville Member (Table 28). Isolated specimens occur in other parts of the section, but they are relatively uncommon. With few exceptions, each species is restricted to one of the three stratigraphic units. The species are also somewhat restricted in their distribution within the Arbuckle Mountains and nearby Criner Hills.

In the Lower Echinoderm Zone of the Mountain Lake Member, *Diabolocrinus arbucklensis* is probably the most abundant and widespread camerate crinoid, with over 90 collected specimens. It was found to be especially abundant at the Daube Ranch locality, and is represented by specimens from Lick Creek, Amis Ranch, and I-35. *Archaeocrinus conicus* is represented by about two dozen specimens from Fittstown Quarry and Roadcut. Other less common species from the Lower Echinoderm Zone include *Archaeocrinus buckhornensis*, *Bromidocrinus nodosus*, camerate species A, *Cleiocrinus bromidensis*, and *Reteocrinus depressus*. *Cleiocrinus bromidensis* is the only species found in other parts of the Bromide Formation. It also occurs in the Upper Echinoderm Zone of the Mountain Lake Member and in the upper part of the Pooleville Member, where it is most abundant.

Camerate crinoids are relatively uncommon in the Upper Echinoderm Zone of the Mountain Lake Member. Six species are represented: *Cleiocrinus bromidensis*, *Archaeocrinus buckhornensis*, *Archaeocrinus* sp., *Diabolocrinus constrictus*, *Paradiabolocrinus stellatus*, and *Colpodecrinus quadrifidus* (described in the next chapter). One questionable specimen of *D. arbucklensis* was also found in the Upper Echinoderm Zone.

The upper part of the Pooleville Member contains the most abundant and diverse camerate crinoid fauna in the Bromide Formation. All species are restricted to the Criner Hills. Dominant is *Archaeocrinus subovalis* Strimple (1953b); more than 180 specimens of this species have been collected. It occurs in Echinoderm Zones 1 through 5 but is especially abundant in Zone 1. Other relatively common species include *Anthracocrinus primitivus* Strimple and Watkins (1955), *Diabolocrinus poolevillensis*, and *Pararchaeocrinus decoratus* Strimple and Watkins (1955), all of which are most abundant in Zones 3 through 5. The less common species include *Abludoglytocrinus laticostatus*, *Cleiocrinus bromidensis*, *C. ornatus*, *Crinerocrinus parvicostatus*, *Diabolocrinus oklahomensis*, *Pararchaeocrinus?* sp., and rhodocrinitid species A.

Faunal comparisons.—Rhodocrinitids dominate the Bromide camerate fauna both in number of species and number of specimens collected. Six genera, two of which are new, and 13 species are now known to occur in these rocks, more than twice as many rhodocrinitid species as have been recorded from any other Middle Ordovician locality.

None of the Bromide camerate crinoid species are known outside Oklahoma; therefore, comparisons of this fauna with Middle Ordovician camerates from other localities must be based mainly on similarities and differences at the generic and family levels. The Bromide camerates show greatest

Table 28. Stratigraphic distribution of camerate crinoids in the Bromide Formation.

	Bromide Formation		
	Mountain Lake Member		Pooleville Member
	Lower Echinoderm Zone	Upper Echinoderm Zone	Pooleville Echinoderm Zones 1 to 5
Abludoglyptocrinus laticostatus, n. gen. and sp.	-	-	X
Anthracocrinus primitivus Strimple & Watkins	-	-	X
Archaeocrinus buckhornensis, n. sp.	X	X	-
Archaeocrinus conicus, n. sp.	X	-	-
Archaeocrinus subovalis Strimple	-	-	X
Archaeocrinus sp.	-	X	-
Bromidocrinus nodosus, n. gen. and sp.	X	-	-
Camerate species A	X	-	-
Cleiocrinus bromidensis, n. sp.	X	X	X
Cleiocrinus ornatus, n. sp.	-	-	X
Colpodecrinus quadrifidus, n. gen. and sp.	-	X	-
Crinerocrinus parvicostatus, n. gen. and sp.	-	-	X
Diabolocrinus arbucklensis, n. sp.	X	?X	-
Diabolocrinus oklahomensis, n. sp.	-	-	X
Diabolocrinus poolevillensis, n. sp.	-	-	X
Diabolocrinus constrictus, n. sp.	-	X	-
Pararchaeocrinus decoratus Strimple & Watkins	-	-	X
Pararchaeocrinus? sp.	-	-	X
Paradiabolocrinus stellatus, n. sp.	-	X	-
Reteocrinus depressus, n. sp.	X	-	-
Rhodocrinitid species A	-	-	X

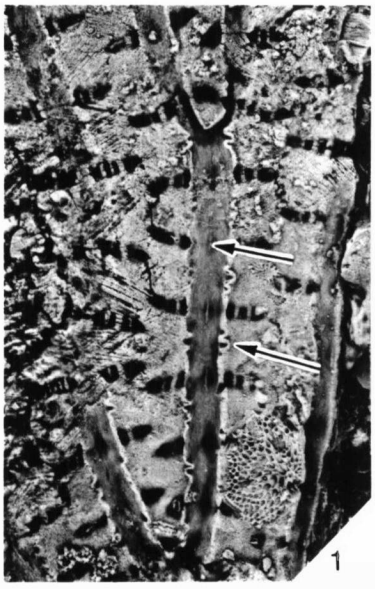
similarity to camerates from the Middle Ordovician Benbolt and allied formations of southwestern Virginia and eastern Tennessee. Both faunas are well-represented by *Diabolocrinus*, *Paradiabolocrinus*, *Archaeocrinus*, *Pararchaeocrinus*, and *Cleiocrinus*. Further, the species of each of these genera indicate a close relationship between the two faunas. *Diabolocrinus arbucklensis* and *D. poolevillensis* are similar to *D. vesperalis* (White, 1880), and *Archaeocrinus conicus* is very similar to *A. peculiaris* Miller and Gurley (1894). At present, *Paradiabolocrinus* and *Pararchaeocrinus* are known only from the Oklahoma and the Virginina-Tennessee localities. Both Benbolt and Bromide camerates are characterized by low, massive calyces with thick, robust plates, which suggest that both faunas adapted to very similar environments.

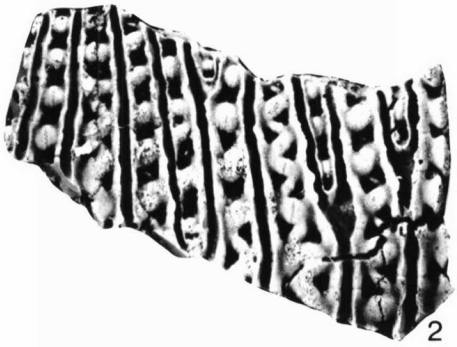
The Bromide camerates also show some taxonomic affinity to camerates from the Middle Ordovician Black River and Trenton groups of southern Ontario, Canada, particularly in such congeneric forms as *Archaeocrinus*, *Cleiocrinus*, *Reteocrinus*, and *Abludoglyptocrinus*.

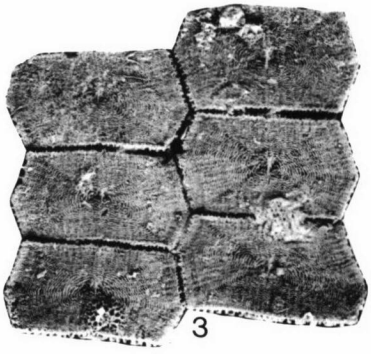
The Middle Ordovician crinoid fauna of the Platteville and Galena (lower part only) groups of northern Illinois and southern Wisconsin, as presently known, has only two genera in common with the Bromide fauna, *Reteocrinus* and *Abludoglyptocrinus*. The most obvious difference between these two faunas is the lack of rhodocrinitid genera in the Illinois-Wisconsin area.

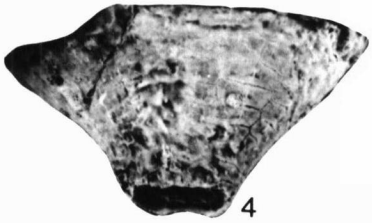
Of the camerate crinoids recorded from Upper Ordovician Girvan district of southwestern Scotland, *Diabolocrinus* is the only genus also present in the Bromide.

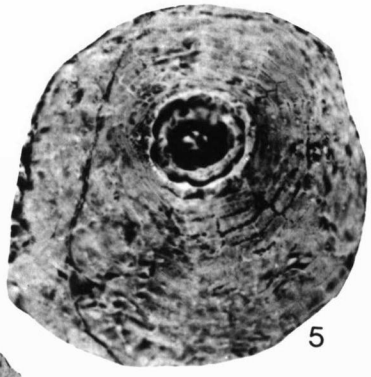
Terminology and measurements.—The morphological terms and abbreviations used in this study generally follow those used in Part T of the *Treatise on Invertebrate Paleontology*, except that the term interradial, rejected in the *Treatise*, is retained herein. Interradial is defined as the interray plate(s) that lies between the radials and is in contact with a basal. Measurements of the aboral cup and individual plates within the cup are given in most descriptions. Because plates tend to vary slightly in size, an attempt was made to measure the largest plate in a circlet or series. Measuring the same plates on all specimens was impossible because many crinoids were either incomplete or not completely removed from the matrix.

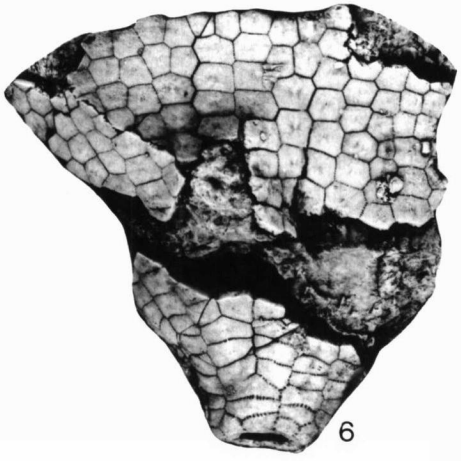


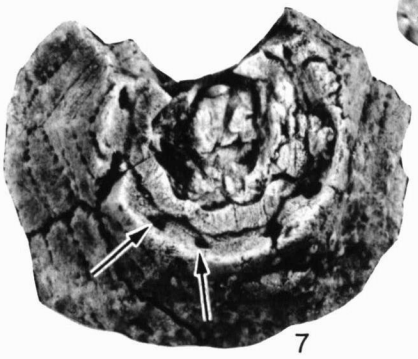


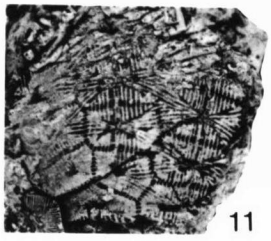


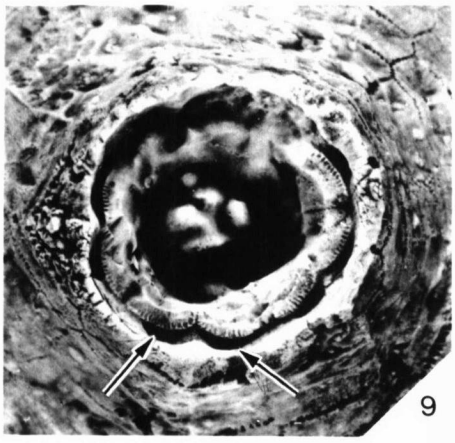


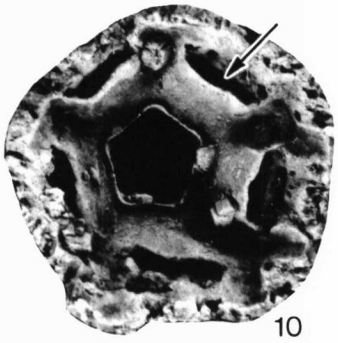


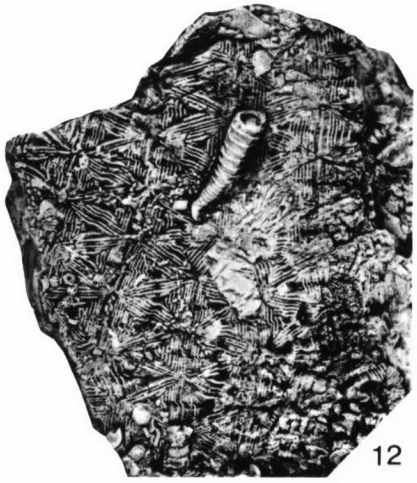












Subclass CAMERATA Wachsmuth and Springer, 1885

Order DIPLOBATHRIDA Moore and Laudon, 1943

Suborder ZYGODIPLOBATHRINA Ubaghs, 1953

Diagnosis.—Dicyclic camerate crinoids with radials interposed alternately between basals, forming a circlet of 10 plates projecting downward over infrabasals.

Discussion.—Ubaghs (1953) erected the suborder Zygodiplobathrina to receive *Cleiocrinus* (Middle Ordovician) and *Spyridiocrinus* (Early to Middle Devonian), both of which are characterized by a basal-radial circlet that projects down over the infrabasals. *Cleiocrinus* is an unusual dicyclic camerate because it lacks interbrachs, and the brachials of adjacent rays are joined above the radials and basals except where separated by the anal series of the CD interray. The abundant sutural pores between the fixed brachials and all calyx plates are also unique to *Cleiocrinus*. This unusual morphology and the lack of species intermediate between *Cleiocrinus* and other dicyclic camerates make the evolutionary history of *Cleiocrinus* uncertain.

The morphology of *Spyridiocrinus*, however, is not so perplexing as that of *Cleiocrinus*. As pointed out by Brower (1975, p. 643), *Spyridiocrinus* possesses a relatively large basal concavity and few interbrachs, but the overall crown habit is "typical rhodocrinitid." The only similarity between the two genera is the basal-radial circlet. Brower (1975, p. 643) argued that the morphological similarities between *Spyridiocrinus* and Silurian-Devonian rhodocrinitids such as *Anthemocrinus*, *Paulocrinus*, and *Condylocrinus* are greater than those between *Spyridiocrinus* and *Cleiocrinus* and that the ancestral stock of *Spyridiocrinus* is within one of these rhodocrinitid genera. This suggests a polyphyletic origin for the zygodiplobathrines. If these arguments are valid, then it would be advisable to assign *Spyridiocrinus* to the suborder Eudiplobathrina. Until the ancestry of *Cleiocrinus* is better known, however, I prefer to retain its assignment to the suborder Zygodiplobathrina.

Occurrence.—Middle Ordovician.

Family CLEIOCRINIDAE Miller, 1889

Diagnosis.—Dicyclic camerate crinoids with alternating basals and radials forming a circlet of 10 plates projecting down over proximal columnals and concealing 5 infrabasals; interbrachs lacking; brachials in lateral contact except at anal side; anal series in a single column resting on CD basal, not reaching top of cup; cup plate sutures crenulate and loosely articulated, perforated by numerous sutural pores; mouth apparently subtegminal; arms pinnulate.

Genus CLEIOCRINUS Billings, 1857

Type species.—*Cleiocrinus regius* Billings, 1857.

Diagnosis.—Characters as for family.

Discussion.—Species of *Cleiocrinus* are differentiated mainly on size and shape of the aboral cup, number of arms, number and shape of sutural pores, and ornament.

Occurrence.—Middle Ordovician (Champlainian); United States (Illinois, Iowa, Kentucky, Oklahoma, Tennessee, Virginia, Wisconsin) and Canada (Ontario).

PLATE 16.

Fig. 1-10. *Cleiocrinus bromidensis* Kolata, n. sp.; 1-5, 8, 9 from Pooleville Member, Dunn Quarry, Criner Hills; 6, 10 from Upper Echinoderm Zone, Mountain Lake Member, Sulphur, Arbuckle Mountains; 7 from Upper Echinoderm Zone, Mountain Lake Member, Buckhorn Ranch, Arbuckle Mountains. 1. Grooves on interior surface of cup brachials, paratype OU 8898, upper arrow points to narrow ridge at center of grooves, lower arrow points to indentations in sides of grooves; X3.5. 2. Grooves on interior surface of cup brachials, paratype OU 8899; X3.5. 3. Detail of 6 cup brachials showing surface ornament, paratype OU 8900; X3. 4, 5. Side and aboral views of holotype OU 8891; X1.5. 6. Side view of paratype OU 8902; X1.5. 7. Aboral view of paratype OU 8906, arrows point to small pores that pass to interior of cup; X5.5. 8. Edge of paratype OU 8900 showing sutural pores on 2 adjacent brachials; outer suface of plates is facing up; X6.6. 9. Aboral view of holotype OU 8891, arrows point to small pores that pass to interior of cup; X4.5. 10. Interior of aboral cup of paratype OU 8904 showing 5 interradial vestibules; X5.5.

Fig. 11, 12. *Cleiocrinus ornatus* Kolata, n. sp.; Pooleville Member, Dunn Quarry, Criner Hills; paratype OU 8909 and holotype OU 8908; X2.

CLEIOCRINUS BROMIDENSIS Kolata, n. sp.

Plate 16, figures 1-10

Diagnosis.—*Cleiocrinus* characterized by a moderately large crown having an expansion angle of 65° from the horizontal up to primibrach 2, then flaring out to 45°; approximately 30 sutural pores in 5 mm; fixed arms bifurcating 4 times in aboral cup.

Description.—Aboral cup moderately large (Table 29), funnel-shaped, expansion angle 65° from the horizontal up to primibrach 2, at this point wall of cup bending abruptly to 45°; this angle maintained to top of cup. Cup plates slightly convex to slightly concave, either smooth or with very fine, sinuous, concentric ridges resembling growth lines (Pl. 16, fig. 3); brachial plates commonly with small central depression divided in 2 parts by a narrow vertical ridge that may extend between plates; numerous very fine ridges radiating from plate center to septae between sutural pores in some individuals; some specimens possessing faint ridges extending between brachials of adjacent rays. Broad, low, median ray ridges present in lower part of cup, particularly below secundibrachs. Approximately 30 sutural pores per 5 mm between cup plates.

Infrabasals 5, wider than high, confined to basal concavity. Small channel encircling the infrabasal circlet between crenulate facet of proximal columnal and circlet of basals and radials. The small pores, 2 per infrabasal, passing from channel between infrabasals and basal-radial circlet at juncture of radials and basals to interior of aboral cup (Pl. 16, fig. 7, 9), position of pores corresponding to 5 longitudinal depressions of pentagonal column. Within cup, pores opening into 5 small interradial vestibules (Pl. 16, fig. 10). (It appears that 2 pores, one from each adjacent infrabasal, pass to each vestibule.)

Five basals alternate with 5 radials to form a circlet of 10 plates projecting down over infrabasals and proximal 2 or 3 columnals. Basals slightly wider than high, approximately equivalent in size, pentagonal; CD basal quadrangular and smaller. Radials wider than high, irregularly pentagonal, smaller than primibrachs, approximately equivalent in size to basals, larger than basals in smaller (presumably immature) specimens. Lower edge of radials slightly angular and projecting down along longitudinal depressions of pentagonal stem. Primibrach 2 axillary; succeeding axillaries on secundibrachs 3 through 5, tertibrachs 4 through 8, and quartibrachs 6 through 8. Width of brachials about twice height in lower part of cup, but decreasing progressively toward top, width and height at top equal.

Table 29. Measurements (mm) of *Cleiocrinus bromidensis* Kolata, n. sp.

Measurements	Specimens					
	OU 8891	OU 8902	OU 8893	OU 8894	OU 8905	OU 8904
Aboral cup height	20.0	---	30.0	16.0	10.0	---
Aboral cup width	35.0	---	60.0	32.0	---	---
Basal height	2.0	2.0	---	---	1.5	1.5
Basal width	3.3	2.5	---	---	2.0	1.5
Radial height	1.4	1.5	---	---	1.0	2.2
Radial width	3.0	3.0	---	---	2.0	1.3
Diameter of proximal stem	9.0	6.5	---	5.0	5.0	4.3

Median groove on interior surface of brachials extending from base of cup, where 5 main branches radiate from a circular channel surrounding axial canal, upward in a radial position, bifurcating on each axillary, extending into arms. Groove may be relatively shallow, particularly in lower part of cup, or so deeply sunken within plate that the sides of groove project above plate surface and nearly cover groove (Pl. 16, fig. 2). Two or 3 lateral indentations common on sides of groove near center of each brachial. One to 4 sutural pores (approximately 0.5 mm in diameter) passing through cup wall at juncture between brachials of same branch. Before reaching outer surface of cup, each pore partitioned into as many as 8 to 12 smaller pores by wedge-shaped septae formed from skeletal extensions between adjacent plates (Pl. 16, fig. 8). Articulation surfaces between brachials consisting of interlocking crenulae. Pores supplied to sides of plates by adjacent rows of brachials alternating along zigzag sutures. Interbrachs not present.

Anal series a single row of from 10 to 15 plates resting on upper edge of CD basal, plates generally wider than high and pentagonal to heptagonal in outline, interlocking with adjacent brachials and extending up to about two-thirds height of cup. Tegmen not preserved.

Free arms not preserved. (I suspect that the fixed brachials bifurcate no more than 4 times within the cup and give rise to approximately 80 arms.)

Stem known only from several proximal columnals; columnals straight-sided, pentalobate, with symplectic articulation. Axial canal large, pentalobate.

Discussion.—*Cleiocrinus regius* Billings (1857) and *C. magnificus* Billings (1859) from the Trentonian Cobourg beds near Ottawa, Ontario, differ from *C. bromidensis* in that the former two species have a smaller, more elongate aboral cup with well-developed median ray ridges and the latter has a larger, broader aboral cup and, apparently, a greater number of arms. *Cleiocrinus tesselatus* (Troost, 1849) from the Blackriveran Lebanon Limestone near Columbia, Maury County, Tennessee, can be distinguished from the new species by its more elongate aboral cup. The well-defined ridges and pustules on the brachials of *C. sculptus* Springer (1911) from the Trentonian Curdsville Limestone of Mercer County, Kentucky, serve to distinguish it from *C. bromidensis*. The new species most closely resembles *C. perforatus* Hudson (1911) from the Chazyan Valcour Limestone of Valcour Island, Lake Champlain, New York. Specimens of both species possess brachials that have a median vertical ridge with shallow depressions on each side. The new species, however, is characterized by a greater number of sutural pores.

The specimens described here reveal several distinctive internal structures of the aboral cup which were associated with the viscera. Radially positioned grooves are particularly prominent on the interior walls of the cup. A comparison with living crinoids suggests that the grooves housed coelomic tubes and nerves that extended from the base of the cup up into the arms. According to this interpretation, the dorsal nerve ring and/or chambered organ rested in the base of the cup and five main branches passed radially to the tips of the arms. Other branches passed downward through the basal concavity into the axial canal. The nerves were probably attached along the narrow ridges (Pl. 16, fig. 1) at the center of the grooves. The indentations in the sides of the grooves appear to be attachment sites for coelomic tissue (Pl. 16, fig. 1). The sutural pores may have been openings in the skeletal wall to allow water to bathe the visceral tissue, and thus would have had a respiratory and excretory function. The five interradially positioned vestibules in the base of the cup and the intricate system of channels and pores between the basal-radial and infrabasal circlets appear to have been part of the coelomic system (Bruce N. Haugh, pers. commun., 1977).

Dimensions.—Measurements of selected specimens are given in Table 29.

Types.—The holotype is OU 8891 and paratypes are OU 8892-8907, OU 8922-8926, 1124TX1-2, 1108-TX2, 1106TX11, 1113TX13, 1279TX160, and 1222TX4.

Occurrence.—The holotype is from the Pooleville Member 0.3 m below the Viola Limestone, Bromide Formation, at Dunn Quarry. The species is known also from 2.2, 2.5, and 7.5 m below the Viola Limestone in the Pooleville Member at Dunn Quarry; from the Upper Echinoderm Zone, Mountain Lake Member, at Sulphur, Buckhorn Ranch, Lick Creek, North I-35, and Bromide; Upper and Lower Echinoderm Zones at Fittstown Roadcut and Quarry; and Lower Echinoderm Zone at McLish Ranch.

Name.—The specific name refers to the Bromide Formation where the species occurs.

CLEIOCRINUS ORNATUS Kolata, n. sp.

Plate 16, figures 11, 12

Diagnosis.—*Cleiocrinus* with numerous fine, narrow ridges arranged in rhombic patterns on cup plates.

Description.—Aboral cup plates ornamented with numerous straight, narrow (0.2 to 0.3 mm wide) elevated ridges arranged in rhombic patterns. Each brachial with 2 relatively large half-rhombs shared with brachials above and below. Rhombs consisting of 15 or 16 vertical ridges; median ridge slightly wider, continuous throughout brachial series. Four additional smaller half-rhombs with up to 7 ridges situated in dislateral and proximalateral corners of brachial plates. Sutural pores at plate margins in depressions between ridges.

Discussion.—Although this species is based on only two aboral cup fragments, it is judged to be sufficiently distinct to warrant assignment to a new species. However, the distinctive narrow ridges in these specimens may have been caused by differential weathering of a cleiocrinid with smooth plates that was exposed to chemical action on the sea floor. On one of the specimens (Pl. 16, fig. 12), a cornulitid is attached to the aboral cup, thus indicating that the apparent ornament was present while the organism was exposed to the sea water.

The rhombic pattern of ridges and pores in *C. ornatus* superficially resembles the conjunct pec-

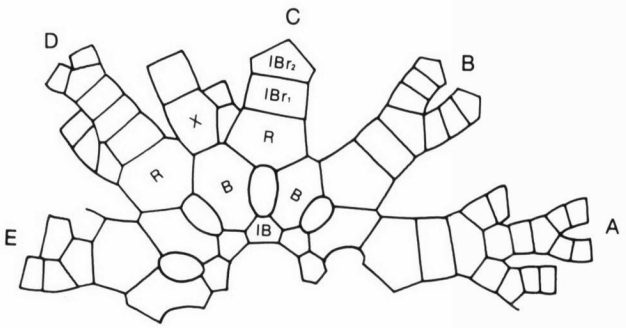


Fig. 49. *Reteocrinus depressus* Kolata, n. sp., Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains. Diagrammatic representation of calyx based on paratype OU 8913, X4.

tinirhombs of some rhombiferan cystoids. Cystoid rhombs differ, however, in that they are specialized areas of the theca in which the thecal wall is very thin and is thrown into a number of isoclinal folds. These structures do not open into the body cavity. In contrast, the rhombs in *C. ornatus* consist of thick ridges and sutural pores that open directly into the body cavity.

Types.—The holotype is OU 8908 and the single paratype is OU 8909.

Occurrence.—The holotype and paratype were found in the Pooleville Member (in upper 12.5 m and 2.5 m below the Viola Limestone, respectively), Bromide Formation, at Dunn Quarry.

Name.—The specific name refers to the prominent ornament on the aboral cup.

Suborder EUDIPLOBATHRINA Ubaghs, 1953

Diagnosis.—Dicyclic camerate crinoids; radials and basals forming 2 distinct circlets.

Occurrence.—Middle Ordovician to Early Carboniferous.

Superfamily RHODOCRINITACEA Roemer, 1855

Diagnosis.—Dicyclic camerate crinoids; radials separated by 1 or more interradials, interradials in contact with basals.

Occurrence.—Middle Ordovician to Early Carboniferous.

Family RETEOCRINIDAE Wachsmuth and Springer, 1885

Diagnosis.—Dicyclic camerate crinoids; depressed interray areas composed of numerous, small, irregular interradials and interbrachs; median ray ridges; prominent median anal ridge; uniserial arms.

Occurrence.—Middle and Late Ordovician.

Genus RETEOCRINUS Billings, 1859

Type species.—*Reteocrinus stellaris* Billings, 1859.

Diagnosis.—Reteocrinid crinoid with relatively small crown; interinfrabasal spaces either small or absent; nonpinnulate arms.

Discussion.—Species of *Reteocrinus* are differentiated mainly by shape of the aboral cup, ornament, and the number of primibrachs and secundibrachs.

Occurrence.—Middle Ordovician (Champlainian) and Late Ordovician (Cincinnatian); United States (Illinois, Kentucky, Oklahoma, Tennessee, Wisconsin) and Canada (Ontario).

RETEOCRINUS DEPRESSUS Kolata, n. sp.

Plate 17, figures 6, 7; Figure 49

Diagnosis.—*Reteocrinus* with smooth, evenly rounded plates on aboral cups; small interbasal spaces; radials axillary or primibrachs 1 and 2 axillary; wide interray areas; round stem.

Description.—Aboral cup small (Table 30), low; width at level of radials nearly 3 times height. Cup plates thick, smooth, evenly rounded; sutures flush. Infrabasals 5, small, pentagonal, wider than high. Basals 5, higher than wide; in contact with 2 infrabasals and 2 radials; small spaces between infrabasals, basals, and radials; CD basal supporting primanal. Radials 5, largest plates in cup, wider than high; D- and E-ray radials axillary in holotype (Fig. 49), A-, B-, and C-ray radials supporting 2 primibrachs. Primibrachs 1 and 2 wider than high. Secundibrachs wider than high, secundibrachs 2 or 3 axillary. Interray areas

relatively wide; no plates preserved. Primanal higher than wide, in contact with D-ray primibrach 1, followed by anal series. Tegmen unknown. Arms uniserial, branching isotomously 3 or 4 times. Stem round, proximal part consisting of alternating thick, well-rounded nodals and thin, slightly rounded internodals; distal stem unknown.

Discussion.—Two crowns, each having a small section of stem attached, were available for study. The new species differs from other reteocrinids in having a low aboral cup with smooth, evenly rounded plates. In addition, the first bifurcation of the arms is either on the radials or primibrachs 1 or 2, whereas in all other known species, primibrachs 3 to 6 are axillary.

The axillary radials that characterize this species represent an unusual condition that is very rare or possibly unknown among other dicyclic camerate crinoids. As both the holotype and paratype possess axillary radials, it does not seem likely that this feature is due to an injury or developmental irregularity.

Both of the specimens studied here have small interbasal spaces, but neither specimen is preserved well enough to determine whether the spaces were occupied by small plates or whether they were merely covered by a thin integument.

Dimensions.—Measurements of the new species are given in Table 30.

Types.—The holotype is OU 8912 and single paratype is OU 8913.

Occurrence.—The holotype is from the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, at Lick Creek; the paratype was found in the same zone at Daube Ranch.

Name.—The specific name refers to the low aboral cup.

Table 30. Measurements (mm) of *Reteocrinus depressus* Kolata, n. sp.

Measurements	Specimens	
	OU 8912	OU 8913
Aboral cup height (base of cup to distal edge of radials)	4.5	3.6
Aboral cup width	---	9.5
Infrabasal height	1.2	---
Infrabasal width	1.5	---
Basal height	2.6	2.5
Basal width	1.8	2.2
Radial height	2.1	2.1
Radial width	3.1	3.1
Stem diameter (base of cup)	2.9	2.9

Family ANTHRACOCRINIDAE
Strimple and Watkins, 1955

Diagnosis.—Dicyclic camerate crinoids with subconical aboral cup; 5 elongate infrabasals forming a tubular basal concavity deep within cup; radials separated all around by 1 large interradial in each interray; lateral interray plates regular, not contiguous with tegmen except on posterior side; proximal brachials and pinnules incorporated in aboral cup; tegmen composed of numerous small, irregular plates; 3 arms per ray, uniserial; stem round.

Discussion.—*Anthracocrinus*, the type genus of the family Anthracocrinidae, most closely resembles Hudson's (1907) *Hercocrinus* and *Deocrinus*. All three genera are characterized by fixed pinnules that separate the interbrachs from the tegmen, except in the CD interray of *Anthracocrinus*. *Anthracocrinus* differs from *Hercocrinus* and *Deocrinus* as well as the more typical rhodocrinitids in possessing three arms per ray instead of two or multiples of two.

Occurrence.—Middle Ordovician (Champlainian); United States (Oklahoma).

Genus ANTHRACOCRINUS Strimple and Watkins, 1955

Type species.—*Anthracocrinus primitivus* Strimple and Watkins, 1955.

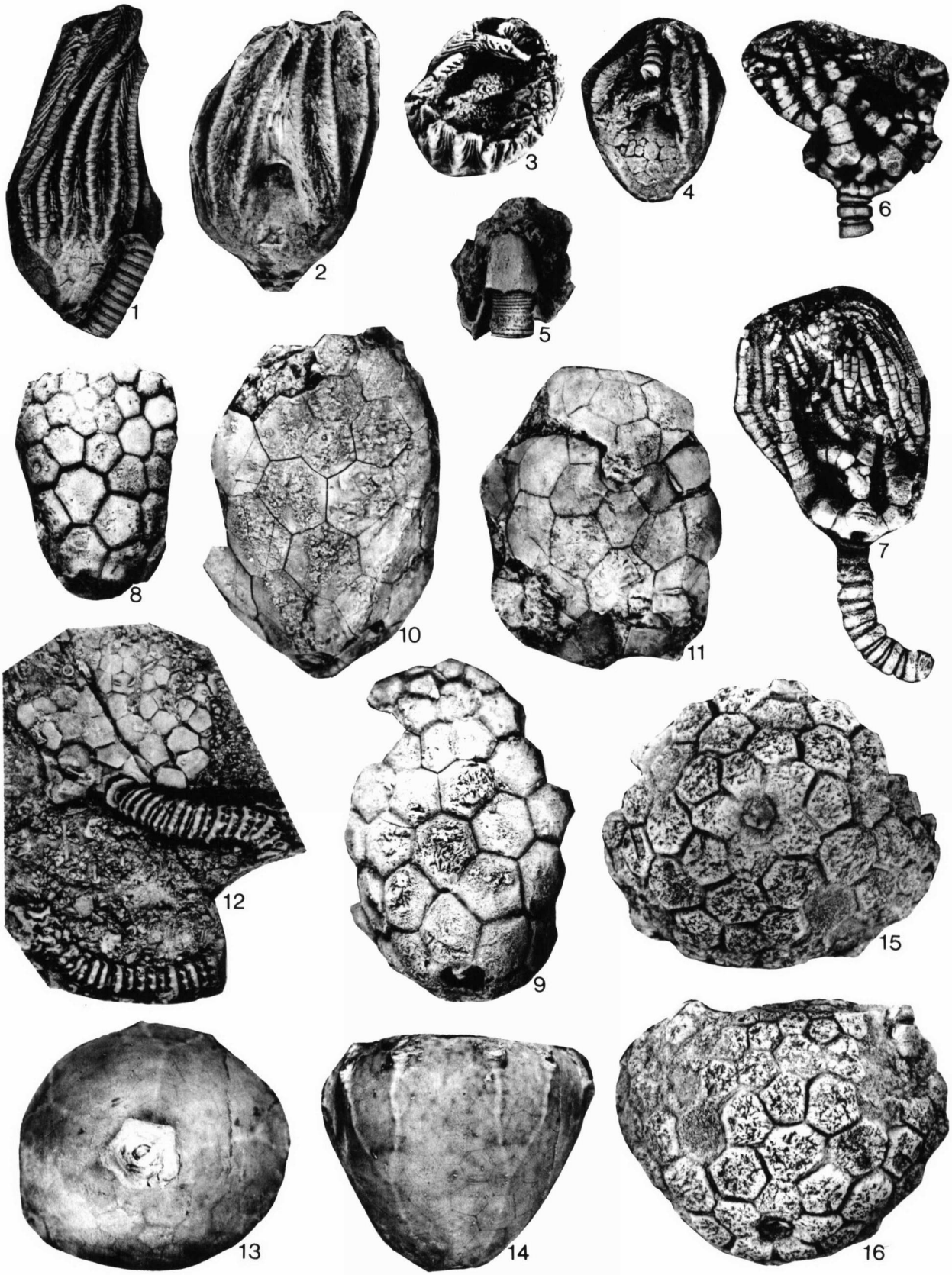
Diagnosis.—Characters as for family.

Occurrence.—Middle Ordovician (Champlainian); United States (Oklahoma).

ANTHRACOCRINUS PRIMITIVUS
Strimple and Watkins, 1955

Plate 17, figures 1-5; Figure 50

Description.—Aboral cup subconical; expansion angle 30 to 40° from horizontal; height of cup slightly less than width (Table 31); outline (in basal view) obscurely pentagonal at level of radials. Aboral cup plates flat to slightly convex, finely punctate, sutures slightly depressed, nar-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row grooves along edges of plates. Median ray ridges broad and low in lower part of cup, narrow and keeled at top of cup and on proximal part of arms.

Infrabasals 5, pentagonal, twice as high as wide; infrabasal circlet forming a tubular structure extending up within aboral cup approximately to level of secundibrach 1 (Pl. 17, fig. 5). Basals 5, heptagonal; each in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial; proximal edge of basal bent sharply at basal concavity, V-shaped in transverse section; thick triangular process at lower edge of each basal forming a prominent pentagonal rim at base of cup. Radials 5, pentagonal (C- and D-ray radials hexagonal or heptagonal); each in contact with 2 basals, 2 interradials, and primibrach 1; C- and D-ray radials in contact with 1 or 2 interbrachs 1; upper suture less than full width of plate; C-ray radial largest. Primibrach 1 slightly smaller than radial, quadrangular (C- and D-ray primibrach 1 may be pentagonal), wider than high. Primibrach 2 pentagonal, axillary. Secundibrach 1 wider than high, smaller than primibrachs, quadrangular to hexagonal, rarely axillary. Secundibrach 2 approximately same size as secundibrach 1, pentagonal, axillary, bearing either 2 arms or 1 arm and 1 large fixed pinnule; fixed pinnule invariably situated on outer side of half-ray adjacent to interray plates; located on right side of A, B, C, and E rays and on left of D ray (Fig. 50). Tertibrach 1 wider than high, quadrangular to hexagonal. Tertibrach 2 axillary, bearing 1 fixed pinnule and quartibrach 1. Quartibrach 2 axillary, bearing fixed pinnule and succeeding brachials; all brachials above quartibrach 2 bearing a single pinnule on alternate sides of arm. One large intersecundibrach followed by 1 or 2 smaller intersecundibrachs; 1 or 2 intertertibrachs present in some individuals.

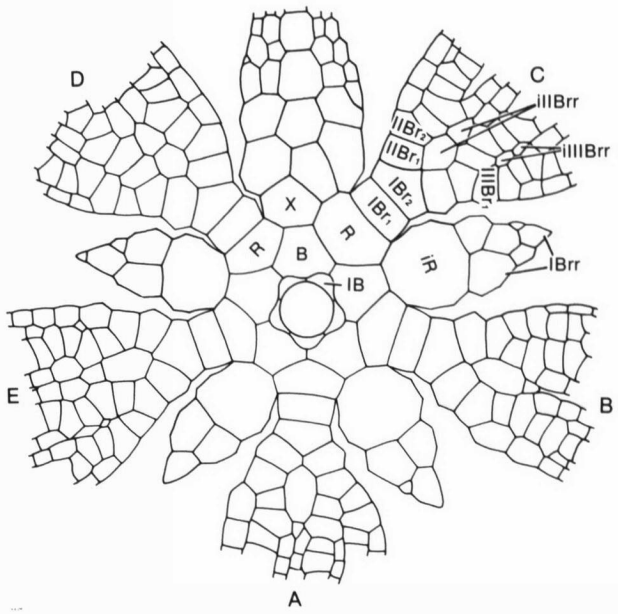


Fig. 50. *Anthracocrinus primitivus* Strimple and Watkins (1955), Pooleville Member, Bromide Formation, Criner Hills. Plate diagram based on OU 8888, X2.5.

Interray areas relatively wide, not contiguous with tegmen, composed of 4 to 7 plates. Interradial largest plate in cup, followed by 2 large interbrachs 1. CD interray widest, continuous with tegmen. Primanal pentagonal to octagonal, smaller than interradials. Anal series consisting of 4 or 5 relatively large plates, plates wider than high; first plate of anal series on upper right sloping edge of primanal, also in contact with upper left edge of C-ray radial; anal series flanked by 1 or 2 interbrachs.

PLATE 17.

Fig. 1-5. *Anthracocrinus primitivus* Strimple and Watkins (1955); 1-4 from Pooleville Member, Rudd Quarry, Criner Hills; 5 from Pooleville Member, Culley Creek, Criner Hills. 1. Anterior view of OU 8889; X2.5. 2. Posterior view of OU 8888; X2. 3. Adoral view of 1123TX7 showing tegmen; X2. 4. Posterior view of OU 8929 showing median anal series; X2. 5. Interior view of infrabasal circlet in 1122TX50 with basals stripped away; X3.

Fig. 6, 7. *Reteocrinus depressus* Kolata, n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Arbuckle Mountains. 6. Anterior view of paratype OU 8913, Daube Ranch; X2. 7. Anterior view of holotype OU 8912, Lick Creek; X2.

Fig. 8, 9. *Archaeocrinus conicus* Kolata, n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Fittstown Roadcut, northeastern Arbuckle Mountains. 8. Paratype OU 8857; X1.5. 9. Holotype OU 8856; X1.5.

Fig. 10, 11. *Archaeocrinus buckhornensis* Kolata, n. sp.; Upper Echinoderm Zone, Mountain Lake Member, Buckhorn Ranch, central Arbuckle Mountains. 10. Side view of holotype OU 8846; X1.5. 11. Aboral view of paratype OU 8847; X1.

Fig. 12-14. *Archaeocrinus subovalis* Strimple (1953b); Pooleville Member, Criner Hills. 12. Specimen OU 8936 showing proximal stem, Culley Creek; X1. 13, 14. Aboral and side views of OU 8930, Rock Crossing; X1.3.

Fig. 15, 16. *Archaeocrinus* sp.; Upper Echinoderm Zone, Mountain Lake Member, North I-35 locality, northern Arbuckle Mountains; aboral and side views of 1222TX2; X1.

Table 31. Measurements (mm) of *Anthracocrinus primitivus* Strimple and Watkins (1955).

Measurements	Specimens				
	OU 8888	OU 8889	1122 TX30	OU 8890	1112 TX31
Aboral cup height	9.0	7.0	8.0	5.5	6.0
Aboral cup width	14.0	---	---	---	---
Basal height	2.5	2.4	2.5	1.7	2.3
Basal width	2.3	2.2	2.3	1.5	2.2
Radial height	1.7	1.5	1.8	1.1	1.6
Radial width	2.7	2.2	2.9	1.8	2.5
Interradial height	3.0	2.3	---	1.7	2.5
Interradial width	3.6	2.3	---	1.7	2.2

Tegmen slightly concave; consisting of numerous small, irregular plates; anal tube small, low, cone-shaped, positioned near edge of tegmen (Pl. 17, fig. 3).

Arms 15, uniserial, length slightly more than twice height of aboral cup, free above quartibrach 4. Pinnules closely spaced, stout, gradually tapering, compressed; consisting of about 10 pinnulars.

Stem round, heteromorphic; proximal columnals very thin in contact with tubular infrabasal circlet; alternating thick prominent nodals and thin small internodals; internodals becoming progressively thicker, increasing to 3 or 4 in number distally; very small pustules on distal internodals; nodal epifacets curved back toward distal end; 20 to 25 short spines on epifacets of proximal half of column.

Discussion.—*Anthracocrinus primitivus* Strimple and Watkins (1955) most closely resembles *Deocrinus asperatus* (Billings, 1859) from the Chazyan Aylmer Formation near Montreal, Canada. The aboral cups of both species are similar and both have large fixed pinnules that separate the lateral interray plates from the tegmen. The latter differs mainly in having 10 arms instead of 15.

Dimensions.—Measurements of *Anthracocrinus primitivus* are shown in Table 31.

Material.—Approximately 35 specimens, several well preserved and showing previously unknown details of the crown, were available for study. Figured specimens include OU 8888, OU 8889, OU 8929, 1122TX50, and 1123TX7.

Occurrence.—The specimens studied here are from the Pooleville Member, 1.7 to 2.5 m below the Viola Limestone, Bromide Formation, at Rudd Quarry; and Zone 3, 9 to 10 m below the Viola, Zone 4, 10.0 to 11.5 m below the Viola, and Zone 5, 11.5 to 13.5 m below the Viola, of the Pooleville Member at Culley Creek. The holotype and four paratypes were collected from an unspecified horizon of the Pooleville Member at Culley Creek.

Family RHODOCRINITIDAE Bassler, 1938

Diagnosis.—Dicyclic camerate crinoids with conical to subglobular aboral cup; infrabasals confined to basal concavity; interrays not markedly depressed; radials separated all around by 1 or more regular interradials; interbrachs regular; median ray and anal ridges well developed in some species.

Discussion.—The rhodocrinitids are a diverse group of dicyclic camerate crinoids distinguished mainly by the radials, which are separated by one or more regular interradials in contact with the basals, and by the infrabasals, which are confined to a basal concavity. Moore and Laudon (1943) stated that the rhodocrinitids differ from the closely related Archaeocrinidae in having small nondepressed interray areas, rounded globular aboral cups, and median ray ridges that are weak or absent. These features, however, are highly variable, and the differences among certain genera presently assigned to the two families are not very great. The distinction between the two families, as shown by Moore and Laudon (1943), was obscured somewhat by the unfortunate selection of *Archaeocrinus* as the type genus of the family Archaeocrinidae. In the type species, *Archaeocrinus lacunosus* (Billings, 1857), the infrabasals are confined to a basal concavity, as they are in most species of the Rhodocrinitidae. It is shown by Moore and Laudon (1943) in figure 13 and implicit in the family description that *Archaeocrinus* has upflared infrabasals that are visible in the side of the cup. As noted by Strimple and Watkins (1955), the paratype of *Thysanocrinus pyriformis* Billings (1857) was used as the basis for Moore and Laudon's diagram of the genus *Archaeocrinus*.

In this report all of the Bromide dicyclic camerates (except *Anthracocrinus*) whose radials and basals form distinct circlets and whose infrabasals are confined to a basal concavity are assigned to the family Rhodocrinitidae. The family Archaeocrinidae is not recognized here.

Six rhodocrinitid genera have been identified from the Bromide Formation: *Archaeocrinus*, *Diabolocrinus*, *Paradiabolocrinus*, *Pararchaeocrinus*, *Bromidocrinus*, n. gen., and *Crinerocrinus*, n. gen.

Table 32. Characteristic features of rhodocrinitid genera occuring in the Bromide Formation of southern Oklahoma.

Genera	Characteristics			
	Aboral cup	Ray plates/arms	Interray plates/anal series	Tegmen
Archaeocrinus	High, conical, large	Median ray ridges present in some species; arms 10; transitional between uniserial and biserial; free above secundibrach 5 or 6	Interradial followed by interbrachs arranged 2, 3, 3, 4; primanal followed by 3 interbrachs 1	Unknown
Bromidocrinus, n. gen.	High, rotund, large; prominent grooves at base of cup	Median ray ridges low, inconspicuous; arms 10, biserial; free above secundibrach 4 or 5	2 or 3 interradials followed by numerous irregular interbrachs; anal series not distinct	Arched; large, subcentral anal tube
Crinerocrinus, n. gen.	Low, bowl-shaped, large	Median ray ridges prominent; arms 20?	Interradial followed by interbrachs arranged 3, 4; primanal followed by 3 interbrachs 1 and 5 interbrachs 2	Unknown
Diabolocrinus	Low, globose, medium-sized	Median ray ridges prominent; arms 10, biserial; arm bases generally lobate and protuberant	Large interradial followed by 2 interbrachs; supplementary plates common in some individuals; anal series not distinct	Arched thick, rigid
Paradiabolocrinus	Low, globose, small	Like Diabolocrinus; small intersecundibrachs present	2 or 3 interradials followed by numerous irregular interbrachs	Like Diabolocrinus
Pararchaeocrinus	Low, globose, medium-sized	Median ray ridges prominent; arms 10, transitional between uniserial and biserial	Interradial followed by 3 interbrachs; anal series distinct, with well-developed median anal ridge	Arched, relatively thin; long slender anal tube

Characteristic features of all six genera are shown in Table 32.

Occurrence.—Ordovician to Mississippian.

Genus ARCHAEOCRINUS
Wachsmuth and Springer, 1881

Type species.—*Glyptocrinus lacunosus* Billings, 1857.

Diagnosis.—A rhodocrinitid crinoid with conical or globose aboral cup; small infrabasal circlet confined to basal concavity; interrays composed of 1 interradial followed by 2 interbrachs 1; CD interray widest, primanal followed by 3 interbrachs 1, the middle plate being part of anal series. Arms 10, biserial, branching isotomously several times.

Occurrence.—Middle Ordovician (Champlainian); United States (Ohio, Oklahoma, Tennessee, Virginia) and Canada (Ontario).

ARCHAEOCRINUS BUCKHORNENSIS Kolata, n. sp.

Plate 17, figures 10, 11

Diagnosis.—*Archaeocrinus* having a large, high aboral cup; smooth, flush plates; wide, low median ray ridges; relatively small basals and large interradials and primibrachs.

Description.—Known only from fragments of aboral cup. Cup large (Table 33), relatively high; plates smooth and flush; broad, low, median ray ridges. Infrabasals 5, small, wider than high, pentagonal, confined to shallow basal concavity;

Table 33. Measurements (mm) of *Archaeocrinus buckhornensis* Kolata, n. sp.

Measurements	Specimens				
	OU 8846	OU 8847	1109 TX8	OU 8849	OU 8848
Aboral cup height	~35.0	---	30.0	---	---
Aboral cup width	---	---	25.0	---	~35.0
Basal height	5.8	8.7	7.2	5.0	6.5
Basal width	5.8	8.5	6.8	6.5	7.0
Radial height	7.2	11.0	7.5	6.8	9.0
Radial width	7.2	10.0	7.5	6.8	7.0
Interradial height	9.5	13.0	9.0	7.6	---
Interradial width	9.0	13.0	8.0	8.0	---
Primibrach 1 height	9.0	---	7.5	7.0	---
Primibrach 1 width	8.8	---	6.8	7.5	---

deep impression on outer surface of infrabasal circlet at juncture with proximal columnal. Basals 5, relatively small, height and width approximately equal, heptagonal; in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial; proximal edge confined to basal concavity. Radials 5, height and width approximately equal, pentagonal (D-ray radial hexagonal), separated by interradial; wide, low, median ray ridges passing upward from radials to top of cup. Primibrach 1 generally larger than radial, hexagonal, slightly higher than wide. Primibrach 2 relatively large, heptagonal, axillary. Secundibrach 1 hexagonal, followed by at least 2 secundibrachs 2 (above this point cup not preserved). Secundibrachs separated by 1 hexagonal intersecundibrach followed by 2 intersecundibrachs. Interradials largest plates in cup, heptagonal, higher than wide; followed by 2 interbrachs 1 and 3 interbrachs 2. CD interray widest. Primanal octagonal; followed by at least 2 ranges having 3 interbrachs 1, in turn followed by at least 2 ranges having 3 interbrachs each (medial plate of each range is an anal series element).

Tegmen, arms, and stem unknown.

Discussion.—*Archaeocrinus buckhornensis* is most similar to *A. subovalis* Strimple (1953b) from the Pooleville Member, Bromide Formation, of southern Oklahoma. Both species are characterized by large, high, aboral cups composed of thin, smooth, flush plates. *Archaeocrinus buckhornensis* differs in having relatively small basals and radials, whereas the primibrachs and interradials are large. The interradials are the largest plates in the cup. Further, the median ray ridges in *A. subovalis* are narrow and prominent at the top of the cup, whereas in *A. buckhornensis* they are wide and not well developed. A thick rim around the basal concavity of *A. subovalis* is lacking in *A. buckhornensis*. *Archaeocrinus conicus* differs in having a conical aboral cup that lacks median ray ridges and has prominent depressed sutures.

Dimensions.—Measurements of selected specimens are given in Table 33.

Types.—The holotype (OU 8846) is an incomplete aboral cup consisting of a basal circlet and parts of 2 rays and an interray. In addition to the holotype, 9 incomplete cups were available for study. These include paratypes OU 8847-8854 and 1109TX8.

Occurrence.—The holotype and 8 paratypes were found in the Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation at Buckhorn Ranch. One paratype (1109TX8) is from the Lower Echinoderm Zone of the Mountain Lake Member at Amis Ranch.

Name.—The specific name refers to Buckhorn Ranch, where most of the type material was discovered.

ARCHAEOCRINUS CONICUS Kolata, n. sp.

Plate 17, figure 8, 9

Diagnosis.—*Archaeocrinus* having a high conical aboral cup, lacking median ray ridges; strongly depressed sutures.

Description.—Known only from fragments of aboral cup. Cup conical, relatively high; plates smooth and convex; sutures depressed; median ray ridges lacking.

Infrabasals 5, pentagonal; confined to basal concavity; infrabasal circlet forming a tubular structure extending up into body cavity and enclosing a large lumen, lumen continuous with axial canal. Basals 5, 7.0 mm high by 6.7 mm wide in holotype; in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial; distal edge at contact with interradial so short that lateral angles of adjacent radials close to each other; very small area of basals confined to basal concavity. Radials pentagonal, 7.0 mm high by 7.8 mm wide in holotype; separated by interradials. Primibrach 1 hexagonal, 6.6 mm high by 7.5 mm wide in holotype, smaller than radial. Primibrach 2 heptagonal, axillary. Secundibrach 1 hexagonal or heptagonal; cup unknown above level of secundibrach 2. Interradials heptagonal, 8.5 mm high by 7.5 mm wide in holotype, followed by 2 interbrachs 1, 3 inter-

brachs 2, and 3 interbrachs 3. CD interray widest. Primanal octagonal, higher than wide; followed by 3 interbrachs 1.

Tegmen, arms, and stem unknown.

Discussion.—The high, conical-shaped aboral cup and depressed sutures clearly distinguish *A. conicus* from other species of *Archaeocrinus*. *Archaeocrinus peculiaris* Miller and Gurley (1894) from the Middle Ordovician rocks of eastern Tennessee also has depressed sutures, but the cup has a low, globose shape.

Types.—The holotype is OU 8856; paratypes include OU 8857 and 1279TX164-184, 186.

Occurrence.—The holotype and the OU paratype are from the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation at Fittstown Roadcut; the other paratypes are from the same zone at the nearby Fittstown Quarry.

Name.—The specific name refers to the conical shape of the aboral cup.

ARCHAEOCRINUS SUBOVALIS Strimple, 1953b

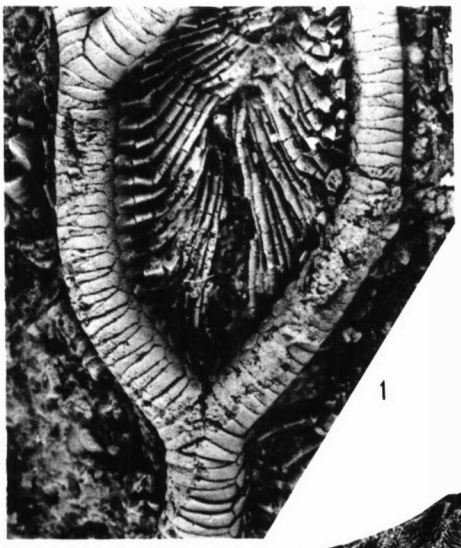
Plate 17, figures 12-14; Plate 18, figures 1-3

Diagnosis.—*Archaeocrinus* with large, relatively high aboral cup having generally smooth, flush plates; median ray ridges low and narrow; small spines on nodal epifacets of columnals.

Description.—Aboral cup large, height and width approximately equal (Table 34), widest at level of secundibrach 3; expansion angle ranging from 35 to 40°; constricted at level of arm bases; circular in basal view; shallow, funnel-shaped basal concavity. Cup plates generally smooth and flush, but some individuals (e.g., OU 8843) with very fine ridges radiating from plate centers to adjacent plates, others with small, low pustules, especially in basal part of cup (e.g., OU 8844); none of ornament prominent. Low, narrow median ray ridges; in some individuals faint ridges similar to median ray ridges extending between basals and interradials and branching to right and left interbrach 1.

Infrabasals 5, small, pentagonal, height and width approximately equal, confined to basal concavity; deep impression on outer surface of infrabasal circlet at juncture with proximal columnal. Basals 5, heptagonal, slightly wider than high; in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial. Thick pentagonal rim on lower edge of basal circlet. Radials 5, pentagonal; height and width approximately equal; in contact with 2 basals, 2 interradials, and 1 primibrach; D-ray radial commonly hexagonal and in contact with 1 interbrach 1; radials separated by interradial; upper suture less than full width of plate. Median ray ridges passing upward from adjacent basals, converging on radials, gradually becoming more prominent toward top of cup. Primibrach 1 generally hexagonal, wider than high, approximately equal in size to radial, rarely axillary (e.g., OU 8843); lower suture wider than upper suture. Primibrach 2 heptagonal, wider than high, axillary, smaller. Secundibrach 1 irregularly hexagonal, followed by 4 or 5 secundibrachs becoming progressively smaller distally. Arm bases diverging at secundibrach 5 or 6. Secundibrach 2 of same ray separated by a large hexagonal intersecundibrach 1 commonly followed by 2 intersecundibrachs 2 and 2 or 3 intersecundibrachs 3. Interradial large, heptagonal, height and width approximately the same, equal in size to radial, followed above by 2 interbrachs 1; interbrachs 1 irregularly hexagonal, followed by 5 or 6 ranges having 3 or 4 smaller irregular interbrachs contiguous with tegmen. CD interray widest and with more numerous plates than other interrays. Primanal heptagonal or octagonal, followed by 2 or 3 interbrachs 1, followed by 4 interbrachs 2, and then by about 4 ranges with 4 or 5 interbrachs each. Anal series not distinct. Tegmen unknown.

Arms 10, length approximately 3 times height of aboral cup, aboral surface evenly rounded, hemicylindrical, free above secundibrachs 5 or 6, uniserial; each arm branching isotomously 4 or 5 times. Brachials wedge-shaped, bearing pinnules on alternate sides of arm; articulation surfaces crenulate. Shapes and relative sizes of brachials and pinnules changing along arms; at proximal end near aboral cup (below first bifurcation) brachials approximately 6 times wider than high, interlocked at sides of arms with pinnular 1 of each pinnule (Pl. 18, fig. 1). Pinnular 1 smooth, slightly curved plate incorporated in arm, in contact with 3 brachials, 2 pinnulars 1, and 2 pinnulars 2. Pinnular 2 keeled and free. Distally, width-to-height ratio of brachials decreasing to about 2:1 (Pl. 18, fig. 2). Above second bifurcation, first pinnular free and keeled. Pinnules relatively small and slender, aboral surface keeled, sides flat; approximately 1,000 pinnules per ray; each pinnule composed of about 15 pinnulars, pinnulars longer than wide; narrow groove on adoral surface; very small lappets along adoral surface.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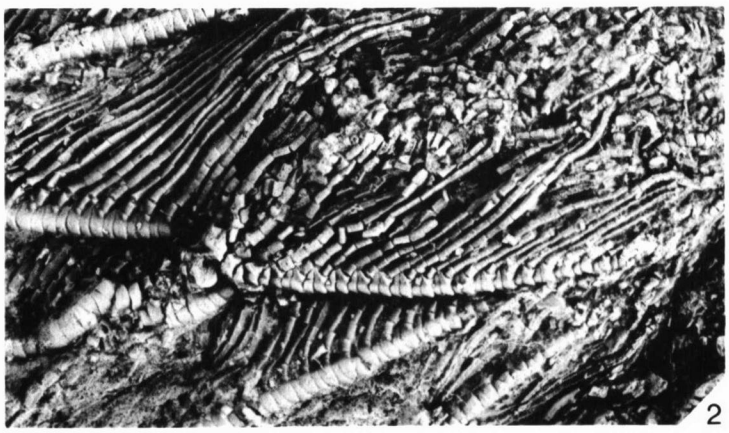
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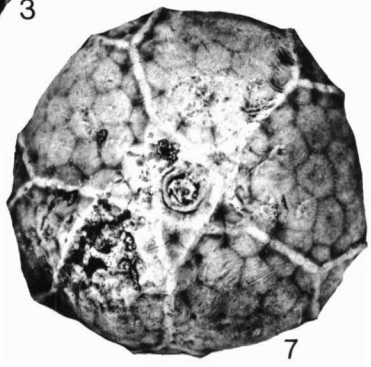
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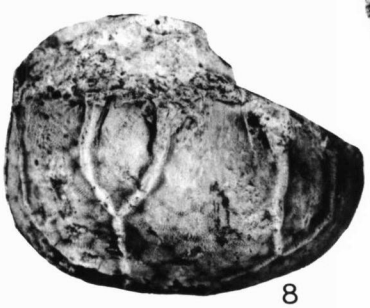
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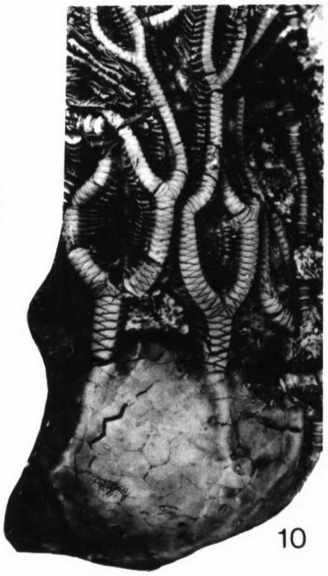
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Table 34. Measurements (mm) of *Archaeocrinus subovalis* Strimple (1953b).

Measurements	Specimens							
	OU 8931	OU 8843	OU 8845	OU 8930	OU 8844	OU 8932	OU 8933	OU 8927
Aboral cup height	16.0	18.0	25.0	28.0	---	40.0	47.0	50.0
Aboral cup width	16.0	23.0	28.0	30.0	---	40.0	40.0	55.0
Basal height	2.0	3.5	3.2	4.0	5.2	6.5	---	6.0
Basal width	3.5	4.7	3.6	5.2	7.8	7.2	---	9.0
Radial height	2.8	4.7	4.7	5.3	7.6	8.0	---	10.0
Radial width	3.2	5.0	5.2	5.8	7.7	---	---	10.0
Interradial height	3.0	5.0	5.7	6.0	8.0	9.5	---	---
Interradial width	3.2	5.7	6.1	6.7	8.2	10.5	---	---
Stem diameter (base of cup)	4.0	3.3	5.5	5.0	6.5	6.0	---	7.5

Stem round, heteromorphic, large; proximal part of stem consisting of closely spaced nodals with wide epifacets, outer edges of epifacets with short spines curving away from crown. Distally, spiny nodals separated by as many as 10 round, thin, straight-sided internodals. Distal-most stem uncertain, but associated columnals with smaller and more numerous spines on epifacets and only 3 or 4 internodals. Symplectic articulation.

Discussion.—*Archaeocrinus subovalis* Strimple (1953b) can be distinguished from most other species of this genus by its large, relatively high aboral cup having generally smooth, flush plates and prominent median ray ridges. The small spines on the nodal epifacets of the stem also help distinguish this species. *Archaeocrinus buckhornensis* differs in the relative sizes and shapes of the aboral cup plates. The radials and basals in the latter are small relative to the primibrachs and interradials. The interradials are typically the largest plates in the cup. In addition, *A. buckhornensis* lacks a thick rim around the basal concavity. *Archaeocrinus conicus* differs in having a conical aboral cup that lacks median ray ridges and has prominent depressed sutures.

Dimensions.—Measurements of selected specimens are given in Table 34.

Material.—Approximately 180 specimens were available for study, many of them well preserved and showing previously unknown morphological details. One exceptionally well-preserved specimen (OU 8845) is complete with arms, calyx, and a small part of the proximal stem (Pl. 18, fig. 3).

Occurrence.—Pooleville Member, Bromide Formation, at the following localities: the upper 13.5 m of the Pooleville at Culley Creek; 0.3, 2.2 11.0, and 15.5 m below the Viola Limestone at Dunn Quarry; 2.2 m below the Viola at Rudd Quarry; and the upper 7.5 m of the Pooleville at Rock Crossing.

ARCHAEOCRINUS sp.

Plate 17, figures 15, 16

Description.—Represented by a single, fragmentary, bowl-shaped aboral cup 35 mm high by 45 mm wide; cup plates recrystallized, all surface ornamentation destroyed; unusually thick plates (up to 5 mm) and depressed sutures apparently alterations developed during diagenesis; median ray ridges apparently lacking.

Infrabasals 5, small, confined to basal concavity. Basals 5, 7.0 mm high by 7.5 mm wide, heptagonal, in contact with 2 infrabasals, 2 basals,

PLATE 18.

Fig. 1-3. *Archaeocrinus subovalis* Strimple (1953b); Pooleville Member, Culley Creek, Criner Hills, OU 8845. 1. Proximal part of arm showing brachials and modified pinnules; X4. 2. Distal part of arms showing uniserial brachials; X4. 3. View of complete crown, plates of aboral cup outlined with pencil; X1.

Fig. 4-10. *Pararchaeocrinus decoratus* Strimple and Watkins (1955); Pooleville Member, Criner Hills; 5, 9, 10 from Rudd Quarry, 4, 6-8 from Culley Creek. 4. Posterior side of OU 8839 showing prominent anal ridge; X2. 5. Side view of tegmen, OU 8935; X2.5. 6. Specimen OU 8934 showing ornament on cup plates; X1.5. 7, 8. Aboral and side views of OU 8921; X1.5. 9. Immature individual; note conical cup and relatively large stem; OU 8937; X2. 10. Specimen OU 8842 showing biserial brachials; X1.5.

2 radials, and 1 interradial. Radials 5, 8.5 mm high by 9.0 mm wide, all pentagonal except D ray, D ray hexagonal. Primibrach 1 larger than radial, hexagonal, 9.5 mm high by 9.5 mm wide. Primibrach 2 relatively large, probably axillary. Interradial large, 10.0 mm high by 10.0 mm wide; followed by 2 interbrachs 1 and 3 interbrachs 2. CD interray widest. Primanal heptagonal; followed by 3 interbrachs 1 at level of primibrachs (median plate part of anal series), 4 interbrachs 2, 5 interbrachs 3, all at level of secundibrachs. Tegmen, arms, and stem unknown.

Discussion.—The structure of the cup and relative sizes and shapes of the plates are similar to those in *A. buckhornensis*, which also is from the Upper Echinoderm Zone in the Mountain Lake Member of the Bromide Formation. The form described here differs in having depressed sutures, but this feature may be an artifact of preservation. If *Archaeocrinus* sp. did have depressed sutures and if the globular shape is due to distortion of a cup that was originally conical, then it may be a poorly preserved specimen of *A. conicus*. Because of poor preservation and lack of sufficient study material, I prefer not to assign this form to a particular species at this time.

Material and occurrence.—The single figured specimen (1222TX2) was found in the Upper Echinoderm Zone of the Mountain Lake Member, Bromide Formation, at the North I-35 locality.

Genus BROMIDOCRINUS Kolata, new

Type species.—*Bromidocrinus nodosus* Kolata, n. sp., here designated.

Diagnosis.—Rhodocrinitid crinoids with large, high, rotund aboral cup; large basals traversed by prominent grooves; radials and primibrachs higher than wide; wide lateral interrays consisting of approximately 20 irregular interbrachs contiguous with tegmen; 2 or 3 interradials; CD interray differing little from other interrays; primanal and anal series not readily distinguishable; 10 unbranched, biserial arms; prominent pentagonal stem.

Discussion.—*Bromidocrinus* is assigned to the Rhodocrinitidae because it possesses a subglobular dicyclic aboral cup whose radials are separated all around, it has low inconspicuous median ray ridges, and it lacks depressed lateral interrays and a median anal ridge. The new genus also has two primibrachs and it has infrabasals that are confined to a basal concavity; both features are common to other rhodocrinitid genera.

Bromidocrinus most closely resembles *Hercocrinus* Hudson (1907) of the Chazyan Valcour Limestone of Valcour Island, Lake Champlain, New York. Like *Hercocrinus*, *Bromidocrinus* has irregular interray interbrachs and two or three interradials. It differs greatly in its larger size, prominent grooves on the basals, and wider interrays that are contiguous with the tegmen. From all other rhodocrinitids, the new genus can be distinguished by the size and shape of its aboral cup and the arrangement of plates in the interrays (Fig. 51).

Occurrence.—Middle Ordovician (Champlainian); United States (Oklahoma).

BROMIDOCRINUS NODOSUS Kolata, n. sp.

Plate 19, figures 1-20; Figure 51

Diagnosis.—Characters as for genus.

Description.—Represented by a well-preserved theca (holotype 1113TX1) from McLish Ranch lacking arms and tip of anal tube; weathered free from matrix, original shape apparently unaltered. Several hundred columnals and about 40 aboral cup plates found at same locality along with 2 largely disarticulated specimens having parts of arms and stem.

Aboral cup globose, obovate in basal view; C ray protruding slightly; 30 mm high by 31 mm wide; widest at level of primibrach 2; expansion angle 55 to 65° from horizontal; dorsal diameter approximately two-thirds ventral diameter. Plates thick (1 to 2 mm), closely appressed, boundaries indistinct, dark gray-brown to black; some plates with irregular, saw-toothed edges; fine crenulae approximately 0.1 mm wide aligned perpendicular to plate at sutures. Aboral cup, tegmen, and anal tube bearing numerous sharp, highly elevated ridges and nodes. (These allow easy recognition of this species, even from disarticulated plates.) Median ray ridges consisting of 3 to 5 thin ridges originating on basals, continuing across sutures to slightly above centers of 2 adjacent radials, passing upward to primibrach 2, becoming discontinuous, merging with nodose ornament. Median ray ridges above primibrach 2 marked by a slightly elevated area at midline of ray plates, area continuous with curvature of arms. Interray areas with

numerous nodes, some nodes fused, forming cockscomb and vermiform structures. Nodes generally not continuous between adjacent plates. Tegmen and anal tube bearing very small pustules in addition to a few scattered nodes. Median ray grooves up to 1.5 mm wide and 1.0 mm deep, impressed on inner surface of aboral cup, extending up from basals to radial and primibrachs in a pattern similar to that of external median ray ridges. Deep basal concavity formed by infrabasals and part of basals.

Infrabasals 5, small, pentagonal, 4.0 mm high by 4.5 mm wide, bearing crenulate articulation surface at juncture with proximal columnal, confined to basal concavity. Infrabasal circlet forming tubular structure deep within base of cup; innermost edge reaching level of radials. Basals 5, largest plate in cup, CD basal 8.0 mm high by 10.5 mm wide, generally octagonal, in contact with 2 infrabasals, 2 basals, 2 radials, and 2 or 3 interradials, broadly curved from sides of cup into basal concavity. Each basal traversed by a prominent rounded groove up to 4.5 mm wide and 3 mm deep, groove flaring upward from basal concavity, terminating near center of plate; intergroove areas consisting of thickened angular process formed by 2 adjacent basals, basals curving around base of cup, their vertices pointing toward stem (Pl. 19, fig. 4). Three or 4 thin ridges continuous between basals on thickened angular processes between prominent medial grooves. All ridges together forming a triangular pattern; vertices near centers of basals and radials (Pl. 19, fig. 2, 3). Some disarticulated basals with deep angular notches at midline of plate along interbasal sutures (Pl. 19, fig. 16, 17). (The basal circlet formed by such plates would have had 5 diamond-shaped interbasal spaces.) This feature not present in holotype.

Radials 5, heptagonal to decagonal, in contact with 2 basals, 2 interradials, 2 to 5 interbrachs, and 1 primibrach, separated by 2 or 3 interradials; A- and B-ray radials smaller than others; A-ray radial 8.5 mm high by 6.0 mm wide; upper suture less than full width of plate; some radials with irregular saw-toothed outlines (Pl. 19, fig. 18). Primibrach 1 heptagonal or octagonal, slightly higher than wide. Primibrach 2 pentagonal to heptagonal, smaller than primibrach 1, axillary, bearing proximal secundibrachs. Secundibrachs pentagonal to heptagonal, wider than high, biserial above secundibrachs 3 or 4, lacking intersecundibrachs. Lateral interrays relatively wide; consisting of from 14 to 22 plates at and below level

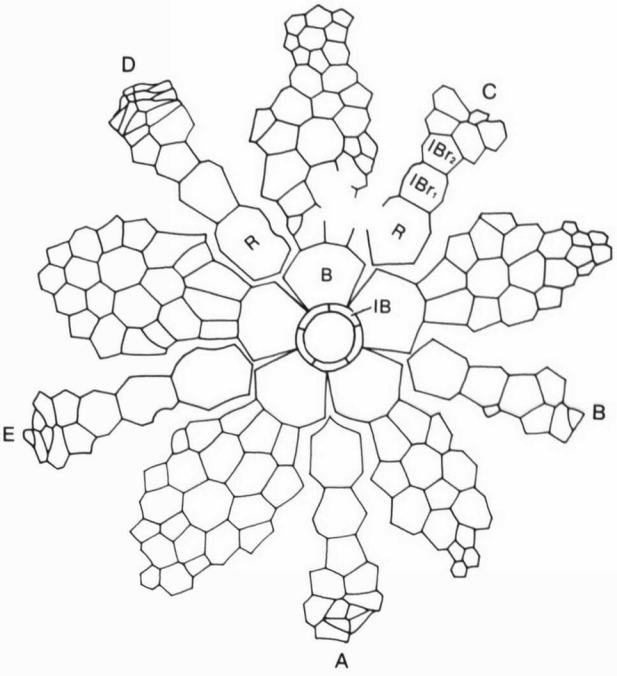

Fig. 51. *Bromidocrinus nodosus* Kolata, n. gen., n. sp., Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, eastern Arbuckle Mountains. Plate diagram based on holotype 1113TX1, X1.3.

of secundibrachs; AE and DE interrays widest. Interradials 2 or 3 per interray, generally pentagonal, higher than wide, followed by 3 or 4 interbrachs 1. Medial interbrach 1 or 2 largest interray plate; interbrachs decreasing in size and number distally.

(Some plates at the base of the CD interray are broken off the holotype, but the approximate plate outlines can be reconstructed by reflecting light from optically oriented crystals within each fragmented plate.) Structure of the CD interray apparently differing little from that of other interrays (Fig. 51). Primanal and anal series not readily distinguishable.

Tegmen gently arched; consisting of numerous small, irregular plates in small area between base of anal tube and arms. Openings for arms consisting of 4 closely spaced pores per ray (2 pores per arm), pores separated by thin wall of calcite; upper pore of each arm elongate and appearing to pass upward into body cavity; lower pore circular, projecting downward within body cavity. Anal tube large, elongate, displaced toward posterior side; axis of tube projecting between C and D rays; tube plates mostly hexagonal, larger than other tegminal plates; anal opening unknown.

Arms 10, free above secundibrach 4 or 5, bise-

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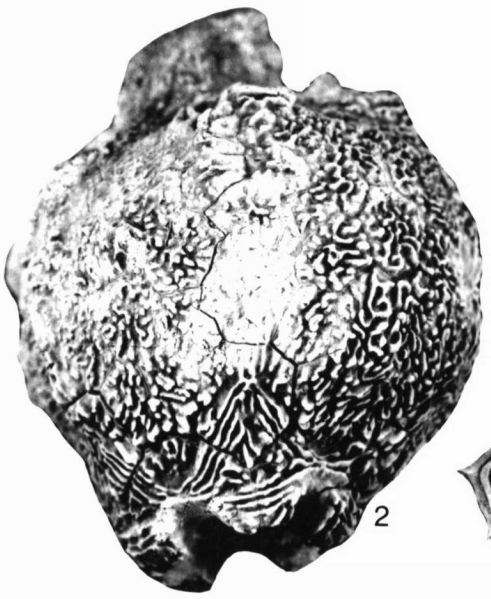
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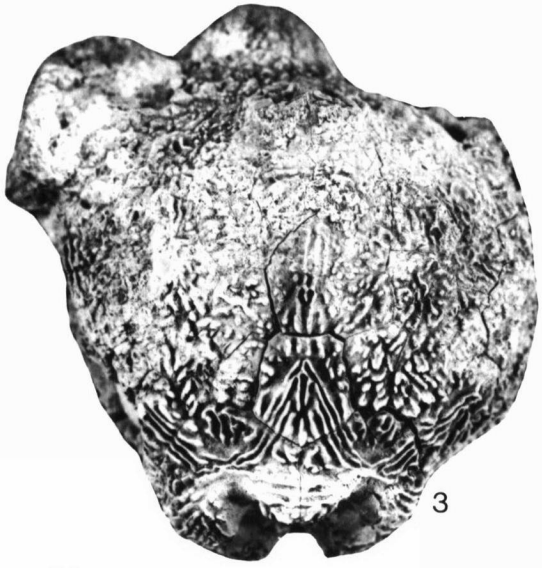
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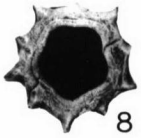
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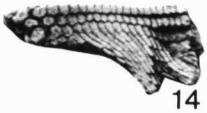
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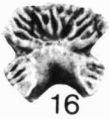
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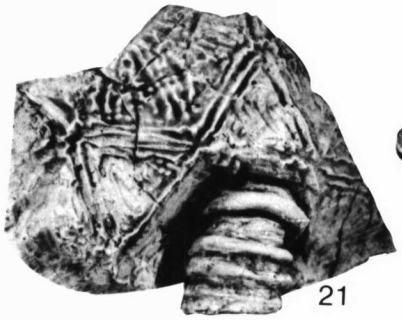
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rial, aboral surface evenly rounded. Pinnules blade-shaped, probably 200 or more per arm; each pinnule composed of about 10 pinnulars; first 2 pinnulars of each pinnule thick hexagonal or pentagonal plates interlocking along a zigzag suture and forming 2 prominent rows along length of arms (Pl. 19, fig. 15), these succeeded by graduated series of 7 to 8 pinnulars, pinnulars much longer than wide; sides flat; deep groove on ventral surface.

Stem subpentagonal to angularly pentagonal, heteromorphic, diameter 6.5 mm at base of cup; noditaxes of 5 columnals (possibly fewer along some regions of stem); cockscomb structure at angles of stem, aligned parallel to longitudinal axis of stem (Pl. 19, fig. 5-11); small blunt spines sometimes occurring in interangle areas of nodals; internodals thin, subpentagonal, straight-sided, some thickened at angles; symplectic articulation; axial canal large, pentalobate.

Discussion.—One of the more unusual aspects of *Bromidocrinus nodosus* is that prominent interradial grooves bisect the basals at the base of the aboral cup. The grooves are aligned with the outer points of the pentastellate nodals of the proximal stem, but the columnal points do not conform exactly to the broad curvature of the grooves. Other than providing a space for the proximal one or two nodals to fit into the basal concavity, the function of the grooves is not clear.

The holotype and most of the disarticulated plates of *B. nodosus* are distinguished by their dark gray to black coloration. The significance of the color is uncertain, however, because a few fragments of this species are light tan or gray.

Types.—The holotype is 1113TX1. Figured paratypes include 1113TX33-44 and 46-49; unfigured paratypes, 1113TX50 and 1279TX314-316.

Occurrence.—The holotype and numerous thecal and stem fragments were found in the Lower Echinoderm Zone of the Mountain Lake Member, Bromide Formation, at McLish Ranch. The holotype was discovered by Sprinkle on the east side of the road at the south end of the McLish C exposure in a pile of material that apparently had been bladed off the road. Two other specimens that were mostly disarticulated were found by Sprinkle in the road approximately 90 m north of the holotype near the north end of the McLish C exposure, and in a ditch about 60 m south of the holotype near the north end of the McLish A exposure. Other thecal plates and columnals were collected from the McLish A, B, and C exposures. In addition, two infrabasal-basal sets and two articulated basals and a radial were found in the Lower Echinoderm Zone at Fittstown Quarry.

Name.—The generic name refers to the Bromide Formation where the holotype was found. The specific name refers to the prominent nodose ornament on the calyx.

Genus CRINEROCRINUS Kolata, new

Type species.—*Crinerocrinus parvicostatus* Kolata, n. sp., here designated.

Diagnosis.—A rhodocrinitid crinoid with large, low, bowl-shaped aboral cup; large, shallow basal concavity formed by infrabasals and proximal edges of basals; wide lateral interrays formed by 1 interradial followed by 3 interbrachs 1; wide CD interray consisting of primanal followed by 3 interbrachs 1 and 5 interbrachs 2; median ray ridges present.

Discussion.—*Crinerocrinus* is assigned to the Rhodocrinitidae on the basis of its low, bowl-shaped, dicyclic aboral cup having radials separated all around. In addition, it possesses median ray ridges, five infrabasals that are confined to a basal concavity, and two primibrachs.

Crinerocrinus most closely resembles *Pararchaeocrinus* Strimple and Watkins (1955). Both genera have low, subglobular aboral cups with wide interrays that have one interradial followed by three interbrachs 1. However, *Pararchaeocrinus* has a smaller basal concavity, 10 arms instead of the more than 20 arms of *Crinerocrinus*, and two or three interradials (one of which is primanal) in

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PLATE 19.

Fig. 1-20. *Bromidocrinus nodosus* Kolata, n. gen. and sp.; Lower Echinoderm Zone, Mountain Lake Member, McLish Ranch, eastern Arbuckle Mountains. 1-4. AE interray, A ray, B ray, and aboral views of holotype 1113TX1; X2. 5-11. Fragments of heteromorphic stem, 1113TX33-39, respectively; X1.5. 12-15. Arm fragments, 1113TX46-49, respectively; X1.5. 16, 17. Basal plates; note deeply notched sides where apparent interbasal spaces existed, 1113TX40, 41; X1.5. 18. Radial plate; note irregular margins, 1113TX42; X1.5. 19, 20. Interior surface of a radial and a primibrach showing median ray grooves, 1113TX43, 44; X1.5.

Fig. 21. Rhodocrinitid species A; Pooleville Member, Culley Creek, Criner Hills; OU 8859; X2.

Fig. 22. *Diabolocrinus oklahomensis* Kolata, n. sp.; Pooleville Member, Culley Creek, Criner Hills; holotype OU 8911; X3.5.

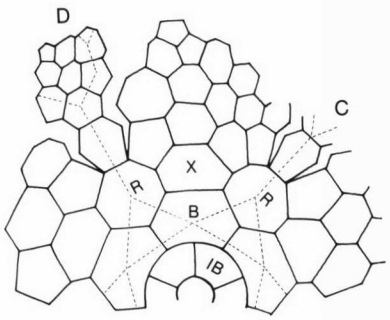


Fig. 52. *Crinerocrinus parvicostatus* Kolata, n. gen., n. sp., Pooleville Member, Bromide Formation, Criner Hills. Plate diagram of posterior side based on holotype OU 8858. Dashed lines represent median ray ridges, X1.5.

contact with the CD interray basal.

Occurrence.—Middle Ordovician (Champlainian); United States (Oklahoma).

CRINEROCRINUS PARVICOSTATUS Kolata, n. sp.

Plate 21, figures 7, 8; Figure 52

Diagnosis.—Characters as for genus.

Description.—Species based on 1 aboral cup; anterior side distorted, partly disarticulated; original shape probably best shown along curvature of D ray. Secundibrachs 2 mark upper limit of preservation.

Aboral cup large, approximately 30 mm high by 50 mm wide, bowl-shaped, flat base; wide, pentagonal, shallow basal concavity. Cup plates slightly convex; ornament consisting of very fine ridges and nodes radiating from plate centers, intercepting sutures at right angles. Median ray ridges originating at centers of basals and passing to adjacent radials, there converging and passing upward to arms. A similar ridge following edge of basal concavity and passing from center of one basal to center of another, producing 5 triangular patterns on basals and radials and a prominent stellate pattern on base of cup.

Infrabasals 5, pentagonal, wider than high, confined to basal concavity. Basals 5, heptagonal, in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial, CD basal 5.0 mm high by 13.0 mm wide, proximal edge bent sharply into basal concavity. Radials 5, heptagonal; except C-ray radial octagonal; D-ray radial 11.0 mm high by 10.5 mm wide. Primibrach 1 slightly higher than wide, irregularly hexagonal, smaller than radial, proximal end tapered, narrowly in contact with radial. Primibrach 2 wider than high, hexagonal, axillary. Secundibrach 1 pentagonal or hexagonal, smaller than primibrach 2. Secundibrach 2 axillary, indicating at least 20 arms were present. Secundibrachs separated by 1 intersecundibrach 1 that is followed by 2 intersecundibrachs 2. Upper part of cup unknown. Interradial hexagonal, 7.5 mm high by 9.5 mm wide, broadly in contact with basal plate, followed by 3 interbrachs 1, followed by 3 or 4 interbrachs 2. CD interray widest. Primanal hexagonal, followed by 3 interbrachs 1, 5 interbrachs 2, and 6 interbrachs 3 (Fig. 52).

Tegmen, arms, and stem unknown.

Type.—The holotype is OU 8858.

Occurrence.—The holotype was found in Zone 3 of the Pooleville Member, 9 to 10 m below the Viola Limestone, Bromide Formation, at Culley Creek.

Name.—The generic name refers to the Criner Hills, where the holotype was discovered, and the specific name refers to the very fine ridges on the cup plates.

Genus DIABOLOCRINUS
Wachsmuth and Springer, 1897

Type species.—*Rhodocrinus vesperalis* White, 1880.

Diagnosis.—A rhodocrinitid crinoid with low, medium-sized, globose, aboral cup; relatively wide lateral interrays consisting of 1 interradial followed by 2 interbrachs; lobate and protuberant arm bases; thick, rigid tegmen; 10 robust, biserial arms.

Discussion.—*Diabolocrinus* closely resembles *Paradiabolocrinus* Brower and Veinus (1974), but the latter differs mainly in having intersecundibrachs. Species of *Diabolocrinus* are distinguished primarily by the shape of the aboral cup and relative sizes and shapes of the cup plates, ornament, and arms. Certain species show considerable variation in the size, shape, and number of interray plates.

Occurrence.—Middle Ordovician (Champlainian) to Late Ordovician (Caradocian); United States (Oklahoma, Tennessee, Virginia) and Scotland (Girvan).

Table 35. Measurements (mm) of *Diabolocrinus arbucklensis* Kolata, n. sp.

Measurements	Specimens									
	OU 8886	1121 TX81	OU 8874	OU 8882	OU 8875	OU 8884	OU 8877	1121 TX88	OU 8883	OU 8885
Aboral cup height	3.0	3.0	3.0	5.0	7.0	7.0	7.0	7.0	9.0	10.0
Aboral cup width	5.0	7.0	9.0	12.0	16.0	16.0	18.0	19.5	20.0	22.0
Basal height*	1.7	1.9	2.0	2.2	2.7	3.4	3.3	3.3	3.8	5.0
Basal width	2.1	2.2	2.6	3.1	4.3	5.0	4.9	5.0	5.7	6.0
Radial height	1.7	1.9	2.0	3.0	3.8	4.0	4.7	4.4	5.0	5.3
Radial width	2.2	2.5	2.6	3.4	4.2	5.0	5.3	5.2	6.0	7.2
Interradial height	1.2	1.3	2.0	3.0	3.5	4.0	4.5	3.7	5.5	7.0
Interradial width	1.6	1.6	2.5	3.8	4.2	4.7	5.8	5.2	7.2	9.0
Arm width, proximal	1.6	2.0	2.0	2.2	---	2.5	---	2.8	3.2	3.0

*Measured from distal edge to bend at basal concavity.

DIABOLOCRINUS ARBUCKLENSIS Kolata, n. sp.

Plate 20, figures 1-10; Figure 53

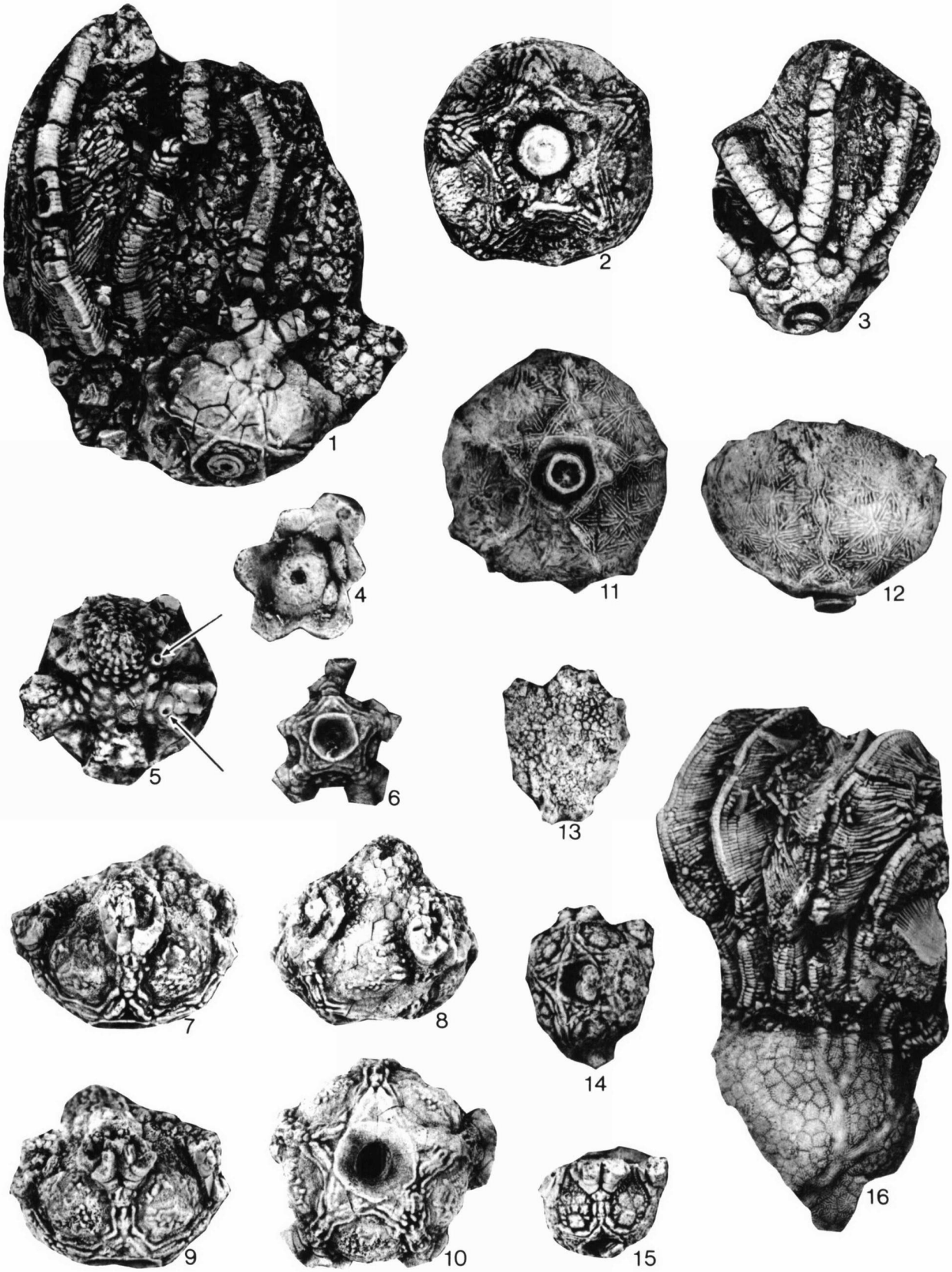
Diagnosis.—*Diabolocrinus* with prominent median ray ridges; variable ornament consisting of sinuous and stellate ridges, nodes, and pustules; interradial largest plate in cup; robust arms.

Description.—Aboral cup low, bowl-shaped, flat at bottom, width approximately twice height; largest specimen 10 mm high and 22 mm wide; average size of mature individuals 8 mm high and 16 mm wide (Table 35); cup widest at level of primibrach 2. Cup plates slightly convex, thick, ornamented by sinuous ridges, stellate ridges, nodes, and pustules; ornament variable. Prominent median ray ridges forming stellate pattern in basal view.

Infrabasals small, pentagonal, height and width approximately equal, confined to basal concavity; infrabasal circlet hemispherical in interior view (Pl. 20, fig. 4); deep impression on outer surface of infrabasal circlet at juncture with proximal columnal. Basals 5, heptagonal, in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial; height and width approximately equal. Each basal bent abruptly at midline into basal concavity. Thick angular process at lower edge of each basal forming a prominent pentagonal ridge at base of aboral cup (Pl. 20, fig. 2, 10). Radials 5, pentagonal, slightly wider than high, separated by interradials, in contact with 2 basals, 2 interradials, and primibrach 1; distal suture less than full width of plate. Median ray ridges consisting of 2 or 3 smaller ridges and nodes passing upward from 2 adjacent basals and converging on radials; small ridges and nodes continuing upward and merging with backs of arms. Primibrach 1 wider than high, pentagonal or hexagonal, rarely axillary (e.g., OU 8873). Primibrach 2 wider than high, pentagonal or hexagonal, axillary, smaller than primibrach 1. Secundibrach 1 about twice as wide as high, all brachials biserial above secundibrach 1. Secundibrachs 1 bearing large, thick, fixed pinnules on lateral interray side. Secundibrach 1 and 2 of each half-ray closely appressed to adjacent secundibrachs of same ray.

Interray areas relatively wide and bulging slightly, generally fewer than 5 interray plates at and below level of secundibrachs. Interradials usually heptagonal, slightly larger than radials, usually followed above by 2 relatively large interbrachs 1; small supplementary plates interspersed between interradial and interbrachs in some individuals. Interbrachs 2 smaller than interbrachs 1, irregular in shape, generally 2 or 3 in number, followed above by small irregular interbrachs grading imperceptibly into tegmen. CD interray widest with more supplementary plates (Fig. 53). Primanal irregularly heptagonal to nonagonal, approximately same size as interradial, located between radials and primibrachs, followed by 2 (upper left plate part of anal series) or 3 plates (central plate part of anal series); small supplementary interbrachs commonly occurring adjacent to C ray. Numerous very fine, straight ridges extending across sutures between interray and ray plates in aboral cups of some individuals.

Tegmen domed; ambulacral areas large and lobate; interambulacral areas narrow and depressed, composed of relatively large regular plates; largest plates near center gradually diminishing in size toward arms; plates continuous with interray plates. Tegmen plates slightly convex to nodose. Orals not differentiated. Arm openings large, elongate; sides constricted near center of open-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ings. Anal tube low, rounded, cone-shaped, positioned near posterior side; anal series continuing distally along anal tube; plates diminishing in size toward top of anal tube. Anal opening small, elliptical, directed between C and D rays.

Ambulacral areas terminating in a relatively large plate commonly with a distinctive, highly elevated, conical tubercle bearing pore at top (Pl. 20, fig. 5). Tubercle further differentiated in some individuals by longitudinal striations and very fine pustules. Tubercle most common in D and E rays, less common in A and C rays, rare in B ray; generally present in only 1 or 2 rays. Opening at top of tubercle may be hydropore.

Arms 10, robust, free, and biserial above secundibrach 1; length approximately 5 times height of aboral cup; constant width throughout length of arm, tapering rapidly at end; aboral surface evenly rounded. Pinnules long (10 mm in paratype OU 8883), blade-shaped, approximately 100 per arm; each pinnule composed of about 10 pinnulars, pinnulars longer than wide, each with broad flat sides and very narrow, slitlike groove on adoral surface.

Stem round, heteromorphic; proximal portion of alternating well-rounded nodals and partially hidden internodals; internodals becoming prominent distally; axial canal pentalobate; symplectic articulation; distal stem unknown.

Ontogeny.—Ontogeny is based on an examination of 20 specimens having aboral cups that range in a generally continuous sequence of sizes from 3 mm high by 5 mm wide to 10 mm high by 22 mm wide (Table 35). Immature individuals possess narrow interray areas that have relatively small interradials and interbrachs, and few supplementary plates. During growth the interradials become the largest plates in the calyx and the interray areas become wider than the rays. As a result, the shape of the aboral cup changes from slightly conical to globose. During ontogeny, width of the basals, radials, and interradials increases more rapidly than height. Other notable ontogenetic changes include an increase in size of the anal tube and development of more slender arms. Poriferous tubercles located at the ends of the ambulacra on the tegmen are present in the smallest individuals.

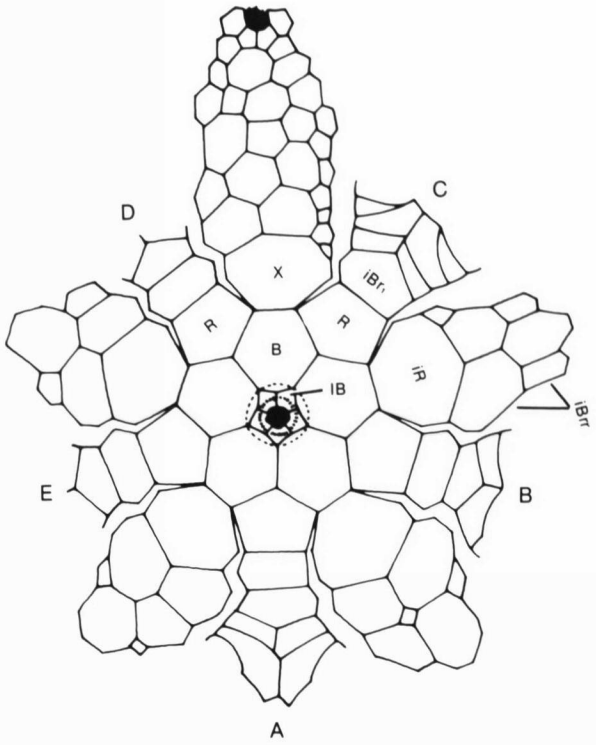


Fig. 53. *Diabolocrinus arbucklensis* Kolata, n. sp., Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains. Plate diagram of aboral cup based on holotype OU 8873, X2.4.

Discussion.—*Diabolocrinus arbucklensis* from the middle Mountain Lake Member of the Bromide Formation differs from *D. poolevillensis* from the Pooleville Member in having fewer interray plates, larger interradials, deeper basal concavity, and

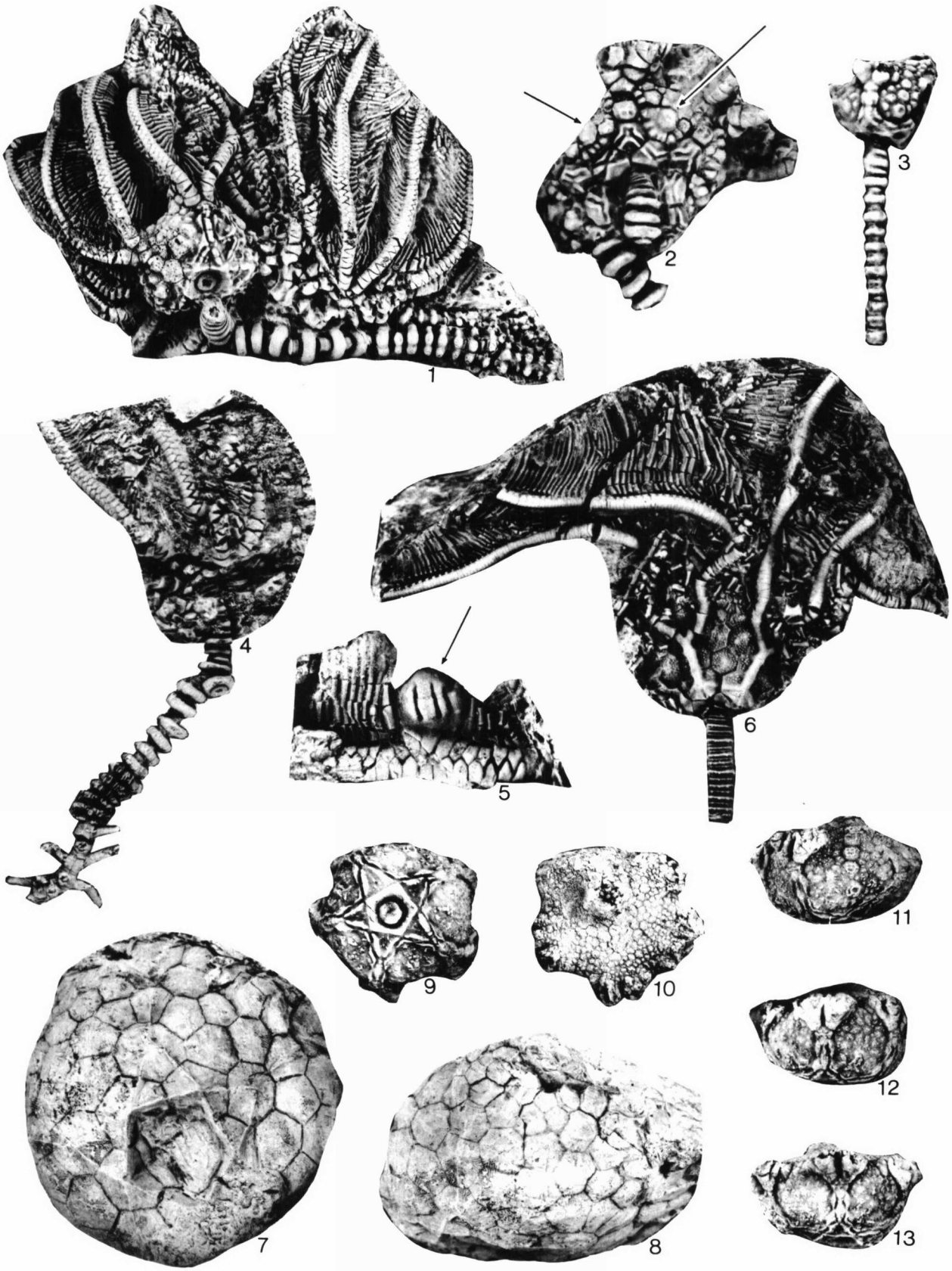
PLATE 20.

Fig. 1-10. *Diabolocrinus arbucklensis* Kolata, n. sp.; 1, 3, 5-10 from Lower Echinoderm Zone, Mountain Lake Member, Daube Ranch, southern Arbuckle Mountains; 2 from lower part of *Carabocrinus* Beds, Mountain Lake Member, North-Central I-35 locality, Arbuckle Mountains; 4 from Lower Echinoderm Zone, Amis Ranch, Arbuckle Mountains. 1. Partly crushed crown OU 8883 showing stellate ornament at base of cup; X1.5. 2. Aboral view of paratype 1276TX11; note different ornament in 10 below; X2. 3. Paratype OU 8886; X3. 4. Interior of aboral cup showing infrabasal and basal circlets, paratype 1109TX9; X2. 5. Adoral view of paratype OU 8881; arrows point to 2 poriferous tubercles at ends of the D- and E-ray ambulacra; X2. 6. Aboral view of paratype OU 8887; X2. 7-10. E ray, CD interray, A ray, and aboral views of holotype OU 8873; X2.

Fig. 11, 12. *Pararchaeocrinus?* sp.; Pooleville Member, Culley Creek, Criner Hills; aboral and side views of OU 8910; X2.

Fig. 13-15. *Diabolocrinus constrictus* Kolata, n. sp.; Upper Echinoderm Zone, Mountain Lake Member, Lick Creek, Arbuckle Mountains; adoral, aboral, and side views of holotype OU 8862; X2.

Fig. 16. Camerate species A; Lower Echinoderm Zone, Mountain Lake Member, Daube Ranch, southern Arbuckle Mountains; OU 8860; X1.5.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more robust arms. The stellate pattern of ridges on the basal circlet and radials and the prominent median ray ridges distinguish *D. arbucklensis* from *D. vesperalis* (White, 1880) and probable conspecific forms (see Brower and Veinus, 1974) such as *D. "perplexus," D. "hieroglyphicus," D. "asperatus," D. "parvus,"* and *D. "knoxensis,"* all from the Middle Ordovician of southwestern Virginia and eastern Tennessee.

D. globularis Ramsbottom (1961) of the Caradocian Craighead Limestone of the Girvan district in southwestern Scotland is similar in size and shape to *D. arbucklensis* but in the former the arm bases do not protrude as much and the cup plates are smoother. The extremely low cup and 20 arms of *D. craigheadensis* Ramsbottom (1961), also from the Craighead Limestone of the Girvan district, differ greatly from those of *D. arbucklensis*.

Diabolocrinus arbucklensis is characterized by highly variable ornament, which ranges from small inconspicuous nodes in some individuals (OU 8883) to prominent, closely spaced nodes and ridges in others (1276TX11). Similarly, Brower and Veinus (1974) noted a high degree of variability in the ornament of *D. vesperalis* (White, 1880): on the basis of graphs, statistical analyses, and observations on the geographical distribution of specimens, they showed that *D. vesperalis* is synonymous with five other species. These species were defined primarily on the basis of apparent differences in ornament.

One specimen (OU 8919) that consists of an incomplete aboral cup from Daube Ranch has a peculiar arrangement of the basal and radial plates. One of the basals is irregular in shape and is unusually small. Instead of being in contact with two radials and a central interradial, it is followed only by an interradial. Two radials and the arms borne by them are missing. As a result the aboral cup has developed a conical rather than globular shape.

Dimensions.—Measurements made on selected specimens are given in Table 35.

Types.—The holotype (OU 8873) is a well-preserved theca that lacks arms and stem and is completely free of matrix. In addition to the holotype, approximately 90 specimens consisting of complete or nearly complete calyces were available for study. Numbered paratypes include 1109TX9-14, 1121TX68, 73-101, 1221TX11a, 11b, 12, 13, 18, 1276TX11, OU 8874-8877, and OU 8920.

Occurrence.—The holotype is from the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, at Daube Ranch, as are a number of paratypes. The new species also occurs in the same zone at Lick Creek, Amis Ranch; 14 to 18½ m below the Upper Echinoderm Zone, Mountain Lake Member, on the north bank of Lick Creek (Eckert Coll.; see Eckert, 1951); lower part of *Carabocrinus* Beds, B-cut, North-Central I-35; one questionable specimen from the Upper Echinoderm Zone, center strip roadcut at the North I-35 locality.

Name.—The specific name refers to the Arbuckle Mountains, where the species occurs.

DIABOLOCRINUS CONSTRICTUS Kolata, n. sp.

Plate 20, figures 13-15

Diagnosis.—*Diabolocrinus* having fixed pinnules of adjacent rays either in contact or nearly so, thus separating interray plates from tegmen except on posterior side; sutures depressed.

Description.—Species represented by a single calyx with several proximal columnals attached. Aboral cup low, globose, 5.0 mm high by 9.5 mm wide. Cup plates thick, ornamented with small nodes and pustules. Prominent median ray ridges form stellate pattern in basal view. Sutures depressed.

Infrabasals small, confined to basal concavity.

PLATE 21.

Fig. 1-5. *Diabolocrinus poolevillensis* Kolata, n. sp.; Pooleville Member, Culley Creek, Criner Hills. 1. Holotype OU 8863; X1.5. 2. Paratype 1122TX92 showing interradials (at arrows) surrounded by small supplementary interbrachs; X2. 3. Posterior side of paratype 1122TX73; X2. 4. Paratype OU 8871 showing complete, heteromorphic stem; crown has been crushed and partly disarticulated; X1.5. 5. Tumorlike structure (at arrow) formed by pinnules at base of arm on paratype OU 8870; X3.

Fig. 6. *Abludoglyptocrinus laticostatus* Kolata n. gen. and sp.; Pooleville Member, Rudd Quarry, Criner Hills; holotype OU 8914; X2.

Fig. 7, 8. *Crinerocrinus parvicostatus* Kolata, n. gen. and sp.; Pooleville Member, Culley Creek, Criner Hills; aboral and posterior views of holotype OU 8858, plate boundaries have been outlined with pencil; X1.

Fig. 9-13. *Paradiabolocrinus stellatus* Kolata, n. sp.; Upper Echinoderm Zone, Mountain Lake Member, North I-35 locality, Arbuckle Mountains; aboral, adoral, posterior, E ray, and A ray views of holotype 1106TX10; X2.

Basals 5, 1.2 mm high by 2.5 mm wide, bent abruptly at midline into basal concavity, heptagonal; CD basal nonagonal. Radials 5, 2.1 mm high by 2.3 mm wide, mainly heptagonal except with 12 or more sides where bordered by very small supplementary interbrachs. Median ray ridges consisting of 2 smaller ridges passing upward from each adjacent basal and converging on radials; at midpoint of radials, ridges merging to form 3 ridges passing upward to primibrach 2. Primibrach 1 wider than high. Primibrach 2 wider than high, pentagonal or hexagonal, axillary, smaller than primibrach 1. Secundibrach 1 wider than high; bearing large fixed pinnules on interray side. Fixed pinnules of adjacent rays either in contact or very close, except widely separated on posterior side. Secundibrach 1 and 2 of each half-ray closely appressed to adjacent secundibrachs of same ray.

Interradials smaller than radials, height and width approximately equal, in contact with basal, 2 radials, and numerous small supplementary interbrachs; very small ridges located in sutural depressions extending across sutures to adjacent plates. Interradial followed by approximately 15 small irregular interbrachs, interbrachs not contiguous with tegmen except on posterior side. CD interray widest; numerous large plates. CD basal followed by relatively small plate on upper left edge and large plate, probably primanal, on upper right edge. Primanal larger than interradial, followed by anal series consisting of 4 relatively large plates. Approximately 25 interbrachs on each side of anal series and contiguous with tegmen.

Tegmen convex, consisting of relatively small nodose plates; ambulacral areas not lobate. Anal tube low and inconspicuous, positioned near posterior side.

Arms 10, free above secundibrach 1, not preserved beyond secundibrach 3. Stem represented by 5 or 6 proximal columnals, columnals relatively thin with narrow epifacets and symplectic articulation.

Discussion.—The shape of the aboral cup, the median ray ridges, and the surface ornament in *D. constrictus* most closely resemble those of *D. arbucklensis*. *Diabolocrinus constrictus* differs from the latter and all other species of *Diabolocrinus* in having fixed pinnules of adjacent rays either in contact or nearly so, thus separating the interray plates from the tegmen except on the posterior side.

The numerous irregular interbrachs; low, evenly rounded tegmen; anal series; and ornament on the base of the cup in *D. constrictus* are all similar to those of *Paradiabolocrinus stellatus*, which occurs in the same zone. The latter differs in that it lacks depressed sutures, has wider interrays that are contiguous with the tegmen, and has intersecundibrachs.

Type.—The holotype is OU 8862.

Occurrence.—The holotype was found in the Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, at Lick Creek.

Name.—The specific name refers to the constriction of the interrays by the fixed pinnules.

DIABOLOCRINUS OKLAHOMENSIS Kolata, n. sp.

Plate 19, figure 22

Diagnosis.—*Diabolocrinus* with very fine, sinuous ridges on aboral cup and arms; relatively deep basal concavity ornamented with small pustules; lacking median ray ridges.

Description.—Species represented by one crown with a small section of stem attached. Aboral cup low, globose, 4.0 mm high by 6.0 mm wide; arm bases not appreciably lobate and protuberant; plates thick, convex; fine sinuous ridges and nodes on cup and arms; lacking median ray ridges; sutures depressed.

Infrabasals 5, very small, confined to deep basal concavity. Basals 5, 1.7 mm high (outer end to bend at basal concavity) by 2.4 mm wide, heptagonal, in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial. Lower part of basals bent sharply into basal concavity; nearly half surface area confined to basal concavity; small pustules on surface of basal concavity; flangelike elevation extending between adjacent basals to form a thick pentagonal rim. Radials 5, 2.0 mm high by 2.3 mm wide, pentagonal, separated by interradial. Primibrach 1 twice as wide as high, hexagonal. Primibrach 2 wider than high, pentagonal, axillary. Secundibrach 1 and 2 of each half-ray closely appressed to adjacent secundibrachs. Interrays relatively narrow; 3 plates at and below level of secundibrach 1. Interradial heptagonal, 1.5 mm high by 2.0 mm wide, followed by 2 interbrachs 1. CD interray not exposed.

Arms 10, uniserial, free above secundibrach 2, aboral surface evenly rounded. Pinnules stout, composed of about 10 pinnulars, pinnulars longer than wide, each having broad flat sides.

Stem known only from proximal section. Proximal columnals round, consisting of relatively thick,

well rounded nodals and small, thin, straight-sided internodals; symplectic articulation.

Discussion.—One specimen, consisting of aboral cup, arms, and proximal stem, was available for study. Relatively small, it may be the remains of an immature individual. It differs from other Bromide *Diabolocrinus (D. arbucklensis, D. constrictus,* and *D. poolevillensis)* of comparable size in lacking median ray ridges. The new species differs from *D. vesperalis* (White, 1880) in having a deeper basal concavity and numerous fine, sinuous ridges on the aboral cup and arms.

Type.—The holotype is OU 8911.

Occurrence.—The single specimen was found at the top of Zone 5 of the Pooleville Member, 11.5 to 13.5 m below the Viola Limestone, Bromide Formation, at Culley Creek.

Name.—The specific name refers to the state of Oklahoma, where the species occurs.

DIABOLOCRINUS POOLEVILLENSIS Kolata, n. sp.

Plate 21, figures 1-5

Diagnosis.—*Diabolocrinus* with 1 or 2 interradials; 7 to 25 interbrachs below level of secundibrachs; nodose ornament on lateral interray and tegminal plates; shallow basal concavity; relatively slender arms; median ray ridges; heptagonal radials wider than high.

Description.—Aboral cup low and globose, width approximately twice height (Table 36); up to 10 mm high and 23 mm wide; circular in basal view; arm bases not appreciably lobate or protuberant; plates nodose; prominent median ray ridges; sutures depressed.

Infrabasals 5, small, pentagonal, height and width approximately equal; confined to shallow basal concavity; deep impression on outer surface of infrabasal circlet at juncture with proximal columnal. Basals 5, generally heptagonal, in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial (3 or 4 small interradials may be in contact with distal edge of basal, making basals octagonal or nonagonal), height and width approximately equal. Lower part of basals bent slightly into basal concavity, flangelike elevation extending between adjacent basals at bend into basal concavity, forming a thick pentagonal rim (Pl. 21, fig. 1-3). One or 2 ridges passing from the flangelike elevation to each adjacent radial, ridges constricted at sutures. In some individuals 1 or 2 ridges pass between basals and interradials. Together, ridges forming a stellate pattern in basal view; each point lying near center of a radial. Radials 5, generally heptagonal, but with 9 or more sides in individuals having numerous supplementary plates, wider than high, separated by interradials; in contact with 2 basals, 2 interradials (commonly), 2 interbrachs, 1 primibrach; upper suture less than full width of plate. Median ray ridges generally consisting of 3 small parallel ridges passing upward from 2 adjacent basals and converging on radials; these ridges continuing upward and merging with backs of arms (Pl. 21, fig. 1). Center ridge usually the most prominent, commonly widest near plate margins but constricted and depressed at sutures. Primibrach 1 wider than high, hexagonal to octagonal, rarely axillary (1122TX88). Primibrach 2 wider than high, hexagonal or heptagonal, axillary, smaller than primibrach 1. Secundibrach 1 bearing large, fixed pinnules. Secundibrach 1 and 2 of each half-ray closely appressed to adjacent secundibrachs of same ray. Interray areas relatively wide, generally 9 to 12 interray plates at and below level of secundibrach 1; however, some individuals with as many as 30 plates per interray. Interradials varying in size, shape, and number; in some specimens interradial considerably higher than wide, in others height and width approximately equal; interradials smaller than radials or basals; generally 1 or 2 interradials between radials, interradial commonly encircled by numerous small supplementary plates (Pl. 21, fig. 2). Interray interbrachs irregular in shape, decreasing in size but increasing in number distally, grading into tegmen. All interray plates nodose, interradial and interbrachs 1 commonly with a small central depression. CD interray slightly wider than other interrays, anal series not distinct.

Tegmen domed, composed of relatively large plates, continuous with interrays. Anal tube low, rounded, cone-shaped, positioned near posterior side; very small plates at top of anal tube.

Arms 10, free and biserial above secundibrach 2, length approximately 5 times height of aboral cup, tapering gradually, aboral surface evenly rounded. Very fine crenulations on articulation surface between brachials. Pinnules long, approximately 100 per arm, small spines along sides in some individuals; each pinnule of about 12 pinnulars, pinnulars longer than wide, with broad flat sides and a very narrow, deep, slitlike groove on adoral surface.

Table 36. Measurements (mm) of *Diabolocrinus poolevillensis* Kolata, n. sp.

Measurements	Specimens									
	OU* 8863	OU 8870	OU 8864	OU 8869	OU 8872	1122 TX73	1122 TX74	1122 TX70	1122 TX75	1122 TX88
Aboral cup height	4.0	10.0	---	7.0	---	4.0	---	---	---	---
Aboral cup width	14.0	23.0	---	23.0	---	8.0	---	---	---	---
Basal height**	2.5	4.4	2.4	2.7	1.8	1.5	2.2	2.6	1.9	1.4
Basal width	3.8	5.7	3.9	5.0	3.2	2.0	4.0	3.5	3.5	3.0
Radial height	3.6	5.5	3.6	4.4	2.8	1.9	3.1	3.5	3.1	2.5
Radial width	4.0	7.7	4.0	4.5	3.1	2.2	3.4	3.7	3.3	2.5
Interradial height	3.5	6.3	2.6	3.5	2.0	1.4	---	2.7	---	2.0
Interradial width	4.0	4.5	2.7	3.5	2.0	1.5	---	2.7	---	2.4
Arm width, proximal	1.4	2.1	1.7	2.5	1.7	1.2	---	1.6	---	1.4

*Holotype.
**Measured from upper edge to bend at basal cavity.

Stem relatively short (Pl. 21, fig. 4), 38 to 46 mm long in 2 nearly complete specimens, heteromorphic, differentiated longitudinally into several distinct zones. Proximal stem round, consisting of thick, well-rounded nodals and small, thin, partially hidden, straight-sided internodals (Pl. 21, fig. 1, 4); internodals increasing in number distally from 2 or 3 at base of cup to 6 or 7 near midzone; very fine, longitudinally aligned ridges curving around nodals. Near midzone ridges becoming thicker, developed into wrinkled, barblike projections. (In some individuals the ridges and projections are in clumps that impart a pentalobate outline to each columnal.) Rootlike holdfast at distal end of column (Pl. 21, fig. 4). Symplectic articulation; axial canal pentalobate.

Smallest specimen (paratype 1122TX73) available for study (aboral cup height 4 mm, width 8 mm) a calyx with part of stem attached (Pl. 21, fig. 3); similar in most respects to larger, presumably more mature individuals.

Discussion.—The size, shape, and number of interray plates is highly variable in *D. poolevillensis*. Specimens from the same locality have from 9 to 30 plates below the level of the secundibrachs in each interray, but are alike in all other features. The interradial position may be occupied by a single large interradial that is usually higher than wide, or by two smaller plates that are equidimensional. Very commonly a single, large interradial is surrounded by 5 to 10 very small supplementary plates (Pl. 21, fig. 2). The interray structure of *D. poolevillensis*, particularly in those individuals with 20 or more lateral interray plates, is suggestive of the condition in species of *Paradiabolocrinus* Brower and Veinus (1974). The latter, however, differs in having intersecundibrachs.

Diabolocrinus poolevillensis most closely resembles *D. arbucklensis* of the Mountain Lake Member, Bromide Formation, of Oklahoma. Both species possess aboral cups that are comparable in size and shape, and they both have prominent median ray ridges and a stellate pattern of ridges in basal view. *Diabolocrinus poolevillensis* differs from the Mountain Lake species in its greater variation of the lateral interray plates. Some individuals possess as many as 30 plates, whereas *D. arbucklensis* rarely has more than eight. Further, *D. poolevillensis* differs in having more slender arms, a shallower basal concavity, and smaller interradials.

Diabolocrinus vesperalis (White, 1880), and probable conspecific forms (see Brower and Veinus, 1974) from the Middle Ordovician of southwestern Virginia and eastern Tennessee, differ from *D. poolevillensis* in that they lack median ray ridges and they have at most 10 interray plates.

Diabolocrinus globularis (Nicholson and Etheridge, 1881), from the Caradocian Craighead Limestone of the Girvan district in southwestern Scotland has smooth plates and no supplementary interray plates and thus differs from the new species.

Six of the studied specimens have a peculiar, tumorlike structure located on the ventral surface of the arm, usually close to the tegmen (Pl. 21, fig. 5). The structure consists of 4 or 5 pinnules that have fused to form a sphere approximately 4 mm in diameter. The functional significance of the structure is not clear, but its obstruction of the food groove and infrequent occurrence suggest that it was pathological in origin. It resembles a myzostomid cyst, a parasitic polychaete annelid that causes similar swellings on the arms and pinnules in living crinoids.

Dimensions.—Measurements of selected specimens

are given in Table 36.

Types.—The holotype (OU 8863) is a well-preserved crown having a long section of stem lying adjacent. The arms and disarticulated calyx of a second specimen are partially embedded in the matrix next to the holotype. In addition to the holotype, approximately 40 specimens were available for study. Many of these specimens are partially or completely disarticulated. Numbered paratypes include 1122TX48-49 and 1122TX70-100; OU 8864-8871.

Occurrence.—The holotype and several paratypes were found at the top of Zone 5 of the Pooleville Member, 11.5 to 13.5 m below the Viola Limestone, Bromide Formation, at Culley Creek. The species also occurs in Zones 3 and 4 of the Pooleville 9 to 10 m and 10 to 11.5 m below the Viola Limestone at the same locality.

Name.—The specific name refers to the Pooleville Member, in which the new species was found.

Genus PARARCHAEOCRINUS
Strimple and Watkins, 1955

Type species.—*Pararchaeocrinus decoratus* Strimple and Watkins, 1955.

Diagnosis.—A rhodocrinitid crinoid with a low, globular aboral cup; lateral interrays consisting of 1 interradial followed by 3 interbrachs in first range; 2 or 3 interradials on posterior side (1 is primanal); thin-plated tegmen with long slender anal tube; arms 10, uniserial transitional to biserial, branching 3 or 4 times.

Occurrence.—Middle Ordovician (Champlainian); United States (Oklahoma, Tennessee).

PARARCHAEOCRINUS DECORATUS
Strimple and Watkins, 1955

Plate 18, figures 4-10; Figure 54

Diagnosis.—*Pararchaeocrinus* with median ray ridges; flat to slightly convex aboral cup plates with flush sutures; fine ridges radiating from center of plates; thick, sinuous ridges and nodes on walls of basal concavity.

Description.—Many new specimens showing previously unknown features of the crown available for study. Aboral cup low, globular, width greater than height (Table 37); up to 32 mm wide, widest at level of secundibrach 3; plates flat to slightly convex, ornamented with fine ridges radiating from plate center and usually connecting with ridges on adjacent plate; narrow, relatively deep basal concavity; prominent, narrow median anal and ray ridges.

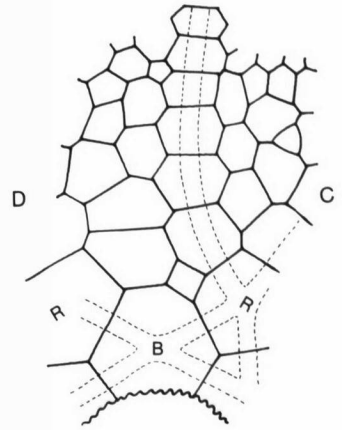

Fig. 54. *Pararchaeocrinus decoratus* Strimple and Watkins (1955), Pooleville Member, Bromide Formation, Criner Hills. Diagrammatic representation of posterior side based on OU 8841. Dashed lines show position of median anal and median ray ridges, X6.

Infrabasals 5, small, confined to basal concavity; deep impression on outer surface of infrabasal circlet at juncture with proximal columnal. Basals 5, heptagonal (except CD-interray basal), wider than high; in contact with 2 infrabasals, 2 basals, 2 radials, and 1 interradial; CD-interray basal in contact with 2 or 3 interradials, one interradial primanal (Fig. 54); proximal edge of basals bent sharply into basal concavity; concavity ornamented with prominent thick, sinuous ridges and nodes; low, rounded ridge encircling basal concavity and continuous with median ray ridge, median ray ridge originating on basals and passing upward to adjacent radials. Radials 5, heptagonal, height and width approximately equal; separated by interradial; upper suture less than full width of plate. Primibrach 1 hexagonal, wider than high. Primibrach 2 generally pentagonal, height and width approximately equal, axillary. Secundibrach 1 irregularly hexagonal or heptagonal, followed by 4 fixed secundibrachs. Small ridge bifurcating from median ray ridges on secundibrach 2 and passing upward on lateral interray brachials to tegmen. Secundibrach 2 of same half-ray either in contact with or separated by 1 intersecundibrach

commonly followed by 1 or 2 additional intersecundibrachs. Interradials hexagonal, height and width approximately the same; followed by 3 interbrachs 1 and 4 interbrachs 2. CD interray widest with more numerous plates. Two or 3 interradials separating C- and D-ray radials (Fig. 54). No clearly differentiated primanal. The first well-defined anal plate with median anal ridge located on upper left sloping edge of C-ray radial, plate followed by row of generally hexagonal plates (anal series) continuing above cup along surface of anal tube. Prominent median anal ridge marking anal series (Pl. 18, fig. 6, 7). Anal series gradually curving back toward C ray.

Tegmen gently arched, divided into 5 lobate ambulacral areas bifurcating near 10 arm bases. A second smaller lobe bifurcating toward interray side and continuous with ridge originating on secundibrach 2, discussed above (Pl. 18, fig. 9). Small nodes and spines on ambulacral plates. Interambulacral plates numerous, smooth to finely pustulose. Openings for arms large, elongate, set on beveled junction of aboral cup and tegmen. Anal tube slender, elongate (approximately 10 mm long in OU 8839), curved inward distally, located on edge of tegmen; posterior side consisting of smooth anal series with prominent median ridge; ventral surface consisting of numerous, small, irregular, nodose plates.

Arms 10, free above secundibrach 4, slender, length approximately 5 times height of aboral cup, aboral surface evenly rounded, bifurcating at least 3 times. Arms basically uniserial, but in some larger individuals, proximal arms (below second bifurcation) composed of immature biserial wedge-shaped brachials with curved proximal and distal faces (Pl. 18, fig. 10). Pinnules relatively small and slender (6 mm long in OU 8842), approximately 500 per arm, aboral surface keeled, sides flat; each pinnule composed of approximately 12 pinnulars, pinnulars longer than wide, with narrow slitlike groove on adoral surface.

Stem round to slightly pentalobate; noditaxis consisting of 5 columnals, all relatively thin; nodals with wide epifacets and sharp edges; internodals thinner, with narrower epifacets (Pl. 18, fig. 5). Axial canal large, round to slightly pentalobate; symplectic articulation. Approximately 12 thin columnals confined to basal concavity.

Ontogeny.—Ontogeny is based on 26 specimens that have aboral cups in a generally continuous range of sizes from 3 mm high by 5 mm wide to 12 mm high by 30 mm wide (Table 37). Immature individuals possess conical aboral cups (Pl. 18, fig. 4) with relatively large basals and radials. During growth the interray areas increase in size at a greater rate than the basal circlet or ray plates. As a result, the cup gradually develops a low, globular shape. The fine ridges on the cup plates and the thick ridges and nodes in the basal concavity are present in the smallest specimens. Growth of the brachials proceeds from uniserial to immature biserial. The stem is large relative to the cup in the immature specimens (Pl. 18, fig. 4).

Discussion.—*Pararchaeocrinus decoratus* Strimple and Watkins (1955) differs from *P. convexus* Brower and Veinus (1974) of the Wardell Formation in eastern Tennessee in having flat to slightly convex cup plates and flush sutures, median ray ridges, anal ridge, and numerous fine ridges that radiate from the plate centers. This species commonly occurs with *Anthracocrinus primitivus* Strimple and Watkins (1955).

On one of the larger specimens (OU 8921), the posterior side has a peculiar bulge between the CD basal and the C- and D-ray primibrach 1. The bulge is not present in any of the other specimens studied, and it is believed to be pathological in origin.

Dimensions.—Measurements of selected specimens are given in Table 37.

Material.—Twenty-six specimens were available for study. Figured specimens include OU 8837, OU 8839, OU 8921, OU 8934, and OU 8935.

Occurrence.—The holotype and paratypes came from Zone 5 of the Pooleville Member, 11.5 to 13.5 m below the Viola Limestone, Bromide Formation, at Culley Creek (formerly called the Spring Creek locality). The specimens described here are from Zone 3, 9 to 10 m below the Viola, Zone 4, 10 to 11.5 m below the Viola, and Zone 5 of the Pooleville Member at Culley Creek and from the upper Pooleville Member, 2.2 to 2.5 m below the Viola at Rudd Quarry.

PARARCHAEOCRINUS? sp.

Plate 20, figures 11, 12

Discussion.—This crinoid is represented by a single well-preserved aboral cup attached to a small segment of stem. The shape of the cup most closely resembles that of *Pararchaeocrinus*. In two of the interrays (one of which is probably the

Table 37. Measurements (mm) of *Pararchaeocrinus decoratus* Strimple and Watkins (1955).

Measurements	Specimens						
	OU 8837	OU 8838	OU 8839	OU 8840	OU 8841	OU 8842	OU 8821
Aboral cup height	3.0	5.5	5.5	6.0	11.0	18.0	20.0
Aboral cup width	5.0	10.0	13.5	13.0	17.0	---	32.0
Basal height	1.5	2.0	2.5	2.2	2.6	4.5	4.0
Basal width	1.7	2.0	2.5	2.5	3.3	5.5	4.6
Radial height	1.5	2.0	2.7	2.4	3.1	5.3	4.7
Radial width	1.5	2.2	2.8	2.6	3.1	5.2	5.3

CD interray) the interradial is followed by three interbrachs, an arrangement that is also like that in *Pararchaeocrinus*. In the remaining three interrays, the interradial is followed by two interbrachs, and thus is more like *Archaeocrinus*. The most peculiar aspect of this cup is that there are only four basals; the position of the missing basal is occupied by one of the radials. As a result, two radial plates are in contact, whereas the others are separated by an interradial. Another feature of this crinoid which rarely occurs in the Rhodocrinitidae is that one of the rays has three primibrachs.

I suspect that this crinoid is an aberrant individual that probably belongs to *Pararchaeocrinus*. The specimen has relatively coarse ridges on the cup and lacks a prominent anal ridge; thus, it differs from *P. decoratus* Strimple and Watkins (1955).

Material and occurrence.—The single specimen (OU 8910) was found in the Pooleville Member, Zone 3, 9 to 10 m below the Viola Limestone, Bromide Formation, at Culley Creek.

Genus PARADIABOLOCRINUS
Brower and Veinus, 1974

Type species.—*Paradiabolocrinus irregularis* Brower and Veinus, 1974.

Diagnosis.—A rhodocrinitid crinoid with a low, globular aboral cup; median ray ridges; intersecundibrachs numerous, irregularly shaped interradials and interbrachs.

Discussion.—*Paradiabolocrinus* is most similar to *Diabolocrinus*, differing primarily in having intersecundibrachs. *Paradiabolocrinus* is also characterized by having numerous interradial and interbrach plates. Although this is not generally the condition in *Diabolocrinus*, certain species show considerable variation in the size, shape, and number of interray plates.

Occurrence.—Middle Ordovician (Champlainian); United States (Oklahoma, Tennessee, Virginia).

PARADIABOLOCRINUS STELLATUS Kolata, n. sp.

Plate 21, figures 9-13; Figure 55

Diagnosis.—*Paradiabolocrinus* with a prominent stellate pattern of ridges at base of aboral cup; irregular nodes and very small pustules on interray plates; intersecundibrachs small or lacking; lacking lobate ambulacral areas.

Description.—Species represented by a single well-preserved aboral cup. Aboral cup low, bowl-shaped, flat at base, 6.0 mm high by 15.0 mm wide; arm bases lobate and protuberant. Cup plates slightly convex, ornamented with small irregular nodes and very small pustules; prominent median ray ridges consisting of 2 narrow elevated ridges bounding a narrow groove and passing upward from 2 adjacent basals and converging on radials; at this point 4 narrow ridges (2 from each basal) joining to form 3 narrow ridges bounding 2 grooves, all terminating on primibrach 2; median ray ridges forming prominent stellate pattern in basal view (Pl. 21, fig. 9).

Infrabasals 5, small, confined to basal concavity. Basals 5, 2.6 mm high by 3.0 mm wide, octagonal or nonagonal, in contact with 2 infrabasals, 2 basals, 2 radials, 2 or 3 interradials; thick angular process at bend into basal concavity. Radials 5, 2.8 mm high by 2.0 mm wide. Primibrach 1 height and width approximately equal.

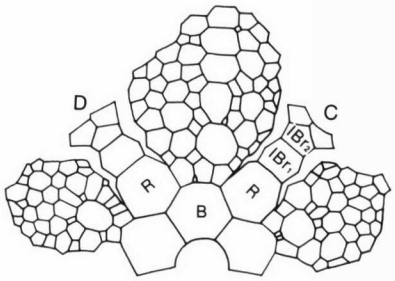

Fig. 55. *Paradiabolocrinus stellatus* Kolata, n. sp., Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, northern Arbuckle Mountains. Plate diagram of posterior side based on holotype 1106TX10, X4.7.

Primibrach 2 slightly wider than high, axillary. Radials and primibrachs variable in shape because of numerous irregular interradials and interbrachs. Secundibrach 1 bearing large fixed pinnule on interray side; biserial brachials above this plate. Small intersecundibrach between secundibrachs 2 (seen only in 2 rays).

Interrays relatively wide; 20 to 30 plates below level of secundibrach 2. Interradials 2 or 3, irregular, or 1 large plate surrounded by small supplementary plates. Interbrachs numerous and irregular. CD interray widest and with more plates. Median anal series consisting of 5 relatively large plates, plates more tumid than surrounding interbrachs (Fig. 55). Primanal not distinct.

Tegmen low, convex, composed of numerous small, irregular plates; not differentiated into ambulacral and interambulacral areas; arm openings small, 2 ambulacral openings per arm. Anal tube small, positioned near posterior side (Pl. 21, fig. 10). Arms 10, free above secundibrach 3. Stem unknown.

Discussion.—This species is assigned to *Paradiabolocrinus* with some hesitation because the intersecundibrachs are either very small or absent. The new species, however, does possess numerous interray interbrachs, which is a prominent characteristic of the type species of *Paradiabolocrinus*.

Paradiabolocrinus irregularis Brower and Veinus (1974), from the Middle Ordovician (Champlainian) rocks of southwestern Virginia and eastern Tennessee, differs from the new species in having lobate ambulacral areas, larger and fewer tegminal plates, and more widely separated secundibrachs 1 and 2. *Paradiabolocrinus sinuorugosus* Brower and Veinus (1974), from the same locality as *P. irregularis*, differs in having sinuous ridges on the cup plates. The new species also has a more distinct anal series than either of the above-mentioned *Paradiabolocrinus*.

Type.—The holotype is 1106TX10.

Occurrence.—The holotype was found in the Upper Echinoderm Zone of the Mountain Lake Member, Bromide Formation, at the A cut, North I-35 locality.

Name.—The specific name refers to the prominent stellate pattern of ridges on the base of the aboral cup.

Rhodocrinitid species A

Plate 19, figure 21

Discussion.—This species is represented by one incomplete aboral cup and a small part of the proximal stem. The cup consists of five infrabasals that are confined to a wide basal concavity formed in part by the basal circlet. Each of the five heptagonal basals are in contact with two infrabasals, two basals, two radials, and one interradial. The five radials are separated by one interradial. Except for a few disarticulated plates embedded in the matrix near the cup, no other cup plates are preserved. The stem consists of prominent thick, rounded nodals that are separated by approximately five smaller, thin internodals. The axial canal is large and round. The columnals have symplectic articulation.

The cup plates have distinct ornamentation that consists of highly elevated ridges and nodes. One of the most prominent ridges forms a pentagonal rim around the basal concavity and extends from the center of one basal plate to the center of another. Another series of ridges extends from the centers of the basal plates to the centers of the adjacent radial plates. The triangular areas outlined by the ridges are occupied by nodes and sinuous ridges. In total, the ornament produces prominent stellate patterns on the base of the cup.

The wide basal concavity is suggestive of *Crinerocrinus parvicostatus* from the same stratigraphic unit and locality. The lack of ray and interray plates precludes assignment to a genus or species at this time.

Material and occurrence.—One incomplete aboral cup (OU 8859) was found in Zone 2 of the Pooleville Member, 9 to 10 m below the Viola Limestone, Bromide Formation, at Culley Creek.

Order MONOBATHRIDA Moore and Laudon, 1943

Suborder GLYPTOCRININA Moore, 1952

Diagnosis.—Monocyclic camerate crinoids with a pentagonal base; radials in contact all around, primanal situated above radials.

Occurrence.—Middle Ordovician to Permian.

Family GLYPTOCRINIDAE Zittel, 1879

Diagnosis.—Monocyclic camerate crinoids with 5 basals, radials in contact all around, median ray ridges; interray areas slightly depressed; extra plates on posterior side.

Occurrence.—Ordovician to Early Silurian.

Genus ABLUDOGLYPTOCRINUS Kolata, new

Type species.—*Glyptocrinus charltoni* Kolata, 1975.

Diagnosis.—A glyptocrinid with 10 uniserial arms free above secundibrach 3 to 5; median anal and ray ridges present; variable ornamentation consisting of small pustules or fine ridges, some species possessing smooth plates.

Discussion.—Four genera, including *Abludoglyptocrinus*, new genus, are presently assigned to the Glyptocrinidae. The three other glyptocrinid genera differ from *Abludoglyptocrinus* in the following ways: *Periglyptocrinus* Wachsmuth and Springer (1897) differs in having 20 biserial arms and relatively large basals. *Glyptocrinus* Hall (1847) possesses 20 arms and commonly has a very ornate aboral cup exhibiting coarse, highly elevated ridges. *Schizocrinus* Hall (1847) differs from the new genus in having 20 arms, three or four primibrachs, and very regular and symmetrical interbrachs.

Four species that were formerly assigned to *Glyptocrinus*, including *G. ornatus* Billings (1857), *G. insperatus* Rowley (1904), *G. charltoni* Kolata (1975), and *G. pustulosis* Kolata (1975), are here reassigned to *Abludoglyptocrinus*.

Occurrence.—Middle Ordovician (Champlainian) to Early Silurian (Alexandrian); United States (Illinois, Missouri, Oklahoma, Wisconsin).

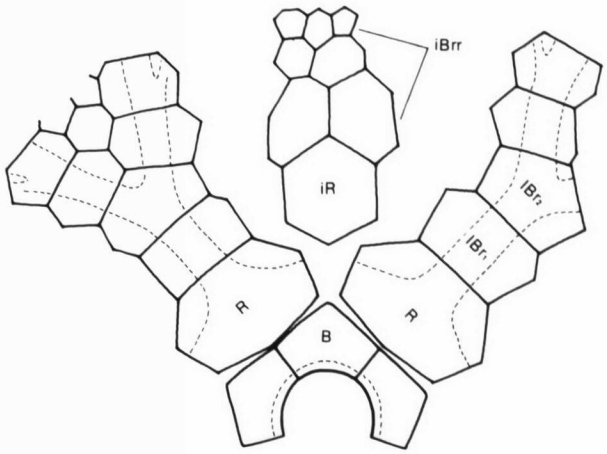

Fig. 56. *Abludoglyptocrinus laticostatus* Kolata, n. gen., n. sp., Pooleville Member, Bromide Formation, Criner Hills. Plate diagram based on holotype OU 8914. Dashed lines show position of median ray ridges, X5.5.

ABLUDOGLYPTOCRINUS LATICOSTATUS Kolata, n. sp.

Plate 21, figure 6; Figure 56

Diagnosis.—*Abludoglyptocrinus* with broad, elevated, rounded median ray ridges; prominent pustulose ornament; radials and primibrachs wider than high.

Description.—Aboral cup relatively small (Table 38), bowl-shaped, height and width approximately equal. Cup plates flat to slightly convex; areas between median ray ridges covered with numerous small pustules; sutures flush. Median ray ridges very prominent beginning at distal half of radials extending into free arms; median ray ridges broad, evenly rounded, and elevated.

Basals 5, small, pentagonal, wider than high; prominent, sharp, downward-projecting rim forming a shallow basal concavity at juncture of basals and stem. Radials 5, largest plates in cup, wider than high, heptagonal, in contact with 2 basals, 2 radials, 2 interbrachs, and 1 primibrach. Primibrach 1 wider than high, pentagonal or hexagonal. Primibrach 2 wider than high, pentagonal or hexagonal, axillary. Secundibrachs 1 through 5 fixed, wider than high; secundibrach 2 bearing fixed pinnule on interray side. Small intersecundibrachs arranged 1, 2, and 2. Interray areas depressed. Interbrach 1 large, followed by 2 interbrachs 2 and 2 interbrachs 3 (Fig. 56). CD interray poorly preserved; appearing to consist of primanal followed by anal series plate and 2 interbrachs on either side (see OU 8917); median anal ridge ex-

tending from C- and D-ray radials to primanal and upward along anal series. Tegmen unknown.

Arms 10, long, slender, evenly rounded, uniserial, free above secundibrach 5. Brachials wedge-shaped, wider than high; crenulate articulation surface between brachials. Pinnules long (11 mm long in holotype), slender, approximately 150 per arm, keeled aboral surface; each pinnule composed of approximately 10 pinnulars, pinnulars longer than wide, sides flat.

Stem round, heteromorphic, proximal columnals thin but with wide epifacets and sharp edges; distally noditaxes consisting of relatively thick nodals with numerous short spines on edges, spines curving away from crown; internodals thin, straight-sided; symplectic articulation. Distal stem unknown.

Ontogeny.—In addition to the holotype and a paratype (OU 8915) of comparable size, five relatively small specimens are here assigned to the new species (Table 38). The specimens do not show a continuous sequence of sizes, but a few ontogenetic observations can be noted. The smaller specimens have narrow interray areas and relatively small interbrachs. During growth the interbrachs grew at a faster rate than the ray plates, and as a result the cup changed from conical to bowl-shaped. In addition, the width-to-height ratio of the free brachials increased significantly during growth.

Discussion.—The new species most closely resembles *Abludoglyptocrinus charltoni* (Kolata, 1975) from the Blackriveran Platteville Group of northern Illinois and southern Wisconsin. The size and shape of the aboral cup, the proximal stem, and the arms are similar in the two species. The new species differs in having broader, more highly elevated median ray ridges and more prominent pustulose ornament. In addition, the angle between the median rays on the fixed secundibrachs is greater in the new species.

Abludoglyptocrinus insperatus (Rowley, 1904) from the Edgewood Limestone (Lower Silurian) near Edgewood, Pike County, Missouri, differs from the new species in having larger, higher basals, a prominent Y-shaped ridge, and a single pustule per interbrach. *Abludoglyptocrinus ornatus* (Billings, 1857) from the Ottawa Formation (Middle Ordovician) at Ottawa and Kirkfield, Ontario, differs in having fine ridges that radiate from the cup plate centers, forming prominent stellate patterns. *Abludoglyptocrinus pustulosis* (Kolata, 1975) from the Platteville Group (Middle Ordovician) or northern Illinois and southern Wisconsin has a conical aboral cup and primibrachs that are higher than wide.

Table 38. Measurements (mm) of *Abludoglyptocrinus laticostatus* Kolata, n. gen., n. sp.

Measurements	Specimens OU 8916	OU 8917	OU 8915	OU 8914
Aboral cup height	3.4	4.0	---	8.0
Aboral cup width*	4.0	4.5	---	12.0
Basal height	0.8	0.7	0.9	1.5
Basal width	0.7	0.7	1.1	1.9
Radial height	0.9	0.7	1.5	2.7
Radial width	1.4	2.0	2.0	4.0
Stem diameter (base of cup)	0.9	---	---	2.5

*Most specimens are crushed; width estimated.

Dimensions.—Measurements of *Abludoglyptocrinus laticostatus* are given in Table 38.

Types.—The holotype is OU 8914 and paratypes are OU 8915-8918.

Occurrence.—The holotype and paratypes are from the upper Pooleville Member 2.5 m below the Viola Limestone, Bromide Formation, at Rudd Quarry. Two unnumbered specimens in the W. T. Watkins Collection were found in an unknown zone of the Pooleville Member at Culley Creek.

Name.—The generic name refers to the fact that the new genus is related to but slightly different from *Glyptocrinus*. The specific name refers to the wide median ray ridges.

Order, Family, and Genus Unknown

Camerate species A

Plate 20, figure 16

Discussion.—This species is represented by one specimen that consists of part of the upper aboral cup to which several arms are attached. One ray shows a probable primibrach 1 followed by an axillary primibrach 2, which is followed by two secundibrachs, the second being axillary. Median ray ridges are low and inconspicuous. The arms are free above tertibrach 5. Intersecundibrachs and intertertibrachs are present. The interrays consist of numerous irregular interbrachs. All of the cup plates have very fine nodes and ridges that

radiate from the plate centers and terminate at the sutures. This crinoid has 20 biserial, unbranched, pinnulate arms.

The lack of definitive proximal circlets precludes assignment to any known camerate crinoid group at this time.

Material and occurrence.—The single specimen (OU 8860) was found in the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, at Daube Ranch.

"RHOMB-BEARING" CAMERATE

James Sprinkle and Dennis R. Kolata

University of Texas at Austin;
Illinois State Geological Survey

Among the specimens recovered by Fay and Graffham from the Upper Echinoderm Zone at Buckhorn Ranch were two partial calyces, a separate stem segment, and numerous cup plates of a large, unusual, pseudodicyclic, camerate crinoid. This crinoid has only four infrabasals and four basals, foldlike "rhombs" on the sutures between almost all aboral cup plates, radials that are in contact all around, a four-part stem with tetrameres centered beneath the infrabasals, and 10 endotomously branched arms that apparently lack pinnules. The crinoid is known from the Bromide only at this single locality in the Upper Echinoderm Zone, but similar plates have been found in the Oil Creek Formation, three formations below the Bromide in the Arbuckle Mountains (Lewis, 1982), and in the Antelope Valley Limestone of Nevada (Sprinkle, 1971, fig. 1, 41-44). In addition, a single poorly preserved specimen of a similar crinoid has been collected from the "Ottosee Group" near Heiskell, northeastern Tennessee (Pl. 22, fig. 17-20), and is here assigned to the same genus.

The pseudodicyclic nature of the lower aboral cup (see Warn, 1975), the four basals, and the numerous interbrachial plates that are incorporated into the aboral cup indicate probable monobathrid affinities for this crinoid. However, it cannot be assigned to any established family in the order Monobathrida. The features are so unusual that this crinoid is herein assigned to a new family, genus, and species.

Order ?MONOBATHRIDA Moore and Laudon, 1943

Family COLPODECRINIDAE
Sprinkle and Kolata, new

Diagnosis.—Pseudodicyclic camerate crinoids having only 4 infrabasals and 4 basals; most cup plates with prominent depressed sutural foldlike "rhombs" shared with each neighboring plate; aboral cup steeply conical, radials in contact all around; CD interray slightly wider than others but lacking ray ridge; tetragonal stem; 10 arms showing endotomous branching but apparently lacking pinnules.

Discussion.—The new "rhomb-bearing" crinoid from the Bromide differs significantly from all other known families of monocyclic or dicyclic camerates. It is the only camerate crinoid known having a pseudodicyclic cup (Warn, 1975), four infrabasals and four basals, foldlike "rhombs" between nearly all the cup plates, and a four-part stem. Some monocyclic camerate crinoids have four basals, but these plates are usually unequal in size, arranged in a circlet with a hexagonal outline, and not attached to a tetramere-bearing stem. No other camerate crinoids can be assigned to this new family at present.

Genus COLPODECRINUS
Sprinkle and Kolata, new

Type species.—*Colpodecrinus quadrifidus* Sprinkle and Kolata, n. sp.

Diagnosis.—Pseudodicyclic camerate crinoids with a steeply conical aboral cup made up of plates bearing depressed sutural foldlike "rhombs" separated by radiating ridges, 4 relatively large infrabasals, 4 large basals, 5 large radials (one directly above AB basal) all in contact, primibrachs relatively large without a prominent ray ridge, fixed cup brachials present through secundibrach 2 or 3; interbrachial areas wide and only slightly depressed, each containing 6 to 10 medium-sized interbrachials, posterior interray slightly wider than others with more plates but lacking ray ridge; 10 large uniserial arms showing endotomous branching, pinnules apparently absent; rhombs between all cup plates except near edge of tegmen, 1 to 2 per suture, made up of thin folds; stem tetragonal, heteromorphic, tetramere lobes matching infrabasal centers, lumen lobes sutural.

Occurrence.—Middle Ordovician, Oklahoma, Tennessee, and ?Nevada.

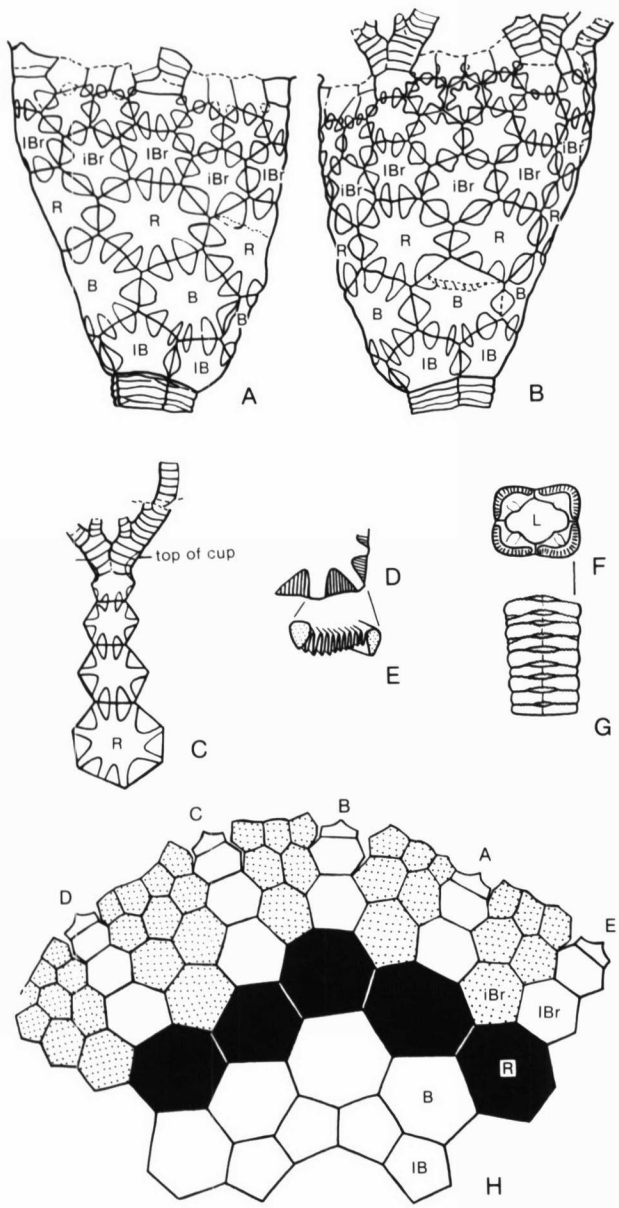

Fig. 57. *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp., Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Buckhorn Ranch, central Arbuckles, southern Oklahoma. A, B, Front (A ray) and back (CD interray) views of holotype OU 8946 showing shape, calyx plating, proximal arms, and proximal stem, X1.2. C, D-ray of holotype showing cup plates and preserved proximal arm plating, X1.2. D, E, Top and edge views of sutural rhomb in a basal of paratype OU 8947 showing isoclinal folds and strengthening ridges to corner and side, X1.2, X2.2. F, G, Top and side views of proximal stem OU 8948 showing tetrameres in stem, alternation of columnal types, and large rhombic shaped lumen (L), X2. H, Side layout of calyx plating (centered on B ray) showing 4 IBB, 4 BB, 5 RR (black), 2 to 3 IBrr, and 6 to 10 iBrr (stippled) in each ray or interray, based on holotype OU 8946.

Etymology.—The generic name is derived from *kolpodes* (Gr.), full of bays, folded, referring to the distinctive fold-bearing rhombs that embay the sutural margins of nearly all the aboral cup plates.

Discussion.—*Colpodecrinus* exhibits both primitive and advanced features. The slender, steep-sided aboral cup with four infrabasals and four basals, the four-part stem, and the relatively simple arms that apparently lack pinnules all appear to be primitive features. The five radials in contact, the lack of prominent ray ridges, and the wide and only slightly depressed interbrachial areas with few medium-sized plates seem to be advanced features. The fact that the radials are in contact all around (primanal rests on upper sloping edges of C and D radials) is also suggestive of an advanced condition.

The distinctive "rhombs" of *Colpodecrinus* are very similar to the goniospires in the Ordovician inadunate crinoid *Porocrinus* (Kesling and Paul, 1968, p. 7). In both genera the "rhombs" consist of several thin-walled calcareous folds that are continuous across the sutures between adjacent plates. In *Porocrinus*, these structures are located at the adjacent corners of three cup plates at nearly every tri-juncture; the folds bend at an angle of about 60° at the plate sutures. In *Colpodecrinus*, the folds are shared by only two adjacent plates and are straight. The folds in both *Colpodecrinus* and *Porocrinus* are similar in structure, and probably function, to the conjunct pectinirhombs of rhombiferan cystoids (see Paul, 1968b, p. 702-705). Pectinirhombs, goniospires, and the similar rhombs in *Colpodecrinus* are inferred to have been respiratory structures. No other known camerate crinoid has extensive rhomb-like structures of this type.

COLPODECRINUS QUADRIFIDUS
Sprinkle and Kolata, n. sp.

Plate 22, figures 1-16; Figure 57A-H; Table 39

Diagnosis.—A large species with prominent rhombs between nearly all cup plates, rhombs occupying one-quarter to one-half of each plate and bearing 6 to 17 folds, most plate centers flat to slightly depressed, with some nodular ornament.

Description.—Two complete specimens, a stem segment, and about 50 separate cup plates of this species available for study.

Aboral cup large, steeply conical in shape, basal angle 40 to 50°, nearly pentagonal in basal

view, widest at level of secundibrach 1 to 2 near top of cup. Tegmen unknown, probably slightly domed. Aboral cup in complete holotype 32 to 33 mm high, 27 to 28 mm in maximum width (moderately crushed); stem facet about 8.0 mm in diameter originally. Plates large and fairly thick (1.0 to 1.5 mm) except along depressed sutural rhombs, polygonal in complete specimens but stellate in disarticulated plates with rhomb areas missing; thick central part of plates (50 percent of area) slightly convex to slightly concave, with ridges (about 20 percent) extending out to plate corners and sometimes to sides around rhomb areas (about 30 percent); some plate centers ornamented with moderate-sized nodes.

Rhombs present on sutured margins of all cup plates up to primibrach 2 or 3 and top row of cup interbrachs (Pl. 22, fig. 3; Fig. 57A-C). Rhombs triangular or diamond-shaped depressed areas centered on sutures between 2 adjacent cup plates, composed of numerous isoclinal folds of thin plate material (walls about 0.04 to 0.05 mm thick) extending perpendicularly across suture, resembling conjunct pectinirhombs of some rhombiferan cystoids. Rhombs occupying 30 percent or more of plate surface and surrounded by ridges extending to plate corners and sometimes to sides, probably for strengthening these weak areas. Large rhombs containing as many as 17 folds and ranging up to 3.0 mm long (from plate center to plate center) and 4.0 mm wide along suture, although many smaller in size. Longest folds extending at least 1.0 mm deep into coelomic cavity (Pl. 22, fig. 11), and internal folds and external slits appearing to be equally developed (Fig. 57E). Fold spacing usually about 3.5 to 4 folds/mm.

Infrabasals 4 (B-ray infrabasal missing), medium-sized (see Table 39), pentagonal, width somewhat greater than height, moderately convex with smooth surfaces and apparently thicker than most other cup plates, lower edges forming nearly flat base of cup. Each bearing 1 rhomb on inter-infrabasal sutures, and 1 small and 1 medium-sized rhomb on each infrabasal-basal suture; rhombs surrounded by thick ridges extending around stem facet, to infrabasal sides, and as smaller ridges to plate corners. Infrabasals centered directly above stem tetrameres (Pl. 22, fig. 10).

Table 39. Measurements of the two partly complete specimens of *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp.

Measurement	Holotype OU 8946	Paratype OU 8947
Aboral cup length	32-33 mm	------
Aboral cup width	23-25 mm (est.)	------
Basal angle	40-50°	------
Proximal stem diameter	~8.0 mm	6.5 mm
Infrabasal height	5.9 mm	5.2 mm
Infrabasal width	7.9 mm	6.0 mm
Basal height	10.0 mm	7.4 mm
Basal width	10.6 mm	8.4 mm
Radial height	9.4 mm	------
Radial width	11.7 mm	~9.0 mm
Primibrach 1 height	6.2 mm	------
Primibrach 1 width	7.5 mm	------
Interbrachial 1 height	7.4 mm	------
Interbrachial 1 width	7.8 mm	------
No. folds in IB-IB rhomb	7-9	7-8
No. folds in IB-B rhomb	9-12 (⅓+ sut.)	8-9 (⅓+ sut.)
No. folds in B-B rhomb	15-17	10-11
No. folds in B-R rhomb	10-15 (½ sut.)	9-10 (½ sut.)
No. folds in R-R rhomb	12-14	------
No. folds in R-iBr rhomb	13-15	------

Basals 4 (BC basal missing), large (see Table 39), hexagonal to heptagonal, slightly wider than high, slightly convex in transverse profile, ornamented with small nodes. Basals bearing rhombs on all plate margins, 1 large rhomb on each interbasal suture, 2 with each infrabasal, and 2 medium-large rhombs with each radial. Ridges surrounding rhombs and extending to corner of each basal plate and to centers of all infrabasal and radial su-

PLATE 22.

Fig. 1-16. *Colpodecrinus quadrifidus* Sprinkle and Kolata, n. gen., n. sp.; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Buckhorn Ranch, central Arbuckle Mountains, southern Oklahoma. 1-5. Front (A ray), base, back (CD interray), right, and left sides of holotype crown OU 8946 showing cup shape, amount of crushing, rhombs between most of cup plates, proximal arms, and few attached stem segments; X1.5. 6, 7. Outside and inside views of hexagonal plate OU 8950 (probably a lower interbrachial); note depressed center, weathered-out rhombs, and ridges to the plate corners; X2. 8-9. Outside and inside views of heptagonal plate OU 8949 (possible a radial) showing nodular ornament and numerous rhombs; X2. 10-12. Side, adoral end, and tip of stem of incomplete paratype OU 8947; note well-preserved infrabasals, basals, and 1 radial, well-preserved fold-bearing rhombs between cup plates, and proximal stem with depressed sutures and tetrameres; X2, X3. 13-16. End views (13, 14), side, and front views of proximal stem segment OU 8948 showing rounded rectangular shape, tetrameres, rhombic-shaped lumen, and change in columnal types from distal (lower) to proximal (upper) end; X4, X2.

Fig. 17-20. *Colpodecrinus* sp.; "Ottosee Group," locality HK-2., roadcut about 3.2 km northeast of Heiskell, Powell 7½ minute Quadrangle, northeastern Tennessee. Poorly preserved crown MCZ 3555 showing arm segments (17), aboral cup and proximal stem (18), and enlargements of rhomb-bearing plates (19) and distinctive rhomb-bearing infrabasals (20) attached to a tetragonal stem; X1.5, X3.

tures. Basals alternate with infrabasals and with 4 (of 5) radials.

Radials 5, usually largest plates in aboral cup (see Table 39), hexagonal to heptagonal, wider than high, nearly flat in longitudinal profile, convex in transverse profile (B and E radials on edges of crushed holotype strongly convex without evidence of breakage; see Pl. 22, fig. 4, 5). Radials all in contact; 4 radials alternating with basals; fifth radial (B ray) directly above basal and somewhat higher in dorsal cup than others (see Fig. 57H). Radials bearing rhombs on all plate margins; 1 each on interradial and radial-interbrachial sutures, 2 each on radial-basal and radial-primibrach 1 sutures; all rhombs medium-large. Ridges surrounding rhombs and extending to each corner and to centers of basal and primibrach sutures.

Primibrachs 3 to 4, lower ones hexagonal, like other rhomb-bearing cup plates, decreasing in size upward (Fig. 57C). Primibrach 1 fairly large, slightly wider than high, with rhombs on all margins, 1 each with interbrachials, 2 on margins with radial and primibrach 2. Eight ridges, 1 to each corner plus 1 to centers of both radial and primibrach 2 sutures (representing a minor ray ridge). Primibrach 2 hexagonal in C and D rays and like primibrach 1, except smaller (Fig. 57C). Primibrach 2 in A, B, and E rays and primibrach 3 in C and D rays hexagonal to heptagonal, flat-topped in most rays but perhaps axillary in D ray, bearing 2 rhombs on lower margin and 1 on each lower-lateral margin with interbrachs. Primibrach 3 in A, B, and E rays and primibrach 4 in C and perhaps D rays small, axillary, pentagonal, much wider than high, without rhombs; representing lower armlike cup brachial (Fig. 57C). First arm branching at primibrach 3 to 4 isotomous to produce 10 arms; all higher branches apparently endotomous.

Secundibrachs 3 to 4, tetragonal to pentagonal, much wider than high, moderately convex, about 0.8 to 1.0 mm high and 3.0 mm wide; secundibrachs 1, 2, and sometimes 3 of adjacent arms in contact, without inter-half-ray interbrachs, and also in contact with top interbrachials in cup (Fig. 57C). Therefore, secundibrach 2 or 3 top cup brachial. Ten arms free above this point, branching endotomously, but lacking pinnules; longest arm segment on holotype about 18 mm.

Tertibrachs 4 to 6 in main branch, tetragonal to pentagonal, much wider than high, moderately convex, slightly smaller in width than secundibrachs (Fig. 57C); small endotomous branch with 3 to 6 tertibrachs, about half size of main branch tertibrachs; lower 2 to 3 tertibrachs in main and side branches in contact.

Quartibrachs 2 to ?10 in main branch, like tertibrachs below; quartibrachs 2 or more in small branch, first 2 to 3 quartibrachs in contact in both branches; unclear whether higher-order branches present in longest arm segment of holotype or whether small branches branch further.

Interbrachial areas large, rounded V-shaped, composed of 6 to 10 interbrachial plates decreasing in size adorally; CD interray slightly wider than others but otherwise similar. Interbrach 1 (primanal in CD interray) largest plate in series, hexagonal, slightly concave, located above radials and between primibrachs 1 (except in BC interray where interbrach 1 higher, not in contact with C-ray radial but beside C-ray primibrachs 1 and 2). Interbrach 1 with 6 rhombs shared with radials below, primibrachs laterally, and next row of interbrachs above; ridges extending to all plate corners. Interbrachs 2 and 3 in next row above, medium-sized, hexagonal, each with 6 rhombs separated by ridges extending to corners. Interbrachs 4, 5, and 6 in CD and DE interrays lower on dorsal cup and like interbrach plates below only smaller, having lower ridges not quite reaching plate corners, more depressed centers. Interbrachs 4, 5, and 6 in EA, AB, and BC interrays and interbrachs 7 to 10 in CD and DE interays smaller, pentagonal, convex, with rhombs mostly on lower margins, curving inward to form edge of tegmen (Fig. 57A, B).

Stem long, rounded rectangular to almost square in cross section, heteromorphic, composed of tetrameres. Longest segment (Pl. 22, fig. 15, 16) about 34 mm; longest attached segment (Pl. 22, fig. 10-12) about 16 mm. One to two columnal types (thick and thin) distally, columnals tightly articulated with flush or slightly depressed crenulate sutures. Three columnal types proximally (Fig. 57F); thick columnals becoming bulbous at corners, thin columnals bulging slightly away from corners, and third order thin wedge-shaped segments added between others at tetramere sutures. Intercolumnal sutures becoming greatly depressed proximally with exposed crenulae (see Pl. 22, fig. 10, 11), probably implying greater stem flexibility near cup. Stem tetrameres centered below infrabasals. Lumen fairly large, occupying about 50 percent of cross section, rounded diamond or rhombic-shaped with projections extending out to tetramere sutures (Pl. 22, fig. 13). Areola on each tetramere fairly large, crescent-shaped.

Etymology.—The species name *quadrifidus* (L),

split into four parts, refers to the distinctive four-part stem, four infrabasals, and four basals found in this species.

Material.—Holotype OU 8946, paratypes OU 8947-8950, all collected by Fay and Graffham; additional plate material, OU 8952 and 1111TX21. Holotype OU 8946 is a large, nearly complete, slightly crushed aboral cup with the proximal arms and several stem segments attached; it was excavated using needles and an air abrasive machine with dolomite powder (most of the matrix was too hard for sodium bicarbonate). Paratype OU 8947 is a partial aboral cup (infrabasals, basals, and one radial) with an attached proximal stem in soft, easily cleaned matrix. The separate stem segment (OU 8948) and most of the separate plates (OU 8948-8950) were weathered free and required only minor cleaning.

Occurrence.—Found only in the Upper Echinoderm Zone near the top of the Mountain Lake Member, Bromide Formation, at Buckhorn Ranch in the central Arbuckles, southern Oklahoma.

Discussion.—The most unusual feature of *Colpodecrinus* is the apparent pseudodicyclic cup with only four infrabasals and four basals. A similar four-sided condition is known to occur in malformed individuals of certain crinoid species (see *Pararchaeocrinus?* sp., Kolata, herein), but these are rare individuals in an otherwise normal population. The fact that all of the available specimens possess four-part infrabasal and basal circlets as well as four-part stems strongly suggests that these are not aberrant individuals but rather are members of a distinct and unusual species. It would be difficult to place *Colpodecrinus* among the known camerate crinoids, even if it possessed the normal five-part infrabasal and basal circlets, because of the contiguous radial circlet, "rhombs," and endotomously branched arms that lack pinnules. There are no known intermediates between *Colpodecrinus* and other camerate species. *Colpodecrinus* apparently was a specialized crinoid that left no known descendants.

COLPODECRINUS sp.

Plate 22, figures 17-20

A poorly preserved and partly silicified crinoid specimen with rhombs was found by Sprinkle in 1967 in the "Ottosee Group," at locality HK-2 (Sprinkle, 1973), a roadcut some 3.2 km northeast of Heiskell, northeastern Tennessee. This crinoid remained unidentified until the better preserved Bromide specimens of *Colpodecrinus* were studied and the close resemblance noted; this specimen is here described as *Colpodecrinus* sp.

The specimen (MCZ 3555) is preserved in two pieces (Pl. 22, fig. 17, 18), which were chipped off a limestone slab. They contain the proximal stem, mostly disarticulated aboral cup, and several arm fragments. All four segments of the quadrate proximal stem are present, along with parts of three infrabasals, three basals, at least four radials, several primibrachs, several interradials, and a segment of branched arm. The aboral cup appears to be steeply conical (basal angle about 40°, height 32+ mm) although it is crushed and weathered; nearly all exposed aboral cup plates have folded rhombs on their margins, usually one or two per suture (Pl. 22, fig. 19, 20). Infrabasals are convex plates 5.5 mm high by about 5.4 mm wide, basals at least 6.7 mm high, and radials about 9.0 mm high. Nine to 10 folds are present on each infrabasal-infrabasal suture, 14 to 15 on each basal-basal suture, and 11 to 12 on each radial-radial or radial-interbrachial suture. The proximal stem, although crushed, was probably between 5.5 to 6.0 mm in diameter and composed of at least two types of columnals (thick and thin) developed in tetrameres (Pl. 22, fig. 20). The arm segment is at least 13 mm long, made up of wide U-shaped uniserial brachials about 2.3 mm wide and 0.7 to 0.8 mm long, and has at least two smaller uniserial branches (longest has 11 brachials) off one side; the armlet brachials are a rounded V-shape, 1.2 mm wide by 0.7 mm long by 0.9 mm deep, with a small U-shaped adoral food groove.

Discussion.—This specimen of *Colpodecrinus* is too poorly preserved to determine if it is the same as *C. quadrifidus* from the Bromide or a new species. It has the same apparent type of stem, plating arrangement, rhombs, and arm branching as *C. quadrifidus*, but many of the details of ornament, rhombs, and interbrachial plating cannot be determined. The Middle Ordovician "Ottosee Group" in Virginia and Tennessee has many echinoderm genera (but few species) in common with the Bromide, and so the discovery of a *Colpodecrinus* specimen in the Ottosee similar to those in the Bromide is not completely unexpected.

PARACRINOIDS

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The Paracrinoidea are primarily a North American group of short-lived (Middle to Late Ordovician) primitive Echinodermata. They are unusually well represented in the Mountain Lake Member of the Bromide Formation in the Arbuckle Mountains and Criner Hills, but have not been found in the overlying or underlying formations in Oklahoma. Paracrinoids are found in all of the major echinoderm zones and beds of the Mountain Lake Member, and more than 5,700 specimens representing five genera and seven species have been collected. Ninety-seven percent of the Upper Echinoderm Zone echinoderm fauna is made up of paracrinoids, mostly *Oklahomacystis*. Except for *Platycystites levatus*, paracrinoids of the Lower Echinoderm Zone do not extend into the Upper Echinoderm Zone. Specimens of *Platycystites* from the *Carabocrinus* Beds show close affinities with those of the Lower Echinoderm Zone, while paracrinoids from the *Bromidocystis* Bed are more closely related to those of the Upper Echinoderm Zone.

Most paracrinoids of the Bromide were described by Parsley and Mintz (1975). Their work has been in part modified by Frest, Strimple, and McGinnis (1976) and Frest, Strimple, and Coney (1979). Reexamination of new Bromide material has necessitated the revision of some of the classification. One new genus, *Arbucklecystis*, and two new species, *Arbucklecystis pyriformis* and *Oklahomacystis bibrachiatus*, are established. *Bistomiacystis* Sprinkle and Parsley, an unusual new platycystitid paracrinoid from the Lower Echinoderm Zone, is described in the following chapter.

The discovery that rare specimens of *Sinclairocystis* either lack sutural pores or have pores reduced to a vestigial state necessitates the redefinition of the Comarocystitidae. In exceptional situations, the juvenile or neotenic state of the thecal plates is retained, i.e., sutural pores do not form on the margins of the solid core of the plate; or the pore structures are seemingly incomplete or vestigial and when they do form, occur later (farther from the center) in the plate's ontogeny. The rarity of this feature seen in the *Bromidocystis* Bed (two specimens) and the Upper Echinoderm Zone (one specimen) suggests that a recessive trait may have produced this paedomorphic condition. Frest and others (1980) have described a similar specimen and have placed this modified form into a new species of *Oklahomacystis*, *O. spissus*. I disagree with their generic assignment, and for reasons given below feel that the new species represents unnecessary splitting.

The term arm in the following descriptions refers to the main ambulacral branches, whether erect (exothecal) or recumbent (epithecal), which, via their lumina, have internal coelomic continuity. This continues the usage of Parsley and Mintz (1975, p. 11-14).

Class PARACRINOIDEA Regnéll, 1945

Order COMAROCYSTITIDA Parsley and Mintz, 1975

Diagnosis.—Paracrinoids with transversely elongate sutural pores or, exceptionally, without them; arms exothecal or epithecal (recumbent); thecal plates numerous. (Modified from Parsley and Mintz, 1975, p. 27.)

Discussion.—Two genera and three species of comarocyctitids are known from the Mountain Lake Member. They are restricted to the *Bromidocystis* Bed and the Upper Echinoderm Zone near the top of the member. *Sinclairocystis praedicta* and *Oklahomacystis tribrachiatus* from the Upper Echinoderm Zone are well known. A new species, *Oklahomacystis bibrachiatus*, a possible ancestor of *O. tribrachiatus*, has been found in limited numbers (seven specimens) in the Upper Echinoderm Zone in the southwestern Arbuckles.

Family COMAROCYSTITIDAE Bather, 1899

Diagnosis.—Comarocystitida with concave thecal

plates; sutural pores numerous, exceptionally missing or vestigial; arms exothecal or epithecal. (Modified from Parsley and Mintz, 1975, p. 28.)

Discussion.—The slight modification of the ordinal and familial definitions is necessitated by the discovery of rare *Sinclairocystis praedicta* specimens completely without, or with vestigial, sutural pores.

Genus SINCLAIROCYSTIS Bassler, 1950

Type species.—*Sinclairocystis praedicta* Bassler, 1950.

Diagnosis.—Theca subspheroidal to nearly fusiform; nearly circular to broadly oval in cross section; composed of about 37 generally hexagonal, externally concave plates with slitlike subepistereomal sutural pores, pores rarely vestigial or missing. Two recumbent, uniserial arms extending transversely from peristome and both extending nearly to, or onto basals. Peristome transversely oval, subaxial; gonopore on its posterior lip; hydropore slitlike, juxtaposed to right. (Modified from Parsley and Mintz, 1975, p. 37-38; see ibid., p. 38 for synonymy.)

SINCLAIROCYSTIS PRAEDICTA Bassler, 1950

Plate 23, figures 1-6, 8

Diagnosis.—Characters as for genus.

Description.—Theca varying considerably in profile, typically subrounded to oval; in cross section theca circular to transversely, broadly oval.

Theca plates numbering about 37; typically hexagonal, externally concave with elevated sutures (Pl. 23, fig. 6).

Excepting basals and peristomals, thecal plates not in recognizable order. Plate number varying from 27 to 52, averaging 37. Thecal size (from 8.2 to over 32 mm high) only slightly related to number of thecal plates.

Intercalaries forming above basals, especially in lower, right-lateral part of theca. Left-lateral, left, and central parts of anterior and posterior faces with larger plates showing little evidence of intercalation.

Slitlike sutural pores, completely roofed over by epistereome, present on all thecal plates. Number of pores on each side of plate varying with size; ranging from 3 to 9, with 6 and 7 most common. Length of each pore on internal surface of thecal plates varying because of triangular arrangement of pore field. Pores in center of field (essentially bisecting adjacent plate suture) longest and oldest; those at edges of triangular field (near plate corners) shortest and youngest. Pore structures completely open to interior of theca. Unweathered plates externally covered with low, rounded tubercles in approximate radial alignment.

Small, oval peristome formed by 3, sometimes 4, peristomals.

Round, slightly elevated gonopore on posterior lip of peristome; repeated in some specimens; second opening smaller and just ventral to first, or slightly offset to right. Elevated, slitlike hydropore between left and right posterior peristomals and a thecal plate.

Anomalous pore(s) occurring on approximately 50 percent of specimens; in some, gonoporelike opening occurring near, or in center of, thecal plate located ventral to periproct, either above or below ambitus; in others, opening on anterior face, near recumbent arm.

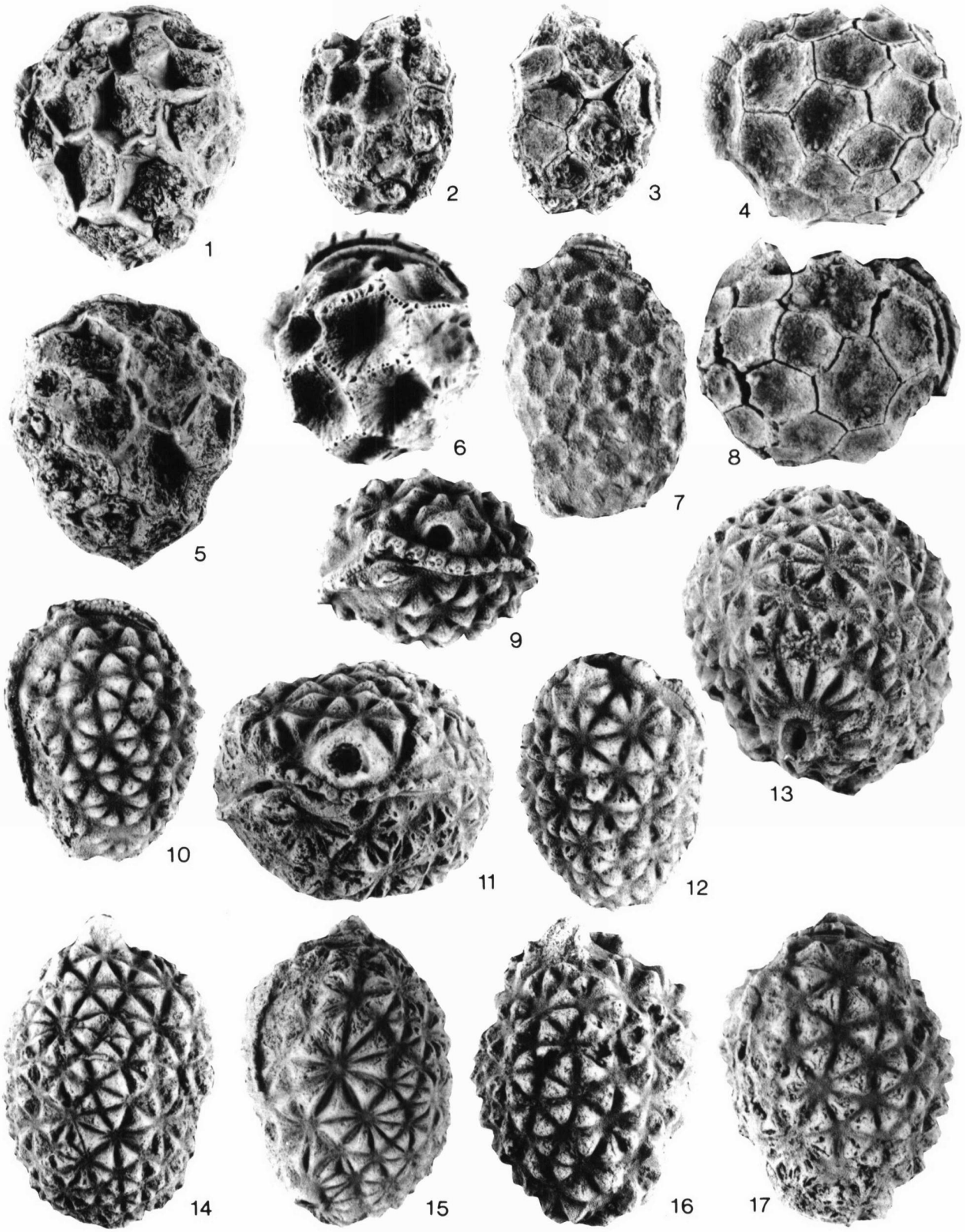
Periproct slightly subapical, usually on posterior face, in some specimens on anterior, bounded by "periproctal" series of 4 thecal plates. Anal pyramid with 6 wedge-shaped covering plates.

Positions of uniserial, recumbent arms variable; that of right arms determining whether periproct on anterior or posterior face.

Arms uniform in height and width except near tips, tapering near tips. Each arm with 15 to 22 ossicles, top of each ossicle with a concave, rounded, pinnule facet; short food groove extending from facet, terminating at upper margin of main food groove. Pinnules or covering plates over food grooves unknown.

Lumen unusually large in proximal arm segments; in cross section, ovoid to subclavate, with a small protuberance extending under main food groove. Floor of lumen thecal callus material. Enlarged part of lumen apparently limited to proximal 4 or 5 ossicles; distally lumen sharply reduced to flattened, elliptical opening between callus and basal part of arm ossicle.

Theca calluses underlying arms, apparently stimulated by overlying arm(s) but secreted by thecal tissues. Upper surface of each callus slightly elevated above thecal surface and providing even platform for arm. Thecal callus deposits thickest in middle of concave thecal plates, thinnest across plate sutures. Calluses not covering sutures, indicating their thecal origin. Upper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surface of callus concave, bounded by low, rounded ridges on margins.

Column unknown. (Condensed from Parsley and Mintz, 1975, p. 38-41.)

Discussion.—Redescribed by Parsley and Mintz in 1975 (p. 37-43), *Sinclairocystis* is closely related to exothecally-armed *Comarocystites* Billings, as evidenced by the similar concave thecal plates. Those of *Sinclairocystis* are without foerstepores, which are present in *Comarocystites* (see Parsley, 1978), and in *Sinclairocystis* the ontogenetically older parts of the slitlike sutural pores, i.e., toward the centers of the plates, secondarily fill in with stereome. The overall similarity in thecal morphology argues for a *Comarocystites*-like ancestor for *Sinclairocystis*, in which the arms not only became recumbent but their lumina moved adthecally so that each lumen is partly formed by thecal (callus) material.

Considerable variation exists in *Sinclairocystis*, but it is considered to be at the subspecific level. The periproct can be on the anterior or posterior face depending on the course, during ontogeny, of the right recumbent arm; variable coursing of the arms altered thecal shape: the theca is more tumid under them; and rarely a recumbent arm splits.

The new material collected by Sprinkle and Fay for this project has yielded three specimens from three different localities and two different horizons (*Bromidocystis* Bed and Upper Echinoderm Zone) in which the slitlike sutural pores are either missing or vestigial, or both in a single specimen. Because no other feature sets these specimens off from *S. predicta*, it is assumed that the lack of greatly diminished pores represents a rare variant in which the nonporous condition of very young juveniles, or of small intercalated plates, is paedomorphically retained (Pl. 23, fig. 1-5, 8). Possibly this is a manifestation of a combination of recessive genes which occurred only rarely (one in 100?). For an opposing view of these variants, see Frest and others (1980, p. 217-228).

In the vestigial condition, the pores are at best cylindrical in cross section, not transverse slits. The specimen from the Sulphur locality (Pl. 23, fig. 4, 8) has vestigial pores on some of its plate faces. These are deeply inset and either not visible at the outer surface, or, if it is slightly worn, visible as very small pores, slightly widening the suture line.

Material and occurrence.—Of the approximately 90 specimens examined by the author, 64 came from the locality at Sulphur (1 specimen with vestigial pores). Other localities in the northern and central Arbuckles include Lick Creek (18 specimens), Buckhorn Ranch (3 specimens), Nebo (1 specimen), and Amis Ranch (1 specimen), all from the Upper Echinoderm Zone at the top of the Mountain Lake Member. Two specimens lacking pores are known from the *Bromidocystis* Bed in the middle Mountain Lake Member, one from the D cut at North-Central I-35, the other from Daube Ranch.

Family AMYGDALOCYSTITIDAE Jackel, 1900
Emended Parsley and Mintz, 1975

Genus OKLAHOMACYSTIS Parsley and Mintz, 1975
Emended herein

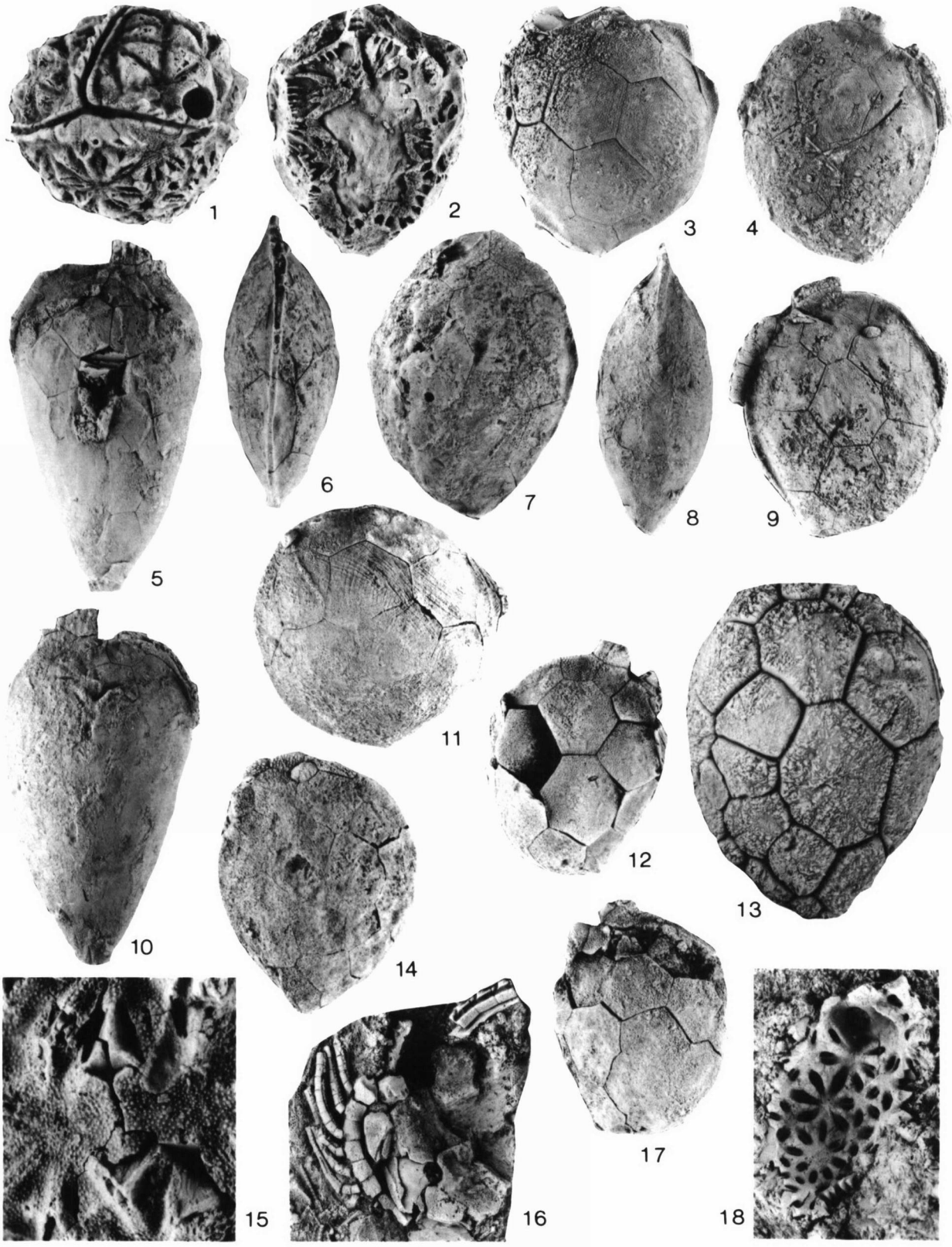
Type species.—*Amygdalocystites tribrachiatus* Bassler, 1943.

Diagnosis.—Theca globose to elongate, cross section transversely oval in juveniles, inflated in adults; thecal prosopon composed of raised triact ridges; left arm either single or bifurcated with branch extending over anterior face; periproct anterior to unbranched right arm. (Emended from Parsley and Mintz, 1975, p. 52.)

PLATE 23.

Fig. 1-6, 8. Thecal morphology of *Sinclairocystis praedicta* Bassler, 1950; Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1, 5 from *Bromidocystis* Bed at North-Central I-35; 2, 3 from same zone at Daube Ranch; 4, 6, 8 from Upper Echinoderm Zone at Sulphur. 1, 5. Posterior and anterior views of theca 1391TX1 without sutural pores; X1.5. 2, 3. Posterior and anterior views of small theca OU 9109 (Fay Coll.) without sutural pores; X2. 4, 8. Posterior and anterior views of theca OU 9110 without sutural pores or with apparent vestigial pores on some suture; X3. 6. Posterior face of holotype theca USNM 116332 with normal sutural slits; X3.

Fig. 7, 9-17. Thecal morphology of *Oklahomacystis bibrachiatus* Parsley, n. sp.; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Johnston Ranch, southwestern Arbuckle Mountains, southern Oklahoma. 7. Posterior view of paratype theca 1117TX27 with late-forming triacts; note the superficial resemblence of the slightly concave plates to those of *Sinclairocystis*; X4. 9, 10, 12. Dorsal, posterior, and anterior views of paratype theca 1117TX26 with recumbent arms well preserved; X3, X2.5, X2.5. 11, 13-15. Dorsal, oblique ventral, anterior, and posterior views of holotype OU 9111; X2, X2, X1.5, X1.5. 16, 17. Anterior and posterior views of paratype theca OU 9112; X1.5.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Discussion.—Modification of the generic diagnosis is necessitated by the discovery of a new species with an unbranched left arm. Frest and others (1980, p. 223-226) have modified the generic concept by the placing of *Sinclairocystis* specimens with vestigial pores into this genus. I disagree with their assignment.

OKLAHOMACYSTIS TRIBRACHIATUS (Bassler), 1943

Plate 24, figures 1, 2, 18

Amygdalocystites tribrachiatus Bassler, 1943, p. 695-696, pl. 1, fig. 14, 15.

Oklahomacystis tribrachiatus (Bassler), Parsley and Mintz, 1975, p. 57, pl. 6, fig. 1-13

Diagnosis.—*Oklahomacystis* with bifurcated left arm; branch extending over anterior face of theca.

Description.—Theca oval to nearly subcircular in profile, slightly compressed into transversely oval cross section, anterior face more protuberant than slightly flattened posterior face.

Theca of 30 to about 95 plates, observed in specimens ranging from 8 to 30 mm high. No observed relationship between thecal size and plate number. (Intensive intercalation of plates must occur in early juveniles, but ample evidence is present that intercalation continues throughout ontogeny, albeit at a slower rate.) Most intercalaries above basals on right side of theca. Right side of theca more protuberant than left, with more and smaller plates than rest of theca. No apparent plate order, only basals, peristomal series, and at least part of periproctal series regularized.

Thecal plates from four- to nine-sided, most commonly six-sided. Centers of plates solid, slightly concave to slightly convex, pustulose in larger specimens. Each plate corner at junction with 2 other plates. Sharply raised, keeled, distally expanding rays extending from nonporous central area of each plate to corners. Rays at juncture of 3 plates collectively forming raised triacts (trigonal pyramids); resulting pattern of raised rosettes of 4 to 5 triacts, depending on number of plate angles.

Paired internally opening transverse pore slits crossing most thecal plate sutures (Pl. 24, fig. 18). Paired slits near internal surface of plate closely spaced and lying between raised trigonal pyramids. Extending outward through thickness of the plate, each slit coming to thinly underlie face of adjacent raised triact (Pl. 24, fig. 2). Each triact with pore slit on each face, slit completely closed to exterior; no evidence for internal connection between slits along sides or near tops of triacts.

Four peristomal plates; anterior peristomal pentagonal, comprising most of anterior part of opening. Posterior peristomal larger, irregularly

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PLATE 24.

Fig. 1, 2, 18. Thecal morphology of *Oklahomacystis tribrachiatus* (Bassler), 1943; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1 from Sulphur; 2 from Nebo; 18 from Lick Creek. 1. Dorsal view of theca OU 7920; note presence of hydropore and gonopore on posterior face and periproct on anterior face; X2. 2. Fractured theca OU 9113 showing cross sections of sutural slits; X2. 18. Internal surfaces of thecal plates in OU 9114; note paired slits that lead to triacts and periproct opening at top of specimen; X2.

Fig. 3, 11-14, 16, 17. Thecal morphology of *Platycystites levatus* Bassler, 1943; Lower Echinoderm Zone (except 3, 13), Mountain Lake Member, Bromide Formation, Arbuckle Mountains and Criner Hills, southern Oklahoma; 3 from Upper Echinoderm Zone, North I-35 (A cut); 11, 12, 14, 17 from Amis Ranch; 13 from *Carabocrinus* Beds, North-Central I-35 (A cut); 16 from ?Lower Echinoderm Zone, "8 miles S.S.W., Ardmore, Oklahoma" (= ?Rock Crossing), Criner Hills. 3. Posterior face of theca 1106TX14; X1.25. 11. Posterior view of theca OU 9115; X1.25 12, 17. Anterior and posterior faces of OU 9116; note absence of A10 and A11 from anterior face; they are missing or make up part of the right lateral intercalary zone; X1.5. 13. Anterior face of very large theca 1276TX8, one of the largest specimens known; note split A7 plate and the calcite overgrowths on the plates; X1. 14. Posterior view of juvenile theca OU 9117; note lack of bulge on right side giving a close similarity to type species *P. faberi* Miller, 1889; X2.5. 16. Partial holotype theca USNM 93339 of *Platycystites levatus* Bassler, 1943; X1.5.

Fig. 4, 6, 7, 9. Thecal morphology of *Platycystites cristatus* Bassler, 1943; Upper Echinoderm Zone, Mountain Lake Member, Arbuckle Mountains, southern Oklahoma; 4, 9 from Johnston Ranch; 6, 7 from "south side of Arbuckle Mountains." 4, 9. Anterior and posterior views of theca 1117TX16; X1.75. 6, 7. Left-lateral and posterior views of holotype theca USNM 93334; X1.25.

Fig. 5, 8, 10. Posterior, right-lateral, and anterior views, respectively, of *Arbucklecystis pyriformis* Parsley and Sprinkle, n. gen., n. sp.; holotype 1393TX2 (Sprinkle Coll.), *Bromidocystis* Bed, upper Mountain Lake Member, North-Central I-35 (D cut), Arbuckle Mountains, southern Oklahoma; X1.5, X1.25, X1.5.

Fig. 15. Detail of weathered triacts on theca of *Oklahomacystis bibrachiatus* Parsley, n. sp.; paratype OU 9118 from Upper Echinoderm Zone, Mountain Lake Member, Johnston Ranch, southwestern Arbuckle Mountains, southern Oklahoma; X7.

hexagonal, with frustumlike gonopore centrally situated. Lateral peristomals forming sharply rounded ends of transversely oval peristome. Food groove splitting on left peristomal and extending into left lateral and anterior recumbent arms. Right lateral peristomal joining with posterior peristomal and another thecal plate to form raised hydropore slit at their juncture (Pl. 24, fig. 1).

High relief hydropore closely juxtaposed to gonopore, paralleling right arm, resembling raised trigonal pyramid. (Possibly the hydropore is a modified sutural pore.) Periproct subapical, adjacent to right arm, on anterior face. Margin of periproct sharply upturned into thin, rounded lip.

Anomalous frustumlike pore in larger specimens in central area of thecal plate, generally on posterior face. Morphology and location of pore similar to that of anomalous pore in *Sinclairocystis*.

Three basals subequal, offset to left; anterior and posterior basals making up most of column lumen perimeter, right basal restricted to right side of transversely oval lumen.

Three recumbent arms. Transverse left arm bifurcating adjacent to peristome and sending branch across anterior face (Pl. 24, fig. 1). Right and left arm in mature specimens averaging 15 to 16 ossicles, anterior arm averaging about 14 ossicles. Edges of concavely excavated underlying calluses rarely extending more than 0.5 mm above general plate surface, middle may be excavated slightly below plate surface. Overall result low arm profile. Primary ossicle greatly enlarged on right and left arms, much less so on anterior arm. Pinnules unknown; covering plates, so far as understood, closely resembling those of *Amygdalocystites* (Parsley and Mintz, 1975, text-fig. 1).

Arms extending varying lengths down theca with varying degrees of curvature to right. Left and right arms may extend nearly to column attachment, then curve sharply upward; typically, arms extending about two-thirds distance down theca.

Central lumen limited; best developed in left arm, there extending nearly to end of fourth ossicle. Lumen floored by callus except at opening to interior of theca via pore under primary ossicle. Right arm lumen not extending past third ossicle, opening to interior of theca under primary ossicle. Anterior arm without lumen. (Diagnosis and condensed description from Parsley and Mintz, 1975, p. 52-56.)

Material and occurrence.—*Oklahomacystis tribrachiatus* is the most common paracrinoid in the Upper Echinoderm Zone, and one of the two most common echinoderms in the entire Bromide Formation. The specimens on hand for this study are as follows: Buckhorn Ranch (856), Lick Creek (229), Sulphur (58), Amis Ranch (52), Chapman Ranch (22), North I-35 section (9), and Fittstown Roadcut (2). Allen Graffham (pers. commun. to Sprinkle, Aug., 1976) estimated that he had collected about 2,000 additional specimens of this species from the trench at Buckhorn Ranch.

OKLAHOMACYSTIS BIBRACHIATUS Parsley, n. sp.

Plate 23, figures 7, 9-17; Plate 24, figure 15

Diagnosis.—*Oklahomacystis* with 2 unbranched recumbent arms, periproct in large specimens elevated into low chimney.

Description.—Based on theca and recumbent arms; column and exothecal pinnules unknown. Theca amygdaloid to broadly oval in profile (Pl. 23, fig. 10, 14, 16), cross section elliptical in juveniles, subcircular in mature individuals (Pl. 23, fig. 9, 11). Theca made up of 70 to 80 plates, little correlation between thecal height (14 to 35 mm in known specimens) and number of plates. Thecal growth primarily by peripheral growth of early formed plates. Right side of theca protuberant. Gonopore on posterior lip of peristome and adjacent right hydropore at triplate juncture typical for the genus (Pl. 23, fig. 9). No anomalous pores on posterior face.

Disposition of thecal plates, including peristomals (4), periproctals (4), and basals (3), and their outlines (mostly hexagonal) essentially as in *O. tribrachiatus* (see Parsley and Mintz, 1975, p. 53-55). Pore structures, expresssed as raised triacts centering at plate corners (junctures of 3 plates), as in type species. Each face of triact made up of 2 plates, the common suture bisecting the triangular face. Each face of a triact with inner and outer walls, joining along raised triact edges. Space between inner and very thin outer wall for circulation of body fluids, connecting with body cavity via one of transverse slits developed on inner surfaces of plates (Pl. 24, fig. 15). Other slit connecting to space on triact at opposite end of plate facet. Space between walls of triact face triangular, in largest specimens about 0.5 mm across.

Peristome typically offset to left, periproct at apex, on anterior face, produced into prominent anal chimney (Pl. 23, fig. 9, 11, 12, 14-17). Basals typically sharply offset to left, triacts

(sutural pores) not formed between basals. Column lumen transversely oval, as is column attachment facet (Pl. 23, fig. 13).

Two unbranched, transversely arranged, recumbent arms. Main food groove posterior in left arm, anterior in right arm as is typical in paracrinoids. Right arm with 13 to 29 segments, tapering slightly to rounded end. Right arm slightly to considerably deflected by anal chimney, generally returning to transverse (lateral) position (Pl. 23, fig. 9, 11), sometimes curving slightly toward posterior face. Left arm straight or curving slightly toward anterior face, 11 to 18 segments in known specimens, about 20 percent fewer segments than in right arm. Covering plates over main food grooves similar to those in *Amygdalocystites* (see Parsley and Mintz, 1975, text-fig. 1). Adthecal (ventral) covering plates averaging about 3 per arm segment and covering half to three-fifths of groove. Each adthecal cover plate with 2 alternating, imperfectly opposed abthecal (dorsal) covering plates. Suture between 2 series irregularly zigzag. Tightness of suture suggesting main food groove covering plates unopenable. Abthecal covering plates only on lateral (side) food grooves of arms and presumably on (as yet unknown) exothecal pinnules.

Discussion.—*Oklahomacystis bibrachiatus* is nearly identical to *O. tribrachiatus* except for having two arms instead of three, a more prominently elevated periproct, and a tendency for the theca to be broadly transversely oval in cross section because the deployment of the arms is transverse. Because *O. bibrachiatus* is found coevally with *O. tribrachiatus*, it is difficult to determine if the former represents an ancestral form or a case of allopatric speciation from a common ancestor.

Fortuitous preservation of the triacts-sutured pores in *O. bibrachiatus* have increased our knowledge of these unusual respiratory structures. Their complete anatomy has now been observed, from inside the theca of *O. tribrachiatus* (Pl. 24, fig. 18) and exteriorly in *O. bibrachiatus* by various stages of weathering away of the exterior triact walls (Pl. 24, fig. 15). Except for the solid cores of the plates and the ridges of the raised triacts, the rest of the plate area (about 60 percent) is underlain by the sutural pore-triact cavities. The large transsutural slit that opens into the cavities suggests efficient circulation of body fluids, and the thinness of the outer triact walls (epistereome) further suggests efficient gaseous exchange.

The thecal plates are slightly concave with pustulose prosopon. If the triacts form late in juveniles, there is a strong, albeit superficial, resemblance to *Sinclairocystis* (Pl. 23, fig. 7). This trait may be part of the reasoning of Frest and others (1980) in placing aberrant *Sinclairocystis* (their *O. spissus)* into this genus. Late-forming pores may result from rapid growth under favorable conditions.

Finally, the transversely oval column attachment facet and the similarly-shaped lumen through the basals (Pl. 23, fig. 13) suggest streamlining with the attached theca standing off the bottom with its left side facing into the current. This rheophilic mode of life for similarly offset paracrinoids has been discussed by Parsley and Mintz (1975, p. 20-23). Burial of the column and proximal end of the theca into the substrate has been favored by Frest and others (1979, p. 385-386) but seems unlikely. If a relatively globose genus like *Oklahomacystis* shows rheophilic adaptations, then more streamlined forms, e.g., *Amygdalocystites* and *Platycystites*, probably lived off the bottom as well.

Material and occurrence.—Seven specimens of *Oklahomacystis bibrachiatus* are known, including the holotype OU 9111 and paratypes OU 9112, OU 9118-9119, and 1117TX26-28. All are from the Upper Echinoderm Zone, Johnston Ranch, in the southwestern Arbuckle Mountains.

Order PLATYCYSTITIDA Parsley and Mintz, 1975
Emended herein

Diagnosis.—Paracrinoids without sutural pores, arms epithecal, branched or unbranched, rarely with 2 separate, reversed ambulacral systems and 2 mouth openings; thecal plates generally smooth with pustulose prosopon. (Emended from Parsley and Mintz, 1975, p. 57.)

Discussion.—It is necessary to emend this order primarily to accommodate the enigmatic new genus *Bistomiacystis* Sprinkle and Parsley, which is described in the following chapter.

Family PLATYCYSTITIDAE Parsley and Mintz, 1975

Diagnosis.—Ovoid to amygdaloid theca with pair of transverse, primarily epithecal arms (Parsley and Mintz, 1975, p. 58).

Discussion.—Restudy of the Bromide platycystitids indicates that *Platycystites*, which is found throughout the Mountain Lake Member, is represented by two species: *P. levatus* Bassler, which is most common in the Lower Echinoderm Zone and the *Carabocrinus* Beds although it rarely extends into the Upper Echinoderm Zone; and *P. cristatus*, which is found only in the Upper Echinoderm Zone. A new genus and species, *Arbucklecystis pyriformis*, is based on a single specimen from the *Bromidocystis* Bed.

Genus PLATYCYSTITES Miller, 1899

Type species.—*Platycystites faberi* Miller, 1899.

Diagnosis.—Theca amygdaloidal, compressed to broadly oval and inflated in cross section, theca with approximately 27 identifiable plates in juvenile specimens, intercalaries along right lateral margin in some species. Peristome usually only slightly offset to left, periproct on posterior face near upper margin. Two epithecal arms (1 split in a few) extending varying distances along lateral margins. (Emended from Parsley and Mintz, 1975.)

Discussion.—Frest and others (1979) have correctly pointed out that Parsley and Mintz (1975) based most of their discussion of this genus not on the type species, *P. faberi*, but on *P. cristatus* (= *P. levatus* herein, correct name) from the Lower Echinoderm Zone of the Bromide Formation. Their work has revealed the plate pattern of the type species and has, in my opinion, correctly shown that much of the proliferation of thecal plates in the bulging right side of the various species other than the type species is caused by the splitting of plates. Some of these plates intercalated along the right side appear regularly enough to be given plate designation with an "I" for intercalary. The plates associated with orifices and the normal tracks of the recumbent arms are the same in all species of *Platycystites* (and *Globulocystites*). The right arm of "bulged" species usually extends to at least R4 and in some cases R5 (= A9 of Frest and others, 1979). In some specimens an intercalary positions R5 slightly anterior of lateral and almost invariably the arm bends slightly to cross this plate. It should be noted that even though the arms are sometimes deflected across other plates, normal subarm ridges still form on the regular plates (see Parsley and Mintz, 1975, pl. 8, fig. 12, 13). Because most but not all differences in plate pattern occur in the bulge area, and because the bulge so increases the length of the right side that the right arm cannot extend to the column (an important trait in Frest and others' 1979 concept of *Platycystites*), it seems wiser to me to recognize the bulge area, its variation in plate patterns, and changes in relative lengths of the arms, especially the right arm, as species traits. This more conservative view seems justified because small specimens of "bulged" species are very similar in outline (amygdaloidal) to the type species (see Pl. 24, fig. 14). *Globulocystites* of Frest and others (1979) is therefore probably best retained in the genus *Platycystites*.

Large numbers of *Platycystites* from the Lower Echinoderm Zone have been examined, and observed variations seem to fit into a continuum of thecal shape and plate arrangement changes; all are easily encompassed within a single species, *P. levatus*. Similarly, most Upper Echinoderm Zone specimens probably belong to a single species, *P. cristatus*.

A large number of species of *Platycystites* have been synonymized by Parsley and Mintz (1975 and herein). The rationale is that the variation in thecal plates through several meters of strata is limited; most of it, as pointed out by Frest and others (1979, p. 385), results from splitting of thecal plates primarily near the proximal end of the theca. Plates transversed by recumbent arms or making up part of the peristome, periproct, hydropore, and/or gonopore are generally fixed in position and usually not subject to splitting.

Synonymizing Lower Echinoderm Zone "species" produces taxa with a fairly limited range of specific variability occurring through a rather narrow stratigraphic thickness (Parsley and Mintz, 1975, p. 58-59). A limited range of variability is also demonstrated for the Upper Echinoderm Zone, where most *Platycystites* from the southern and southwestern Arbuckles belong to a single species (*P. cristatus*) but with less variation than is found in the Lower Echinoderm Zone. *Platycystites levatus* rarely extends into the Upper Echinoderm Zone in the northern and northeastern Arbuckles but is easily distinguished from the more compressed *P. cristatus*.

Parsley and Mintz (1975, p. 58-70) synonymized all of the Bromide species of *Platycystites* into a single species, *P. cristatus*. While the specimens they surveyed were from the Lower Echinoderm Zone, Bassler's holotype of *P. cristatus* is in fact from

the Upper Echinoderm Zone as evidenced by its morphology. Hence, a new species name must be chosen for the *Platycystites* of the Lower Echinoderm Zone; *P. levatus* is taken as this species on the basis of page priority and because its type is the best preserved of the original types apparently from the Lower Echinoderm Zone. For the Upper Echinoderm Zone, *P. cristatus* is the predominant species.

PLATYCYSTITES LEVATUS Bassler, 1943

Plate 24, figures 3, 11-14, 16, 17; Figure 58

Platycystites levatus Bassler, 1943, p. 697, pl. 1, fig. 13.
Platycystites fimbriatus Bassler, 1943, p. 698, pl. 1, fig. 12.
Platycystites bromidensis Bassler, 1943, p. 698, pl. 1, fig. 10.
Platycystites cf. *bromidensis* Bassler, Sinclair, 1945, p. 708, pl. 1, fig. 6.
Platycystites cf. *levatus* Bassler, Sinclair, 1945, p. 708, pl. 1, fig. 7, 8.
Platycystites bassleri Sinclair, 1945, p. 709, pl. 1, fig. 1-5.
Platycystites cristatus Bassler, Parsley and Mintz, 1975, p. 73-74, pl. 7, fig. 6-15, pl. 8, fig. 1-13, pl. 9, fig. 1-14, text-fig. 3-6.
Platycystites cristatus Bassler, Frest and Strimple, 1976, p. 221-228, text-fig. 1-9.
Globocystites cristatus (Bassler), Frest, Strimple, and Coney, 1979, p. 397, pl. 2, fig. 9-12, text-fig. 7C, D.

Diagnosis.—Theca with average of 38 plates, usually somewhat inflated, rounded to oval in anterior-posterior profile in mature specimens. Recumbent arms rarely reaching column. (From Parsley and Mintz, 1975, p. 73.)

Description.—See Parsley and Mintz (1975, p. 58-70, 73-74).

Discussion.—Clearly the most far ranging of all Bromide paracrinoid species, *Platycystites levatus* completely dominates the Lower Echinoderm Zone and is also found in the *Carabocrinus* Beds, rarely in the Upper Echinoderm Zone, and perhaps in the *Bromidocystis* Bed (based on plates). *Platycystites cristatus*, which dominates the Upper Echinoderm Zone, probably is derived from *P. levatus*. Their similar plate patterns attest to their close relationship.

Material and occurrence.—*Platycystites levatus* is the only Bromide paracrinoid found in both the Upper and Lower Echinoderm Zones. Nearly 1,800 specimens have been examined, and Allen Graffham (pers. commun. to Sprinkle, Aug., 1976) estimated that he had collected an additional 500 specimens from the Lower Echinoderm Zone trench at Daube Ranch. Lower Echinoderm Zone specimens have been collected as follows: Lick Creek (583), Daube Ranch (560), Amis Ranch (478), Cornell Ranch (124), McLish Ranch (34), Fittstown Roadcut (1), and Bromide (1). Upper Echinoderm Zone specimens have been collected at North I-35, A cut (1), and BC cut (1). *Carabocrinus* Beds specimens are as follows: North-Central I-35, A cut (1), and C cut (1).

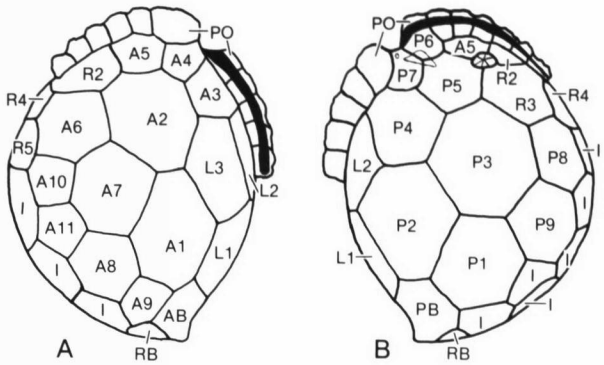

Fig. 58. *Playcystites levatus* Bassler; diagram of thecal plates and their nomenclature. A, Anterior face and B, posterior face; an A prefix indicates an anterior plate; AB, anterior basal; I, intercalated plate; an L prefix, left plate; a P prefix, posterior plate; PB, posterior basal; PO, primary ossicle of a recumbent arm; an R prefix, right plates; RB, right basal (from Parsley and Mintz, 1975).

PLATYCYSTITES CRISTATUS Bassler, 1943

Plate 24, figures 4, 6, 7, 9

Platycystites cristatus Bassler, 1943, p. 697-698, pl. 1, fig. 11.
non Platycystites cristatus Bassler, Parsley and Mintz, 1975, p. 58-70, 73-74, pl. 7, fig. 6-15, pl. 8, fig. 1-13, pl. 9, fig. 1-14, text-fig. 3-6.
Platycystites faberi S. A. Miller, Parsley and Mintz *(pars)*, 1975, p. 71, pl. 7, fig. 4, 5.
non Platycystites cristatus Bassler, Frest and Strimple, 1976, p. 221-228.
Platycystites infundus Frest, Strimple, and McGinnis, 1976, p. 215-218, fig. 7-11.
Platycystites sp. Frest, Strimple, and Coney,

1979, p. 390, pl. 1, fig. 11, 12, text-fig. 6C, D.

non Globulocystites cristatus (Bassler), Frest, Strimple, and Coney, 1979, p. 397, pl. 2, fig. 9-12, text-fig. 7C, D.

Globulocystites infundus (Frest, Strimple, and McGinnis), Frest, Strimple, and Coney, 1979, p. 397-398, text-fig. 7E, F.

Diagnosis.—*Platycystites* with compressed theca, thecal plates above periproct produced into narrow ridge, posterior face of ridge (plates A5, R2) often slightly concave. Anterior right side of theca with reduced number of intercalaries. Left arm usually extending to basals, right arm shorter, rarely extending beyond R5.

Description.—Theca somewhat elongate, with slightly flattened dorsal profile; ventral (proximal) profile narrowed, basals offset to left; in cross section compressed oval. Thecal height ranging from 15 to 46 mm in specimens studied; fragments of specimens suggesting maximum thecal heights of 60 to 70 mm. Small specimens (15 to about 28 mm high) amygdaloidal; thecae over 18 mm high usually showing much profile variation. Peristome offset to left (Pl. 24, fig. 9). Periproct small, somewhat offset to right of dorsal-ventral midline. Posterior face with essentially same plate pattern as *P. levatus;* anterior face somewhat variable, similar to *P. levatus* but without plates A10 and A11 (A9a, A9b, of Frest and others, 1979). Plates A8 and A9 (A8a, A8b of Frest and others, 1979) present in lower right lateral area (as in *P. levatus).* Dorsal right side of theca produced into narrow ridge, posterior side of ridge (plates A5 and R2) slightly concave (Pl. 24, fig. 6). Lateral edges of theca sharply angled (keeled).

Transversely lateral recumbent arms resting on sharply angled sides of theca. Left arm usually extending to basals and, in some, nearly to, or rarely onto, column (Pl. 24, fig. 6); right arm usually extending to about midline of right side (Pl. 24, fig. 9). Arm segments thin, but standing as high as or slightly higher than those in *P. levatus* (Pl. 24, fig. 4, 9). Pinnules unknown. Column poorly known except for few proximal columnals showing typical offset curvature toward right.

Discussion.—As indicated in the synonymy above, several species have been named for specimens found in the Upper Echinoderm Zone. With the specimens now in hand, it is correct to include most of them in *P. cristatus.* Variation in plate patterns along the right (usually anterior) face is minor, at about the same or a lesser level as in *P. levatus* of the Lower Echinoderm Zone. The compressed nature of the theca with the right subarm ridge slightly concave on its adoral posterior side, the small periproct, and the narrow arm segments resting on a sharply laterally curved or keeled theca are sufficient to clearly establish the distinct nature of this species. The plate pattern on the anterior face, although distinctive, is often poorly preserved and thus not usually reliable in species identification.

Occurrence.—Many fewer specimens of *Platycystites cristatus* were available for study than of *P. levatus.* They are from the Upper Echinoderm Zone as follows: Johnston Ranch (25), Amis Ranch (2), North I-35 (1), Tulip Creek (1), and Putman Ranch (1).

Genus ARBUCKLECYSTIS
Parsley and Sprinkle, new

Type species.—*Arbucklecystis pyriformis* Parsley and Sprinkle, n. sp.

Diagnosis.—Platycystitid with pyriform thecal profile, peristome and column attachment opposed, thecal plates numerous, about 74; intercalaries in right and left lateral area. Recumbent arms short, extending aborally about one-third height of theca.

ARBUCKLECYSTIS PYRIFORMIS
Parsley and Sprinkle, n. sp.

Plate 24, figures 5, 8, 10; Figure 59A, B

Diagnosis.—Characters as for genus.

Description.—Theca pyriform in profile, elliptical in cross section. Only known specimen 36 mm high, maximum width 21 mm just aboral of terminal recumbent arm segments. Theca of 74 plates, many appearing to be split or fragmented (Fig. 59A, B). (Only those plates associated with arms and orifices, and the 3 basals, can be identified with certainty when compared with closely related *Platycystites.)* Peristome formed by A3, A4, P6, and P7; hydropore at juncture of P5, P6, and P7; periproct small, surrounded by A5, P5, R2, and R3. At least 8 plates split to form pairs, some lateral plates apparently fragmented into at least 3 plates (see Fig. 59A, B). All orifices in same positions as in *Platycystites* except peristome directly opposed to column attachment and not canted to left as in most paracrinoids.

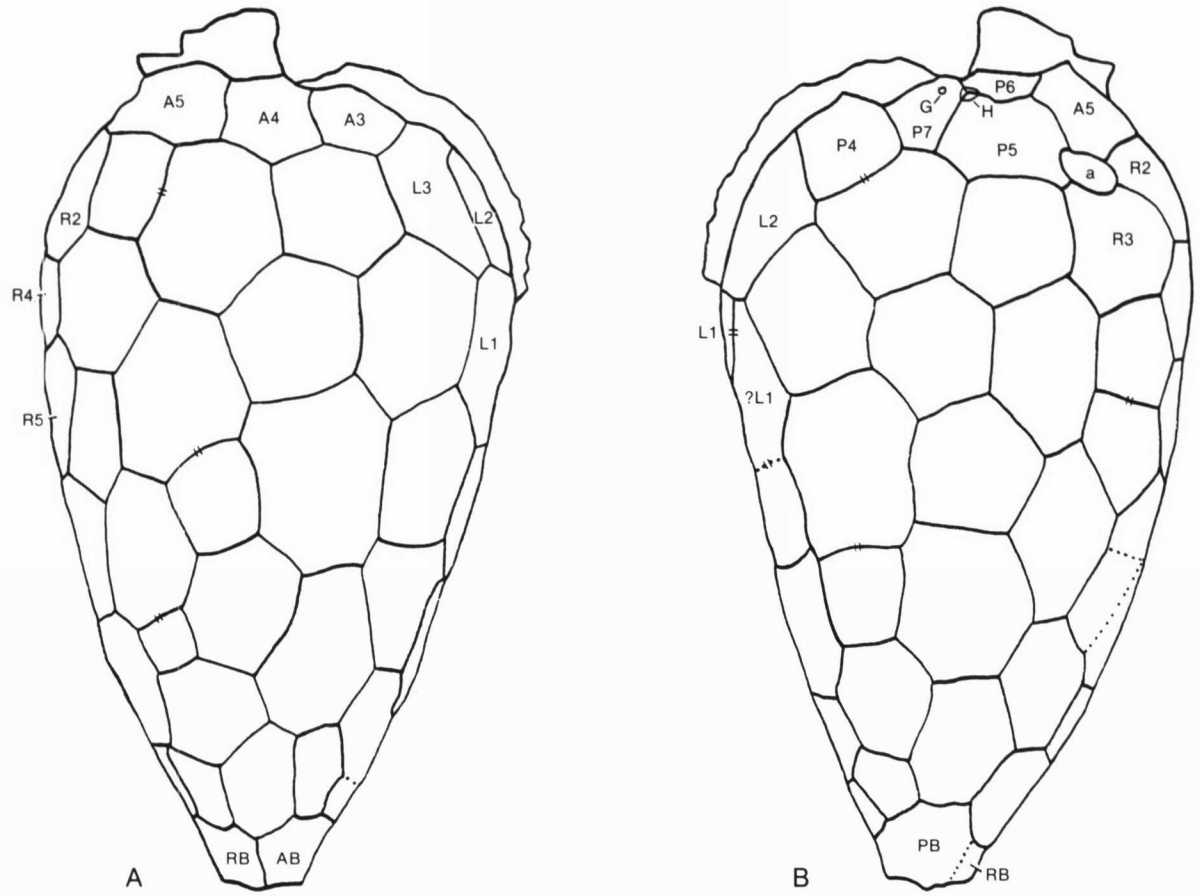

Fig. 59. *Arbucklecystis pyriformis* Parsley and Sprinkle, n. gen., n. sp. A, Anterior plate pattern and B, posterior plate pattern; cross-hatched sutures between probable split plates. Designated plates are considered homologous with those of *Platycystites;* see legend of Figure 58 for plate terminology. Thecal openings labeled on B are a, anal opening; G, gonopore; and H, hydropore.

Recumbent arm segments high, sides somewhat tapering rather than straight, continuous with slope of theca. Arms short, extending about one-third distance down theca (seemingly rather small subvective area for size of theca); left arm with 15 segments, right arm estimated 15 to 17 segments, pinnules unknown.

Material and occurrence.—A single specimen, holotype 1393TX2, from the *Bromidocystis* Bed, middle Mountain Lake Member, Bromide Formation, North-Central I-35 (D cut), northern Arbuckle Mountains, Oklahoma.

Discussion.—Variability in platycystitids is rather high, especially in thecal outlines and plate patterns of the right lateral thecal region. Normally it is inadvisable to name new platycystitid species on the basis of single specimens when similar forms are found at the same stratigraphic level. Subsequent study usually indicates, when numerous specimens are available, that such named species are within the normal range of species variability and should be synonymized.

Arbucklecystis is closely related to *Platycystites* as evidenced by the homology of plates around the orifices and recumbent arms, but is clearly a new genus because of its more numerous plates. In profile the theca resembles a juvenile *P. cristatus* or *P. levatus* with its amygdaloid shape. Possibly this shape represents a paedomorphic lineage derived from an earlier species, e.g., *P. levatus*. The short arms also suggest a neotenic state.

The high degree of profile symmetry is similar to that of the type species *P. faberi* and suggests a similar ecological setting for both species, perhaps in a moderate oscillatory current regime. The offset symmetry of many paracrinoids seems adapted for unidirectional currents. While the column is unknown, it seems reasonable to assume that it was at least long enough to tether the theca a short distance above the sea floor.

"GOLF-BALL" PARACRINOID

James Sprinkle and Ronald L. Parsley

University of Texas at Austin;
Tulane University

Eleven specimens of an unusual globular echinoderm, some of which resemble a golf ball in size and shape, have been collected from four localities of the Lower Echinoderm Zone of the Bromide Formation. These specimens are almost spherical, range from 8 to about 60 mm in diameter, and have numerous irregularly arranged thecal plates. The most diagnostic and puzzling feature in these specimens is that they have two external mouths and two separate ambulacral systems on the summit. Each mouth is elliptical and has two ambulacral branches which curve counterclockwise and are asymmetrical with all the appendages branching off the outer (right) side and a food groove extending along the inner (left) side. Despite their unusual form and reversed symmetry, these ambulacral features are similar to those of *Canadocystis*, a platycystitid paracrinoid. Other paracrinoid features include the bilateral symmetry of the three basals around the stem facet, the numerous thin thecal plates lacking respiratory structures, and the position of the mouths and ambulacra relative to the hydropore and periproct.

However, some features are so different from those of any other known paracrinoids that inclusion of this genus almost necessitates a revision of the class definition. The two external mouths and ambulacral systems are unknown in any other fossil echinoderm. The ambulacra are asymmetrical in a way different from that in nearly all other known paracrinoids; in this new form the ambulacra are right-lateral, curving counterclockwise away from the mouth, instead of left-lateral, curving clockwise (see Sprinkle, 1973, p. 184-185; Parsley and Mintz, 1975, p. 12). The ambulacral plates also make up the thecal wall instead of being mounted on thecal plates, a difference from most other paracrinoids except perhaps *Canadocystis* and *Malocystites*. These ambulacral plates also bear only half of the main food groove; the other half is supported by a single elongate crescent-shaped plate in each ambulacral branch. This new form also has a distinctively shaped terminal ambulacral plate that apparently remains in the same relative position during growth of the ambulacra; new ambulacral plates are apparently inserted as thin wedges just adoral of it instead of being budded off the end of the ambulacrum. A further difference is that the appendage fragments attached to these ambulacral plates appear to be biserial instead of uniserial as in all other paracrinoids. Most of the other thecal features are shared by paracrinoids and several other classes of stemmed echinoderms.

This new form represents a new family, genus, and species, which is assigned to the paracrinoid order Platycystitida (Parsley and Mintz, 1975), based on the thin plates lacking respiratory structures and slight similarity of the ambulacral system to that of *Canadocystis*.

Order PLATYCYSTITIDA Parsley and Mintz, 1975

Family BISTOMIACYSTIDAE Sprinkle and Parsley, new

Diagnosis.—Paracrinoids having a nearly spherical theca composed of numerous, thin, irregularly arranged plates; ambulacral system composed of 2 external mouths each with a double-branched curved ambulacrum bearing facets for appendages only on the right side; anus on right side of summit, hydropore between and below mouths; stem facet at aboral end of theca.

Discussion.—The new genus *Bistomiacystis* is sufficiently different in its morphology from all other paracrinoids in the order Platycystitida that a new family is necessary for it. Most of the differences involve the arrangement of the ambulacral system on the summit. Only one genus and species is known to belong to this family at present.

Genus BISTOMIACYSTIS Sprinkle and Parsley, new

Type species.—*Bistomiacystis globosa* Sprinkle and Parsley, n. sp.

Diagnosis.—Paracrinoids having a globular the-

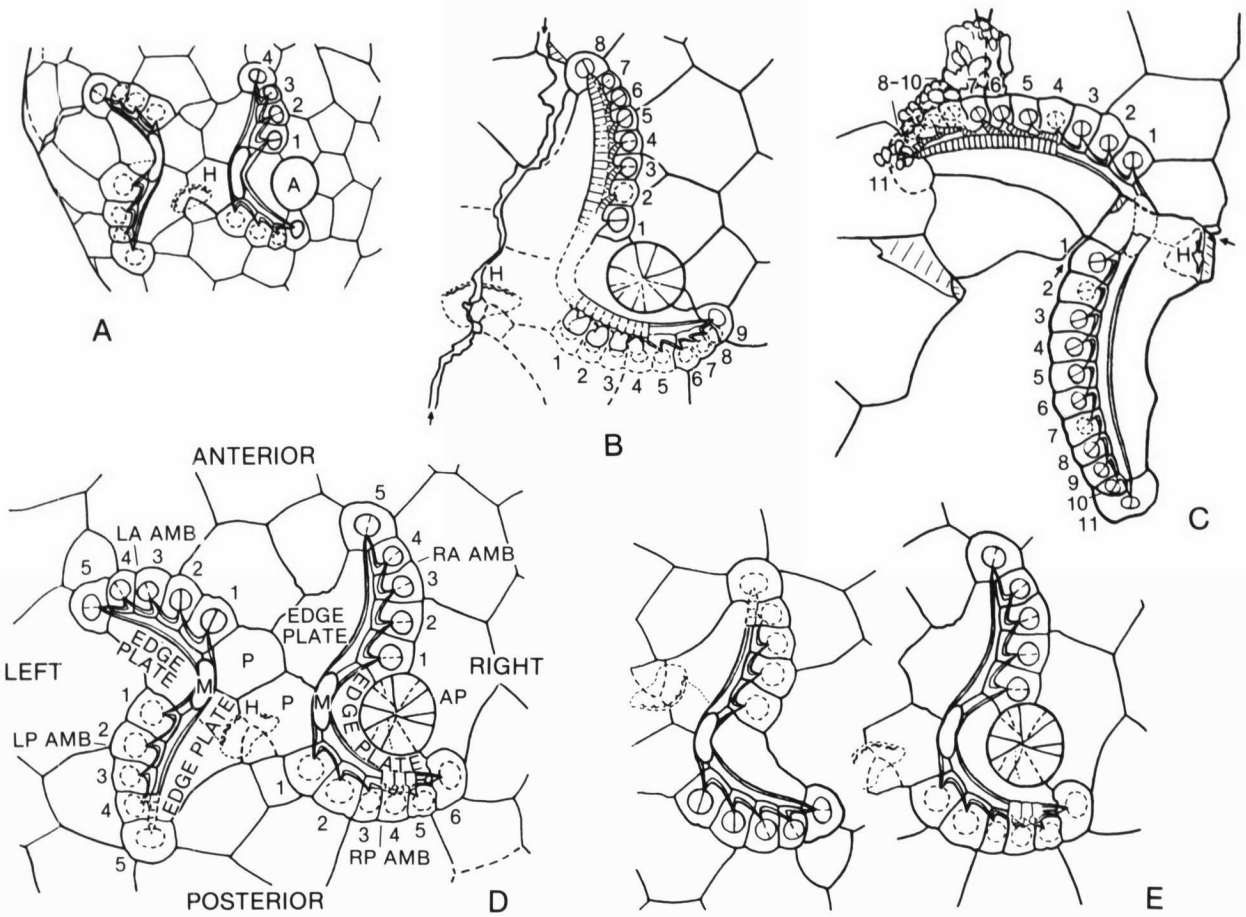

Fig. 60. *Bistomiacystis globosa* Sprinkle and Parsley, n. gen., n. sp., Lower Echinoderm Zone, Bromide Formation, southern Oklahoma. A, Paratype OU 8939 from Daube Ranch showing summit with 2 ambulacral systems and mouths, central hydropore (H), periproct at right (A), and 4 appendage facets per ambulacral branch, X3.5. B, Paratype OU 8938 from Daube Ranch showing well-preserved right-hand ambulacrum on right side of summit with 8 to 9 appendage facets in each branch, most of ambulacral cover plates still in place, and basal appendage plates (?biserial) on facets 1 through 4 of RP branch (small arrows mark major crack through theca), X3.7. C, Paratype 1279TX159 from Fittstown Quarry showing well-preserved left-hand ambulacrum from largest known specimen; note 11 appendage facets in each branch, appendage fragments above LA branch and attached to terminal ambulacral plate, very elongate ambulacral edge plates, and small new ambulacral plate (#10) in LP branch (small arrows mark major crack in fragment), X3.1. D, Holotype OU 8937 from Lick Creek with right- and left-hand ambulacra and other summit and orientation features labeled; note 5 to 6 appendage facets on ambulacral plates and terminal ambulacral plate, ambulacral edge plates, 2 separate mouths (M), anal pyramid (AP), and peristomal plates (P) bearing hydropore (H), X5.1. E, Same specimen, view, and enlargement as Figure D with left-hand ambulacrum rotated 180° to show great similarity between left- and right-hand ambulacra.

ca made up of 75 to 285 irregularly arranged thecal plates, plates very thin, lacking respiratory structures; 3 basals present around relatively small stem facet, 1 larger, 2 smaller, in a bilaterally symmetrical arrangement; summit complex composed of several large peristomal plates between 2 external mouths, each having a separate ambulacral system with 2 anteroposterior branches; ambulacral branches all right-lateral, curving counterclockwise, 1 branch in each pair showing moderate curvature, the other strong curvature; ambulacral plates incorporated into theca, between 3 and 11 flat plates per branch, including a distinctive semicircular terminal plate; ambulacral plates bearing appendage facets and half of ambulacral food groove, other half of ambulacral food groove carried by elongate crescent-shaped edge plate; 1 ambulacral branch curving around lateral anus covered by a low pyramid; elongate domed slitlike hydropore located between and just below mouths; appendages attached to ambulacral plates possibly biserial; thecal ornament granular.

Occurrence.—Middle Ordovician, Oklahoma.

Etymology.—The generic name is derived from

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bi, bis (L.), double, and *stomias* (Gr.), large-mouthed animal, referring to the two oral openings on the summit of the theca.

Discussion.—*Bistomiacystis* does not closely resemble any of the other genera in the order Platycystitida. The globular theca with numerous plates resembles that of *Malocystites*, and the ambulacra show some similarities to those of *Canadocystis*. However, these genera have fewer plates, asymmetrical ambulacra that have left-lateral asymmetry and somewhat different construction, and only one mouth and ambulacral system. At present, *Bistomiacystis* is known only from the Lower Echinoderm Zone of the Bromide Formation in Oklahoma.

BISTOMIACYSTIS GLOBOSA
Sprinkle and Parsley, n. sp.

Plate 25; Figure 60A-E; Table 40

Diagnosis.—Characters as for genus.

Description.—The 11 available specimens ranging from complete, well-preserved (holotype OU 8937) to partial, badly crushed, poorly preserved. Thecal shape almost spherical, height only slightly greater than diameter. Stem attachment and part of summit (especially hydropore) slightly raised, increasing height (Pl. 25, fig. 2, 20). Complete specimens ranging from about 8 to 36 or 37 mm in diameter; however, a very large but incomplete fragment (1279TX159) probably came from a specimen approaching 60 mm in diameter.

Theca containing about 75 plates in smallest specimen to about 285 plates in largest complete specimen (Table 40). Most thecal plates fairly small, polygonal with 4 to 7 sides, irregularly arranged (not in circlets or columns). Thecal plates very thin, ranging from less than 0.25 to 0.33 mm thick. Number of thecal plates appearing to increase gradually with increasing thecal size, new small plates probably added randomly to all parts of theca, but more numerous just above basals. Thecal plates ranging from about 3 mm long in small specimens to about 11 mm long in largest fragment. Plates lacking respiratory structures (pores or slits), showing moderate granular ornament (or prosopon).

Basal plates 3, arranged in bilaterally symmetrical grouping (Pl. 25, fig. 28) with 1 somewhat larger plate located on left-anterior side of stem facet and 2 smaller ones on left-posterior and right sides. Interbasal sutures so arranged that each basal has 120° segment of stem facet. Each basal with 6 to 8 sides, smaller plates usually overlying moderate-sized basals. Stem facet fairly small; in holotype, approximately 2.5 mm in diameter, half of diameter occupied by nearly circular lumen. In several specimens a single columnal attached to basal plates; columnal round, same size as stem facet, about 0.3 mm high (Pl. 25, fig. 23).

Several thecal plates near mouth appearing constant in position, possibly peristomal (or oral) plates. Two peristomal plates (plus 2 ambulacral edge plates) forming area between separate mouths on summit, plates moderate-sized, six-sided. One peristomal plate and an ambulacral edge plate forming adoral side of raised hydropore; third small wedge-shaped thecal plate forming aboral side (Fig. 60A).

Two ambulacral systems on summit of theca near-

PLATE 25.

Fig. 1-28. *Bistomiacystis globosa* Sprinkle and Parsley, n. gen., n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1-3 from Lick Creek; 4-19, 23-28 from Daube Ranch; 20-22 from Fittstown Quarry. 1-3. Top, side, and basal views of holotype OU 8937 showing uncrushed, nearly spherical theca, 2 well-developed ambulacral systems, anal pyramid, and stem facet at base; X1.5. 4-8. Top, side, basal, uncrushed side, and enlarged summit views of paratype OU 8939; note obliquely crushed-in lower theca, numerous thecal plates, 2 mouths and ambulacral systems with 4 facets in each branch, central raised hydropore, and lateral anal opening on summit; X1.5, X5. 9-11. Top, side, and basal views of damaged paratype OU 8940; note bryozoan crushed into hole in theca (9, 10) and small plates near damaged base; X2. 12. Side view of poorly preserved and broken paratype OU 8944; X1.5. 13, 14. Front and back views of crushed paratype OU 8943 showing thecal plates; X1.5. 15-17. Top, side, and basal views of very small paratype 1404TX1 (Watkins Coll.), which has a distorted thecal shape; X2. 18, 19. Top and bottom of broken paratype OU 8941, which only has part of 1 ambulacral system; X1.5. 20-22. Exterior, right edge, and left edge (of LP ambulacral branch) from very large summit fragment (paratype 1279TX159) showing complete left-hand ambulacral system with 11 facets in each branch, granular ornament, thecal curvature and slightly depressed mouth (21), and calcite crystals growing into thecal interior from small ambulacral plates forming thecal wall (22); X2. 23-25. Basal, front, and back views of badly crushed but nearly complete paratype OU 8942; note 2 ambulacral branches (top, 24) and single columnal attached to stem facet at base; X1.5. 26-28. Top, side, and basal views of largest complete paratype OU 8938 showing damaged, caliche-covered summit with good right-hand ambulacral system and anal pyramid, cracks where theca has been broken and glued together, granular ornament, and 3 basals with part of first columnal; X1.5.

ly opposite stem facet, extending across about half thecal diameter in top view (Pl. 25, fig. 1), together probably occupying less than 10 percent of thecal area. If theca oriented in top view with hydropore toward observer (posterior), 1 ambulacral system (and mouth) located just above and to right of hydropore near anus (R system); the other just above and to left (L system) (Fig. 60D). Each ambulacral system consisting of 2 branches diverging from opposite ends of mouth; branches extending anterior (away from hydropore) designated A, branches extending posterior (past hydropore) designated P. (Thus, each ambulacral branch has a specific designation: RA, RP, LA, LP; see Fig. 60D.)

One branch of each ambulacral system (RA, LP) curving only slightly in counterclockwise direction, other branch (RP and LA) curving quite strongly counterclockwise. In both branches, curvature decreasing away from mouth. Angle of ambulacral curvature from tip-to-mouth-to-tip decreasing from about 120° in small specimens to about 100 to 105° in largest ones. RP ambulacral branch strongly curving around anal opening on right side of summit (Fig. 60D). Each ambulacral branch with curved main food groove surrounded by 3 to 4 types of plates (Fig. 60D): 1) row of small ambulacral plates forming right side (looking aborally), each bearing an appendage facet; 2) distinctively shaped terminal ambulacral plate bearing an appendage facet; 3) elongate ambulacral edge plate without facets forming nearly entire left margin; and 4) peristomal plates in some ambulacral branches forming one side of food groove near mouth.

Two external mouths located on summit about 3 to 5 mm apart in most complete specimens. Each mouth of bent elliptical or "bean" shape, about 2.0 mm long and 0.5 mm wide. One ambulacral edge plate forming outer side with blunt projection constricting mouth slightly; other ambulacral edge plate plus peristomal plate forming inner side. With cover plates in place, each mouth slightly depressed below surrounding thecal surface (Pl. 25, fig. 21). Mouths converging slightly beneath central peristomal plates, but no evidence of common subperistomal opening floored by thecal plates.

Each ambulacral system ranging from 5.0 to 5.5 mm in length (measured tip-to-tip in straight line) with 3 to 4 facet-bearing ambulacral plates in each branch in a small specimen (Pl. 25, fig. 15; Table 40) to 14 to 15 mm in length with 8 to 9 facet-bearing ambulacral plates in each branch in largest complete specimen (Pl. 25, fig. 26). Largest summit fragment with ambulacral system about 22 mm in length bearing 11 facet-bearing ambulacral plates in each branch (Pl. 25, fig. 20). Separate ambulacral systems R and L very similar in plating, curvature, and adjacent peristomal plates (see Fig. 60E).

Ambulacral plates serial, small, flat, rounded-rectangular, bearing facets forming right margin (looking aborally) of each ambulacral branch, part of thecal wall (like the proximal ambulacrals in *Canadocystis*), lacking underlying thecal plates. Each ambulacral plate about 1.0 to 1.5 mm long, 1.5 to 2.0 mm wide, approximately rectangular in shape, with lateral margins convex, margins between ambulacrals slightly curved. Ambulacral plates gradually decreasing in size aborally (Pl. 25, fig. 20), bearing 25 to 50 percent of main ambulacral food groove along left margin, plus short V-shaped side food groove leading to single nearly round appendage facet near center of each ambulacral plate (Fig. 60C). Adoral-most ambulacral plate in branch RA sometimes forming small margin of anal opening, a feature also present in some other paracrinoids (see Parsley and Mintz, 1975, pl. 6, fig. 13).

Terminal ambulacral plate in each branch larger and differently shaped than other ambulacral plates and extending across entire ambulacral width, essentially "capping" ambulacral branch. Terminal plate roughly semicircular in shape, 1.0 to 1.5 mm long by 1.5 to 2.5 mm wide in large specimen, abutting an ambulacral plate on its adoral right edge, ambulacral edge plate on its adoral left edge, and 1 to 3 thecal plates laterally and aborally with convex sutures (Fig. 60D). In small to medium-sized specimens, RP terminal ambulacral plate also forming small segment of anal margin (Fig. 60A). Each terminal ambulacral plate bearing aboral tip of main food groove (actually about same size as side food groove) and single appendage facet just to right of plate center, like those on adjacent ambulacral plates. (This distinctive "capping" plate seems to have maintained its terminal position on each ambulacral branch throughout growth and was apparently "pushed" aborally between adjacent thecal plates by the addition of new ambulacral plates on the right adoral side and elongation of the ambulacral edge plate on the left.) New ambulacral plates apparently inserted as small thin wedges just adoral of terminal plate; LP branch of largest paratype (see Fig. 60C) with thin new plate in this position bearing normal-sized appendage facet on

its surface. No other known paracrinoid shows this type of ambulacral growth.

Each ambulacral branch with elongate ambulacral edge plate forming almost entire left margin. This apparent thecal plate modified to support half or more of main food groove and part of margin around mouth, plus other summit structures. In small specimens, edge plates about 3.0 to 3.5 mm long by 1.5 to 2.0 mm wide, becoming much more elongate during growth, 12.5 to 13.0 mm long by 3.0 mm wide in largest fragment. As new ambulacral plates added, aboral end of edge plate growing to maintain correct curve for ambulacral branch.

Fairly large and deep U-shaped main food groove extending from central mouth out left side of each ambulacral branch to terminal ambulacral plate. In largest fragment, food groove about 13 mm long, tapering from about 1.0 mm wide and 0.6 mm deep adorally to 0.3 mm wide and 0.2 mm deep at terminal ambulacral plate. Suture between ambulacral edge plate and ambulacral plates usually running down center or right side of groove, which is otherwise almost smooth. Side food grooves short lateral branches with narrow V-shape, coming off right-hand side of main food grove at 50 to 60° angle, each leading to appendage facet on ambulacral plate. Each side food groove in largest fragment about 0.6 mm long and 0.3 mm wide and deep at junction with main food groove. Both main and side food grooves with shelf about 0.1 mm wide on each side about 0.1 mm below top of groove (Fig. 60D) for attachment of ambulacral cover plates. Shelf especially prominent along margin of ambulacral edge plates, probably because larger series of cover plates attached here.

Ambulacral food grooves protected by biserial set of tiny arched ambulacral cover plates; paratype OU 8938 (Pl. 25, fig. 26; Fig. 60B) with nearly complete set on RA branch. Largest cover plates along left-hand side of each main food groove; plates rectangular, with raised pustular ridges, 0.5 to 0.8 mm long and 0.25 to 0.5 mm wide. Right-hand side of main food groove with series of smaller ambulacral cover plates, branching off to cover most of side food groove to each appendage facet, probably continuing up appendage, plates about half size of larger series, averaging about 0.3 mm long by 0.1 to 0.2 mm wide. Tinier cover plates occurring in some specimens where each side food groove joins main food groove. Cover plates becoming larger adorally on each ambulacral branch; over each mouth tightly sutured, flush with thecal surface and difficult to see. (These ambulacral cover plates in *Bistomiacystis*

Table 40. Thecal and ambulacral measurements (mm) for the best-preserved specimens of *Bistomiacystis globosa*, n. gen., n. sp.

Specimen No.	Condition	Theca (diam., ht.)	No. Thecal Plates	Ambulacra	
				Spread	Plates/ Branch
OU 8945	Slightly abraded	7.5, 8.5	75-80	4.5	3-4
1404 TX1	Slightly crushed, abraded	7.5, 9.5	90-95	5-5.5	3-4
OU 8940	Nearly complete	13-14, 13-14	145*	7.0	4
OU 8941	Badly crushed; part missing	18-21, 18-21	----	8.5-9	?4
OU 8939	Complete, base crushed	19-20, 19-20	150-160	8.0	4
OU 8942	Crushed flat, incomplete	25, 23*	135*	----	?4-5
OU 8937 holotype	Complete	21, 23	150-160	8-8.5	5-6
OU 8938	Complete	36-37, 36-37	275-285	14-15	8-9
1279 TX159	Fragment of summit	60**	----	22.0	11

* Approximate figure.
**Estimated figure.

are similar in arrangement to those reported in other paracrinoids; see Parsley and Mintz, 1975, text-fig. 1, 6.)

An appendage facet on each ambulacral plate (including terminal one). Appendage facets almost circular (slightly wider than long), slightly depressed into plate surface, consisting of a slightly raised rim, a central ridge, and 2 elongate depressions on either side (Fig. 60C); ranging from about 0.5 mm wide in small specimens to about 1.0 mm wide in largest one; all facets in single ambulacral branch about same size, similar in shape to facets found in other paracrinoids except bearing only 2 depressions instead of 3. A few specimens showing traces of appendages, either as fragments on thecal surface near an ambulacrum, or as lowest plate attached to appendage facet. These attached fragments appearing biserially plated, unlike uniserial pinnules found in other paracrinoids. Broken-up appendages also appearing biserial, made up of small semicircular pieces

(Fig. 40C). (Biserial appendages would represent a major difference separating *Bistomiacystis* from other known paracrinoids.)

Periproct adjacent to right-hand mouth, with RP ambulacral branch curving around lower edge. Periproct slightly sunken circular opening about 1.5 to 2.5 mm in diameter (Fig. 60A), bordered by RP ambulacral edge plate adorally, by 1 to 2 thecal plates, by single RA ambulacral plate, and sometimes by small edge of RP terminal ambulacral plate. Periproct capped by low pyramid containing 10 to 16 wedge-shaped plates (Pl. 25, fig. 1, 26; Fig. 60B,D).

Hydropore a wavy sutural slit in elongate, raised area between and slightly posterior to 2 mouths, oriented at slight angle to line connecting mouths. Slit about 1.5 to 2.5 mm long in most specimens, near junction of 3 plates: peristomal plate adjacent to right-hand mouth, LP ambulacral edge plate, and small wedge-shaped thecal plate (Fig. 60A). No associated gonopore observed on summit.

Thecal plates, ambulacral edge and ambulacral plates, and ambulacral cover plates ornamented with medium-sized granules sometimes arranged in rows parallel or perpendicular to adjacent sutures; ornament (or prosopon) very similar to that found in other such paracrinoids as *Platycystites* or *Malocystites* (Parsley and Mintz, 1975). Granular ornament somewhat better developed in largest specimens.

Etymology.—The species name *globosa* (L.), rounded, globular, refers to the characteristic theca shape found in these specimens.

Material.—Holotype OU 8937, paratypes OU 8938-8945 (all Fay and Graffham Coll.); 1279TX159 (Sprinkle Coll.), 1404TX1 (Watkins Coll.).

Occurrence.—Found only in the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation; seven paratypes are from the trench at Daube Ranch and one paratype is from Cornell Ranch in the southern Arbuckles. The holotype is from Lick Creek in the northern Arbuckles, and one paratype is from Fittstown Quarry in the northeastern Arbuckles, southern Oklahoma.

Discussion.—The unusual double ambulacral system of *Bistomiacystis* shows some similarity to that of the platycystitid *Canadocystis*. Both genera incorporate the ambulacral plates into the theca and have the main food groove about equally floored with thecal and ambulacral plates. The number, symmetry, and mode of growth of the ambulacra differ in these two genera, and in *Canadocystis* the aboral ends of the ambulacra may be exothecal. In *Bistomiacystis* the ambulacra are completely recumbent and have four instead of two branches. Also, in *Canadocystis* the ambulacral area is considerably offset relative to the stem. In *Bistomiacystis* the ambulacra and stem attachment are dorsoventrally aligned.

The unusual split ambulacral system was probably derived from a transversely oriented system typical of most paracrinoids. The original oral opening and short transverse main food groove in *Bistomiacystis* have become phylogenetically overgrown or "lost" in the peristomal plates, possibly after the branching of both primordial transverse ambulacra. Selective pressure to increase the number of ambulacra would come with increased thecal volume. If so, then ambulacral branches RA and LP may be secondarily derived compared to those of *Canadocystis*.

The mode of developing two separate oral openings is difficult to conceive. Possibly, in the ancestral stock the main food groove became roofed over, first by ankylosed covering plates and subsequently by the peristomal plates themselves. Under such a protective cover, the transversely oriented oral opening may have elongated to the ends of the main (covered) food groove. Because only the distal ends of the opening would be functional, the central portion was then subsequently lost. The separated ends of the original oral opening then migrated parallel to the recumbent food grooves, resulting in the anteroposterior elliptical orientation of the oral opening seen in *Bistomiacystis*. The loss of the primordial transverse main food groove would explain why no underplating is found under the peristomals.

The mode of life of *Bistomiacystis* was probably similar to that of other paracrinoids: a rheophilic ciliary suspension feeder either held off the bottom by the stem or sitting on the bottom tethered by a short stem. Based on the relatively small size of the stem attachment, it is reasonable to assume that the stem was rather short.

Considering the volume of *Bistomiacystis*, which is large in relation to its external surface area, and the lack of apparent respiratory structure (pores, slits, etc.), gaseous exchange must have taken place primarily across the thin, stroma-filled, thecal plates. The large volume of the theca and lack of respiratory structures argues for its being a rheophilic animal which had a high volume of oxygenated water passing over the theca.

CYLINDRICAL AND GLOBULAR RHOMBIFERANS

James Sprinkle

University of Texas at Austin

Six genera and at least nine species of cylindrical or globular rhombiferans occur in the Bromide Formation in southern Oklahoma; four of these genera and six species are newly described here. Two additional genera and species of pleurocystitid rhombiferans are described in a separate chapter by Parsley, bringing the total rhombiferan fauna to eight genera and at least 11 species. The cylindrical or globular rhombiferans are found in all three of the rich echinoderm zones in the Bromide over most of the studied area. However, with only about 440 specimens collected, these rhombiferans make up a relatively small part of the total echinoderm fauna in each of the rich zones (about 6.3 percent of specimens in the Lower Echinoderm Zone fauna, about 0.5 percent in the Upper Echinoderm Zone fauna, and about 3.4 percent in the Pooleville Zones fauna). Rhombiferan plates and stems are also common in those parts of the Bromide where few or no other complete echinoderms have been recovered, such as the "cystoid shale" of Longman (1976) just above the basal sandstone unit.

All of the cylindrical or globular rhombiferans in the Bromide appear to belong to one family, the Glyptocystitidae; six of the seven genera in this family are now known for certain only from the Bromide Formation, implying a considerable "burst" in diversity here. This group of Bromide genera has rather conservative plating, with a standardized formula of four basals (BB, sing. B), five infralaterals (ILL, sing. IL), five laterals (LL, sing. L), six radials (RR, sing. R), and seven orals (OO, sing. O), three to four plates around the small to medium-sized periproct, and a fairly stable arrangement of respiratory rhombs (usually between 8 to 22 total). However, this family now shows a considerable range of variation in ambulacral development, from short ambulacra confined to the summit, to medium or long ambulacra extending down over the thecal plates or in deep radial sinuses, to medium-length ambulacra with multiple brachioles mounted on each flooring plate set, an arrangement never before found in any blastozoan echinoderm.

The distribution pattern of Bromide rhombiferans is best observed in the Lower Echinoderm Zone, which has the largest echinoderm fauna and the greatest number of collecting localities. The two most common rhombiferan species occur together at most localities and are especially abundant along the hingeline in the most favorable shallow-water shelf environments. Rare species seem to be confined either to the shallowest-water, storm-dominated localities on the platform in the northeastern or eastern Arbuckles or to deeper water localities down in the aulacogen in the southwestern Arbuckles or Criner Hills. The rhombiferans in the Upper Echinoderm Zone and Pooleville Zones are less abundant and diverse but again appear to be concentrated in the shallow-water, subtidal shelf environments most favorable for echinoderms. This suggests that geographically wide-ranging, abundant species occurred where conditions were most favorable for rhombiferans and other echinoderms, in shallow-water shelf environments at or just above effective wave-base. Rare species were confined to the margins of the area with less favorable conditions, in very shallow-water nearshore areas with severe effects from storms or in quiet deeper water environments with less primary production. Almost all of the Bromide rhombiferans appear to have been unattached, mobile, suspension feeders that could use the enlarged proximal stem for short bursts of swimming. Such forms may have been well adapted to very shallow, storm-dominated environments with much current or wave action and rapid sedimentation (such as the cystoid shale); these forms may well have been opportunists. However, not many complete specimens were buried intact in these environments, and most of these localities have produced only rhombiferan plates.

About 80 percent of the approximately 410 rhombiferans from the Lower and Upper Echinoderm Zones of the Mountain Lake Member have a large distinctive "black spot" on the side of the theca. This spot is a pale brown to black, elliptical, stained area within the thecal plates on one side; it occurs in different places on the theca, but in crushed specimens, it is always on one of the

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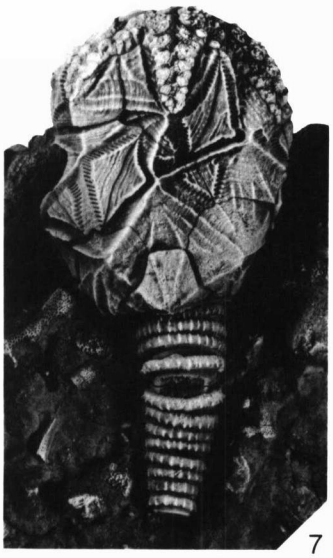
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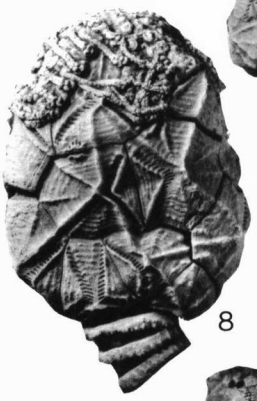
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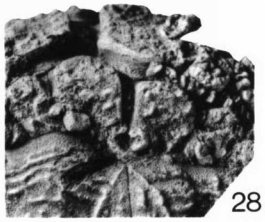
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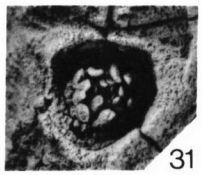
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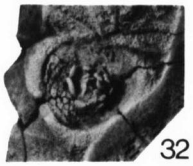
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flattened sides. In these two zones, a black spot is present in almost all large specimens of *Glyptocystella*, *Pirocystella*, n. gen., and *Strabocystis*, n. gen. (Pl. 26, fig. 2; Pl. 31, fig. 21) but occurs in less than 50 percent of the smaller specimens. A spot like this occurs in 10 to 30 percent of the common crinoids, such as *Hybocrinus* and *Palaeocrinus*, that occur with these rhombiferans, but the spot is usually very small and light-colored, nowhere near so strongly developed as in the rhombiferans (Pl. 26, fig. 14).

This black spot has not yet been analyzed for its composition, but appears to be either solid hydrocarbons or finely disseminated pyrite within the plate structure, apparently resulting from breakdown of the organic content of the coelomic cavity. It appears to represent a top or bottom indicator for the final resting position of the dead rhombiferan during burial on the sea floor. A bottom position appears somewhat more likely because the dead rhombiferan would be lying in soft mud on the sea floor. The mud probably had reducing conditions that preserved hydrocarbons or pyrite, in contrast to the oxidizing conditions in and around the theca exposed above the bottom. Further work is needed to determine why the black spot is better developed in the rhombiferans of the Mountain Lake Member than in crinoids from the same beds and if its presence is related to surrounding sediment type (?shales). Whether it is present in rhombiferans from other areas is also unknown.

Subphylum BLASTOZOA Sprinkle, 1973

Class RHOMBIFERA Zittel, 1879
Emended Paul, 1968b

Order DICHOPORITA Jaekel, 1899

Superfamily GLYPTOCYSTITIDA Bather, 1899

Family GLYPTOCYSTITIDAE Bather, 1899
Emended Paul, 1972b, and herein

Diagnosis.—Thecal shape cylindrical, ovoid, or pyriform; periproct relatively small, flush or recessed, surrounded by 3 to 4 thecal plates, anal pyramid surrounded by narrow area of periproctal plates; plating formula 4 BB, 5 ILL, 5 LL, 6 RR, 7

PLATE 26.

Fig. 1-32. *Glyptocystella loeblichi* (Bassler); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation; 1-7, 10, 13, 14, 16, 19-22, 27, 28, 30 from Lick Creek, northern Arbuckles; 8, 9, 11, 15, 17, 18, 31 from Daube Ranch, southern Arbuckles; 12, 29, 32 from Amis Ranch, central Arbuckles; 23, 24 from Bromide, eastern Arbuckles; 25, 26 from Fittstown Roadcut, northeastern Arbuckles, all from southern Oklahoma. 1, 2. Very large specimen OU 9080 on limestone slab coated with ammonium chloride sublimate and immersed in water, showing long ambulacra with relatively short brachioles and large "black spot" staining thecal plates (but not overlying brachioles); X1.5. 3, 4. Side views of very large specimen OU 9084; note thecal shape, ornament, long ambulacra extending down theca, and periproctal indentation (4); X1.5. 5, 27, 30. Side view of crushed medium-sized specimen OU 9065 plus enlarged stem and periproct showing thecal plating, several complete brachioles (5), long stem with moderately enlarged proximal region with ridged outer columnals and nearly undifferentiated distal region (27), and crushed anal pyramid with surrounding periproctal plates (30); X1.5, X2.5, X3. 6, 28. Side and oblique summit of large flattened specimen OU 9068; note plating, ornament, and aborted ambulacrum represented by only a single large brachiole (28); X1.5, X3. 7. Side view of large crushed specimen OU 9081 on shale slab showing long ambulacra, plating, ornament, and coarsely ribbed proximal stem; X1.5. 8, 9. Side views of large crushed specimen OU 9079; note plating, ornament with growth lines, brachioles draped over ambulacra (8), and location of periproct (9, left); X1.5. 10. Side view of medium-sized specimen OU 9070 showing slanted theca, stem size and taper, pectinirhombs with raised central diamonds, and unusual four-point junction between B3-IL2-IL3-L3 (lower center); X1.5. 11. Medium-sized specimen OU 9083; theca slants away from periproctal side (right); note holes in theca caused by impressed bryozoans (center and upper left); X1.5. 12, 29. Very small specimen OU 9074 showing thecal shape and well-preserved periproct with anal pyramid and surrounding periproctal membrane; X2, X4. 13, 14. Coated and immersed side views of medium-sized specimen OU 9066; note slanted theca, indented periproct at left, and large "black spot"; X1.5. 15. Medium-sized specimen OU 9075 showing slanted theca and well-exposed pectinirhombs including unusual L3-R3 rhomb or 2 demirhombs; X1.5. 16. Periproctal side view of medium-sized specimen OU 9076; note anal pyramid and coarsely-ribbed stem; X1.5. 17, 18. Side views of relatively small specimen 1221TX32 showing thecal shape, large number of closely spaced dichopores in pectinirhombs, and anal pyramid in rounded-triangular periproct; X2. 19-22. Three side views and an oral view of very small specimen OU 9086; note thecal shape, small pectinirhombs with mostly confluent dichopores, size of proximal stem, short ambulacra already projecting off summit, and tiny hydropore and gonopore (22); X2, X3. 23, 24. Side views of holotype of *Glyptocystites loeblichae* Bassler, USNM 93484, showing thecal shape, damaged summit, and rapidly tapering proximal stem; X1.5. 25, 26. Side views of holotype of *Cheirocrinus? loeblichi* Bassler, USNM 113107; note missing summit, thecal plating, periproct in 25, and medium-sized stem; X1.5. 31. Enlargement of periproct of medium-sized specimen OU 9067 showing anal pyramid and periproctal plates; X4. 32. Enlargement of periproct in medium-sized specimen 1109TX25; note 3 to 4 rows of periproctal plates surrounding central anal pyramid; X3.

Table 41. Comparison of pectinirhomb positions in all Bromide cylindrical or globular rhombiferans known from several complete specimens plus *Glyptocystites*. R = complete rhomb, d = demirhomb, -- = no rhomb, no sut. = no common suture between these plates, ? = questionable or variable rhomb occurrence or morphology.

Position	Glyptocystella loeblichi (Bassler), 1943	Pirocystella strimplei, n. gen., n. sp.	Pirocystella cooki, n. gen., n. sp.	Pirocystella bassleri, n. gen., n. sp.
1. R5-R6	-- or d	-- or R	d	R
2. R4-R5	d or R	R	d or R	R
3. R3-R4	--	--	--	not seen
4. R2-R3	R	R	R	R
5. R1-R2	d	R	R	R
6. R1-R6	-- or d	--	R	R
7. L5-R6	--	--	-- or R	d
8. L5-R5	-- or d	--	--	--
9. L5-R4	--	--	no sut.	--
10. L4-R4	--	d	--, d, or 2d	d
11. L3-R3	d, 2d, or ?R	d or R	R	R
12. L3-R2	d	-- or d	--	d
13. L3-L4	R	R	R	R
14. L2-R2	--	--	--	--
15. L2-R1	--	--	--	--
16. L1-L2	R	R	R	R
17. 1L4-L5	-- or d	-- or d	-- or d	-- or d
18. 1L4-L4	d	d	d	d
19. 1L4-1L5	-- or d	--	-- or d	-- or d
20. 1L3-L4	--	-- or d	--	--
21. 1L2-L3	--	--	--	--
22. 1L1-L2	--	--	--	--
23. 1L1-L1	--	--	--	--
24. 1L1-1L2	no sut.	no sut.	no sut.	?no sut.
25. B2-1L2	R	R	R	R
26. B2-1L1	R	R	R	R
Total R, d Found	5-7R, 4-8d	5-10R, 2-6d	8-10R, 2-3d	10R, 3-4d

OO; LL circlet open, ILL circlet usually open, R2 enlarged, R6 usually lacking an ambulacrum but sharing those of neighboring RR; ambulacra either short and confined to summit region or medium to long and extending down theca in RR sinuses, between RR, or on surface of thecal plates; ambulacra I and IV lacking brachiole 2, others normal; pectinirhombs disjunct with confluent dichopores, usually between 8 to 22 complete rhombs and demirhombs, vestibule rims usually present around outlet dichopores; stem usually enlarged proximally and flexible with hinged inner and outer columnals, rarely smaller and not greatly enlarged, outer proximal columnals often ridged.

Occurrence.—Middle Ordovician, North America.

Discussion.—Paul (1972b, p. 50-51) discussed diagnostic features found in this family based on the well-known genus *Glyptocystites* Billings (1854) and Paul's new genus *Glyptocystella* described from the Bromide Formation. The transfer of *Hesperocystis* Sinclair (1945) to this family and the description of four new Bromide genera in the following pages require emendation of the family diagnosis. All members of the Glyptocystitidae apparently have a relatively small periproct, six radials with R2 enlarged, ambulacra I and IV lacking brachiole 2, and numerous disjunct pectinirhombs with confluent dichopores; they are confined to the Middle Ordovician of North America. Paul (1972b) mentioned most of these features in his diagnosis. Most Glyptocystitidae have three thecal plates surrounding the periproct (always IL4, L4 and L5), but *Hesperocystis* had added plate R4 to this group and *Quadrocystis*, n. gen., has added plate IL5. The periproct is still much smaller than in the Cheirocrinidae, where five thecal plates surround a wide area of periproctal plates.

The ambulacral system in the Glyptocystitidae is much more variable than as described by Paul (1972b). His description was based on *Glyptocystites* (very long ambulacra extending down over thecal plates) and *Glyptocystella* (medium ambulacra extending between radials). *Hesperocystis*, *Tanaocystis*, n. gen., and *Quadrocystis*, n. gen., have medium ambulacra located in radial sinuses, where they form part of the thecal wall. *Pirocystella*, n. gen., and *Strabocystis*, n. gen., have short to very short ambulacra confined to the slightly to moderately domed summit and only slightly embaying the adjacent radials. These genera with short pentagon-shaped ambulacral sys-

Table 41. Continued

	Hesperocystis deckeri Sinclair, 1945	Strabocystis fayi, n. gen., n. sp.	Tanaocystis watkinsi, n. gen., n. sp.	Quadrocystis graffhami n. gen., n. sp.	Glyptocystites multiporus Billings, 1854
1.	?d	-- or R	d	--	R
2.	d or R	R	R	d or ?R	R
3.	d	d	d	--	R
4.	R	R	d	d or ?R	R
5.	R	R	R	?R	R
6.	d or R	d	--	--	--
7.	d	d or R	R	R	R
8.	d or R	?R	--	--	--
9.	d or R	no sut.	no sut.	no sut.	no sut.
10.	R	d	--	--	--
11.	R	R	R	--	R
12.	--	d	d	--	d
13.	R	R	R	R	R
14.	--	-- or d	--	--	--
15.	d	--	--	--	--
16.	R	R	R	R	R
17.	-- or d	--	--	--	--
18.	d or R	d	--	--	--
19.	d	d	--	--	R
20.	R	--	--	--	--
21.	--	-- or d	--	--	--
22.	d	--	--	--	--
23.	--	-- or d	--	--	--
24.	-- or d	no sut.	no sut.	no sut.	no sut.
25.	?d	R	R	R	R
26.	?d	R	R	R	R
	9-10R, 9-11d	10-11R, 4-6d	8R, 4d	6-8R, 0-2d	12R, 1d

tems were probably derived by paedomorphosis from ancestors with longer ambulacra; their ambulacra resemble those in the paedomorphic edrioasteroid *Timeischytes* figured by Sprinkle and Bell (1978).

All genera in the Glyptocystitidae have an open lateral circlet (interrupted by IL2 and R2), and all except *Hesperocystis* (which has very small basals) have an open infralateral circlet (interrupted by B2 and L2; sometimes also by B3 and L3). These features plus the presence of six radials, the enlarged R2, R6 usually without an ambulacrum, and the small R4 and R5, help to distinguish the family. Some pectinirhombs are also constant in their position; B2-IL1, B2-IL2, L1-L2, L3-L4, R1-R2, and R2-R3 always have a full rhomb (or rarely a demirhomb) (see Table 41). Members of the Glyptocystitidae have more rhombs and a different plating arrangement than similar-appearing members of the Echinoencrinitidae, reviewed recently by Kesling (1968) and Broadhead and Strimple (1978).

The assignment of several old and new genera to the Glyptocystitidae has made this family quite variable in features such as ambulacral length and development. Genera such as *Pirocystella* and *Strabocystis* with their pyriform theca and short ambulacra confined to the summit resemble members of the family Echinoencrinitidae (sensu Broadhead and Strimple, 1978) such as *Echinoencrinites*, but cannot be assigned to this family because they have an R6, the lateral and infralateral circlets open, more numerous pectinirhombs, which are disjunct with confluent dichopores, and other plating, ambulacral, and periproctal differences. Genera such as *Hesperocystis*, *Tanaocystis*, and *Quadrocystis* closely resemble genera such as *Coronocystis* and *Hadrocystis* in the family Cheirocrinidae, but cannot be assigned to this family because they have a smaller periproct surrounded by only three to four thecal plates, an open infralateral circlet, confluent dichopores, and some other differences. At present, it seems best to enlarge the definition of the family Glyptocystitidae to include these transferred and new Bromide genera instead of modifying the definitions of several other families to accommodate them.

Genus GLYPTOCYSTELLA Paul, 1972b

Type species.—*Cheirocrinus? loeblichi* Bassler, 1943.

Diagnosis.—Thecal shape slanted cylindrical;

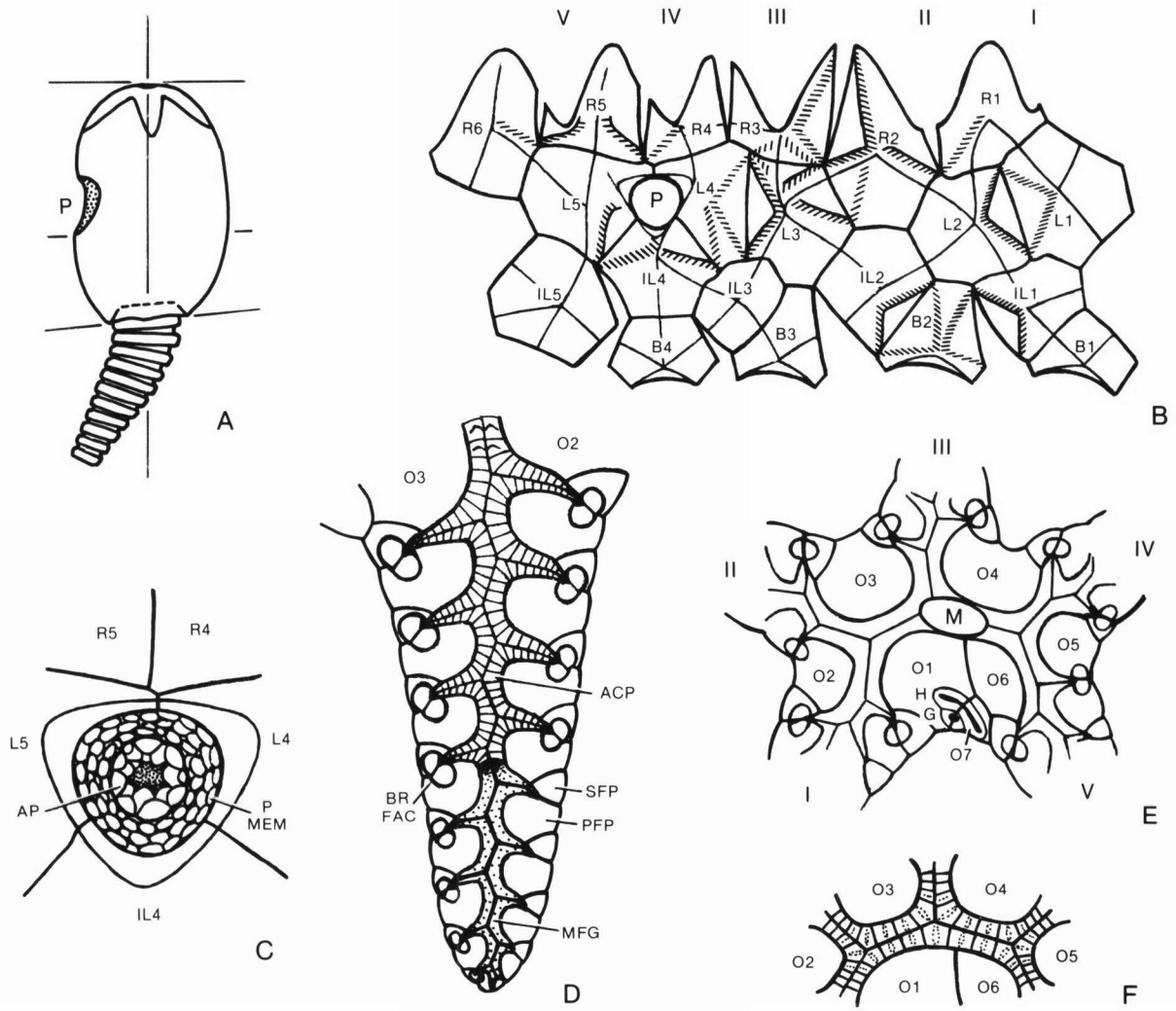


Fig. 61. *Glyptocystella loeblichi* (Bassler), Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, Southern Oklahoma. A, Outline of a medium to large specimen showing thecal shape, medium-length ambulacra, location of periproct (P), maximum diameter (short lines) below midheight, size and taper of proximal stem, size of basal cavity, and stem attachment not perpendicular to thecal axis. B, Plating diagram for a large theca; note ambulacra between RR and in RR sinuses, ILL circlet interrupted in 2 places plus LL circlet interrupted in 1, and ridges (lines) on plates. C, Periproct surrounded by 3 thecal plates showing central anal pyramid (AP), surrounding periproctals in membrane (P MEM), and near-junction of 4 plates just above periproct, much enlarged. D, Ambulacrum II in a very large specimen; note primary and secondary flooring plates (PFP, SFP), brachiole facets (BR FAC) turned about 45° to ambulacral length, and tiny ambulacral cover plates (ACP) protecting wide main (MFG) and side food grooves; mostly based on OU 9073, much enlarged. E, Summit view showing elliptical mouth (M) offset to right, O1 to O7 surrounding mouth with food grooves on their edges forming a "2-1-2" arrangement, slightly curved hydropore (H) and gonopore (G) crossing O1-O7 suture, and first brachioles mounted partly on O2 and O5; mostly based on OU 9085, much enlarged. F, Same summit view as E with oral cover plates in place; note 3-plate junctions and ornamental ridges (dotted); mostly based on 1279TX319, much enlarged.

ILL and LL circlets open, R4 relatively small; periproct surrounded by 3 thecal plates (IL4, L4, and L5); 15 to 16 rhombs and demirhombs; ambulacra medium length, extending down theca in RR sinuses (R3 and R4) and between other RR; proximal stem medium-sized, tapering fairly rapidly, outer columnals coarsely ridged.

Occurrence.—Middle Ordovician, Oklahoma.

Discussion.—Paul (1972b, p. 57) set up the genus *Glyptocystella* based on the type specimens of three of Bassler's (1943) Bromide rhombiferan species and about 30 additional specimens collected by Harrell Strimple in the National Museum. Two of Bassler's type specimens and most of the addi-

tional specimens do belong to *Glyptocystella*, but another genus (*Pirocystella*), which Paul apparently did not recognize, is also present in this Lower Echinoderm Zone material. *Glyptocystella* is the most common rhombiferan in the Lower Echinoderm Zone with about 305 total specimens, comprising from 67 to 100 percent of the rhombiferans at the larger localities along the hingeline through the central Arbuckles and in the northeastern Arbuckles. However, members of the genus have not been found in the southwestern Arbuckles or in the Criner Hills, which apparently had deeper water during deposition of the Lower Echinoderm Zone.

Glyptocystella is a fairly distinctive rhombiferan genus when found complete. Although it commonly occurs with *Pirocystella* and possibly with *Hesperocystis*, it differs from these genera by having an elongate cylindrical theca, fairly long ambulacra both in radial sinuses (R3 and R4) and between the other radials, almost equal numbers of rhombs and demirhombs having a dichopore spacing from 0.25 to 0.36 mm, rather distinctive thecal ornament consisting of central radiating ridges, few subsidiary ridges, and raised "diamonds" inside the rhombs, and a medium-sized proximally enlarged stem that has coarse ridges and tapers fairly rapidly away from the theca. Broken specimens of *Glyptocystella* lacking the distinctive long ambulacra (such as the type specimen of *G. loeblichi*) are more difficult to separate from *Pirocystella*, although stem taper may be diagnostic. *Glyptocystella* differs from all other Bromide rhombiferans, from *Glyptocystites*, and from most members of other rhombiferan families in the location of its ambulacra.

GLYPTOCYSTELLA LOEBLICHI (Bassler), 1943

Plates 26, 27; Figure 61A-F

Cheirocrinus? loeblichi Bassler, 1943, p. 701-702, pl. 1, fig. 1, 2.

Glyptocystites loeblichae Bassler, 1943, p. 702-703, pl. 1, fig. 8, 9.

Glyptocystella loeblichi, Paul, 1972b, p. 57-61, pl. 5, 6, text-fig. 19-21 (but not pl. 7, fig. 7).

Diagnosis.—Thecal shape rounded cylindrical, shallow stem facet not perpendicular to thecal axis; ILL circlet usually open in 2 places; thecal plates ornamented with central radial ridges and concentric growth lines, diamond-shaped areas inside pectinirhombs raised; 10 to 16 relatively short brachioles per ambulacrum; dichopore spacing averaging 0.30 mm.

Description.—About 305 specimens available for study; about 50 used for following description. Theca ranging from very small (7.5 mm long by 5.3 mm in diameter) to large (38 mm long by about 27 mm in diameter). Theca cylindrical in shape in most specimens with a rounded summit and a bowl-shaped base; L to W ratio ranging from 1.3 to 1.6, averaging 1.44, changing little with growth. Most specimens noticeably slanted with medium-sized stem attachment not perpendicular to thecal axis (Fig. 61A; Pl. 26, fig. 10, 11). Theca somewhat indented on periproctal side, maximum diameter at or just below midheight. Summit of theca varying in diameter in different views (Pl. 26, fig. 3, 4).

Thecal plating normal for family (Fig. 61B). BB 4, in closed circlet, medium-sized, fairly wide, forming fairly large stem facet in shallow basal cavity (Pl. 27, fig. 18). Stem facet equaling 23 to 31 percent of thecal length and 35 to 47 percent of thecal width. Growth centers of BB projecting downward slightly over proximal stem to form minor prongs in some specimens (Pl. 26, fig. 17, 18). B1 fairly small, pentagonal, B2 medium, elongate, hexagonal, bearing 2 rhombs, B3 small to medium, either pentagonal or hexagonal, B4 medium, flat-topped, hexagonal. ILL 5, medium to large, in an open circlet (usually interrupted between IL1 and IL2 by B2 and L2 and sometimes between IL2 and IL3 by B3 and L3) (Fig. 61B). IL1 to IL3 pentagonal, IL4 and IL5 hexagonal; IL1 and IL2 usually with 1 rhomb each, IL3 and IL5 lacking rhombs, IL4 usually with 2 rhombs; IL4 forming lower margin of periproct. LL 5, medium to large, in open circlet (interrupted between L2 and L3 by IL2 and R2), periproct between and below L4 and L5; L1 to L3 hexagonal, L4 and L5 heptagonal, L1, L2, and L5 usually with 1 rhomb each, L3 and L4 usually with 2 to 3 rhombs each. RR 6, in closed circlet; R2 large and elongate, hexagonal, R1 and R3 to R6 medium, variously shaped; R1, R4, and R6 usually with 1 rhomb each, R3 and R5 with 2 rhombs each, and R2 with 3 rhombs. Ambulacra moderately to greatly indenting RR, either near centers of plate or along sutures; a near-junction of 4 plates at L4-L5-R4-R5 (Fig. 61C). OO 7, fairly small but wide, in a closed circlet around mouth on summit. O6, O7, and O1 forming group below mouth, bearing hydropore and gonopore (Fig. 61E).

Periproct fairly small, nearly circular, set in triangular depression, slightly depressed below

Ambulacra 5, very short to fairly long, in large specimens extending just over one-third distance down theca either in sinuses or between RR. Summit slightly domed in small specimens with short ambulacra, strongly rounded in large specimens; summit commonly wider across ambulacra I to V sides than across hydropore to ambulacrum III sides (Pl. 27, fig. 16). Ambulacra I and II longest, ambulacrum III shortest, difference not great. Ambulacral sinuses near lateral centers of R3 and R4 and usually between R5 and R6, R6 and R1, and R1 and R2 (Fig. 61B). Arrangement of primary and secondary ambulacral flooring plates normal, plates above edges of adjacent RR, in some ornamented with small nodes; large specimens with as many as 12 to 16 ambulacral flooring plate sets and brachioles in ambulacrum I. Primary flooring plates rhombic with aboral-abmedial edge cut off for rounded triangular secondary flooring plate from set below. Main and side food grooves relatively wide and shallow, protected by biserial sets of small, slightly arched, rectangular cover plates ranging from 0.3 to 0.4 mm long and 0.2 mm wide over side food grooves to 1.0 mm long by 1.2 mm wide over the mouth. Ambulacral and oral cover plates often with marked medial ridge, over mouth this ridge rarely extended into a crest as much as 0.6 mm high (Pl. 27, fig. 10, 11). Brachioles fairly short, small; in large specimen, brachioles 7 to 8 mm long, gradually tapering to a point from a width of 0.9 mm at proximal end. Brachiolar food groove protected by a biserial set of moderately domed cover plates, about 1.5 to 1.6 brachiolar cover plates per brachiolar plate (Pl. 27, fig. 7). Mouth offset toward right side of summit, combined ambulacral food groove from ambulacra I and II and food groove from ambulacrum III meeting before reaching mouth (Fig. 61E; Pl. 27, fig. 19).

Hydropore and gonopore in normal position on O1-O7 suture (Fig. 61E). Hydropore a raised, slightly curved slit about 2.0 to 2.2 mm long and curving through an arc of 30 to 40° in a large specimen (Fig. 61E; Pl. 27, fig. 13-16). Gonopore a small pore about 0.3 mm in diameter on slanted aboral side of raised hydropore; several specimens showing approximately 4 tiny plates covering gonopore (Pl. 27, fig. 15), as reported by Paul (1972b, p. 59). Hydropore slit and gonopore extending directly through thickened O1-O7 suture into thecal interior.

Thecal plates fairly thin, 0.5 to 1.3 mm thick, strengthened by fairly large central ridges radiating from centers of most thecal plates. Smaller subsidiary ridges sometimes present, growth lines also well marked and commonly granular. Rhombs protected by ridges running around exterior and high central ridges just inside the excurrent half-rhomb. The entire triangular or diamond-shaped central area inside rhombs also raised and probably thickened (Pl. 26, fig. 10).

Proximal stem enlarged, of medium size, usually tapering rapidly away from theca (Pl. 26, fig. 5). Diameter of proximal stem ranging from 36 to 50 percent of thecal width and 23 to 31 percent of thecal length, much less than sympatric species of *Pirocystella*. Proximal stem attached in shallow basal cavity (Pl. 27, fig. 18), often moderately curved. In one well-preserved specimen with theca 21 mm long (Pl. 26, fig. 5), proximal stem 15 mm long, with 12 outer and 12 inner columnals grading distally from 6.7 to 2.8 mm in diameter. This specimen also having 11.5 mm of distal stem; here columnals becoming undifferentiated (Pl. 26, fig. 27), all the same size, slightly bulbous, about 3 times as wide as long, slowly decreasing in size distally. Lumen in distal stem apparently less than half stem diameter. Outer columnals in proximal stem strongly ridged with about 12 to 19 ridges per 10 mm of circumference, average 15.6 ridges.

(Several abnormal specimens were found in the present material including 2 in which certain ambulacra did not develop, Pl. 27, fig. 12. One specimen has 3 normal ambulacra, but only single brachioles in the apparent positions of ambulacra I and IV. Another specimen has only a single brachiole in the position of ambulacrum II. One additional specimen was found with a small plate inserted at the edge of the basal cavity below B2; see Pl. 27, fig. 17.)

Studied specimens.—Holotype USNM 113107, paratype USNM 93484, plesiotypes USNM 216603, OU 9065-9088, 1109TX25, 1221TX32-34, and 1279TX319-320; additional specimens in USNM, OU, TX, and several other collections.

Occurrence.—Known only from the Lower Echinoderm Zone of the Mountain Lake Member, Bromide Formation, throughout much of the Arbuckle Mountains in southern Oklahoma: at least 144 specimens from Daube Ranch, 109 from Lick Creek, 37 from Amis Ranch, about 10 from Fittstown Roadcut and Quarry, 4 from Cornell Ranch (Tulip Creek), and 1 from Bromide.

Genus PIROCYSTELLA Sprinkle, new

Type species.—*Pirocystella strimplei* Sprinkle, n. sp.

Diagnosis.—Theca pyriform to barrel-shaped;

summit constricted, slightly domed, not inclined; ILL and LL circlets open, R4 and R5 small; periproct surrounded by 3 thecal plates (IL4, L4, and L5); 10 to 15 rhombs and demirhombs; ambulacra short, confined to pentagonal summit, barely embaying R1 to R5, 5 to 8 long brachioles per ambulacrum; proximal stem medium to very large, tapering slowly away from theca, outer columnals finely ridged.

Occurrence.—Middle Ordovician, Oklahoma.

Etymology.—The generic name is derived from *pirum* (L.), pear, referring to the distinctive pear-shaped theca in the type species.

Discussion.—The new genus *Pirocystella* appears to be represented by four species in the Lower Echinoderm Zone and the *Carabocrinus* Beds of the Bromide Formation. *P. strimplei*, n. sp., the type species, commonly occurs with *Glyptocystella* over much of the Arbuckle Mountains and is represented by at least 80 specimens; *P. cooki*, n. sp., occurs mostly in the northeastern Arbuckles and is represented by five specimens; and *P. bassleri*, n. sp. and *P. ornatus* (Bassler) occur only in the southwestern Arbuckles and Criner Hills and are represented by a total of five specimens. *Pirocystella* differs from *Glyptocystella* and *Hesperocystis*, which also occur in the Lower Echinoderm Zone, by having short ambulacra confined to the slightly domed summit and barely indenting the surrounding radials, a less elongate theca having a different shape, different thecal ornament, a periproct placed higher on the theca, and a somewhat different arrangement of rhombs and demirhombs. *Strabocystis*, which occurs in the Upper Echinoderm Zone, resembles *Pirocystella* in its ambulacral development but differs by having a more elongate theca with an oblique summit, more rhombs and demirhombs, an ambulacrum indenting R6 and not R2, and different ornament. *Pirocystella* differs considerably from *Tanaocystis* and *Quadrocystis* in the Pooleville in its ambulacral development, thecal shape, and other features. *Pirocystella* superficially resembles several genera (such as *Echinoencrinites)* in the family Echinoencrinitidae, but cannot be assigned to this family because it has six radials, different plates around the periproct, open infralateral and lateral circlets, a less reduced summit, and many more rhombs and demirhombs.

The short ambulacra in adult specimens of *Pirocystella* resemble those of early juvenile specimens of *Glyptocystella* (Pl. 26, fig. 22), which suggests that *Pirocystella* was derived from an ancestral glyptocystitid by paedomorphic evolution of the ambulacra and thecal summit; a similar case in edrioasteroids has recently been reported by Sprinkle and Bell (1978). Ambulacral growth was apparently retarded compared to thecal growth, so that both juveniles and adults of *Pirocystella* have short ambulacra with few brachioles. Both *P. cooki* and *P. bassleri* appear to be somewhat less retarded in ambulacral growth than *P. strimplei*. The brachioles in *Pirocystella* appear to have been larger and longer than those of *Glyptocystella*, which had much longer ambulacra and more brachioles, so that the total food-collecting area in the brachiolar nets may have been relatively similar in these two different-appearing genera. Some specimens of *Pirocystella* grew very large (Pl. 28, fig. 3, 4; Pl. 29, fig. 28, 29), so the relatively few brachioles were certainly able to keep the animal adequately fed even at this size.

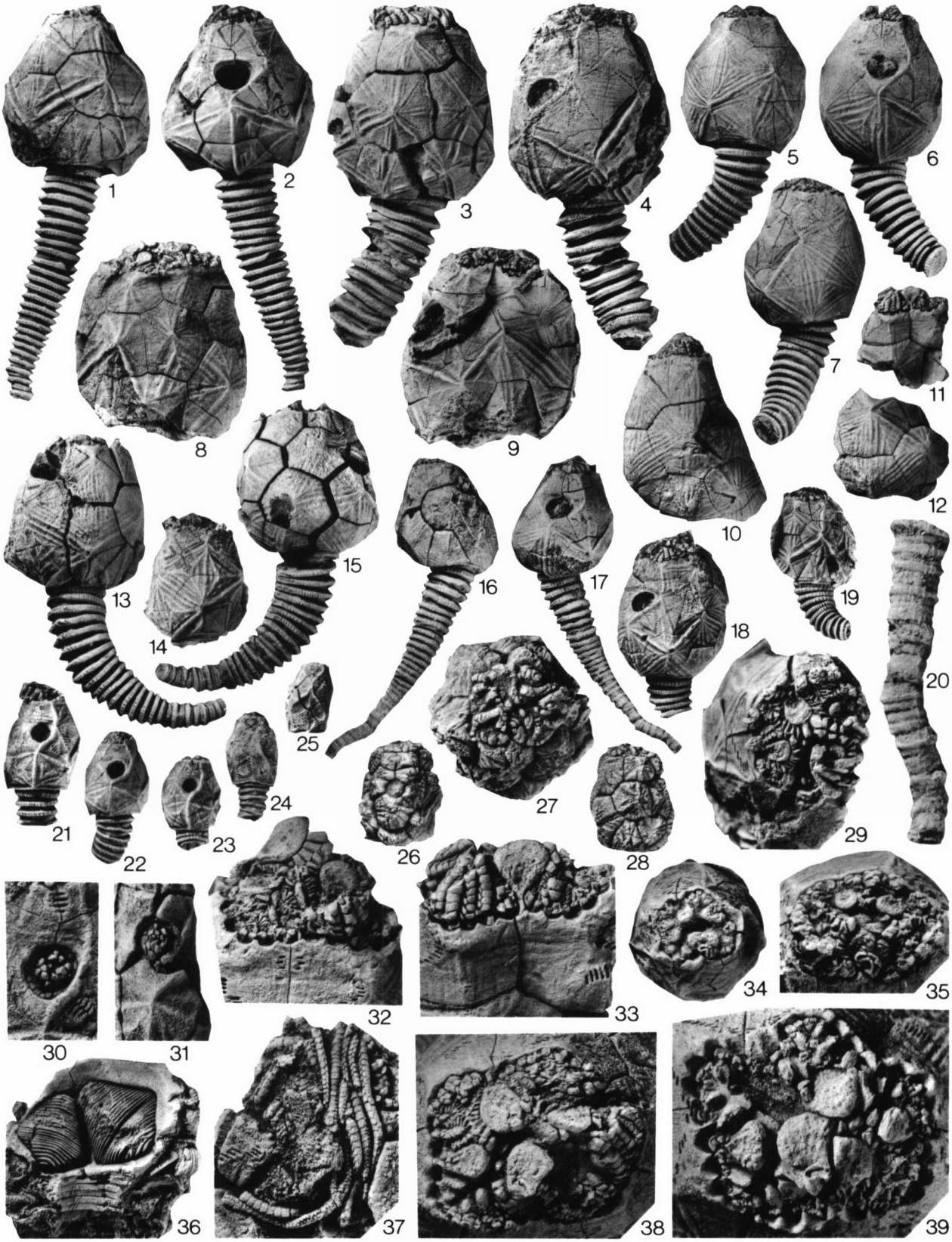
PIROCYSTELLA STRIMPLEI Sprinkle, n. sp.

Plate 28; Figure 62A, B, E-G, I

Diagnosis.—Theca pear-shaped with constricted summit and bulge below periproct; ambulacra short, depressed, with primary flooring plates sharp-crested or domed; usually 8 to 9 rhombs and 2 to 5 demirhombs, dichopore spacing averaging 0.31 mm; weakly plicate ornament on lower theca; proximal stem very large, tapering slowly.

Description.—About 80 specimens available for study, 25 well-preserved types selected. Theca ranging from very small (8 mm long by 5.5 mm in diameter) to large (35 mm long by 31 mm in diameter). Theca slender and barrel-shaped in small specimens to bulbous and pear-shaped in large ones (Pl. 28, fig. 1-25); L to W ratio ranging from 1.06 to 1.6, averaging 1.25, gradually decreasing during growth. Summit slightly to moderately domed, base flat with large stem attachment. Most specimens almost upright with summit and stem attachment perpendicular to thecal axis, but some slightly slanted (stem attachment not perpendicular to axis). Maximum diameter slightly to considerably below midheight, large specimens showing bulge on side of theca below periproct (Fig. 62A).

Thecal plating normal for family (Fig. 62B). BB 4, in closed circlet, medium-sized, wide, forming a large stem facet in a shallow basal cavity (Pl. 28, fig. 36). Stem facet equaling 34 to 50 percent of thecal length and 36 to 67 percent of thecal width, the latter percentage decreasing with increasing size. Growth centers of BB projecting downward over proximal stem to form prominent prongs in some large specimens (Pl. 28, fig.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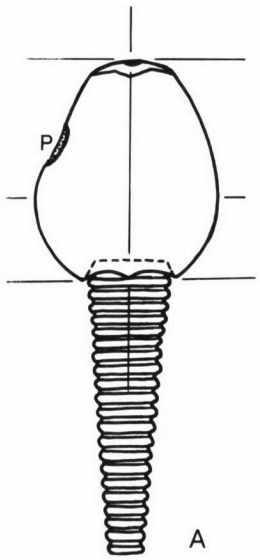
2). B1 fairly small, pentagonal, B2 to B4 medium, flat-topped, hexagonal, B2 bearing 2 rhombs. ILL 5, medium to large, in open circlet (usually interrupted twice, between IL1 and IL2 by B2 and L2 and often between IL2 and IL3 by B3 and L3) (Fig. 62B); IL1 to IL3 pentagonal, IL4 and IL5 hexagonal; IL1, IL2, and IL4 with 1 rhomb each (IL4 sometimes with an extra demirhomb); IL4 forming lower margin of periproct. LL 5, medium to large, in open circlet (interrupted between L2 and L3 by IL2 and R2), L4 and L5 forming top and sides of periproct; L1 to L3 hexagonal, L4 and L5 heptagonal; L1, L2, and L5 usually with 1 rhomb, L3 and L4 usually with 2 to 3 rhombs. RR 6, in closed circlet; R2 large and elongate, hexagonal, R1, R3, and R6 medium-sized, pentagonal, R4 and R5 fairly small and tetragonal; 1 to 2 rhombs per radial (R2 sometimes with 3). Ambulacra only slightly indenting top edge of RR; a near-junction of 4 plates at L4-L5-R4-R5 (Fig. 62F). OO 7, small but very elongate and bulbous, in a closed circlet around mouth on summit. O6, O7, and O1 forming group below mouth with O7-O1 suture bearing hydropore and gonopore (Fig. 62G).

Periproct fairly small, almost circular, set in rounded-triangular depression, nearly flush with thecal surface, tilted toward summit (Pl. 28, fig. 2), located between 50 and 64 percent (average 55 percent) of thecal length from base. Surrounded by usual 3 thecal plates, IL4 below and L4 and L5 laterally and above, each forming about one-third of margin (Fig. 62F). Several paratypes with periproctals and anal pyramid preserved (Pl. 28, fig. 30, 31); in a 13-mm-long theca, periproctals arranged in single to double circlet of small, elongate to polygonal plates 0.3 to 0.4 mm long; anal pyramid central, about 1.5 mm wide and 0.6 mm high, made of 12 to 14 small, rounded, triangular plates 0.6 to 0.7 mm long (Fig. 62F).

Eight to nine rhombs and 2 to 5 demirhombs present (Table 41). Rhombs disjunct, dichopores apparently confluent. Dichopores short to medium in length, fairly widely spaced, lacking rims, some irregularities present. Dichopore spacing ranging from 0.25 to 0.36 mm (increasing with size) and averaging 0.31 mm (19 measurements on 7 specimens). Few thecal ridges outside rhombs, almost no ridges inside rhombs (Pl. 28, fig. 3). In small specimens, B2-IL2 rhomb with many more dichopores than adjacent B2-IL1 rhomb (Pl. 28, fig. 24).

PLATE 28.

Fig. 1-39. *Pirocystella strimplei* Sprinkle, n. gen., n. sp.; Lower Echinoderm Zone (except 26-28 from the overlying *Carabocrinus* Beds), Mountain Lake Member, Bromide Formation; 1-4, 13-19, 24, 29, 31, 36, 39 from Daube Ranch, southern Arbuckles; 5-9, 21-23, 25, 30, 34, 35, 37, 38 from Lick Creek, northern Arbuckles; 10-12, 32, 33 from Fittstown Quarry, northeastern Arbuckles; 26-28 from North-Central I-35, northern Arbuckles; all from southern Oklahoma. 1, 2. Side views of paratype OU 8986 showing pear-shaped theca, plating, large slowly tapering stem, and projecting prongs on BB; X1. 3, 4. Side views of largest complete paratype OU 8985; note thecal plating, ornament, and very large stem; X1. 5-7. Side views of holotype OU 8984 showing thecal shape, large curved stem with medium-ridged outer columnals, slightly domed and constricted summit, and ornament decreasing toward summit; X1. 8, 9. Front and back views of large crushed paratype OU 9026; note plating, short ambulacra, and unusual L3-R2 demirhomb (9); X1. 10-12, 32, 33. Views of three pieces of paratype 1279TX300 and oblique summit views showing characteristic plating and ornament, short ambulacra with cover plates and few brachioles attached, and teardrop-shaped OO; X1, X3. 13, 15. Side views of large paratype OU 8987; note sprung plating and large curved stem; X1. 14. Side view of medium-sized paratype OU 8989 showing thecal ornament; X1. 16, 17, 20. Side views and enlarged distal stem of medium-sized paratype 1121TX106 (Graffham Coll.); note thecal shape and plating, poorly preserved anal pyramid (17), and distal stem with nearly equal-sized flanged outer and grooved inner columnals; X1, X3. 18. Side view of paratype OU 8988 showing ridged ornament; X0.9. 19. Side view of paratype OU 9020; note curved stem and strong thecal ornament; X1. 21. Small paratype OU 8997 showing large stem and flat base of theca; X1.5. 22. Paratype OU 8990; note constricted summit and size of periproct; X1. 23, 34. Side and enlarged summit views of paratype OU 8991 showing thecal shape, ornament, and summit with central mouth, short ambulacra, and hydropore-gonopore; X1, X2.5. 24. Very small paratype OU 9029; note large-diameter stem and smaller B2-IL1 vs. larger B2-IL2 rhombs; X1.5. 25. Smallest paratype OU 8998 showing plating and smaller B2-IL1 vs. larger B2-IL2 rhombs; X1.5. 26-28. Side views and enlarged summit view of medium-sized paratype 1276TX14; note heavily overgrown thecal plates, location of periproct (26), and brachioles and hydropore on summit (27); X1, X2. 29. Enlarged summit of paratype OU 9020 showing OO, ambulacral and oral cover plates, and brachioles at right; X3. 30. Enlarged periproct and surrounding plates of paratype OU 8994; note anal pyramid, 1 to 2 circlets of periproctal plates, and near-junction of 4 plates immediately above periproct; X4. 31. Enlarged periproct of paratype OU 9028 showing protruding anal pyramid; X3. 35. Enlarged summit of medium-sized paratype OU 8995; note OO, some cover plates and brachioles, and curved hydropore and, possibly, covered gonopore; X4. 36. Inside of lower theca of large paratype 1404TX5 (Watkins Coll.) showing size and shape of rhombs B2-IL2 (right) and the slightly smaller B2-IL1 (left); X1.5. 37. Enlarged oblique summit of paratype OU 9030; note long biserial brachioles with an apparent single set of cover plates (bottom); X3. 38. Enlarged summit of holotype OU 8984 (Fig. 5-7) showing most OO, sharp-crested flooring plates in D ray, ambulacral cover plates in E and A rays, and brachioles attached to C ray; X3. 39. Enlarged summit of paratype OU 8986 (Fig. 1, 2); note brachiole facets impressed into surrounding RR, sharp-crested flooring plates, and hydropore-gonopore crossing O1-O7 suture at bottom; X3.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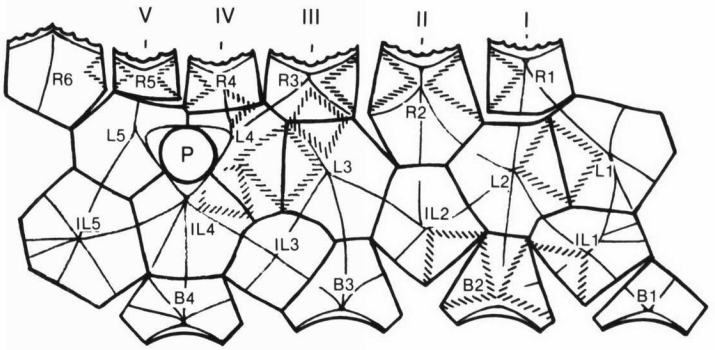
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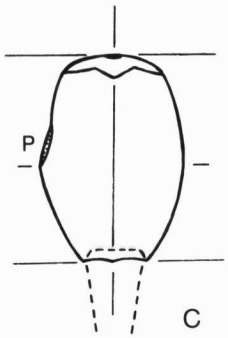
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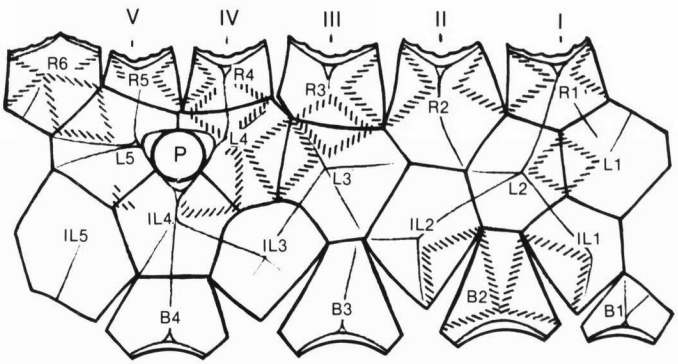
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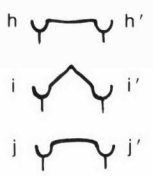
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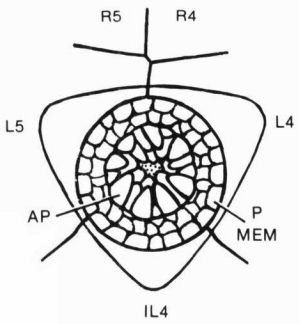
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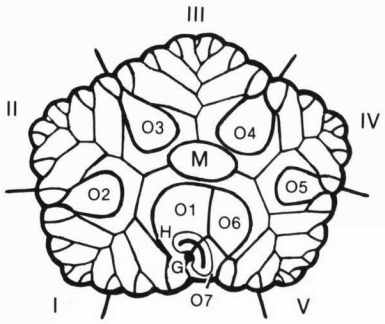
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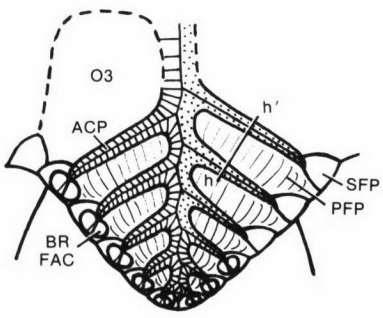
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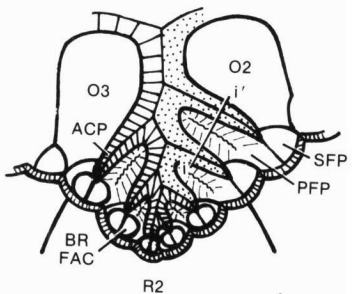
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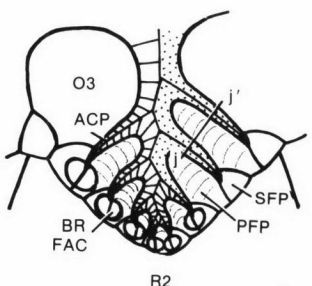
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Ambulacra 5, confined to domed pentagonal summit, only slightly indenting RR. Summit almost perpendicular to thecal axis, not tilted as in *Strabocystis fayi*. Ambulacra short, very wide (Pl. 28, fig. 32, 38), all brachioles mounted around rim of summit, indenting edges of adjacent RR. Small specimens with 2 to 4 flooring plate sets and brachioles per ambulacrum, large specimens with 5 to 9 flooring plate sets and brachioles. Ambulacral tips near lateral centers of R1 to R5, R6 sharing one-third of each adjacent ambulacrum (Fig. 62B). Arrangement of primary and secondary ambulacral flooring plates normal, plates slightly below edge of adjacent RR. Older primary flooring plates very elongate (Fig. 62I), with thin, high, central crest (Pl. 28, fig. 38). Main and side food grooves fairly wide and deep, protected by biserial set of small, arched, rectangular cover plates ranging from 0.3 mm long and 0.1 mm wide over side food grooves to 1.1 mm long and 0.8 mm wide near central mouth. Brachioles large and long, mounted around rim of summit with proximal attachment embaying adjacent RR (Pl. 28, fig. 39). Brachioles at least 17.5 mm long (incomplete distally), 0.8 mm wide, and 1.0 mm deep proximally in medium to large specimens (Pl. 28, fig. 33, 37). Brachioles hemielliptical in cross section, biserially plated, with food groove protected by single set of small, high arched, biserial, brachiolar cover plates with about 1.6 to 1.7 cover plates per brachiolar plate on each side. Several specimens with distal tips of brachioles showing evidence of breakage and regrowth.

Hydropore and gonopore in normal position on O1-O7 suture (Fig. 62G). Hydropore a raised slit curving through an arc of 90 to 120°, about 2.6 mm long in a large specimen, somewhat constricted in center (Pl. 28, fig. 34, 35). Gonopore a small pore about 0.3 mm in diameter on aboral side of hydropore, hydropore curving around gonopore; one specimen showing several tiny plates from possible pyramid over gonopore (Pl. 28, fig. 39). Hydropore slit and gonopore extending directly down thickened O1-O7 suture into thecal interior (Pl. 28, fig. 39).

Thecal plates fairly thin, 0.5 to 1.5 mm thick, with moderately strong central ridges radiating from centers of lower thecal plates, several smaller subsidiary ridges on both sides forming nested "triangles" (Pl. 28, fig. 4, 6), ornament usually not very strong, tending to diminish higher on theca, higher plates ornamented only by fine granules along growth lines (Pl. 28, fig. 9). Ridges usually low around most rhombs, almost no ridges inside rhombs.

Proximal stem greatly enlarged, diameter almost two-thirds thecal width in small specimens, ratio decreasing somewhat during growth, stem tapering very slowly away from theca (Pl. 28, fig. 1, 2, 13, 15-17). Numerous alternating and hinged outer and inner columnals in proximal stem; in specimen with 31-mm-long theca, enlarged proximal stem 40 mm long, made up of 25 outer and 24 inner columnals decreasing from 10.5 and 8.5 mm in diameter proximally to 4.5 and 3.5 mm in diameter distally (Pl. 28, fig. 1, 2). Another specimen having part of slowly tapering distal stem in which columnals neither overlapped nor hinged, but outer columnals still somewhat larger with an equatorial flange (see Pl. 28, fig. 20). Outer columnals in proximal stem with medium to fine vertical ridges, 17 to 21 ridges per 10 mm circumference.

(A single abnormal specimen having only 3 BB—

Fig. 62. *Pirocystella* Sprinkle, n. gen., including *P. strimplei* Sprinkle, n. sp. (A, B, E-G, I), *P. cooki* Sprinkle, n. sp. (C-E, J), and *P. bassleri* Sprinkle, n. sp. (E, H), Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. A, Outline of large specimen of *P. strimplei* showing pear-shaped erect theca, maximum diameter (short lines) below midheight, short ambulacra, location of periproct (P), and large, slowly tapering proximal stem. B, Plating diagram for a large *P. strimplei*; note short ambulacra barely indenting R1 through R5, interrupted ILL and LL circlets, and major ridges (lines) connecting plate centers. C, Outline of a medium-sized specimen of *P. cooki* showing barrel-shaped erect theca, maximum diameter (short lines) near midheight, wider summit, and smaller stem attachment. D, Plating diagram for *P. cooki* based mostly on holotype 1279TX301; note more numerous rhombs than in 62B and noncentral location of ambulacral tips (short vertical lines) on R1 and R5. E, Cross sections of primary flooring plates in *P. bassleri* (top, flat to slightly concave), *P. strimplei* (center, crested), and *P. cooki* (bottom, flat to slightly convex), much enlarged. F, Periproct of *P. strimplei* surrounded by 3 thecal plates showing central anal pyramid (AP), surrounding narrow membrane of periproctals (P MEM), and near-junction of 4 plates above periproct; based mostly on OU 8994 and OU 9028, much enlarged. G, Summit view of *P. strimplei;* note nearly central elliptical mouth (M), O1 to O7 surrounding mouth, short wide ambulacra forming a pentagonal system barely indenting surrounding RR, and strongly curved raised hydropore (H) and gonopore (G) crossing O1-O7 suture, much enlarged. H, Ambulacrum II of *P. bassleri* showing elongate primary and small secondary flooring plates (PFP, SFP), many ambulacral cover plates (ACP) over long side food grooves, and 11 brachiole facets (BR FAC) in this specimen; short line across PFP (right) shows where cross section for 62E taken, much enlarged. I, Ambulacrum II of *P. strimplei;* note that ambulacrum is slightly depressed below adjacent RR, fewer flooring plate sets and brachioles, and shorter side food grooves, much enlarged. J, Ambulacrum II of *P. cooki* showing small cover plates over short side food grooves and wider O3, much enlarged.

B1 missing—plus a possible extra plate, perhaps ?L6, in the LL circlet was found during this study. Although the stem attachment and summit are almost parallel to each other, the theca in between is highly oblique and at an angle of 40 to 45° to the normal axis.)

Etymology.—The species is named for Mr. Harrell L. Strimple of the University of Iowa, Iowa City, who described many Bromide echinoderms in the 1940's and 1950's, collected several of the type specimens of *Pirocystella strimplei*, and has retained his interest in the Bromide echinoderm fauna and this project.

Studied specimens.—Holotype OU 8984, paratypes OU 8985-9000, OU 9020-9031, 1276TX14, 1121TX106, 1279TX300, and USNM 216603/15; additional specimens in OU, TX, and USNM collections.

Occurrence.—All but 1 specimen are from the Lower Echinoderm Zone of the Mountain Lake Member, Bromide Formation, in the northeastern, central, and southern Arbuckles: 45 from Daube Ranch, 32, including the holotype, from Lick Creek, 2 from Cornell Ranch (Tulip Creek), and 1 from Fittstown Quarry. A single complete specimen overgrown with epitaxial calcite (Pl. 28, fig. 26-28) apparently belonging to this species was also found in the *Carabocrinus* Beds about 9 to 11 m above the Lower Echinoderm Zone at the North-Central I-35 section.

Discussion.—*Pirocystella strimplei* commonly occurs with *Glyptocystella loeblichi* in the Lower Echinoderm Zone over much of the Arbuckles; it is the second most common rhombiferan in the Bromide with about 80 known specimens. However, it apparently does not occur in the southwestern Arbuckles or Criner Hills where *P. bassleri* and *P. ornatus* are found and is rare (only one specimen) in the northeastern Arbuckles where *P. cooki* occurs. *P. strimplei* seems to have preferred fairly shallow-water offshore shelf environments where echinoderms were most abundant during deposition of the Lower Echinoderm Zone. *P. strimplei* differs from *P. bassleri* and *P. ornatus* in having weaker ornament over most of the theca, a larger proximal stem, different dichopore spacing, and a somewhat smaller maximum size; it differs from *P. cooki* by having a pear-shaped theca with a somewhat smaller summit, fewer rhombs, crested ambulacral floor plates, a much larger proximal stem, and less pronounced granular ornament. A single specimen from the overlying *Carabocrinus* Beds from North-Central I-35 also appears to be *P. strimplei*, although it is so badly overgrown on the exterior with epitaxial calcite that many distinctive features are not visible.

Pirocystella strimplei shows some variability in the number of rhombs and in the strength of ornament. One rhomb (R5-R6) and three demirhombs (IL3-IL4, IL4-L5, and L3-R2) may or may not be present (Table 41). Thecal ornament also varies considerably in strength, from very subdued to rather strong with subsidiary ridges and granular growth lines. However, it rarely becomes as strong as in *P. ornatus*, *P. bassleri*, or *P. cooki*. Almost all large specimens of *P. strimplei* have a well-developed black spot on one side of the theca.

PIROCYSTELLA COOKI Sprinkle, n. sp.

Plate 29, figures 1-27; Figures 62C, D, E, J

Diagnosis.—Theca barrel-shaped; ambulacra short, slightly raised, with primary flooring plates flat-topped; 9 to 10 rhombs and 2 to 6 demirhombs, dichopore spacing averaging 0.35 mm; coarse granular radiating ornament on all thecal plates; proximal stem fairly small to medium-sized.

Description.—Four nearly complete specimens and numerous separate plates available for study. Specimens ranging from small to fairly large; holotype a medium-sized specimen 23 mm long by 18 mm in diameter; L to W ratio ranging from 1.2 to 1.4 in these specimens. Theca barrel-shaped, with a bowl-shaped base and a slightly to moderately domed summit (Pl. 29, fig. 1-4, 12-14). Stem facet not quite perpendicular to thecal axis in some specimens, theca in these slightly slanted (Pl. 29, fig. 4). Maximum diameter near midheight.

Thecal plating normal for family; however, holotype abnormal with extra IL diagonally below IL2 and modified B2 and B3. BB 4, in a closed circlet, small to medium-sized, elongate in large specimens, forming a fairly small stem facet in a shallow basal cavity (Pl. 29, fig. 6). Stem facet equaling 20 to 35 percent of thecal length and 27 to 41 percent of thecal diameter, both proportions decreasing with increasing size. B1 fairly small, pentagonal, B2 and B3 medium, usually elongate, flat-topped, hexagonal, B2 bearing 2 rhombs, B4 medium, wide, flat-topped and hexagonal. ILL usually 5, medium to large, in an open circlet (usually interrupted twice between IL1 and IL2 by B2 and L2 and often between IL2 and IL3 by B3 and L3; see Fig. 62D); IL1 and IL2 pentagonal, IL3 to IL5 hexagonal; IL1, IL2, and IL4 with 1 (rarely 2) rhomb each; IL4 forming lower margin of periproct. LL 5, medium to large, in a open circlet (inter-

rupted between L2 and L3 by IL2 and R2); periproct between and below L4 and L5; L1 to L3 hexagonal, L4 to L5 heptagonal; L1 and L2 sharing a rhomb, L3 and L5 usually with 2 rhombs, L4 with 2 to 3 rhombs (Fig. 62D). RR 6, in a closed circlet; R2 large and elongate, hexagonal, R1, R3, and R6 medium, pentagonal or hexagonal (R6), R4 and R5 fairly small, tetragonal; 2 rhombs on each RR except R6 with 3; a near-junction of 4 plates at L4-L5-R4-R5 (Fig. 62D). OO 7, small, bulbous, in a closed circlet around mouth on summit. O6, O7, and O1 forming group below mouth with O7-O1 suture bearing hydropore and gonopore.

Periproct fairly small, nearly circular, lower edge protruding slightly from thecal surface, located at about 60 percent of thecal length from base. Periproct surrounded by usual 3 thecal plates, IL4 below and L4 and L5 laterally and above, each forming about one-third of margin. Holotype and 1 paratype with traces of periproctals preserved, apparently a double row of small, 0.4- to 0.5-mm plates (Pl. 29, fig. 2). No anal pyramid observed.

Nine to ten rhombs and 2 to 6 demirhombs present (Table 41). Rhombs disjunct, dichopores apparently confluent. Dichopores medium in length, completely lacking rims, with slightly raised ornamented areas inside rhombs (Pl. 29, fig. 2). Dichopore spacing ranging from 0.31 to 0.41 mm (increasing with size), averaging 0.35 mm (11 measurements on 4 specimens); early dichopores more closely spaced than later ones (Pl. 29, fig. 13). L4-R4 rhombs unusual (see Table 41); present only in some specimens, consisting of 2 small demirhombs recurving slightly and separated by wide low ridge (Fig. 62D). Low thecal ridges both outside and inside most rhombs.

Ambulacra 5, confined to domed pentagonal summit, slightly to moderately indenting RR. Summit appearing almost perpendicular to thecal axis. All ambulacra short, wide (Pl. 29, fig. 5, 10), with brachioles mounted around rim of summit; 3 to 9 ambulacral flooring plate sets and brachioles per ambulacrum (based on small paratype and medium-sized holotype). Ambulacral tips located near lateral centers of R2 to R4, near right edge of R1, and near left edge of R5 (Fig. 62D); R6 sharing about one-third of each adjacent ambulacrum. Arrangement of ambulacral flooring plates apparently normal, plates slightly above edge of adjacent RR. Older primary flooring plates elongate, with broad, flat-topped surface (Fig. 62E, J) unlike those of *P. strimplei;* secondary flooring plates small and rounded-triangular (Fig. 62J). Main and side food grooves relatively wide, moderately shallow, protected by an alternating biserial set of small, arched, rectangular cover plates ranging from 0.3 mm long and 0.1 mm wide over side food groove to 1.0 mm long and 0.4 mm wide near mouth. Several brachioles preserved on largest and smallest paratypes (Pl. 29, fig. 10, 25); brachioles medium-sized, fairly long, biserially plated with a single biserial set of tiny domed cover plates. Longest segment only about 8 mm long, 0.7 mm wide, and 0.9 mm deep. RR slightly embayed where brachioles attach.

Hydropore preserved only on smallest paratype, on O1-O7 suture (Pl. 29, fig. 10), slit about 1.8 mm long, slightly raised, curving through an arc of about 90°. Gonopore not seen, probably a small pore just aboral to hydropore.

Thecal plates fairly thin; many large separate plates from Fittstown Roadcut and Quarry originally 0.8 to 1.1 mm thick but thickened by layers of diagenetic calcite on interior and exterior surfaces. Ornament fairly distinctive, numerous low ridges radiating from plate centers (central ridges not differentiated), crossed by coarse growth lines, producing a pustular reticulate pattern (Pl. 29, fig. 1-4, 15-22); ornament present over entire theca, not decreasing toward summit. Almost no ridges around rhombs, but entire triangular or rhombic area inside rhombs uplifted and often coarsely ornamented (Pl. 29, fig. 2).

Proximal stem absent from 2 specimens; only first few columnals preserved on other 2 (Pl. 29, fig. 11, 27). Proximal stem enlarged, of medium size, mounted in a relatively shallow basal cavity; diameter ranging from 27 to 41 percent of thecal width, proportion decreasing with increasing size. Proximal columnals showing typical inner and outer columnal alternation, abundant separate columnals from Fittstown (Pl. 29, fig. 23, 24) showing moderate ridging.

(The holotype is abnormal in having an extra plate betweeen B3 and IL2, Pl. 29, fig. 4, which shares a small complete rhomb with B2. This extra plate has greatly modified the shapes of adjacent B3 and IL2, and slightly modified B2, IL3, and L3; it also adds an extra rhomb.)

Etymology.—The species is named for Mr. Donald Cook, coowner and operator of the C & L Wigley Quarry just south of Fittstown in the northeastern Arbuckles where most of the type specimens were found. Don and his wife Dana have given us permission on many occasions to collect at this active quarry, have arranged to strip off and save the Lower Echinoderm Zone shale before blasting on the

south side of the quarry, and have had an active interest in this echinoderm study.

Studied specimens.—Holotype 1279TX301, complete paratypes 1279TX302-303, and 1391TX6, paratype plates 1279TX304-313; additional plates in UT, OU, and MCZ collections.

Occurrence.—Three complete specimens and many plates from the Lower Echinoderm Zone at Fittstown Quarry, many additional plates from Fittstown Roadcut, both in the northeastern Arbuckles; one complete specimen from the shale band immediately below the Lower Echinoderm Zone at Lick Creek Road in the northern Arbuckles.

Discussion.—*Pirocystella cooki* occurs with *Glyptocystella loeblichi* and rare *P. strimplei* in and just below the Lower Echinoderm Zone. *P. cooki* is a fairly distinctive species of *Pirocystella*, differing from the more common *P. strimplei* in its barrel-shaped theca, less constricted summit, much smaller proximal stem, more pustular ornament, differently shaped ambulacral flooring plates, larger dichopore spacing, and possession of one to two more rhombs. It differs from *P. bassleri* and *P. ornatus* in its smaller size, somewhat different ornament, smaller proximal stem, slightly convex ambulacral flooring plates, different dichopore spacing, and disjunct geographic occurrence at the opposite end of the study area from these two species.

The distinctive occurrence pattern of *P. cooki* is closely matched by that of a small pustular inadunate crinoid (*Doliocrinus pustulatus*, described elsewhere in this monograph by John Warn); both forms are represented by three complete specimens in the Lower Echinoderm Zone at Fittstown Quarry plus a single extra specimen from just below the Lower Echinoderm Zone at Lick Creek Road. I believe that these occurrences represent nonoptimal conditions for echinoderms, environments occupied by a distinctive fauna of opportunistic echinoderms that were rare or absent when conditions were optimal (development of a rich Lower Echinoderm Zone fauna). At Fittstown, the nonoptimal conditions appear to have been very shallow water and storm activity (Longman, 1976); the cause for nonoptimal conditions in the shale band just below the Lower Echinoderm Zone at Lick Creek is unknown, but a different cause is suspected.

Separate plates from Fittstown Roadcut and Quarry show that rare demirhombs (about 10 percent of plates) may be present in the IL3-L4, L3-R2, and R5-L5 positions, and that no demirhomb is pre-

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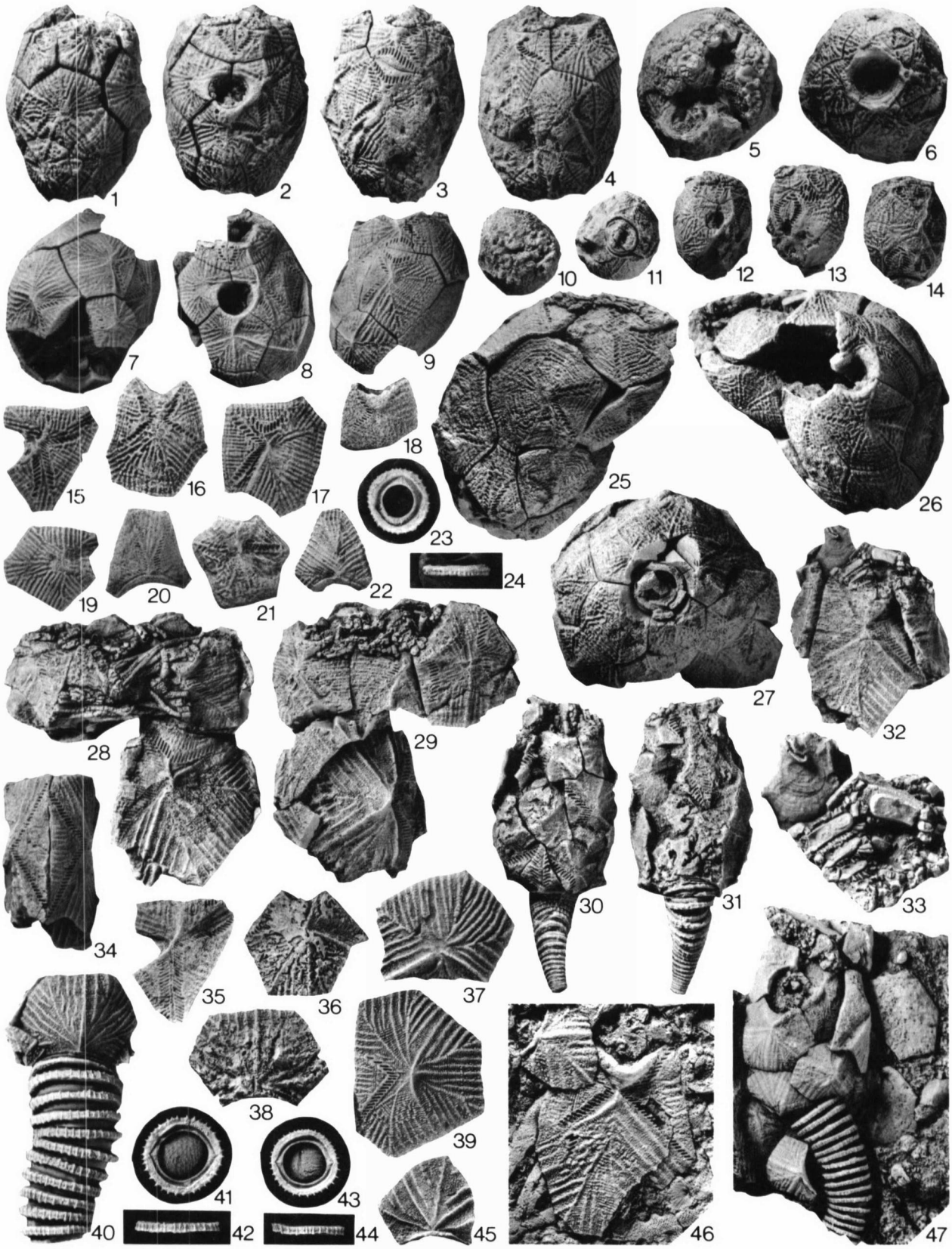
PLATE 29.

Fig. 1-27. *Pirocystella cooki* Sprinkle, n. gen., n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation; 1-9, 15-27 from Fittstown Quarry, northeastern Arbuckles; 10-14 from shale bed immediately below Lower Echinoderm Zone, Lick Creek Road, northern Arbuckles, southern Oklahoma. 1-6. Four side views, a summit view, and a basal view of holotype 1279TX301 showing thecal shape, plating, coarse ornament, wide summit (5), and fairly small stem facet (6) of this species; X1.5. 7-9. Side views of paratype 1279TX303; note incomplete and distorted theca, periproct plus 4-plate junction just above (8), and relatively wide summit (9); X1.5. 10-14. Summit, basal, and 3 side views of small paratype 1391TX6 showing fairly wide summit, small stem, and coarse ornament; X1.5. 15-22. Separate thecal plates L4(15), R2(16), L3(17), R4(18), L5(19), B2(20), IL4(21), and B3(22) (1279TX304-311, respectively); note coarse ornament, ambulacra indenting RR (16, 18), and B3 interrupting ILL circlet (22); X1.5. 23, 24. Single columnal 1279TX312 probably belonging to this species showing large lumen (23), small ridges, and medium thickness (24); X1.5. 25-27. Side views plus basal view of paratype 1279TX302 showing crushed and skewed theca missing most of summit, coarse ornament, and small stem facet; X1.5.

Fig. 28-46. *Pirocystella bassleri* Sprinkle, n. gen., n. sp.; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Johnston Ranch, southwestern Arbuckles, southern Oklahoma. 28, 29. Front and back views of holotype OU 9032, a partial theca with a complete RR circlet and 2 to 3 LL showing wide summit with short ambulacra indenting RR, well-preserved brachioles, and coarse ridgelike ornament on plates; X1.5. 30, 31. Side views of fairly small but crushed paratype 1116-TX1; note size of summit and stem and B2 barely interrupting ILL circlet (30); X1.5. 32, 33. Paratype OU 9033, an upper thecal fragment showing R2 and its ambulacrum (32) with flat to slightly concave ambulacral flooring plates and small cover plates (33), and the hydropore in upside-down O1 (33); X1.5, X3.0. 34. Small fragment of theca (1116TX2) showing L1-L2 sutured edge; X1.5. 35-39, 45. Separate thecal plates L4(35), ?L2(37), L1(39), IL4(36), B4(38), and B3(45) (OU 9040-42 and 1116TX3-5, respectively); note plate shapes, well-developed ridges and growth lines (esp. 39), diagenetic calcite (36, 38), and B3 not interrupting ILL circlet (45); X1.5. 40. Paratype OU 9034, a proximal stem with 2 BB attached showing large ridges and slow stem taper; X1.5. 41-44. Top and edge views of 2 outer columnals (OU 9038-9) apparently belonging to this species; note large ridges, facets, and thin columnals (compare with 23, 24 above); X1.5. 46. Plates on a slab including a very large R2 and a small B3 (upper left) (1116TX6-7); note moderate indentation of ambulacrum and very wide dichopore spacing in R2; X1.5.

Fig. 47. *Pirocystella ornatus* (Bassler); unknown zone (possibly Lower Echinoderm Zone or adjacent beds), Mountain Lake Member, Bromide Formation, Rock Crossing, Criner Hills, southern Oklahoma. Holotype USNM 113106 showing crushed and partly disarticulated theca on limestone slab, note large slowly tapering stem with ridges, 3 plates around periproct, ornamented thecal plates, and R2 and R3 (upper right) with only slight indentations for ambulacra at top; X1.5.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sent in the L4-R4 position in about 60 to 70 percent of the L4 plates examined.

PIROCYSTELLA BASSLERI Sprinkle, n. sp.

Plate 29, figures 28-46; Figure 62E, H

Diagnosis.—Theca very large, apparently barrel-shaped; ambulacra short, slightly raised, with primary flooring plates flat to concave; approximately 10 rhombs and 4 to 6 demirhombs, dichopore spacing averaging 0.38 mm; prominent thecal ornament with many subsidiary ridges decreasing toward summit; proximal stem large, tapering fairly slowly.

Description.—About 5 incomplete specimens and 20 separate plates available for study. Theca apparently barrel-shaped, elongate; only nearly complete paratype (Pl. 29, fig. 30, 31), 22.5 mm long by 14.5 mm wide and somewhat crushed. However, some separate plates from much larger specimens: one separate R2 22.5 mm long and 19.5 mm wide (Pl. 29, fig. 46), and another plate, perhaps an L3, at least 21 mm long and 13 mm wide. These measurements about 1.5 times those of same plates in largest known specimen of *P. strimplei*, with thecal length of 35 mm. Maximum diameter probably at or just below midheight.

Thecal plating apparently normal for family, although many plates not seen. B3 pentagonal, often not interrupting ILL circlet, B4 medium, hexagonal. IL4 medium, hexagonal, forming lower one-third of periproctal margin, 1 demirhomb on extended IL4-L4 suture (Pl. 29, fig. 36), and demirhomb either with IL5 or L5. ILL circlet open (interrupted between IL1 and IL2 by B2 and L2), LL circlet apparently open (interrupted between L2 and L3 by IL2 and R2). LL large, most with 1 to 2 rhombs, but L4 with 1 rhomb and 2 demirhombs (Pl. 29, fig. 35), L4 and L5 forming lateral and upper margin of periproct. RR 6, well preserved on holotype (Pl. 29, fig. 28, 29), in a closed circlet; R2 large to very large and elongate, nearly hexagonal, other RR medium to large, modified tetragonal or hexagonal (R6), 2 to 3 rhombs or demirhombs per RR. Ambulacra moderately indenting top edge of R1 through R5; probably a near-junction of 4 plates at L4-L5-R4-R5. OO poorly preserved on most specimens, probably 7 in a closed circlet around central mouth, small but elongate, O1 on paratype with slitlike hydropore and porelike gonopore on lower right margin (Pl. 29, fig. 33).

Periproct fairly small, surrounded by 3 plates (IL4, L4, and L5), located above middle of theca (Pl. 29, fig. 31). No periproctals or anal pyramid preserved.

Ten rhombs and 3 to 4 demirhombs apparently present (Table 41). Second demirhomb on left side of IL4 variable in position; with either IL5 or L5 (Table 41). Rhombs disjunct, dichopores confluent. Dichopores short to medium in length, widely spaced, mostly lacking rims. Dichopore spacing ranging from 0.34 to 0.46 mm and averaging 0.38 mm (19 measurements on 8 specimens and plates); highest value found in any Bromide rhombiferan. Low ridges around some rhombs but almost no ridges inside rhombs (Pl. 29, fig. 28).

Ambulacra 5, confined to domed pentagonal summit, slightly to moderately indenting RR. Ambulacra short, wide, with brachioles mounted around rim of summit; 6 to 12 ambulacral flooring plate sets and brachioles per ambulacrum (Pl. 29, fig. 33). Ambulacral tips near lateral centers of R2 to R4, near left edge of R5, near right edge of R1; R6 sharing about one-third of each adjacent ambulacrum (Pl. 29, fig. 29). Ambulacral flooring plates normally arranged, above edge of adjacent RR. Primary flooring plates rectangular, older ones very elongate with a broad, flat to slightly concave top surface (Fig. 62E, H; Pl. 29, fig. 33); secondary flooring plates small and rounded-triangular. Main and side food grooves appearing fairly wide and deep, protected by an alternating biserial set of numerous small, slightly arched, elongate cover plates (Pl. 29, fig. 33) ranging from 0.3 mm long by 0.15 mm wide over side food grooves to 0.7 mm long by 0.3 mm wide over main food grooves.

Brachioles well preserved in holotype and 2 paratypes. Brachioles apparently fairly large, biserially plated, nearly circular in cross section, at least 12.0 mm long (incomplete) by 0.9 mm wide and high with a ?single set of high-domed, toothed cover plates, plates about 0.3 mm long and 0.2 mm wide (Pl. 29, fig. 28). About 2.5 to 2.6 brachiolar cover plates per brachiolar plate along length.

Only 1 paratype showing any trace of hydropore and gonopore, with upturned and out-of-place O1 showing half of slightly curved and sinuous hydropore slit in raised tubercle 1.8 mm long crossing thick O1-O7 suture, small circular gonopore just aboral (Pl. 29, fig. 33).

Thecal plates thin, 0.3 to 1.0 mm thick, with low central ridges radiating from centers to edges and numerous subsidiary ridges on both sides of central ridge (Pl. 29, fig. 35-39). Ridges crossed

by concentric growth lines lacking pustules, radial ridges dominant, unlike those on many plates of *P. cooki*. Ornament usually extending up to lower RR, decreasing near ambulacra. Best preserved small paratype lacking nearly all subsidiary ridges, with granules only along growth lines (Pl. 29, fig. 30, 31), apparently belonging to this species because of distinctive thecal shape and wide dichopore spacing.

Proximal stem large, tapering fairly slowly away from theca, composed of alternating ridged outer and smooth inner columnals (Pl. 29, fig. 40-44). Proximal stem in paratype tapering from 11.0 mm to 3.5 mm in diameter in a distance of 31 mm (21 outer and about 21 inner columnals). Outer columnals sharp-cornered, moderately ribbed, some showing trace of a slight equatorial groove (Pl. 29, fig. 40). Between 11 and 19 (average 14) ridges per 10 mm circumference (14 measurements).

Etymology.—This species is named for the late Dr. Ray S. Bassler, who during the 1940's named and described many of the echinoderms known from the Bromide.

Studied specimens.—Holotype OU 9032A,B, paratypes OU 9033-9045 and 1116TX1-9; additional plates OU 9046 and 1116TX10.

Occurrence.—Known only from the Lower Echinoderm Zone and the adjacent cystoid shale (Longman, 1976) of the Mountain Lake Member, Bromide Formation, at Johnston Ranch in the southwestern Arbuckles.

Discussion.—I had originally hoped to assign these specimens from the Lower Echinoderm Zone at Johnston Ranch to *Pirocystella ornatus;* both species are highly ridged forms from adjacent parts of the study area. However, measurements of dichopore spacing showed that the specimens from Johnston Ranch have a much higher average value (0.38 mm) than the holotype of *P. ornatus* (0.28 mm). The two other species of *Pirocystella* have average values for dichopore spacing intermediate between these two (0.31 mm for *P. strimplei* and 0.35 mm for *P. cooki*). Because the holotype of *P. ornatus* is a fairly large and normal-appearing specimen, and because none of the specimens from Johnston Ranch even come close in any of the measurements of dichopore spacing to *P. ornatus*, I have decided to set up the new species *P. bassleri* for these distinctive specimens.

P. bassleri differs from *P. strimplei* by having more prominent ornament, a larger summit with flat-topped primary ambulacral flooring plates, a few different rhombs and demirhombs, much wider dichopore spacing, and a somewhat smaller, more rapidly tapering stem. *P. bassleri* differs from *P. cooki* by having less pustular growth lines (producing a radial instead of reticulate ornament), somewhat different arrangement of rhombs and demirhombs, a slightly larger dichopore spacing, B3 often not interrupting the IL circlet, a larger diameter proximal stem, and an occurrence almost at the opposite end of the study area. *P. bassleri* differs from *P. ornatus* by having much different dichopore spacing, a more rapidly tapering stem, somewhat longer ambulacra and more highly indented radials and somewhat fewer ridges on the outer columnals. Large specimens of *P. bassleri* apparently have some of the highest values for dichopore spacing (0.46 mm) ever reported for any rhombiferan cystoid (see Paul, 1968b, p. 712).

PYROCYSTELLA ORNATUS (Bassler), 1943

Plate 29, figure 47

Echinoencrinites ornatus Bassler, 1943, p. 703, pl. 1, fig. 7.

Glyptocystella loeblichi, Paul, 1972b, p. 57-61, pl. 7, fig. 7.

Diagnosis.—Theca barrel-shaped; ambulacra probably short, unknown; dichopore spacing averaging 0.28 mm; lower theca ornamented with numerous radial ridges and granular growth lines; proximal stem relatively large, tapering slowly.

Description.—Only Bassler's (1943) holotype specimen (USNM 113106) from Rock Crossing in the Criner Hills assigned to this species. (The holotype theca is on a small limestone slab, partly disarticulated, and only about half complete, with the proximal stem and a few short brachiole fragments still present; Pl. 29, fig. 47.) Theca at least 24 mm long (incomplete), about 15 mm in diameter, probably barrel-shaped originally.

Twelve plates visible, 8 nearly in normal positions, 4 lying adjacent to theca. B4 and ?B3 present from BB circlet, IL4, IL3, and ?IL2 present in ILL circlet, L5, L4, and L3 present in LL circlet, R3 and R2 present from RR circlet, ?O5 present from OO circlet, 1 unidentified plate near base (Pl. 29, fig. 47). B4 hexagonal, ?B3 pentagonal, not interrupting ILL circlet. ?IL2 and large hexagonal R2 interrupting LL circlet between L2 and L3. Medium-sized periproct formed by IL4 below, and L4 and L5 laterally and above. R2 and R3 nearly flat-topped with few indentations (Pl. 29, fig. 47), implying short ambulacra, with few

ambulacral plates and brachioles forming a small nearly pentagonal summit. Single ?O5 out of place, teardrop-shaped, with edge of deep food groove adorally.

Seven to eight rhombs and demirhombs present in preserved plates; rhombs at ?IL2-B2, L3-L4, R1-R2, and R2-R3; demirhombs at L3-R2, ?IL2-?, IL4-L4. Rhombs appearing normal, dichopores short and closely spaced, some plates with low ridges outside half-rhombs but almost no ridges inside. Dichopore spacing ranging from 0.25 to 0.30 mm, averaging 0.28 mm (4 measurements), lowest value of any species of *Pirocystella*.

No ambulacral flooring plates present, 2 short brachiole fragments preserved beside the ?O5 displaced to top of LL circlet. Proximal stem well preserved but unattached, 15 to 16 mm long with 15 outer columnals, slightly curved, tapering slowly from 6.5-mm diameter proximally to 4.7-mm diameter distally (Pl. 29, fig. 47). Outer columnals showing relatively fine ridging, about 20 to 30 ridges per 10 mm circumference.

Ornament fairly strong on lower theca, diminishing near top of LL circlet, consisting of low central and numerous low subsidiary ridges radiating from plate centers to sides, crossed by somewhat granular concentric growth lines (Pl. 29, fig. 47).

Studied specimen.—Holotype USNM 113106.

Occurrence.—Unknown zone, probably in the Mountain Lake Member, Bromide Formation, at Rock Crossing.

Discussion.—Paul (1972b, p. 57-61) assigned Bassler's holotype specimen of *Echinoencrinites ornatus* to *Glyptocystella loeblichi*; however, further cleaning has revealed that this holotype specimen has short ambulacra confined to the summit and therefore cannot be a *Glyptocystella*. It is assigned here to the new genus *Pirocystella*. No other specimens of *Pirocystella* in the present collection can be assigned to this species. Several specimens of *Pirocystella* from Johnston Ranch in the Arbuckles are strongly ornamented and have a medium-sized stem like *P. ornatus*, but have very different values for their average dichopore spacing (0.38 mm vs. 0.28 mm) with no overlap in individual measurements. I reluctantly assigned these specimens to *P. bassleri*, n. sp. *P. ornatus* differs from the common and widespread *P. strimplei* by having more highly ornamented lower thecal plates, a somewhat smaller stem, a slightly smaller average dichopore spacing (0.28 mm vs. 0.31 mm), and apparently a different thecal shape. *P. ornatus* differs from *P. cooki* by having somewhat different ornament that dies out lower on the theca, a larger stem, much smaller average dichopore spacing (0.28 mm vs. 0.35 mm), and probably a smaller summit with shorter ambulacra.

The holotype of *P. ornatus* was collected from the "Lower Bromide Formation, Rock Crossing in the Criner Hills" (Bassler, 1943, p. 703); the matrix around this specimen is a brownish-yellow bioclastic limestone that almost certainly came from somewhere in the Mountain Lake Member. However, the Lower Echinoderm Zone has not been found at Rock Crossing, and so I am not certain that the specimen came from this zone although it is the most likely source. No other rhombiferans that could be assigned to this species have been found in the Mountain Lake at Rock Crossing.

Genus HESPEROCYSTIS Sinclair, 1945

Type species.—*Hesperocystis deckeri* Sinclair, 1945.

Diagnosis.—Thecal shape ovoid to globular, summit slightly domed and tilted toward periproct, base subconical; BB narrow with small stem facet, ILL circlet closed, LL circlet open, R5 very small; periproct small, surrounded by 4 thecal plates (IL4, L4, L5, and R4); 20 to 22 rhombs and demirhombs; ambulacra medium length, extending short distance down theca in RR sinuses, 1 to 4 brachioles per flooring plate set, 1 to 3 brachioles on each of 5 OO; stem small, not greatly enlarged proximally, lacking alternating columnals.

Occurrence.—Middle Ordovician, Oklahoma.

Discussion.—The collection of two additional complete *Hesperocystis* specimens at McLish Ranch and the subsequent discovery that the holotype specimen (USNM 112085), although badly crushed, is essentially complete, have required major modifications in the description of this genus given by Sinclair (1945, p. 711-712) and Kesling (1968, p. S177). This new information about *Hesperocystis* has also allowed its removal from the Cystoblastidae, and revealed several new and unusual features. Sinclair's original description was fairly complete, but he apparently did not attempt to clean the large crushed holotype, and described only the exposed plating on the better preserved side. The periproct was not exposed on this side (it is badly crushed on the left edge), and because of this Sinclair (1945, p. 711) misidentified the radials as R1 to R3 (plates 15 to 17 in Bather's system), instead of R2 to R4, although he realized their shapes and arrangement did not

agree with the "standard scheme." He apparently missed the poorly exposed B2-IL2 demirhomb, which would have helped to identify the other thecal plates, and although he showed a small stem facet in his plating reconstruction, did not comment on this unusual feature. Sinclair (1945, p. 709) assigned *Hesperocystis* to the Cheirocrinidae, which was reasonable based on the known morphology.

Kesling (1968, p. S177) reviewed this genus, but apparently did not restudy the holotype specimen. He identified most of the exposed thecal plates correctly except for the RR, which he misidentified (following Sinclair) as R1 to R3, although enlarged R1 now interrupted the lateral circlet between L2 and L3, an unlikely arrangement. Kesling also assigned *Hesperocystis* to the family Cystoblastidae, although it did not closely resemble the type genus *Cystoblastus*.

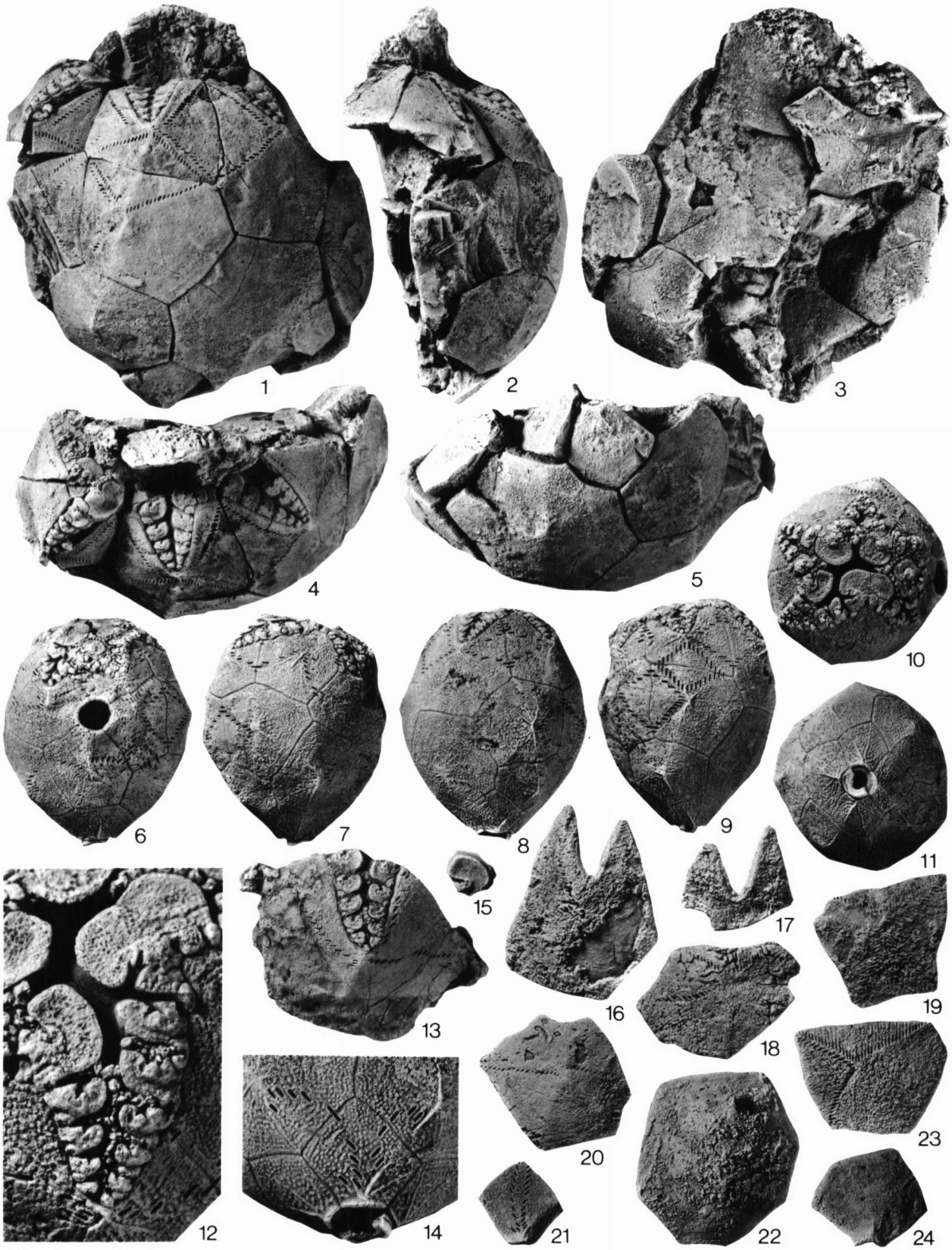
Recent restudy of the holotype at the National Museum has shown that it is almost complete (Plate 30, fig. 1-5) with most of the missing thecal plates crushed in on the back, which had never been cleaned. The newly cleaned holotype and recently collected smaller specimens agree in most features, and have allowed the identification of several hundred separate *Hesperocystis* plates (Pl. 30, fig. 15-24) found at the McLish "C" exposure.

Hesperocystis is an unusual rhombiferan in several respects. Although the periproct is small, it is surrounded by four thecal plates, the three normal plates for a member of the Glyptocystitidae (IL4, L4, and L5), and R4 (also shown by the separate R4 plates; see Pl. 30, fig. 17). This unusual combination of plates surrounding the periproct has not been found in other rhombiferans except for an abnormal specimen of *Pseudocrinites* diagramed by Kesling (1968, fig. 116, *1a*).

The small basals and small diameter of the proximal stem in *Hesperocystis* are another unusual feature. Instead of forming a wide recessed stem facet, the basals are conical in shape and the stem facet and proximal stem are small for a rhombiferan (Fig. 63B). These small basals may also account for the closed infralateral circlet in *Hesperocystis*. Only two to three damaged columnals are attached to the stem facets in the plesiotype specimens (Fig. 63E; Pl. 30, fig. 11), but based on these short stem segments, it appears that: 1) the proximal stem probably was not appreciably enlarged over the distal stem, 2) the proximal stem was not made up of the usual inner and outer columnals, and 3) the stem in *Hesperocystis* may have been attached distally. The unusual small-diameter proximal stem in *Hesperocystis* hints at a different stem morphology and perhaps a sessile mode of life; most other members of the Glyptocystitidae were probably free living.

However, the most unusual feature in *Hesperocystis* is the mounting of multiple brachioles on the ambulacral flooring plate sets and on five of the seven orals. As many as three or even four brachioles were mounted on each set of flooring plates (Fig. 63G; Pl. 30, fig. 12, 13); the brachiole in the normal position on the suture between the inner and outer flooring plates is usually the largest (and presumably oldest). Additional brachioles have apparently been added later in a group just admedial to this one, supported by the large inner flooring plate alone, and having their own separate short branch from the side food groove. Each main oral also has from one to three brachioles mounted on its surface from the first side food groove of the left-hand ambulacrum. These multiple brachioles have never been reported before from any other blastozoan echinoderm (see Sprinkle, 1973, text-fig. 4, 6, p. 19-20), but represent a new, unpredicted, but rather reasonable modification of the ambulacral system for greater food-gathering capacity. By "doubling up" the brachioles during its growth, *Hesperocystis* would not have had to increase its ambulacral length greatly or add many new ambulacral plates. The very large holotype specimen is over twice the length and diameter of the smaller plesiotype, but the ambulacra are less than 1.4 times as long and only one to two new flooring plate sets have been added to each. Thus, because of this modification, *Hesperocystis* did not have to elongate its radial clefts greatly during growth (as did genera such as *Tanaocystis*) to allow room for many new ambulacral plates and their brachioles; it put new brachioles on the ambulacral plates already present. With this modification, *Hesperocystis* has the largest number of brachioles per ambulacrum of any Bromide rhombiferan.

The large nearly smooth plates, small basals and stem facet, closed infralateral circlet, four plates around the periproct, and ambulacral plates and orals supporting multiple brachioles separate *Hesperocystis* from all other rhombiferans. In spite of the several unusual features, *Hesperocystis* appears to be a member of the Glyptocystitidae; the six radials, enlarged R2, R6 sharing one-third of the two adjacent ambulacra, distribution and number of pectinirhombs, and near-normal arrangement of thecal plates around the periproct all agree with this assignment. Complete specimens and abundant plates of *Hesperocystis* have been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found only in the Lower Echinoderm Zone at McLish Ranch in the eastern Arbuckles; rare plates have also been found at adjacent sections such as Bromide, Pickens Ranch, and Rhynes Ranch. *Hesperocystis* was apparently adapted to very shallow-water, nearshore environments often disturbed by storms; it is absent from all of the rich Lower Echinoderm Zone localities representing deeper water, offshore shelf environments.

HESPEROCYSTIS DECKERI Sinclair, 1945

Plate 30; Figure 63

Hesperocystis deckeri Sinclair, 1945, p. 709-712, pl. 1, fig. 9, 10, text-fig. 1; Kesling, 1968, p. S177, fig. 80, 81.

Diagnosis.—Theca medium to very large; 8 to 13 flooring plate sets and 19 to 32 brachioles per ambulacrum; usually 7 to 12 rhombs and 8 to 15 demirhombs, dichopore spacing averaging 0.36 mm; slight granular ornament and tiny ridges near raised plate centers.

Description.—Based on 3 complete specimens, a nearly complete ambulacrum preserved in an R1, and about 200 separate thecal plates.

Theca medium to large, ovoid to globular in shape with slightly domed summit tilted toward periproct, projecting conical base (Pl. 30, fig. 6-9). Badly crushed holotype having maximum length of 46 mm, maximum width of 44 mm, and "thickness" of about 23 mm; reconstructed dimensions of original specimen approximately 40 mm long and 38 to 40 mm in diameter. Smallest complete plesiotype 20 to 21 mm long and about 17 mm in diameter. Maximum diameter apparently just above midheight.

Thecal plating somewhat unusual compared to other genera in this family (Fig. 63B). BB 4, small, in a narrow closed circlet, forming conical base to theca without basal cavity; stem facet small, only 2.8 mm in diameter in smallest plesiotype. B1 to B3 small and pentagonal, B4 slightly larger and hexagonal; B2 with 2 unusual demirhombs (Pl. 30, fig. 14, 21; Fig. 63B). ILL 5, medium to large, in a closed circlet, IL2 heptagonal, other ILL hexagonal; IL4 forming lower margin of periproct (Pl. 30, fig. 6); ILL averaging about 1 rhomb or demirhomb per plate. LL 5, large, in an open circlet (interrupted between L2 and L3), periproct directly between L4 and L5; L1 to L3 large, L4 and L5 medium. L2 and L3 pentagonal, L1 and L4 hexagonal, L5 heptagonal; L4 with several rhombs or demirhombs, L3 with 2 rhombs, others 1 to 2 rhombs each. RR 6, small to large, in a closed circlet, R2 very large and elongate, R1 and R3 large, R4 and R6 medium, and R5 small to very small. Radial sinuses fairly large on R1 to R5, deeply embaying R4 and small R5; R6 with edges of 2 adjacent ambulacra. R4 forming top edge of periproct (unusual). One near-junction of 4 plates at L3-L4-R3-R4 in holotype and most separate plates, but not plesiotype (Fig. 63B). OO 7, small, in a closed circlet surrounding central mouth on summit (Pl. 30, fig. 10), O6, O1, O3, and O4 forming edge of mouth. O2, O3, and O5 rotated slightly so that left adoral corner toward mouth. O1 to O5 bearing brachioles from adjacent left-hand ambulacrum: O6,

PLATE 30.

Fig. 1-24. *Hesperocystis deckeri* Sinclair; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, McLish Ranch, eastern Arbuckle Mountains, southern Oklahoma. 1-5. Front, left side, back, summit, and basal views of holotype USNM 112085 showing crushed thecal shape and plating, medium-length ambulacra, small BB and stem facet (5), and near-junction of 4 plates at L3-L4-R3-R4 (1); X1.6. 6-11. Four side views, a summit view, and a basal view of small plesiotype 1113-TX16; note thecal shape, granular ornament with tiny ridges, summit tilted toward periproctal side (7, 9; almost the same views as 3, 1 above, respectively), small periproct surrounded by 4 thecal plates (6), medium-length ambulacra on summit (10), and small stem facet (11); X2.0. 12. Enlargement of ambulacrum I in R1 sinus of plesiotype 1113TX16 showing bulbous orals, ambulacral flooring plate sets supporting multiple brachioles, first 2 side food grooves branching to the right, 3 brachioles mounted on O1, and cryptic slitlike hydropore plus gonopore on O7-O1 suture; X5.8. 13. Plesiotype OU 8952, a weathered R1 with ambulacrum I still present; note primary and secondary flooring plates and few cover plates; X1.7. 14. Enlarged oblique view of base of plesiotype 1113TX16 showing unusual B2-IL1 and B2-IL2 ?demirhombs, small stem facet with parts of 2 columnals preserved, and granular ornament and tiny central ridges; X4.0 15. Separate ?O2 (plesiotype 1113TX22) showing shape and a brachiole facet. 16. Separate R2 (plesiotype 1113TX23) showing large size, ambulacral sinus, and plate surface exposed in break through diagenetic calcite. 17. Separate R4 (plesiotype 1113TX24) showing deep ambulacral sinus and small segment of periproct margin on lower left edge. 18. Separate L5 (plesiotype 1113TX25) showing small margin of periproct on right edge. 19. Separate L4 (plesiotype 1113-TX26) showing rhombs and small margin of periproct on left edge. 20. Separate IL4 (plesiotype 1113-TX27) showing periproctal margin at top. 21. Separate B2 (plesiotype 1113TX28) showing unusual ?demirhombs occupying nearly full suture (compare Fig. 14). 22. Separate IL2 (plesiotype 1113TX29) showing large size and shape. 23. Separate L3 (plesiotype 1113TX30) showing shape and rhombs. 24. Separate B4 (plesiotype 1113TX31) showing hexagonal shape and small stem facet. All isolated plates (15-24) X1.5.

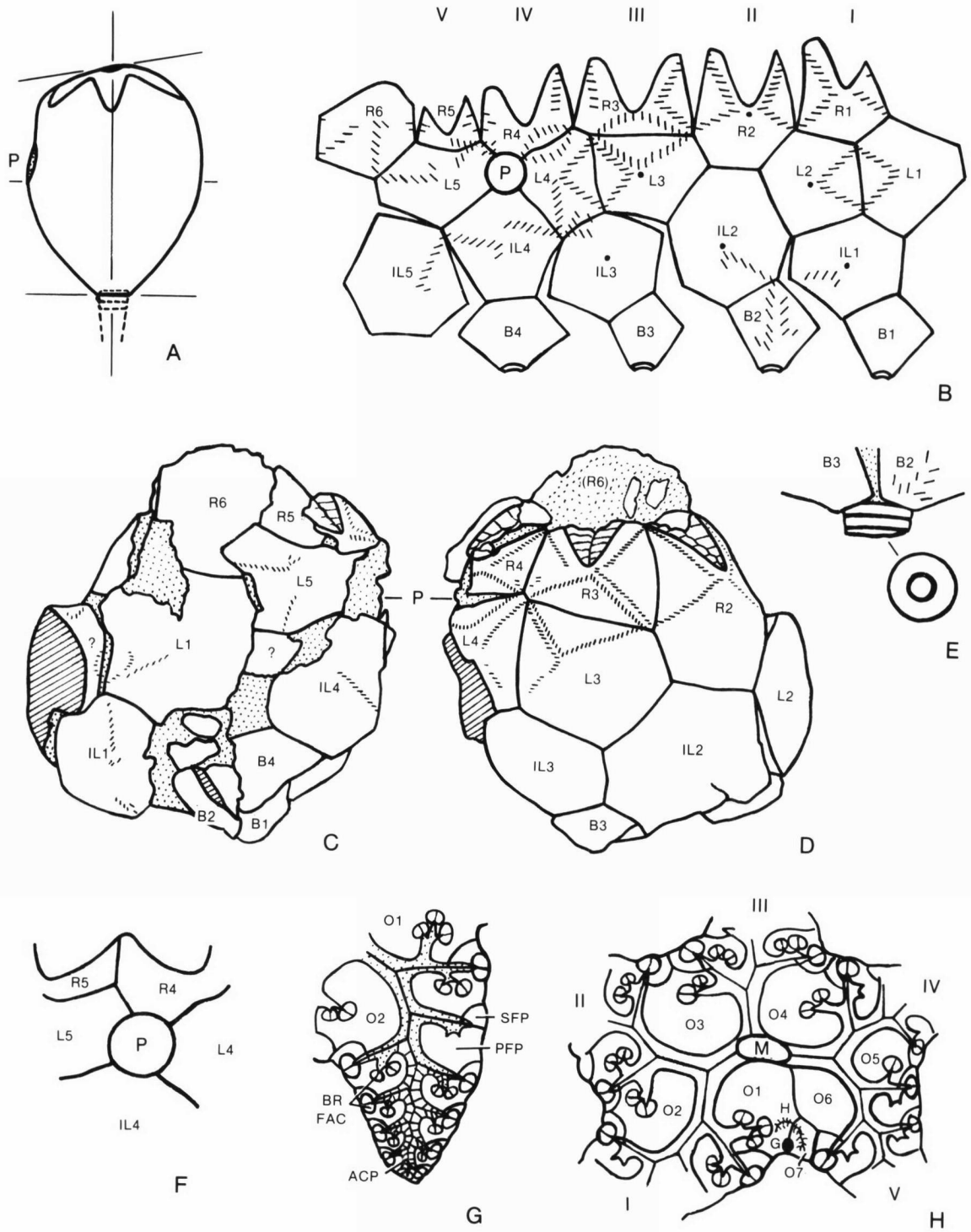


Fig. 63. *Hesperocystis deckeri* Sinclair, Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, McLish Ranch, eastern Arbuckle Mountains, southern Oklahoma. A, Outline of relatively small specimen 1113TX16 showing thecal shape, medium-length ambulacra on summit tilted toward periproct (P), maximum diameter (short lines) near midheight, and small-diameter proximal stem. B, Plating diagram of 1113TX16; note small stem facet on BB, unusual ?demirhombs on B2, closed ILL circlet, 4 plates around periproct (P), raised "points" (dots) at origins of some ILL, LL, and RR plates, small R5, and medium-length ambulacral sinuses. C, D, Back and front of holotype USNM

O7, and O1 forming group below mouth with O7-O1 suture bearing hydropore and gonopore.

Periproct small, round, fairly high on theca, surrounded by 4 plates forming almost equal segments (IL4 below, L4 and L5 laterally, R4 above). Periproct nearly flush with theca, tilted slightly upward toward summit (Pl. 30, fig. 9). In plesiotype, periproct about 2.5 mm in diameter, located at about 60 percent of thecal length from base. No periproctals or anal pyramid preserved in complete specimens.

Nine to ten rhombs and 8 to 9 demirhombs present on small plesiotype specimen (see Table 41); several more indicated by separate plates of larger specimens, bringing total to 7 to 12 rhombs and 8 to 15 demirhombs. Rhombs widely disjunct, dichopores apparently confluent. Dichopores short with a low rim; rhombs not quite reaching corners of most plates, showing many irregularities. B2-IL1 and B2-IL2 ?demirhombs unusual; extending nearly whole length of suture but only barely recurved at B2 plate origin, other half of dichopores nearly or completely missing (Pl. 30, fig. 14, 21). Dichopore spacing ranging from 0.32 to 0.40 mm, averaging 0.36 mm (9 measurements on 3 specimens and plates). Virtually no ridges on plate surface surrounding or inside rhombs.

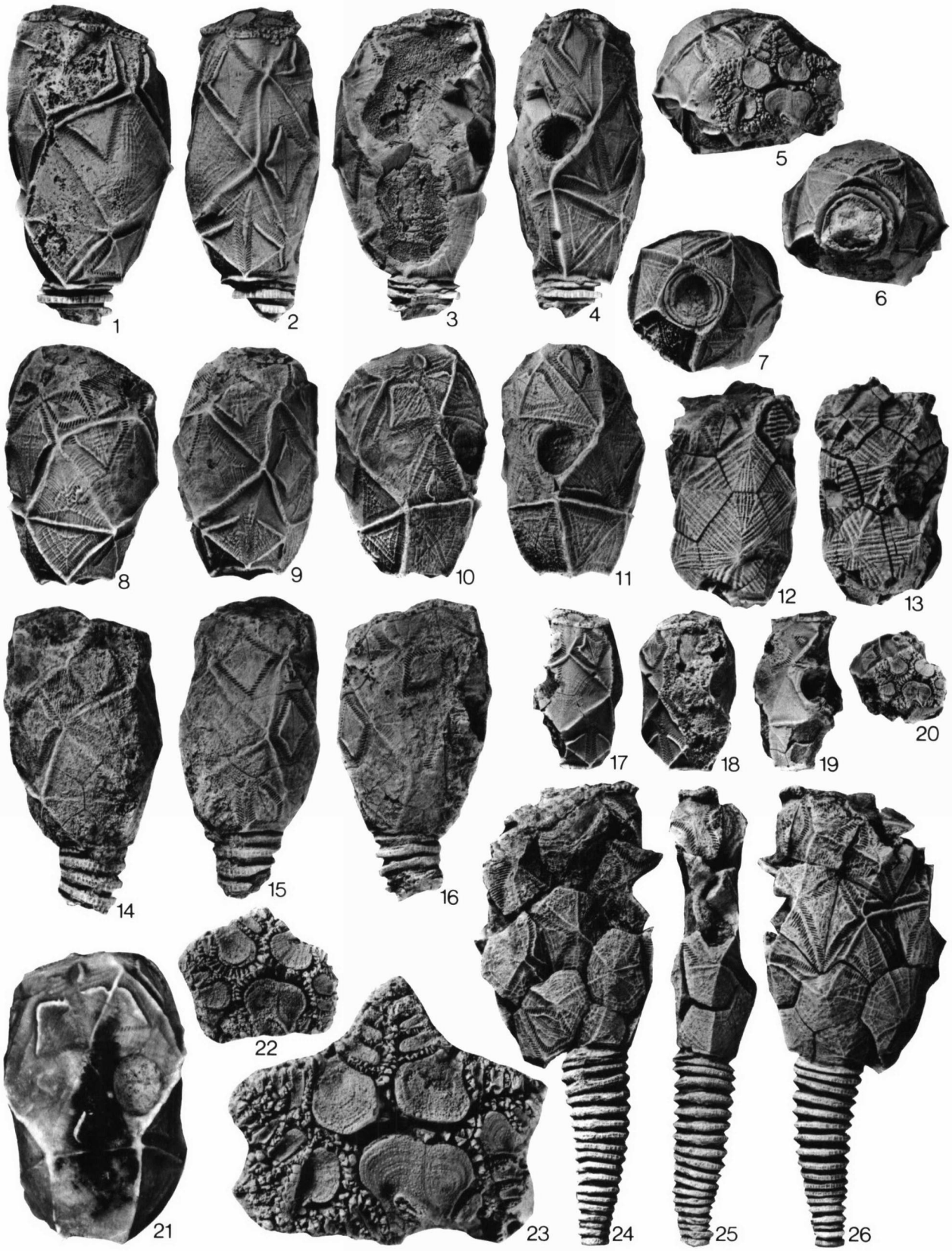
Ambulacra 5, medium length, extending short distance down from summit in medium to deep radial sinuses on R1 to R5. Summit slightly rounded, tilted toward periprocal side (Pl. 30, fig. 9). Ambulacra I and II longest (10 to 11 flooring plate sets), IV and V shortest (7 flooring plate sets). Ambulacral tips fairly close to lateral centers of R1 to R5; R6 lacking tip but sharing about one-third of each adjacent ambulacrum. Ambulacra moderately wide with normal arrangement of inner and outer flooring plates lying on sloping lateral edges of radial sinus. Relatively wide and deep food grooves protected by single set of small biserial cover plates, each bearing a tiny admedial spine (Pl. 30, fig. 12); 1 to 4 brachioles mounted on each flooring plates set (Pl. 30, fig. 12, 13; Fig. 63G). Brachiole in normal position on flooring plate suture at edge of ambulacrum largest and apparently earliest formed. (This is only brachiole on youngest flooring plates near tip of ambulacrum.) Older flooring plates adding 1 to 3 smaller additional brachioles admedial to first on surface of large primary flooring plate (Fig. 63G), with a short branch off existing side food groove. O1 to O5 also with 1 to 3 brachioles mounted on surface from first side food groove of left ambulacrum (Fig. 63H). One brachiole facet large, others (if present) smaller and on either side. Relatively small plesiotype 1113TX16 has ambulacrum II 6.8 mm long (to adoral edge of first side food groove) with 10 to 11 flooring plate sets and 24 to 25 brachioles (including those on O2); much larger holotype USNM 112085 with 11-mm ambulacrum II with 12 to 13 flooring plate sets and about 32 brachioles (assuming 3 present on missing O2).

Hydropore and gonopore in normal position on O1-O7 suture in plesiotype (Pl. 30, fig. 12). Hydropore in curved arc about 1.5 mm long behind largest brachiole on O1, not raised above oral surface; slit not obvious, possibly zigzagged or covered over by tiny plates. Gonopore just aboral to hydropore, small tapering pore 0.4 mm in size externally and 0.25 mm in size internally.

Thecal plates very thin and nearly smooth with only slight granular ornament along growth lines and tiny radial ridges extending out short distance from BB, ILL, and LL raised plate centers ("points"). Most separate plates heavily overgrown on exterior and interior with diagenetic calcite, hiding original surfaces (but see Pl. 30, fig. 16). Large separate plates apparently only 0.3 to 0.5 mm thick originally.

Stem poorly known, only parts of 2 columnals preserved in plesiotype 1113TX16 (Pl. 30, fig. 14) and only 3 columnals preserved in plesiotype 1113TX52 (Fig. 63E). Proximal stem very small for a rhombiferan, only 2.8 mm in diameter in smaller plesiotype; lumen occupying a little over 50 percent of diameter at facet and about 40 percent of third columnal diameter. Proximal columnals all same size, undifferentiated into inner and outer columnals (Fig. 63E); proximal stem appearing to taper slowly, possibly not much enlarged over distal stem. Total stem length and possible distal attachment unknown.

112085 showing crushed-in plating on back, apparent location of periproct (P) on edge, near-junction of 4 plates at L3-L4-R3-R4, and somewhat irregular rhombs with short dichopores; stippled areas are covered with matrix or abraded; lined areas are broken plates, X1.6. E, Three columnals attached to BB in medium-sized specimen 1113TX52; note lack of alternating columnals in proximal stem and lumen making up only about 40 percent of diameter, X4. F, Relatively small periproct (P) in 1113TX16 surrounded by four thecal plates, X4. G, Ambulacrum I in 1113TX16 showing multiple brachioles (BR) mounted on OO, on primary flooring plates (PFP), and on small secondary flooring plates (SFP), plus small ambulacral cover plates (ACP), X5.8. H, Summit view of 1113TX16; note nearly central elliptical mouth (M), bulbous OO bearing 1 to 3 brachiole facets from left-hand ambulacrum, and cryptic curved hydropore (H) and gonopore (G) crossing O1-O7 suture, X5.2.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Studied specimens.—Holotype USNM 112085; complete plesiotype specimens 1113TX16 and 1113TX52; plesiotype ambulacrum in R1 OU 8952; figured separate plates 1113TX22-31; additional material OU 8953 and 1113TX32.

Occurrence.—Known only from the Lower Echinoderm Zone in the eastern Arbuckles; probably the most abundant echinoderm (based on plates) at McLish Ranch, where all complete specimens were found; rare plates also present at Bromide, Rhynes Ranch, and Pickens Ranch localities.

Genus STRABOCYSTIS Sprinkle, n. gen.

Type species.—*Strabocystis fayi* Sprinkle, n. sp.

Diagnosis.—Thecal shape elongate cylindrical, summit tilted away from periproct; ILL and LL circlets open; periproct surrounded by 3 thecal plates (IL4, L4, and L5); 19 to 20 rhombs and demirhombs; ambulacra short, confined to summit and only slightly indenting RR, R2 lacking ambulacral tip; proximal stem medium-sized, tapering fairly slowly.

Occurrence.—Middle Ordovician, Oklahoma.

Etymology.—The generic name is derived from *strabos* (Gr.), oblique, referring to the distinctive tilting of the summit away from the periproctal side in this genus.

Discussion.—*Strabocystis* closely resembles *Pirocystella* in its short ambulacra confined to the summit and only moderately indenting the radials. These short ambulacra may also have been developed by paedomorphosis from an ancestor with longer ambulacra. However, *Strabocystis* has a summit tilted away from the periproctal side, no ambulacral tip on R2 but one on R6 instead, a more elongate thecal shape with no small radials, the infralateral circlet open in only one place, many more rhombs and demirhombs, and an ornament different from that of *Pirocystella*. The short ambulacra and large number of rhombs and demirhombs separate *Strabocystis* from all other members of the Glyptocystitidae.

Strabocystis is the only glyptocystitid rhombiferan normally occurring in the Upper Echinoderm Zone of the Bromide Formation; however, only 15 specimens have been collected from this zone. It is most common in the central and southern Arbuckles and has not been found northeast of Buckhorn Ranch nor southwest of Tulip Creek. Almost half the specimens were found in two small slabs of limestone containing numerous jumbled thecae from the base of the Upper Echinoderm Zone at Buckhorn Ranch about 3 to 3.5 m below the main echinoderm-bearing beds at this locality. Most specimens are very similar in appearance (Pl. 31), but one specimen from Buckhorn Ranch has much coarser ornament with numerous subsidiary ridges crossing most plate sutures (Pl. 31, fig. 12, 13). However, it agrees in most other morphologic features, and is assigned to the type species.

STRABOCYSTIS FAYI Sprinkle, n. sp.

Plate 31; Figure 64

Diagnosis.—Theca elongate, maximum diameter above midheight; B1-B2 and B2-B3 sutures curved, ILL circlet open in one place; dichopore spacing averaging 0.25 mm; ornament consisting of high central radiating ridges, ridges inside and around excurrent rhombs, and slightly granular growth lines.

PLATE 31.

Fig. 1-26. *Strabocystis fayi* Sprinkle, n. gen., n. sp.; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation; 1-6, 17-20, 22, 23 from Nebo, central Arbuckles, 7-11, 21 from Chapman Ranch (Tulip Creek), southern Arbuckles, 12, 13 from Buckhorn Ranch, central Arbuckles, 14-16 from Lick Creek, northern Arbuckles, and 24-26 from North I-35, northern Arbuckles, all from southern Oklahoma. 1-6. Four side views, a summit view, and a basal view of holotype OU 8954; note elongate shape, summit slanting away from periproctal side, high central and minor accessory ridges, and weathered (top) side (3) vs. caliche on bottom (1); X1.5. 7-11. Basal and 4 side views of paratype OU 8955, showing shallow basal cavity (7), slight projection of BB origins downward, ridges and ornament around rhombs, and eroded slanted summit; X1.5. 12, 13. Side views of damaged paratype OU 8959; note unusually strong radial ornament on plates and few periproctal membrane plates; X1.5. 14-16. Side views of somewhat recrystallized paratype OU 8956 showing slanted summit, rhombs, and short ridged stem; X1.5. 17-20. Three side views and summit view of small paratype OU 8957; note eroded (top) side vs. extensive caliche on opposite (bottom) side (18) and subdued ornament; X1.5. 21. Side view of paratype OU 8955 immersed in water to show large elongate "black spot" alongside periproct plus high V-shaped ridges (white) inside excurrent half-rhombs; X1.8. 22, 23. Enlarged summit views of paratype OU 8957 (22) and holotype OU 8954 (23) showing short ambulacra, bulbous OO with growth lines, elongate hydropore at bottom, and ridged ambulacral cover plates opposite each other near mouth; X3.2, X3.7. 24-26. Side views of paratype 1106TX16; note crushed theca with plating well displayed, long slowly tapering ridged stem, and unusual rhomb IL2-L3 and demirhomb IL3-L3 in 26; X1.5.

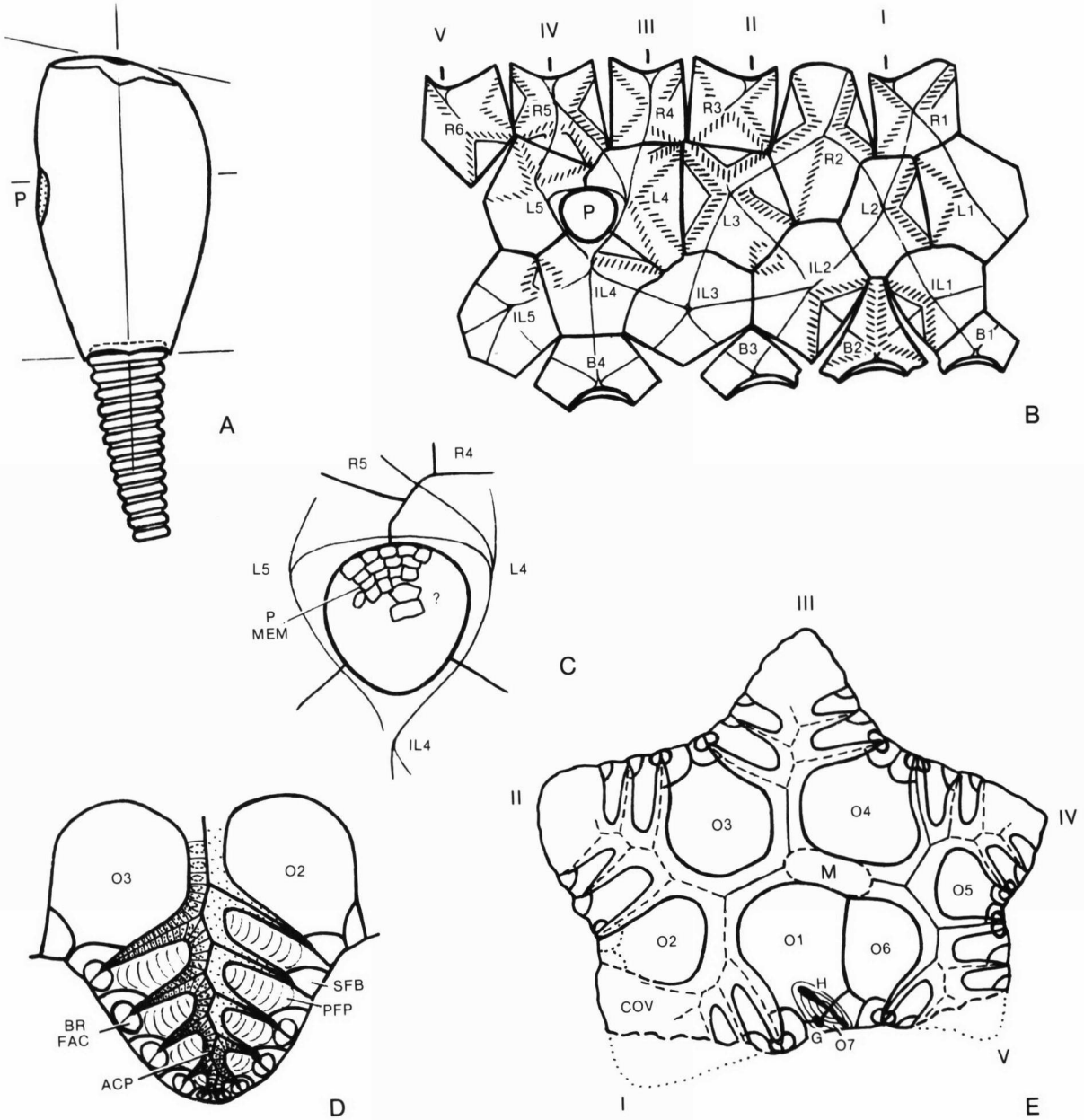

Fig. 64. *Strabocystis fayi* Sprinkle, n. gen., n. sp., Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. A, Outline of a large specimen showing elongate thecal shape, location of periproct (P), relatively short ambulacra on summit tilted away from periproctal side, maximum diameter above mid-height, and medium-sized slowly tapering stem. B, Plating diagram for a large theca; note ambulacral tip on R6 but not R2, no small RR, large number of pectinirhombs, and ridges radiating from plate centers and inside excurrent rhombs. C, Periproct surrounded by 3 thecal plates showing periproctals in membrane (P MEM) and 2 larger plates from possible anal pyramid; based mostly on OU 8955 and 8959, much enlarged. D, Ambulacrum II in a large specimen; note primary and secondary flooring plates (PFP, SFP), slightly concave surface of PFP, brachiole facets (BR FAC) at edge of ambulacrum, and small ridged ambulacral cover plates (ACP), X6. E, Summit view of holotype OU 8954 showing elliptical mouth (M) offset to right (mouth position taken from OU 8955), O1 to O7 surrounding mouth, relatively short ambulacra, and slightly curved, raised, and centrally constricted hydropore (H) and adjacent gonopore (G) crossing O1-O7 suture; part of ambulacrum I and adjacent O2 covered and aboral parts of ambulacra I and V missing, X4.6

Description.—Thecae fairly small to large, darkly colored (medium tan to dark gray) usually with large black spot (Pl. 31, fig. 21). Thecal shape elongate-cylindrical to barrel-shaped with slightly domed summit tilted away from periproct (Pl. 31, fig. 10, 16) and nearly flat base. Holotype OU 8954 32 to 33 mm long and about 18 to 19 mm in diameter; maximum diameter at or just above midheight.

Thecal plating normal for family (Fig. 64B). BB 4, in a closed circlet, fairly small and wide, forming a moderately large stem facet, facet only slightly depressed (Pl. 31, fig. 7). B1 and B3 small and pentgonal, B4 larger and hexagonal, flat-topped, B2 larger, elongate, hexagonal, with 2 rhombs. B1-B2 and B2-B3 sutures slightly curved (Fig. 64B) to allow larger B2 rhombs. ILL 5, medium to large, in an open circlet (interrupted between IL1 and IL2 by B2 and L2), IL1 pentagonal, all others hexagonal, 1 to 2 rhombs or demirhombs per plate, IL4 forming lower margin of periproct. LL 5, fairly large, in an open circlet (interrupted between L2 and L3 by IL2 and R2), periproct between and below L4 and L5; L3 pentagonal, L1 and L2 hexagonal, L4 and L5 heptagonal; most LL with 1 to 3 rhombs or demirhombs but L3 often with 4 to 5 (Pl. 31, fig. 26). RR 6, in a closed circlet, R2 large and elongate, other RR medium; R3 and R4 nearly square, R1, R5, and R6 pentagonal, R2 hexagonal; each with 2 to 4 rhombs or demirhombs; ambulacra only slightly indenting RR. A near-junction of 4 plates at L3-L4-R3-R4 (Pl. 31, fig. 26). OO 7, small but wide, in a closed circlet surrounding mouth on summit (Fig. 64E); O6, O7, and O1 forming group below mouth with O7-O1 suture bearing hydropore and gonopore.

Periproct medium-sized, almost circular, 5.5 mm in diameter in holotype. Periproct slightly recessed and tilted toward summit; located about 50 to 55 percent of thecal length from base. Surrounded by normal 3 thecal plates, IL4 below, L4 and L5 laterally and above, each forming about one-third of margin. Two paratypes with traces of periproctals about 0.4 mm in size, no anal pyramid (Pl. 31, fig. 13; Fig. 64C).

Ten to eleven rhombs and 4 to 6 demirhombs usually present (Table 41). Rhombs disjunct, dichopores apparently confluent. Dichopores short to medium in length, closely spaced, with a noticeable rim. Dichopore spacing ranging from 0.21 to 0.28 mm and averaging 0.25 mm (8 measurement on 4 specimens). Large thecal ridges outside and large V-shaped ridges inside excurrent half-rhombs (Pl. 31, fig. 2).

Ambulacra 5, confined to summit, only moderately indenting RR. Summit slightly rounded, tilted away from periproctal side (about 20° from horizontal) (Pl. 31, fig. 1, 3). All ambulacra short and wide, each with 7 to 10 flooring plate sets and brachioles in holotype. Ambulacral tips near lateral centers of R4 and R5, near edges of R1, R3, and R6; R2 lacking tip (unusual for family) but sharing one-third or more of each adjacent ambulacrum. Arrangement of primary and secondary flooring plates normal, plates raised slightly above surrounding RR, with a slightly concave surface; 1 brachiole attached to each set at lateral edge of ambulacrum. Biserial set of tiny cover plates over main and side food grooves; cover plates nearly square, opposite each other, bearing a prominent ridge (Pl. 31, fig. 23). Largest cover plates (near mouth) about 0.6 mm wide and 0.4 mm long, aboral ones much smaller. Mouth apparently displaced to right in eroded paratype OU 8955 (see Fig. 64E).

Brachioles preserved in a few specimens, at least 13.0 mm long by 1.0 mm wide, biserially plated, slowly tapering. At least 1 set of tiny biserial cover plates protecting adoral food groove.

Hydropore and gonopore in normal position on O7-O1 suture in holotype (Pl. 31, fig. 23). Hydropore slitlike, crested, about 2.0 to 2.5 mm long, slightly dumbbell-shaped, with a raised constricted center (Fig. 64E). Gonopore a small pore about 0.25 mm in diameter on aboral side of crested hydropore.

Thecal plates fairly thin, 0.8 to 1.2 mm thick, with high thin central ridges radiating to sides from plate centers, chevron-shaped ridges just inside excurrent rhombs, and small granules along growth lines (Pl. 31, fig. 8-11). Subsidiary ridges forming nested triangles and diamonds present in a few places but usually not prominent, except extensively developed in paratype OU 8959 (Pl. 31, fig. 12, 13).

Proximal stem enlarged, of medium size, tapering fairly slowly, composed of overlapping outer and inner columnals (Pl. 31, fig. 24-26). Proximal stem about 9.0 mm in diameter in holotype, ranging from 35 to 49 percent of thecal diameter in studied specimens. Paratype 1106TX16 with a proximal stem 22 mm long, 16 outer columnals tapering from 8.5 mm to 3.5 mm in diameter. Outer columnals moderately ridged with 12 to 19 ridges per 10 mm of circumference; columnals in distal stem may also be ridged.

Etymology.—The species is named for Dr. Robert

O. Fay of the Oklahoma Geological Survey, Norman, who collected most of the type specimens of this species and many of the other echinoderms studied for this project.

Studied specimens.—Holotype OU 8954, paratypes OU 8955-8964 and 1106TX16; several additional unfigured fragments with other types (especially OU 8965 from Buckhorn Ranch).

Occurrence.—All specimens are from the Upper Echinoderm Zone near the top of the Mountain Lake Member from the central and southern Arbuckles: 7 from Buckhorn Ranch, 3 (including holotype) from Nebo, 3 from Chapman Ranch (Tulip Creek), 1 each from Lick Creek and North I-35.

Genus TANAOCYSTIS Sprinkle, new

Type Species.—*Tanaocystis watkinsi* Sprinkle, n. sp.

Diagnosis.—Theca cylindrical to rounded subconical, maximum diameter just above base; ILL and LL circlets open; periproct surrounded by 3 (rarely 4) thecal plates (IL4, L4, and L5); 10 to 12 rhombs and demirhombs; ambulacra medium length, extending down theca in RR sinuses; proximal stem medium-sized, tapering fairly slowly, mounted in deep basal cavity, outer columnals "skirted."

Occurrence.—Middle Ordovician, Oklahoma, ?Illinois.

Etymology.—The generic name is derived from *tanaos* (Gr.), long, tall, outstretched, referring to the elongate thecal shape of this large rhombiferan.

Discussion.—*Tanaocystis* is most similar to *Quadrocystis*, with which it occurs in the Upper Pooleville in the Criner Hills; both genera have medium-length ambulacra in radial sinuses on R1 to R5 and large elongate orals extending a short distance down the theca. However, *Tanaocystis* is usually larger and has the maximum diameter in the infralateral circlet just above the base instead of higher on the theca, has more rhombs with numerous shorter dichopores, has only three (instead of four) plates around the anus, has a "skirted" stem without ridges, has curved B2 sutures, and has slightly different thecal ornament. *Tanaocystis* does not resemble any of the other Bromide rhombiferans from the Mountain Lake Member based on its thecal shape, ambulacral development, and distinctive stem.

Tanaocystis is somewhat similar to *Glyptocystites* in its thecal shape and elongate orals, but has much different ambulacral development and different proximal stem morphology. *Tanaocystis* resembles *Coronocystis* in its thecal shape and ambulacral development, but has only three plates around the periproct (thus belonging to a different family), a wider base, and different stem morphology. However, *Tanaocystis watkinsi* from the Bromide shows a very strong resemblance to the form described as *Coronocystis durandensis* by Kolata (1975, p. 16-20) from the Grand Detour Formation of the Platteville Group in northern Illinois and southern Wisconsin. This Platteville species has a large, elongate, ovoid theca with the maximum diameter aboral; plating very similar to that of the Bromide species, especially in the radial circlet; similar plate ornament; very similar medium-length ambulacra, cover plates, and elongate orals; at least eight rhombs and two demirhombs on the known plates (vs. eight rhombs and four demirhombs in the same positions in *T. watkinsi*); and a long proximal stem with the large outer columnals slightly "skirted" and "frilled." Kolata (1975, p. 19) originally reported that the frame around the medium-sized periproct in *C. durandensis* "consists of at least five plates," but after looking at figures of *T. watkinsi* and reexamining the specimens he figured in his pl. 2, fig. 9, 10, Kolata (pers. commun., March 27, 1980) stated: "...the Platteville species has at least four plates in contact with the periproct. ...L4, IL4, and IL5 clearly encircle the periproct ... [and] I feel there must have been a L5 at the top left side of the periproct." This would be the same arrangement of thecal plates around the periproct as shown by *Quadrocystis graffhami* in the Bromide, and if true, then *"C. durandensis"* belongs in the family Glyptocystitidae (three to four plates around the periproct) and not the Cheirocrinidae (five plates around the periproct) and therefore should be removed from *Coronocystis*. Kolata's species is here provisionally assigned to *Tanaocystis* in the Glyptocystitidae as *Tanaocystis? durandensis*. It differs from *T. watkinsi* by having four plates around the somewhat larger periproct, heavier central ridges on the lower plates, and perhaps a slightly different arrangement of rhombs and demirhombs with a slightly larger slit spacing (0.25 to 0.30 mm per slit).

The fact that *Tanaocystis* and *Quadrocystis* have such different proximal stems was the final factor that convinced me that they represented separate genera, and not just separate species in the same genus. Most members of the Glyptocystitidae have fairly similar proximal stems differing only slightly in size, rate of taper, or strength of

ridging; even *Glyptocystites* is similar (see Kesling, 1961, pl. 1). However, *Tanaocystis* has distinctive "skirted" and unridged outer columnals with a projecting ragged distal edge, in contrast to *Quadrocystis* which has thin granule-bearing outer columnals with an equatorial groove. Such a large difference in a usually conservative morphologic feature suggests considerable genetic difference between these two sympatric rhombiferans.

TANAOCYSTIS WATKINSI Sprinkle, n. sp.

Plate 32; Figure 65

Diagnosis.—Theca elongate, indented on periproctal side; B1-B2 and B2-B3 sutures strongly curved, ILL circlet open in 1 place; rhombs with up to 70 dichopores with average spacing of 0.22 mm; thecal plates ornamented with central radiating ridges, ridges inside excurrent rhombs, granular growth lines, and scattered pustules near base; projecting distal edge of "skirted" outer columnals hiding much of inner columnals.

Description.—Of 11 specimens available for study, only one (holotype 1405TX1) complete and uncrushed although broken across middle and abraded in places. Theca fairly small to large, tapering subcylindrical in shape with rounded summit and wide bowl-shaped base. Theca somewhat indented on periproctal side, maximum width just above base in ILL circlet. Holotype 38 mm long and 23 mm in maximum diameter.

Thecal plating fairly normal for family (Fig. 65B). BB 4, in a closed circlet, small to medium in size and very wide, recurved to form a large deep basal cavity (Pl. 32, fig. 13). B1 and B3 relatively small, pentagonal; B4 medium, flat-topped, hexagonal; B2 medium, elongate, hexagonal, bearing 2 rhombs. B1-B2 and B2-B3 sutures strongly curved (among other Bromide rhombiferan genera, only *Strabocystis fayi* showing this feature); curvature lengthening external part of B2 and its rhombs, but retaining one-quarter contribution of B2 to basal cavity (Pl. 32, fig. 13; Fig. 65E). ILL 5, medium to large, in an open circlet (barely interrupted between IL1 and IL2 by B2 and L2), IL1 and IL2 pentagonal, others hexagonal, IL4 forming bottom of periproct, only IL1 and IL2 with rhombs (with B2), a near-junction of 4 plates at B2-IL1-IL2-L2 (Fig. 65B). LL 5, medium to very large, in an open circlet (interrupted between L2 and L3 by IL2 and R2); L3 and L4 pentagonal, L1 and L2 hexagonal, L5 heptagonal; L4 and L5 forming sides and upper edge of periproct; most LL with 1 rhomb each except L3, L3 with 2 rhombs and a demirhomb. RR 6, in a closed circlet, R2 very large and elongate, others medium to fairly large; R3 to R5 modified rectangular, R6 pentagonal, R2 modified hexagonal, R1 irregularly triangular. RR with 2 to 3 rhombs and demirhombs each except for R1, R1 with 1 rhomb; ambulacra in deep radial sinuses near lateral centers of R2 to R5 and right side of R1; sinuses extending almost to aboral edge of R1, R4, and R5; R6 sharing just over one-third of adjacent ambulacrum I. Two near-junctions of 4 plates at L3-L4-R3-R4 and L4-L5-R4-R5 (Fig. 65B). OO 7, medium-sized, very elongate (mushroom-shaped), extending short distance down side of theca, forming a closed circlet around central mouth (Fig. 65C). O6, O7, and O1 forming large group below mouth, bearing nearly central hydropore and gonopore across O7-O1 suture.

Periproct medium-sized, rounded triangular in shape, about 8.0 mm wide in holotype (Pl. 32, fig. 2). Periproct appearing quite recessed on holotype, tilted slightly toward summit; located about 40 percent of thecal length from base. Surrounded by normal 3 thecal plates (IL4, L4, and L5), IL4 forming less than one-third and each of the others slightly more than one-third of margin. No trace of periproctals or anal pyramid.

Eight rhombs and 4 demirhombs present with little variation (Table 41). Rhombs disjunct, dichopores definitely confluent. Rhombs very elongate with numerous (up to 68 or 70), medium-length, closely spaced dichopores each surrounded by a slight rim. Dichopore spacing ranging from 0.20 to 0.24 mm, averaging 0.22 mm (16 measurements on 7 specimens). Medium-sized ridges inside excurrent half-rhombs, these half-rhombs with somewhat shorter and wider dichopores than incurrent half-rhombs (Pl. 32, fig. 20).

Ambulacra 5, medium-length, extending one-third to one-half way down theca in deep radial sinuses on R1 to R5. R6 sharing slightly over one-third of ambulacrum I lying on right side of R1. Summit rounded, OO large, visible in side view. Ambulacra I and II longest, III shortest (Pl. 32, fig. 3); ambulacral plates slightly higher than adjacent RR and ornamented with small granules; 7 to 15 ambulacral flooring plate sets and brachioles per ambulacrum; primary flooring plates large and hexagonal, secondary flooring plates much smaller, rounded triangular except near summit, becoming very elongate and reaching main food groove near summit (Fig. 65C). Main and side food grooves very wide but rather shallow, walls and floor smooth.

Ambulacral cover plates with biserial alternate or opposite arrangement, very long and thin (0.8 by 0.15 mm) except much larger and almost square near mouth (0.8 mm on a side) with a crested admedial suture and one or more surface pustules (Pl. 32, fig. 19). Brachioles large and fairly long. Holotype having brachioles up to 13.0 mm long by 1.0 mm wide and high (see Pl. 32, fig. 12). Food groove protected by ?2 types of brachiolar cover plates, plates highly domed, 0.3 mm long. (The holotype has 1 damaged brachiole on the summit, which has a smaller regenerated distal end; see Pl. 32, fig. 12.) Brachiole facets wide, with 2 symmetrical depressions, mounted near edge of ambulacra except adorally, nearly central on elongate primary and secondary flooring plates adorally (Fig. 65D).

Hydropore and gonopore apparently in normal position on O1-O7 suture in holotype (see Pl. 32, fig. 19). Hydropore elongate, raised, slitlike, slightly curved, about 3.0 mm long. Gonopore in holotype covered by draped brachioles, but probably small pore just aboral to hydropore (Fig. 65C).

Thecal plates thin, 0.4 to 0.8 mm thick, with medium-sized central riges radiating from plate centers to sides, chevron-shaped ridges just inside excurrent half-rhombs, scattered large pustules on lower thecal plates, granular growth lines (Pl. 32, fig. 13). OO and some adoral ambulacral plates showing somewhat stronger granular ornament (Pl. 32, fig. 19).

Proximal stem enlarged, of medium size, tapering fairly slowly, mounted in a large deep basal cavity. Proximal stem composed of larger outer columnals, columnals "skirted," i.e., distal edge projecting to partly cover smaller inner columnals (Pl. 32, fig. 17). Projecting distal edge slightly pleated and often irregular, but most outer columnals lacking obvious ridges of other genera. In holotype, basal cavity 10 to 11 mm in diameter at entrance, at least 3.0 mm deep, containing traces of a proximal outer columnal 7.5 to 8.0 mm in diameter and inner columnal 6.0 mm in diameter. In somewhat smaller paratype, basal cavity at least 4.0 mm deep (Pl. 32, fig. 13). Longest preserved proximal stem somewhat disarticulated, but about 22 to 23 mm long, containing 19 outer columnals tapering from 6.0 or 6.5 mm to 4.0 mm in diameter. Distal stem preserved but disarticulated in another smaller specimen (Pl. 32, fig. 14); distal stem about 18 mm long with at least 11 columnals ranging from 1.1 mm long and 1.8 mm wide proximally to 1.9 mm long and 1.7 mm wide distally; columnals nearly smooth, slightly rounded, of uniform appearance.

Etymology.—This species is named after Mr. William T. Watkins of San Antonio, Texas, who collected and donated the holotype and one paratype of this species. He greatly assisted this project through his continuing interest and enthusiasm and through the loan and gift of unusual specimens from his private collection.

Studied specimens.—Holotype 1405TX1 (Watkins Coll.), paratypes 1281TX11, 1124TX3-4 (both Graffham Coll.), 1405TX2 (Watkins Coll.), and OU 8966-8971 (Graffham and Fay Coll.).

Occurrence.—All 11 specimens are from the top 12 m of the Pooleville Member, Bromide Formation, in the Criner Hills; 7 paratypes from Dunn Quarry (4 m, 9 to 12 m, and 12 m below top), 1 paratype

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PLATE 32.

Fig. 1-20. *Tanaocystis watkinsi* Sprinkle, n. gen., n. sp.; echinoderm zones from the upper Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 1-6, 11, 12, 15, 18, 19 probably from Zone 1 at Culley Creek (Watkins Coll.); 7-10, 14, 16, 20 from Dunn Quarry, 14 from 4.5 m below top of Pooleville, 10, 20 from float 0 to 12 m below top, 7 from 9 to 12 m below top, 8, 9, 16 from 12 m below top; 13 from 7 m below top of Pooleville at Rock Crossing; 14 from 2.5 m below top of Pooleville at Rudd Quarry. 1-6. Four side views, a summit view, and a basal view of complete holotype 1405TX1 showing broken and somewhat weathered theca with elongate shape, indented periproct (2, 3), maximum diameter in ILL circlet, rounded summit, long ambulacra, and basal cavity (6); X1.7. 7. Side view of paratype OU 8968, a crushed lower theca with short attached stem segment; note large R2 at left with long ambulacral sinus; X1.5. 8, 9, 16. Side and edge views of crushed paratype OU 8967 showing proximal stem with "skirted" outer columnals in basal cavity (16), R6, L5, and adjacent disrupted ambulacra (8), and large R2 (9); X1.5, X3.0. 10, 20. Side views of incomplete paratype OU 8966; note near-junction of 4 plates at L3-L4-R3-R4, ambulacra III and IV on R3 and R4 with cover plates still preserved, small R3-R4 demirhomb (20), and OO at top; X1.5, X3.0. 11. Side view of paratype 1405TX2 showing abraded thecal plates with radiating ridges; X1.5. 12, 15, 18, 19. Enlargements of holotype 1405TX1; note regenerated brachioles on ambulacrum III (12, 19), brachioles attached to tip of ambulacrum I (15), long well-preserved ambulacrum II with some cover plates and brachioles attached (18), and oblique summit with a complete brachiole, partly hidden hydropore-gonopore area, and elongate granular OO (19); X2.5 (15), X3.0. 13. Basal view of paratype 1281TX11, a broken theca showing basal cavity, rhombs on B2, and strongly curved B2-B1 and B2-B3 sutures; X2.7. 14. Paratype 1124TX4, a poorly preserved theca (not shown) with an attached proximal and distal stem; note that distal columnals are smooth and undifferentiated; X1.5. 17. Side view of small paratype OU 8970 showing base of theca with B2 rhombs and well-preserved proximal stem with "skirted" columnals; X3.0.

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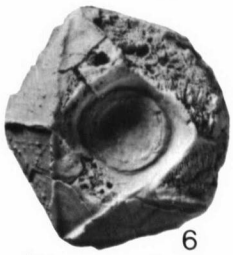
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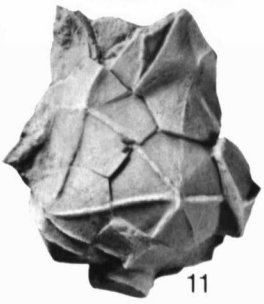
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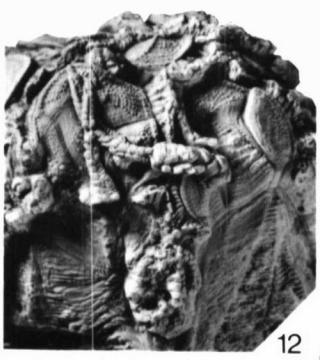
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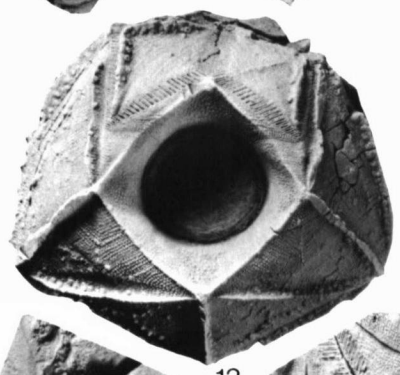
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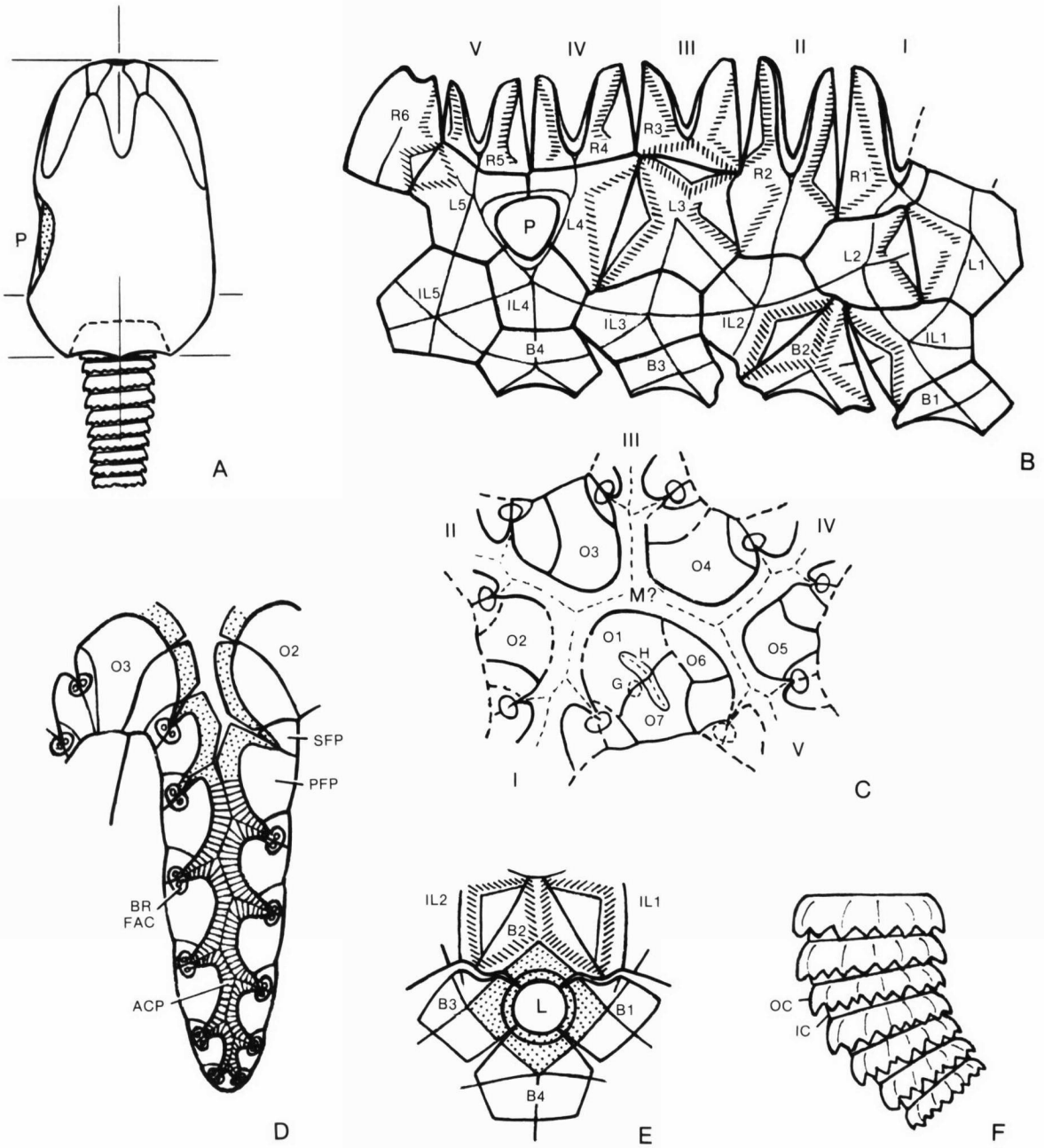

Fig. 65. *Tanaocystis watkinsi* Sprinkle, n. gen., n. sp., upper Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma. A, Outline of a large specimen showing elongate but nearly upright thecal shape, location of periproct (P), long ambulacra extending down theca, OO visible in side view, maximum diameter (short horizontal lines) well below midheight, and unusual skirted stem mounted in deep basal cavity. B, Plating diagram for a large theca; note deeply cleft RR, R1 and R6 sharing ambulacrum I, fairly large periproct (P) surrounded by 3 plates, 4 near-junctions of 4 plates at B2-IL1-IL2-L2, IL3-IL4-L3-L4, L3-L4-R3-R4, and L4-L5-R4-R5, and unusual interbasal sutures on B2. C, Summit view of holotype 1405TX1 showing likely position of mouth (?M; ambulacral grooves hidden by cover plates and matrix), elongate O1 to O7, and position of hydropore (H) and apparent gonopore (G) crossing O1-O7 suture, X3. D, Ambulacrum II in a large specimen; note elongate shape, primary and secondary flooring plates (PFP, SFP), both of which become elongate adorally, brachiole facets (BR FAC) bearing 2 depressions and located away from ambulacral margin adorally, and fairly wide main food groove (shown split adorally) covered by elongate ambulacral cover plates (ACP); based mostly on holotype 1405-TX1, much enlarged. E, Exploded basal view of paratype 1281TX11 showing B1 to B4 making up equal parts of stem facet in deep diamond-shaped basal cavity (stippled), large central lumen (L) into thecal interior, and strongly curved B1-B2 and B2-

from Rudd Quarry (2.5 m below top), the holotype and 1 paratype from Culley Creek (probably from Zone 1 but unknown distance below top), and 1 paratype from Rock Crossing (7 m below top).

Genus QUADROCYSTIS Sprinkle, new

Type species.—*Quadrocystis graffhami* Sprinkle, n. sp.

Diagnosis.—Thecal shape slanted cylindrical, maximum diameter at or below midheight; ILL and LL circlets open; periproct medium-sized, surrounded by 4 thecal plates (IL4, IL5, L4, and L5); 8 rhombs and demirhombs; ambulacra medium length, extending down theca in RR sinuses; proximal stem medium-sized, tapering fairly slowly, mounted in deep basal cavity, outer columnals bearing granules and central equatorial groove.

Occurrence.—Middle Ordovician, Oklahoma.

Etymology.—The generic name is derived from *quadro* (L.), to make four-cornered, square, referring to the nearly square periproct surrounded by four thecal plates.

Discussion.—*Quadrocystis* most closely resembles *Tanaocystis*, with which it occurs in the Upper Pooleville in the Criner Hills. Both genera have medium-length ambulacra confined to deep radial sinuses on R1 through R5, R6 sharing only part of one adjacent ambulacrum. Both also have large elongate orals which are barely visible in side view, and similar plating. However, *Quadrocystis* has four plates surrounding its medium-sized periproct, fewer rhombs and demirhombs having long dichopores which sometimes do not reach the plate corners, a different proximal stem morphology, a smaller slanted theca with a somewhat different shape, and more granular ornament. *Quadrocystis* differs from all other Bromide rhombiferans in its ambulacral development, arrangement of plates around the periproct, and proximal stem morphology.

Quadrocystis is the second genus assigned to the Glyptocystitidae having four plates (IL4, IL5, L4, and L5) surrounding the periproct; *Hesperocystis* also shows this feature, but the periproct is much smaller, nearly circular, and different thecal plates make up the margin (IL4, L4, L5, and R4). Several genera in the families Echinoencrinitidae and Callocystitidae have the same four plates surrounding a medium-sized periproct as in *Quadrocystis*, but these other genera differ considerably in their plating, number of rhombs, and ambulacral development (see Broadhead and Strimple, 1978).

QUADROCYSTIS GRAFFHAMI Sprinkle, n. sp.

Plate 33; Figure 66

Diagnosis.—Theca fairly small, deep stem facet not perpendicular to thecal axis; BB sutures straight, ILL circlet open in 1 place; some rhombs short, dichopores very long (conjunct in early growth stages), dichopore spacing averaging 0.23 mm; thecal plates ornamented with central radiating ridges, few subsidiary ridges, granules along growth lines, raised granular areas inside rhombs.

Description.—Thirteen specimens available for study, including excellent holotype (OU 8972) and several well-preserved paratypes with attached appendages. Theca fairly small; smallest well-preserved specimen 9.0 mm long and 6.0 mm in diameter, holotype (one of largest specimens) 18 to 19 mm long and 12 to 13 mm in diameter. Theca cylindrical to barrel-shaped, slightly slanted (rim of basal cavity not perpendicular to axis of theca) (Pl. 33, fig. 1, 3), with rounded summit and bowl-shaped base. Theca somewhat indented on periproctal side, maximum diameter at or just below midheight.

Thecal plating normal for family (Fig. 66B). BB 4, in a closed circlet, small to medium in size, fairly wide, recurved to form deep basal cavity (Pl. 33, fig. 6). B1 and B3 relatively small, pentagonal; B4 medium, flat-topped, hexagonal; B2 fairly small but elongate, hexagonal, bearing 2 rhombs. B1-B2 and B2-B3 sutures straight (vs. *Tanaocystis watkinsi*), each basal making up about 25 percent of stem cavity. ILL 5, medium to large, in open circlet (barely interrupted between IL1 and IL2 by B2 and L2); IL1 and IL4 pentagonal, others hexagonal; IL1 and IL2 having rhombs (with B2); IL4 and IL5 forming lower lateral margins of periproct (Pl. 33, fig. 23). LL 5, medium to large, in open circlet (interrupted between L2 and L3 by IL2 and R2); L3 pentagonal, all others hexagonal; L4 and L5 forming top-lateral margins of periproct; all LL with 1 rhomb each. RR 6, in closed circlet, R2 large and elongate, R1 and R6 medium, other RR fairly small; R1 to R5 with deep radial sinuses for ambulacra near lateral centers

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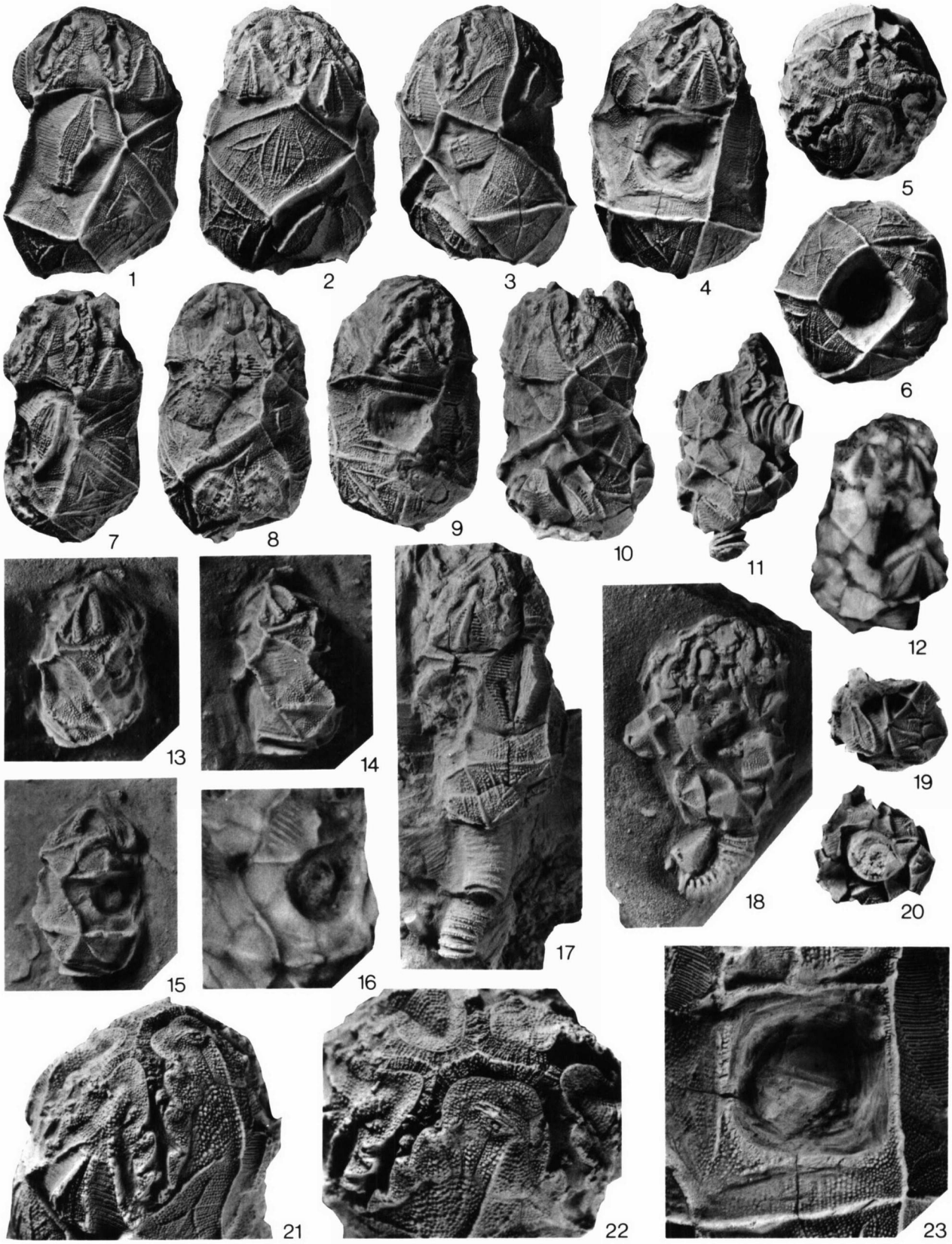
B3 sutures, much enlarged. F, Proximal stem in small paratype OU 8970; note unusual "skirted" outer columnals (OC) partly hiding smaller inner columnals (IC) plus slight pleating at this size, X6.6.



of plates, almost reaching aboral edge of R3 to R5, R6 sharing about one-third of adjacent ambulacrum I; R2 with 2 rhombs, all other RR with 1 rhomb each. A near-junction of 4 plates at L4-L5-R4-R5 (Fig. 66E). OO 7, fairly small but elongate (mushroom-shaped), extending short distance down theca, forming a closed circlet around central mouth (Fig. 66D); O6, O7, and O1 forming medium-sized group below mouth, bearing nearly central hydropore and gonopore across O7-O1 suture.

Periproct medium-sized, rounded-square in shape, about 4.5 mm in diameter in holotype (Pl. 33, fig. 23). Periproct recessed and tilted slightly toward summit; located at about 42 to 50 percent of thecal length from base. Surrounded by 4 thecal plates, L4 (about 30 percent of margin) and L5 (about 25 percent) above and IL4 (about 25 percent) and IL5 (unusual, about 20 percent) below (Fig. 66E). Smallest complete paratype with small edge of IL1 forming about 8 percent of periproctal margin (only specimen like this), also with trace of domed, nearly central, anal pyramid 1.3 to 1.4 mm in diameter made up of small plates about 0.4 to 0.5 mm long surrounded by 2 to 3 rows of tiny elongate periproctals about 0.2 to 0.3 mm long (Pl. 33, fig. 16).

Six rhombs and 2 questionable demirhombs or rhombs present in standardized positions (Table 41); lowest number of rhombs for any member of Glyptocystitidae. Rhombs disjunct in large specimens, dichopores apparently confluent. Rhombs rather short (as few as 4 to 5 dichopores) and in many specimens (especially rhombs L1-L2 and L5-R6) not occupying full width of plate and not reaching central plate suture (Fig. 66F, G). (This implies that some rhombs stop adding dichopores laterally at a certain size.) Dichopores medium to very long (up to 2.1 mm long on L4) with marked rim; small specimens with conjunct rhombs because of elongate dichopores on small plates (Pl. 33, fig. 14, 16). R2-R3 and R4-R5 intermediate between demirhomb and rhomb; occupying almost full width of sutures but rhomb barely recurved toward suture from plate origins (Pl. 33, fig. 2). Dichopore spacing ranging from 0.22 to 0.24 mm, averaging 0.23 mm (13 measurements on 6 specimens). Medium-sized ridges inside excurrent half-rhombs, which have notably shorter and wider dichopores than incurrent half-rhombs; entire triangular, rectangular, or diamond-shaped area between rhomb halves elevated above dichopores (Pl. 33, fig. 2).

Ambulacra 5, medium-length, extending about one-third distance down theca from summit in deep radial sinuses on R1 to R5. R6 sharing slightly over one-third of ambulacrum I. Ambulacrum I longest, III shortest, difference in length not great; 4 to 9 ambulacral flooring plate sets and brachioles per ambulacrum; primary flooring plates fairly large and petaloid, secondary flooring plates much smaller and rounded triangular except more elongate near summit (Fig. 66C). Main and side food grooves wide but rather shallow, walls and floor smooth; side food grooves relatively short. Ambulacral cover plates biserial, alternate, relatively elongate (0.5 mm long by 0.2 mm wide), becoming somewhat larger over mouth (0.8 mm long by 0.4 mm wide). Cover plates highly ornamented with granules and small ridges (Pl. 33, fig. 22). Brachioles moderately long; on smallest complete paratype (9 mm long), brachioles 4.5 to 5.0 mm long by 0.5 mm wide and deep. (This specimen also has a tiny brachiole 0.7 mm long at the tip of ambulacrum V; see Pl. 33, fig. 13.) Brachiolar food groove protected by highly domed cover plates

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PLATE 33.

Fig. 1-23. *Quadrocystis graffhami* Sprinkle, n. gen., n. sp.; echinoderm zones from Upper Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma; 1-6, 10-16, 18-23 from Rock Crossing, of these 11, 19, 20 from 9 to 10 m below top of Pooleville, 10, 12, 18 from 10 m below top, 13-16 from 11 m below top, and 1-6, 21-23 from float 7 to 19 m below top; 7-9, 17 from Dunn Quarry 9 to 12 m below top of Pooleville. 1-6. Four side views, a summit view, and a basal view of holotype OU 8972; note slanted theca, domed summit, elongate dichopores (1, 2), granular ornament, and fairly deep basal cavity (6); X2.5. 7-9. Side views of paratype OU 8973; compare morphology with 1-4 above; X2.5. 10. Side view of paratype OU 8976 showing slightly crushed theca and ambulacrum I; X2.5. 11. Side view of paratype OU 8981; note elongate dichopores on crushed theca and short stem segment at bottom; X2.5. 12. Side view (immersed) of paratype OU 8977 showing thecal plates and "black spot" near middle of one side (only specimen showing this); X2.5. 13-16. Oblique summit, left side, right side, and enlargement of immersed periproct on small paratype OU 8974; note tiny brachiole at tip of ambulacrum V (13, 14), conjunct rhombs at this size, and remains of anal pyramid in periproct which is also bordered by small edge of L1 (15, 16); X3.0, X6.0. 17. Paratype OU 8975 showing part of periproctal margin and proximal stem with thin outer columnals bearing an equatorial groove; X2.5. 18. Paratype OU 8979; note crushed theca with disarticulated plates, brachioles on summit, and short stem segment; X3.0. 19, 20. Side and basal views of paratype OU 8982 showing base of partly disarticulated theca; X2.5. 21-23. Enlarged ambulacrum I, oblique summit, and periproct of holotype OU 8972; note medium-length ambulacra, granular flooring plates and elongate granular OO, nearly straight hydropore and small, possibly covered gonopore, granular oral cover plates, elongate dichopores, and 4 plates surrounding rounded-square periproct; X4.5, X5.3, X5.5.

about 0.2 mm long; about 2 brachiolar cover plates per brachiolar plate on each side.

Hydropore and gonopore in normal position on O1-O7 suture in holotype (Pl. 33, fig. 22). Hydropore elongate, raised, nearly straight slit about 1.9 mm long. Gonopore an elliptical pore about 0.5 by 0.3 mm on aboral side of raised hydropore (Fig. 66D); gonopore possibly covered by tiny-plated pyramid (Pl. 33, fig. 22).

Thecal plates very thin (0.25 to 0.5 mm), with sharp, medium-sized, central ridges radiating from plate centers to sides, plates in larger specimens with several smaller subsidiary ridges parallel to and on either side of main ridges forming nested triangles or diamonds, and small ridges radiating from three-corner junctions toward centers (Pl. 33, fig. 2). Central areas within rhombs raised nearly to height of chevron-shaped ridge just inside excurrent half-rhomb. Strong pustular ornament along growth lines on most plates including OO, ambulacral flooring plates, and ambulacral cover plates (Pl. 33, fig. 21, 22).

Proximal stem enlarged, medium-sized, tapering fairly slowly away from theca, mounted in a fairly large, deep, basal cavity about 2.0 to 2.5 mm deep in holotype (Pl. 33, fig. 6). Proximal stem composed of larger thin outer columnals, each having regularly spaced nodes and a central groove around the circumference (Pl. 33, fig. 17). In paratype OU 8975 (theca about 18 mm long), proximal stem tapering from 3.5 mm to 2.5 mm in diameter over a length of 9.0 mm and 15 outer columals. Distal stem unknown.

Etymology.—The species is named for Mr. A. Allen Graffham of Ardmore, Oklahoma, who collected many of the type specimens and many other Bromide echinoderms studied for this project.

Studied specimens.—Holotype OU 8972, paratypes OU 8973-8983 (all Graffham and Fay Coll.) and 1122TX101 (Graffham Coll.).

Occurrence.—All 13 specimens were found between 7 and 19 m below the top of the Pooleville Member, Bromide Formation, in the Criner Hills. The holotype and 7 paratypes are from Rock Crossing (9 to 10 m, 10 m, 11 m, and in float 7 to 19 m below top); 2 paratypes from Dunn Quarry (9 to 12 m below top); and 1 paratype from zone 3 at Culley Creek (9 to 10 m below top).

ADDITIONAL RHOMBIFERANS

The following three rhombiferans cannot be assigned to any of the known Bromide species represented by more numerous specimens. One named species may not even occur in the Bromide, although it was originally reported from this formation. These specimens are briefly described here to complete coverage of all known or reported Bromide rhombiferans.

CHEIROCYSTIS ARDMORENSIS (Bassler), 1943

Plate 27, figure 23

The holotype (USNM 93471) of *Cheirocrinus ardmorensis* Bassler (1943, p. 699, 701) was redescribed by Paul (1972b, p. 37-40) as *Cheirocystis ardmorensis:* it represents the only member of the family Cheirocrinidae reported from the Bromide. Paul's redescription and plate diagram appear adequate. The ambulacra are apparently fairly short and confined to the summit, and rhomb R1-R2 can be added to those shown in Paul's plate diagram (1972b, text-fig. 10). However, this specimen remains anomalous, because no other cheirocrinids were found in the Bromide during the present study.

We have not been able to locate the original collecting locality, listed as "Simpson group (Cool Creek formation), Criner Hills, north end of Hickory Gap, 8 miles south-southwest of Ardmore, Oklahoma" (Bassler, 1943, p. 701). Bassler (1943) used "Cool Creek formation" to refer to other specimens which are now known to occur in the Mountain Lake Member of the Bromide Formation (see Amsden, 1957, p. 4 and 23). The geographic site description resembles the well-known locality at Rock Crossing, an old road crossing on a bend of Hickory Creek where it cuts through the Bromide about 7 miles south-southwest of Ardmore. However, none of the older collectors (Loeblich, Watkins, or Graffham) nor any of the local residents I talked to had ever heard of this locality being called Hickory Gap. In contrast to the introductory statement by Bassler (1943, p. 694), I discovered that this specimen (and several others with USNM 93 numbers that are described in this paper) came from much older USGS collections; the original label for *C. ardmorensis* has the locality number 202T which belongs to a USGS collection made by C. A. Reeds and E. O. Ulrich in 1908. Unfortunately, this locality is not marked on their field-locality map, which is in the USGS files. Frederickson (?1957) shows no additional Ordovician outcrops along Hickory Creek south of Rock Crossing, where Hickory Gap should be located, and

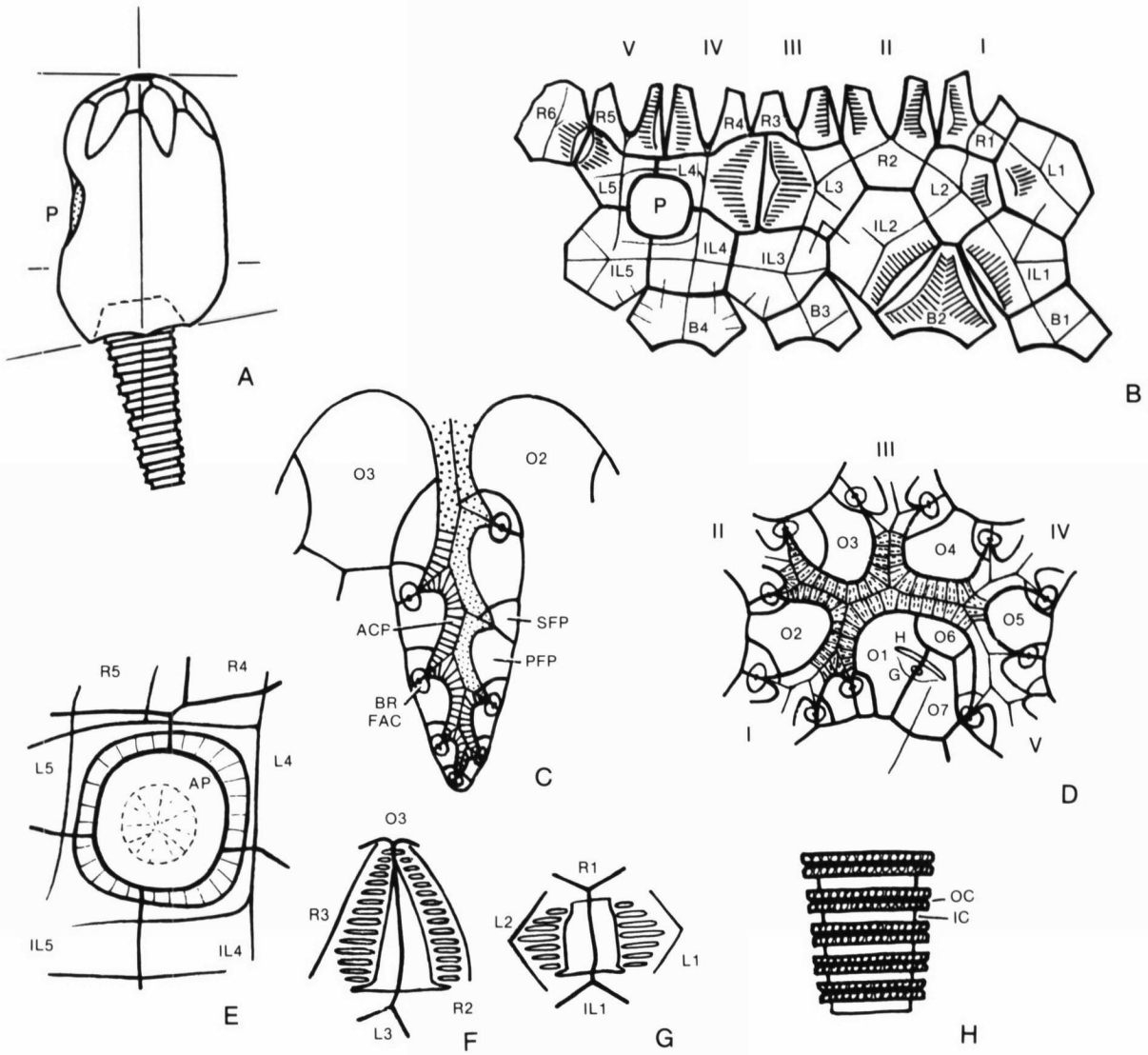

Fig. 66. *Quadrocystis graffhami* Sprinkle, n. gen., n. sp., upper Pooleville Member, Bromide Formation, Criner Hills, southern Oklahoma. A, Outline of a fairly large specimen showing elongate shape with stem attachment not perpendicular to thecal axis, periproct (P) near midheight, maximum width (short horizontal lines) below midheight, fairly long ambulacra extending down theca with OO visible in side view, and stem mounted in deep basal cavity. B, Plating diagram based mostly on holotype OU 8972; note deeply cleft RR, R1 and R6 sharing ambulacrum I, small R3 to R5, medium-sized periproct (P) surrounded by 4 plates, small number of rhombs, some of which have unusual morphology, and straight interbasal sutures on B2. C, Ambulacrum II in a fairly large specimen showing fairly elongate shape, primary and secondary flooring plates (PFP, SFP), wide main food groove protected by small elongate ambulacral cover plates (ACP), and brachiole facets (BR FAC) with a central depression, much enlarged. D, Summit view of holotype OU 8972; note ornamented oral cover plates hiding mouth (same in all other specimens), elongate O1 to O7, and position of nearly straight slitlike hydropore (H) and elliptical gonopore (G) on O1-O7 suture, X4.8. E, Periproct showing 4 surrounding thecal plates with their ridgelike ornament, near-junction of 4 plates at L4-L5-R4-R5, and likely size of central anal pyramid (AP); based on holotype OU 8972 and small paratype OU 8974, X5.2. F, G, Two unusual rhombs in holotype OU 8972; F, R2-R3 demirhomb or rhomb, which occupies nearly entire suture but hardly recurves at lower end; G, L1-L2 rhomb, which does not reach central suture or occupy its entire width, both much enlarged. H, Proximal stem in a fairly large specimen showing outer columnals (OC) with an equatorial groove and rows of pustules and smaller, apparently smooth, inner columnals (IC); mostly based on paratype OU 8975, much enlarged.

he shows the entire Lower Paleozoic section terminated by a fault about a mile an a half southeast of Rock Crossing, to the east of Hickory Creek.

The holotype of *Cheirocystis ardmorensis* may have been collected from the Lower Bromide, or it may have come from a lower formation in the Simpson Group, where cheirocrinids are present (R. D. Lewis, pers. commun.), or even from the top of the Arbuckle Group, both of which are exposed in the Criner Hills (although not along the main part of Hickory Creek). Until additional specimens are found or the locality is conclusively determined, this specimen cannot be definitely assigned to the Bromide Formation.

PIROCYSTELLA? sp. from Fittstown Roadcut

Plate 27, figures 21, 22

A single fairly well-preserved specimen (OU 9089), supposedly from the Lower Echinoderm Zone excavation at Fittstown Roadcut, has unusual surrounding matrix and cannot be assigned to any of the known Bromide species. The matrix is a bioclastic limestone with numerous, floating, well-rounded, quartz grains of medium-sand size. This is an unusual matrix for the Lower Echinoderm Zone at the Fittstown Roadcut, but does occur in the beds just below the zone (see Measured Section 11A in Appendix).

The specimen has a cylindrical theca about 21 mm long by 13 mm wide; the ambulacra are short, confined to the summit, and moderately indent the radials (Pl. 27, fig. 21). The infralateral circlet appears open, but the lateral circlet may be closed with a near-junction of 4 plates at IL2-L2-L3-R2; the medium-sized periproct is surrounded by IL4, L4, and L5. The proximal stem is unusual; it tapers fairly rapidly from a diameter of 6.0 mm at the theca and is made up of fat, innertube-shaped, outer columnals with fine ridges (Pl. 27, fig. 21, 22). Rhombs include B2-IL1, B2-IL2, L1-L2, L3-L4, R1-R6, R1-R2, R2-R3, R4-R5, and R5-R6; demirhombs include IL4-L4, IL4-IL5 (unusual; see Table 41), L3-R2, L3-R3, and L5-R6. Dichopore spacing is about 0.22 mm (3 measurements). Thecal plates have broad central radiating ridges and fine growth lines; the diamond-shaped or triangular areas inside the rhombs are raised. One to two medium-sized biserial brachioles with domed cover plates are preserved on one side of the summit; a second disarticulated specimen is scattered above the summit of the one described here.

This specimen has some features resembling *Pirocystella* (short ambulacra, location of most rhombs), some resembling *Glyptocystella* (thecal shape, plate ornament, stem size), and some not found in either (unusual stem, closed lateral circlet). Based on the surrounding matrix, it may not have come from the Lower Echinoderm Zone, but from the sandy beds immediately below. Because only one specimen is known and because of the unusual morphology, it has not been given a new specific name here.

Pooleville Rhombiferan from Fittstown Roadcut

Plate 27, figure 24

A single rhombiferan specimen (OU 9090), one of the few echinoderms known from the Pooleville Member in the Arbuckle Mountains, was collected by R. O. Fay from the float 12 to 15 m below the top of the Pooleville in his Fittstown Roadcut measured section (see Appendix, Measured Section 11A). This part of the Lower Pooleville was apparently deposited in subtidal conditions, in contrast to the Upper Pooleville at this locality, which was deposited in an intertidal to supratidal environment (Longman, 1976).

The specimen consists of a number of disarticulated thecal plates, a proximal stem segment, and 10 to 12 well-preserved brachioles in several groups (Pl. 27, fig. 24). At least eight thecal plates are present, an unidentified basal, three infralaterals or laterals, R2, R3, and possible ?R1 and ?R6. Based on the nearly flat adoral edges of the radials, this form had short ambulacra, and therefore cannot be assigned to either of the Pooleville genera (*Tanaocystis* or *Quadrocystis*) occurring in the Criner Hills. R2 does not appear to interrupt the lateral circlet (implying a closed circlet), and most plates have high central radiating ridges and granular growth lines. The preserved rhombs (R1-R2, R2-R3, ?L5-R6) and demirhomb (?L3-R2) have elongate dichopores with prominent rims and a spacing of from 0.22 to 0.27 mm (4 measurements). Several incomplete brachioles are 5.0 to 7.0 mm long, biserially plated and of medium size, and have a biserial set of high-domed cover plates (Pl. 27, fig. 24) with about 1.8 brachiolar cover plates per brachiolar plate. The proximal stem is moderately enlarged, tapers fairly slowly away from the thecal attachment, and has coarsely ridged outer columnals, another major

difference from known Pooleville glyptocystitids.

Because of the poor preservation, this rhombiferan specimen cannot be conclusively identified even to family; however, it is not a pleurocystitid, and, based on other Bromide rhombiferans, is more likely to be a glyptocystitid than anything else. The short ambulacra, ridged proximal stem, and apparently open lateral circlet separate it from both Pooleville genera occurring in the Criner Hills, and the elongate dichopores and open lateral circlet separate it from *Strabocystis* in the underlying Upper Echinoderm Zone at the top of the Mountain Lake Member. It also cannot be assigned to any known genus or species occurring lower in the Bromide. Although unidentifiable at present, this specimen is one of the few echinoderms found in the Pooleville Member in the Arbuckle Mountains, and indicates that echinoderms were living in the northeastern Arbuckles during deposition of the lower Pooleville.

PLEUROCYSTITIDS

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Among the Rhombifera, pleurocystitids are probably the most enigmatic in their ancestry. These flattened forms appear to have been bottom sweepers (surface detritus feeders); however, they are probably derived from primitive suspension feeding glyptocystitid ancestors. The adaptation to bottom sweeping involved major modification: thecal flattening, enlargement of the periproct, and development of two long free brachioles.

Praepleurocystis watkinsi (Strimple) of the Pooleville Member, Bromide Formation, shows some morphological features intermediate between those of most flattened pleurocystitids and those of the inferred early glyptocystitid stem group. The generally accepted ancestor of the pleurocystitids is a pentaradial glyptocystitid (see Bather, 1900; Paul, 1968a, 1972b; Sprinkle, 1974; Broadhead, 1974), but an essentially bilateral glyptocystitid stock seems to me a more likely stem group for a number of reasons.

Pleurocystitid phylogeny.—Perhaps the most common recurring theme in the Echinodermata is the establishment of bipentaradial symmetry. This symmetry seemingly originates by splitting of the ends of primitive transverse ambulacra (see Parsley and Mintz, 1975, p. 12) and by an anterior sagittal extension or split adjacent or nearly adjacent to the mouth opening. Posterior sagittal extension has not been observed, probably because of the usually fixed posterior position of the hydropore and gonopore with relation to the peristome. The "interior plumbing" of these pore structures apparently precludes posterior extension of the ambulacra. In *Macrocystella*, the earliest glyptocystitid rhombiferan (Paul, 1968a) or rhombiferan-like genus (an eocrinoid according to Sprinkle, 1973), the bilateral nature of the five-part ambulacral system is strongly evident and the column is rhombiferan in nature, but the pectinirhombs are not yet present.

In the proposed evolutionary scenario for the pleurocystitids, the stem group is even simpler in its ambulacral symmetry than *Macrocystella*. I submit that it had a simple transverse ambulacrum perhaps with brachioles arranged around it as in *Echinoencrinites* von Meyer, from the Lower Ordovician of Europe. (The Echinoencrinitidae, ranging throughout the Ordovician, perhaps retain a number of the primitive features found in the suspension feeding stem group). In all other respects the theca and column of *Macrocystella* relative to the Rhombifera are probably quite primitive. The groups radiating from the proposed stem group manifest two morphological trends, each related to feeding habit. The first of these was enlargement of the subvective system, that is, adaptation of pentaradial symmetry as in *Macrocystella* to increase efficiency of suspension-feeding. The Glyptocystitidae, Cheirocrinidae, etc., exploited this subvective mode. The second morphological trend was modification of the ambulacral system to increase efficiency of feeding on bottom detrital material. At least two lineages are involved, the Pleurocystitidae and a separate group characterized by *Plethoschisma* Sprinkle, a closely related homeomorph.

In exploitation of bottom detrital material, the primitive transverse ambulacrum probably grew shorter and food was collected by an elongated brachiole at each end of the groove. Other brachioles, if ever present, would have been lost, for it is likely that a pair of long brachioles was the most efficient feeding arrangement. Each brachiole could sweep through an arc of 90 degrees on the sea floor and not overlap or interfere with the other. Many brachioles probably would have been inefficient in terms of food gathered relative to energy expended. It is also probable that several of the proximal brachiolar plates were incorporated into the theca (see Parsley, 1970, p. 155). This is an atypical feature among blastozoans, but the size, shape, and continuity of these plates with the more distal brachiolar plates supports the suggestion (Fig. 67, 68).

Attempts to homologize pleurocystitid brachioles with those of supposed pentaradial ancestors are less than convincing. Forms intermediate between the pentaradial ambulacral systems of glyptocystitids and the bilateral system of pleurocystitids have not been seen. Therefore, an evolutionary history without a pentaradial stage is reasonable, given our current knowledge of the fossil record. The scenario is, of course, speculative and depends to some degree on the interpre-

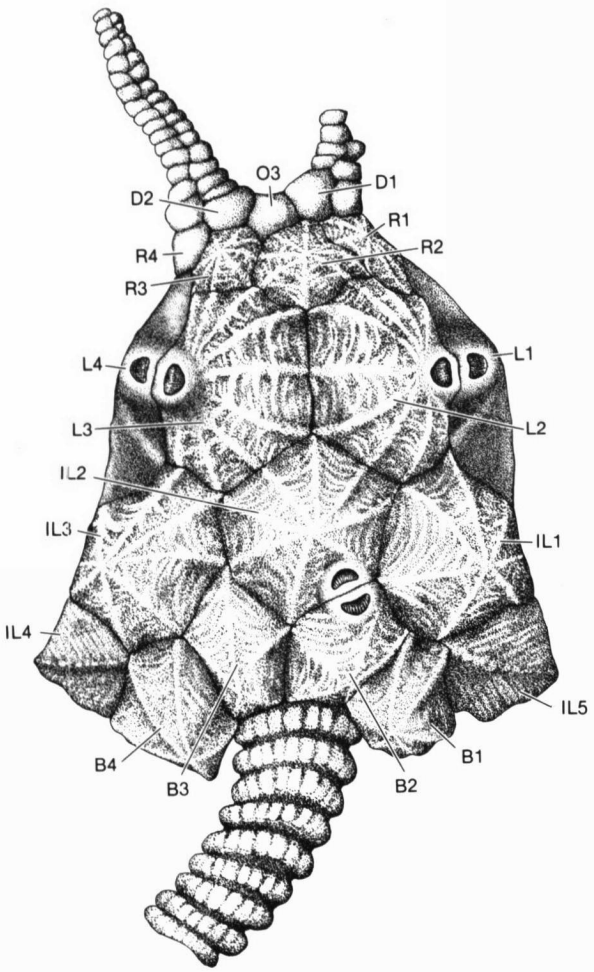


Fig. 67. Reconstruction of dorsal face of *Praepleurocystis watkinsi* (Strimple); plates: B, basal; IL, infralateral; L, lateral; R, radial; O, oral; D, distal plate (probably brachiolar plates incorporated into theca; see Parsley, 1970, p. 140).

tation that brachiole plates have been incorporated in the theca.

Rhomb aquisition, in the primitive stock and in all glyptocystitid lineages, must have occurred quickly (see Paul, 1968a, p. 594-596), with those in the L1-L2, L3-L4, and B2-IL2 positions present and functionally important at an early stage in the pleurocystitids. However, once rhombs were present, there was a recurrent trend to reduce their number and, in some, their size. Usually reduction in rhombs seems to accompany expansion of the periproctal area, for example, in *Amecystis*, which has a very large periproct and no rhombs. In *Deltacystis* Sprinkle (1974), remnants of rhombs are present internally but the periproct is quite small, suggesting that in some genera rhomb reduction was independent of the size of the periproct. Some reduction of rhomb number and size may have been a function of reduction of thecal volume resulting from flattening. Also, periproctal pumping circulated body fluids efficiently past the internal rhomb surfaces so that smaller rhomb areas were needed for gaseous exchange. *Praepleurocystes* has three large functional rhombs and a high thecal volume. Perhaps its relatively small periproct and limited flexibility made large efficient rhombs necessary. Pleurocystitids with large periprocts usually have small platelets over the area, a trait that bespeaks, with reduction in platelet size, the increasing role of internal pumping. In the soft tissues, pumping was probably done by the cloaca (see Broadhead and Strimple, 1975). While pumping probably made possible some increase in subvective efficiency, literally pulling the food string through the gut, its major function was probably respiratory.

Flattening of the theca in pleurocystitids is probably a selective response to the need for hydrodynamic stability. The lower profile would produce less lift in bottom currents. Pectinirhombs and raised prosopon (growth lines and radiating ridges) would act as spoilers to reduce lift, enhance drag, and thereby help keep theca and brachioles on the bottom. The pronounced prosopon of *Praepleurocystis* seems to support the contention that it serves a hydrodynamic function because more flattened pleurocystitids are much smoother.

Superfamily GLYPTOCYSTITIDA Bather, 1899, nom. transl.

Family PLEUROCYSTITIDAE Neumayr, 1889

Genus PRAEPLEUROCYSTIS Paul, 1967b

Type species.—*Pleurocystites watkinsi* Strimple, 1948.

Diagnosis.—Pleurocystitidae with 3 disjunct pectinirhombs; gonopore and hydropore shared by O1 and O6 (modified slightly from Paul, 1967b, p. 120).

PRAEPLEUROCYSTIS WATKINSI (Strimple), 1948

Plate 34, figures 1, 5, 7, 9-11, 13-19; Figures 67, 68

Pleurocystites watkinsi Strimple, 1948, p. 761-764, pl. a, fig. 1-3.

Praepleurocystis watkinsi (Strimple), Paul, 1967b, p. 120.

Pleurocystites watkinsi Strimple, Parsley, 1970, p. 171-177, pl. 24, fig. 2, pl. 28, fig. 3-8, text-fig. 5.

Praepleurocystis nodosus Westphal, 1974a, p. 80-81, pl. 1, fig. 8-11, text-fig. 2, 3.

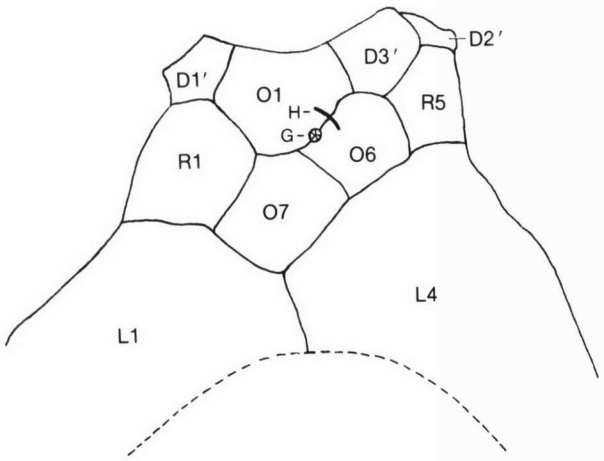


Fig. 68. Plate outlines of the distal ventral surface of *Praepleurocystis watkinsi* (Strimple), much enlarged. Symbols as in Figure 67 except D, ventral distal plate (probably brachiolar plates incorporated into theca); H, hydropore; G, gonopore with valvular pyramid. (Modified from Parsley, 1970, p. 173.)

Diagnosis.—Theca nearly bilaterally symmetrical in outline; anal surface with broad "marginal" plates; periproctal area reduced; rectal lobe only slightly extended; plate O6 present; IL1 and IL3 transversely attaining periproctal margin; dorsal surface markedly convex, with 3 oval, elevated, disjunct pectinirhombs with confluent dichopores.

Description.—Theca subtriangular in outline, nearly bilaterally symmetrical. Rectal and abrectal lobes subequal on anal or ventral surface, but appearing alate (nearly symmetrical) when viewed dorsally (Pl. 34, fig. 1, 5). In transverse profile theca with narrow, alate margin and nearly hemispherically convex dorsal surface. Each side of nearly planate ventral surface sloping gently dorsally toward axial plane.

"Marginal" plates comprising periproctal girdle (B1, B4, IL1, IL3, IL4, IL5, L1, L4) unusually broad, especially at proximal angles and distal ends of L1 and L4 (Pl. 34, fig. 5).

B2 and B3 together forming broad V, distally in some specimens atypically suturing with laterals L2 and L3 respectively (Pl. 34, fig. 1). B2-IL2 suture with pectinirhomb, B1 and B4 lateral to B2 and B3 on dorsal face; usually subquadrate in outline. B2 and B3 forming thin adcolumnal margin on anal face. IL4 and IL5 not produced toward sagittal plane (Fig. 67). (Infralateral series is especially atypical for pleurocystitids in size and plate outline. Most pleurocystitids have an evenly hexagonal IL2 plate, which is in contact with IL1 and IL3; in *P. watkinsi*, the subquadrate IL2 is sometimes completely separated or barely in contact because of the suturing or near-suturing of B2 and B3 with L2 and L3, respectively.) IL1 and IL3 irregular in outline on dorsal face; on ventral face slightly tapering, then flaring toward periproctal margin. IL4 and IL5 subquadrate, occupying proximal or "corner" angles on dorsal and ventral surfaces (Fig. 67; Pl. 34, fig. 5).

"Somatic" lateral plates L2 and L3 as large as or larger than IL2. (IL2 is usually the largest plate on the pleurocystitid dorsal surface.) L2 and L3 lacking normal pentagonal outline of other species; irregular, with gently curved sutures. "Marginal" laterals L1 and L4 essentially vertical on dorsal surface, when viewed in profile subhemispherical in outline on dorsal face; on anal face, largest and widest plates of periproctal girdle (Pl. 34, fig. 5, 9, 16). L1 and L4 attaining greatest width adorally on ventral surfaces adjacent to smaller radial and oral plates; L1-L4 suture longest in any pleurocystitid (Fig. 68). (In most pleurocystitid genera and species, these laterals attenuate adaxially and join with a short suture.)

"Somatic" radials R2 and R3 relatively larger than in most species but similar in outline and position. R4 on dorsal face and R5 on ventral face typical in size, shape, and position. R1 on ventral face unusually long, pentagonal instead of subquadrate, abnormally wide; R1 on dorsal face normal width and shape. Extra ventral distal "somatic" plate, O6, present. (This third element of O1 triad, O1, O6, O7, is present in most glyptocystitids.) Subquadrate O6 sharing hydropore and gonopore with O1 (usually shared by O1 and O7) (Fig. 68).

Aboral portion of O7 partly intercalated between distal adaxial ends of L1 and L4. Because of unusual shortening of O1, pentagonal O7 plate atypically suturing with R1.

Abbreviated O1 plate unevenly pentagonal in outline, not sutured with L1. On dorsal face, O3 (opposed to O1) also relatively reduced in size but typical in pentagonal outline and position.

Three well-developed, oval, disjunct pectinirhombs with confluent dichopores. Adsutural vestibule rim (rhomb cross bar) not present in early juvenile stages, hence, normal conjunct rhombs in early stages. Rarely, adsutural rims not present in adult stages (Pl. 34, fig. 7). Late juvenile and adult adsutural and peripheral rims greatly thickening in ontogeny, adsutural rim often most elevated part of rhomb (Pl. 34, fig. 1, 11, 18, 19). B1-IL2 rhomb with 7 to 10 dichopores; L1-L2 rhomb with 8 to 10 dichopores; L3-L4 rhomb with 8 to 13 dichopores. Number of dichopores somewhat related to theca size; however, some large individuals with fewer dichopores than smaller specimens, especially in L3-L4 and IL2-B2 rhombs. In-

ternally dichopore field oval in outline, rhomb broadly triangular longitudinally (Pl. 34, fig. 17).

Hydropore and gonopore large, usually on O1-O6 suture (Fig. 68), gonopore rarely at O1-O6-O7 junction (Pl. 34, fig. 13). Gonopore in some with unique valvular apparatus of 5 wedge-shaped platelets (Pl. 34, fig. 13).

Prosopon of dorsal surface highly distinctive, resembling that of *Coopericystis* Parsley. Principle radiating ridges extending from umbones of L2, L3, and IL2. On laterals umbo coinciding with abmarginal apex of pectinirhomb rim. Lesser ridge foci near margin of IL1 and IL3; ridges of IL1 and IL3 merging with others on IL2, L2, and L3. Concentric prosopon on each plate manifest as sharp, steep-sided ridges, under normal light dominating radial ridges (except at adoral end of theca where prosopon not well developed). Radial and concentric ridges paralleling plate margins, relatively straight in most specimens, but irregularities in plate outline in some resulting in slightly sinuate ridges (Pl. 34, fig. 1, 11).

Periproct reduced compared to most pleurocystitids, occupying 40 to 55 percent of ventral side, size and shape varying with individual. Periproct margin with incised shelf for anchoring of periproctals; shelf widest on L1 and L4, narrowest around anal pyramid on B4 and IL4 (Pl. 34, fig. 5). Platelets over shelf narrow, elongate parallel to periproct margin (Pl. 34, fig. 5). Central periproct platelets usually irregularly hexagonal, 2 to 3 times thicker than platelets over incised shelf. Sides of central periproct platelets at right angles to outer surface, suggesting little flexibility. Maximum length of central periproctals about 1 mm, maximum thickness about one-third mm.

Paired brachioles typical of pleurocystitids, probably about 1.5 to 2 times length of theca, apparently rotated near mouth so that biserial brachiolar plates covering food groove opening ventrally (Pl. 34, fig. 15). Brachiolar covering plates slightly large for a pleurocystitid, normally opposed to slightly offset. Column essentially as in other pleurocystitids.

Material.—Holotype USNM 4640, Springer Coll.; topotypes from Rock Crossing OU 9163 and 9166; other figured specimens include OU 9164-9165 and 9167-9169; several unfigured specimens and plates in OU, TX, and Watkins collections.

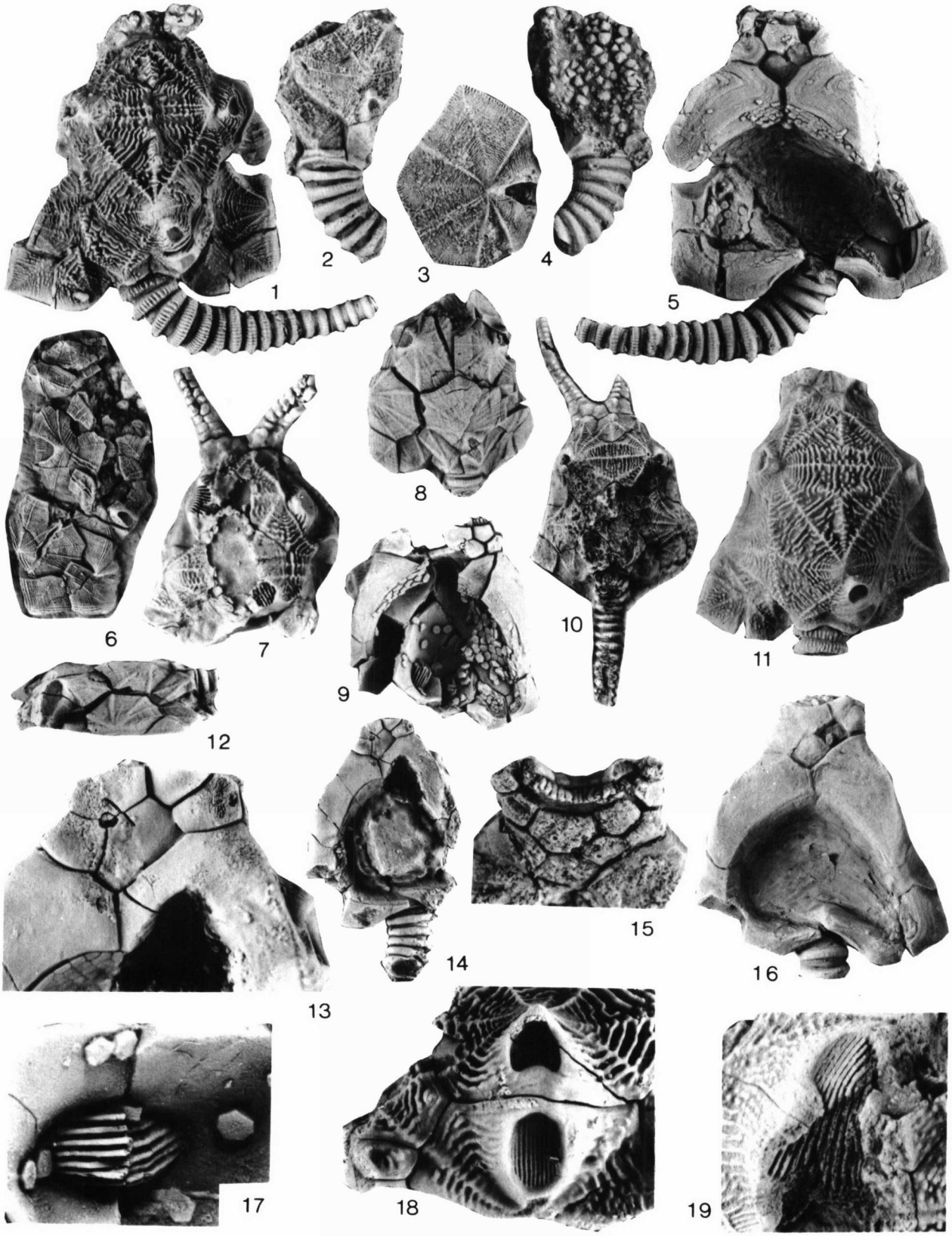
Occurrence.—In Oklahoma this species is found in the Pooleville Member of the Bromide Formation in the Criner Hills: 5 specimens (including holotype) from Rock Crossing; 14 from Dunn Quarry; 1 from Rudd Quarry; 2 from Culley Creek. Outside Oklahoma, 2 specimens are known, one from near Fennimore, Wisconsin in the McGregor Member of the Platteville Formation (as *Praepleurocystis nodosus* Westphal, 1974a) and one from Luttrell, Tennessee in the Lincolnshire Limestone (Parsley, 1970, pl. 24, fig. 2).

Discussion.—Terminology for thecal plates at the oral end of the theca (from Parsley, 1970, p. 155) is based on the assumption that the plates adjacent to the food groove are brachiolars incorporated in the theca, hence D or distal plates. Some authors, for example Paul (1967b, 1968a) and Broadhead (1974), retain a terminology suggesting that the brachioles are homologous with those of a pentaradial glyptocystitid stem group. As noted, I do not hold that view.

Praepleurocystis is unusual for a pleurocystitid with its inflated theca, relatively small periproct, rather inflexible periproctal plating, and coarse prosopon. The relatively smaller periproct is covered with thicker, tightly sutured platelets that suggest a surface less flexible than those of most pleurocystitids. (Whatever the function of this flexible surface in other pleurocystitids, it was probably minimal in *Praepleurocystis.*) If pumping was indeed partly respiratory, the three efficient pectinirhombs probably more than compensated for any pumping inefficiency caused by an inflexible periproctal surface. The elevated rims and the dividing adsutural vestibule rim would enhance flow through the dichopores. Rhomb openings are smaller on L2, L3, and IL2, and larger on L1, L4, and B2. The smaller openings may well be intakes; water propelled through the dichopores by ciliary action would still exert friction so that larger openings for the exhaust would be necessary to promote even flow and to reduce "back pressure." This current direction is opposite to that suggested by Paul (1967b, 1968b). The large dichopore folds extend well into the thecal cavity (Pl. 34, fig. 17) and were doubtless efficient in gaseous exchange with body fluids. The dichopore surface area was also large enough that circulatory aid from a flexible periproctal surface was not necessary.

The brachioles are in most respects typical of those on other pleurocystitids. However, adorally they are rotated so that the food groove and covering plates at and near the mouth face the substrate (Pl. 34, fig. 15). This feature may also characterize *Amecystis*. The purpose of a ventral-facing proximal food groove is unclear.

The hydropore and gonopore are atypically located between O1 and O6. The hydropore is unusually wide for a pleurocystitid. The gonopore is the largest in any pleurocystitid; many specimens pre-



serve a five-plate valvular apparatus, rare among pelmatozoan echinoderms. Perhaps such a large opening indicates the presence of a brood sac. Because not all *Praepleurocystites* specimens seem to have this gonopore pyramid (perhaps only a function of preservation?), some sexual dimorphism may be present. Unless this genus is hermaphroditic, it seems reasonable to assume that the gonopore pyramids found only on some specimens are present in females. This valvular structure was first illustrated by Paul (1967b, p. 113, fig. 8), but he did not comment on it.

Growth is nearly isometric, except that smaller (juvenile) specimens tend to be relatively narrower than larger (adult) specimens.

Westphal's (1974a) new species *Praepleurocystis nodosus* is based on a single solution-worn specimen from the Middle Ordovician Platteville Formation, near Fennimore, Wisconsin. Its nodose ornament appears to be primarily the result of partial solution of the surface. What can be seen of its plates, etc., place it within the range of variability of *P. watkinsi;* hence, its inclusion here in the type species.

Genus PLEUROCYSTITES Billings, 1854

PLEUROCYSTITES SQUAMOSUS Billings, 1854

Plate 34, figures 2-4, 6, 8, 12

Diagnosis.—Theca variable in outline; prosopon on rhomb face variable manifestations of concentric growth lines and radiating ridges; rectal lobe common but usually not greatly produced. Three well-developed pectinirhombs, diamond-shaped to oval in outline. Periproct covered with about 500 usually hexagonal platelets (modified from Parsley, 1970, p. 162).

Description and synonymy.—For description and synonymy of *P. squamosus*, see Parsley (1970, p. 161-166, pl. 21, fig. 1-5; pl. 22, fig. 1-9; pl. 23, fig. 1-6; pl. 24, fig. 3-5, 8, 9; pl. 26, fig. 6-9; text-fig. 1-4).

Material and occurrence.—Three incomplete specimens and several plates of this species are known from the Bromide. One specimen (OU 9070) and an isolated plate (OU 9071) are from the Upper Echinoderm Zone at the top of the Mountain Lake Member at Sulphur. Two specimens (1441TX1, Todd Coll., and OU 9172) are from the overlying Pooleville Member, the first from the lower Pooleville at Fittstown Roadcut in the northeastern Arbuckles, and the second from the upper Pooleville at Culley Creek in the Criner Hills.

Discussion.—Normally *Pleurocystites squamosus* is found in rocks of Trentonian age, and its occurrence in the Bromide greatly extends its range. The Bromide specimens easily fall within the range of species variation (see Parsley, 1970, p. 161-166), and despite the anomalous age of these specimens, there is no reason to create a new species to accommodate them.

The rather high wall-like rims surrounding the rhombs may have aided in reducing turbulence in water entering the large dichopore folds, thus facilitating a more rapid flow rate and increasing respiratory efficiency (Pl. 34, fig. 2, 6).

PLATE 34.

Fig. 1, 5, 7, 9-11, 13-19. Thecal morphology of *Praepleurocystis watkinsi* (Strimple); Pooleville Member, Bromide Formation, Criner Hills, Oklahoma. 1, 5. Dorsal and ventral views of theca with proximal column attached; note holoperipheral growth lines on ventral plates L1 and L4 and atypical adoral extension of B2 and B3 to adjoin L2 and approach L3 (1); OU 9163, Rock Crossing; X1.5. 7. Dorsal view of theca with proximal brachioles attached; note the lack of adsutural vestibule rims on all 3 pectinirhombs, OU 9164, Dunn quarry; X2.5. 9, 17. Ventral views of distorted incomplete theca with interior structure of B2-IL1 pectinirhomb intact, seen in closeup in 17, OU 9165, Dunn Quarry; X1.5, X6. 10. Dorsal view of theca with proximal brachioles and proximal column attached, OU 9166, Rock Crossing; X1.35. 11, 16. Dorsal and ventral views of holotype USNM 4640, Springer Collection, Rock Crossing; X2. 13, 14, 18. Enlargement of adoral ventral theca, ventral view of theca with proximal column attached, and enlarged lateral view of L3-L4 pectinirhomb with well-developed adsutural vestibule rim; note the well-preserved valvular pyramid of the gonopore (13), OU 9167, Dunn Quarry; X4.5, X1.5, X4.5. 15. Adoral ventral view of theca showing ventrally directed food groove and dorsal series of brachiole covering plates, OU 9168, Dunn Quarry; X4. 19. Eroded pectinirhomb with adsutural vestibule rim removed but showing continuous nature of the folds in the pectinirhombs, OU 9169, Rudd Quarry; X2.5.

Fig. 2-4, 6, 8, 12. Thecal and plate morphology of *Pleurocystites squamosus* Billings; upper Mountain Lake and Pooleville members, Bromide Formation, Oklahoma. 2, 4. Dorsal and ventral views of proximal part of theca and proximal end of attached column, OU 9170, Upper Echinoderm Zone, Mountain Lake Member, Sulphur; X2. 3. Isolated plate, probably L3, OU 9171, Upper Echinoderm Zone, Mountain Lake Member, Sulphur; X2. 6. Disarticulated incomplete specimen OU 9172, Pooleville Member, Culley Creek; X2. 8, 12. Dorsal and left lateral views of nearly complete theca 1441TX1, Todd Collection, lower Pooleville Member, Fittstown Roadcut; X2.5.

EUMORPHOCYSTIS

Ronald L. Parsley

Tulane University

Genera of the echinoderm class Diploporita are identified by the presence of diplopores on most of their thecal plates. Thecae are polyplated, with little apparent plate order except for the basals and peristomals. In glyptosphaeritid diploporites, narrow epithecal food grooves cross the theca in paths that range from straight (longitudinal) to branching or zigzag. On each thecal plate that the main groove crosses, there is at least one side branch and a base for what is presumed to have been a biserial, exothecal brachiole. The other generally recognized major superfamily group is the sphaeronitids. The majority of these genera have bunches of brachiole bases set very close to the ends of the short main food grooves. Others have somewhat longer side branches that connect brachiole bases set out from the distal ends of the main grooves but always on the upper surface of the theca.

Many diploporites have a pentameral subvective system (*Eumorphocystis*), but others, especially in the Sphaeronitida, retain the primitive transverse system (Parsley and Mintz, 1975, p. 12), which branches aborally to form a four-part system (*Sinocystis*). The periproct and the hydropore-gonopore systems open in the CD interray of pentagonal diploporites and are regarded as posterior in position. In nonpentagonal diploporites these orifaces are also thought to be in a posterior position.

Among the pentameral diploporites, the Bromide genus *Eumorphocystis* Branson and Peck, 1940, is of special interest because of its unusual epithecal subvective system, which was known previously only from the holotype. Nothing was known, however, of its column or exothecal appendages. New material shows that the genus has exothecal triserial ambulacra that are unique among "pelmatozoan" Echinodermata. These tribrachials are also pinnate, a feature rare among noncrinoid "pelmatozoans." *Eumorphocystis* seems similar to glyptosphaeritid genera in a number of features, but the unusual subvective system warrants placement of the genus in its own superfamily.

Little is known of diplopore growth or the accompanying soft part morphology (see Paul, 1972a, p. 5-7). Most diplopores in *Eumorphocystis* are crowded onto secondary plates added in circlets around the primary thecal plates (see Paul 1971, p. 15-18). Primary plates add diplopores in later stages of ontogeny and thus usually have most diplopores near their margins, with few scattered in the mid-portions. The presence of the later formed diplopore-bearing plates clearly indicates a relationship between diplopore number (presumed respiratory surface area) and thecal volume.

Eumorphocystis has several junior synonyms. *Regnellicystis* Bassler, 1950, from the Benbolt Formation of Virginia is based on an immature specimen made up mostly of primary and small secondary plates. *Strimplecystis* Bassler, 1950, is based on a fragment of a large specimen having both primary and secondary plates as well as part of the ambulacra, with pinnules; the specimen, like all the other Bromide specimens of *Eumorphocystis*, is from the Lower Echinoderm Zone, Mountain Lake Member of the Bromide Formation. *Eumorphocystis* is apparently the only diploporite found in the Bromide Formation.

Class DIPLOPORITA Müller 1854, nom. transl. Paul, 1968b

Superfamily EUMORPHOCYSTOIDEA Branson and Peck, 1940, nom. transl.

Diagnosis.—Diploporites with exothecal triserial pinnulate appendages (tribrachials).

Discussion.—The exothecal appendages and epithecal parts of the subvective system are sufficiently different to remove this monotypic family group from the superfamily Glyptosphaeritida Bernard (see Kesling, 1963, 1968). Other genera of the Glyptosphaeritida do not have exothecal extensions of the main branches of the epithecal subvective system (see Kesling, 1968, p. 234-240).

Family EUMORPHOCYSTIDAE Branson and Peck, 1940, emend.

Diagnosis.—Pentaradial diploporites with pinnulate exothecal tribrachials, brachiole bases retained on epithecal subvective plates.

Discussion.—Kesling (1963, 1968) assigned *Eumorphocystis* to the family Protocrinitidae and, based on the thecal characteristics, it is quite similar to other genera in this family. However, the unique ambulacral system is sufficient to place it in its own monotypic family, the Eumorphocystidae, as proposed by Branson and Peck, 1940.

Genus EUMORPHOCYSTIS Branson and Peck, 1940

Type species.—*Eumorphocystis multiporata* Branson and Peck, 1940.

Diagnosis.—Theca globular to oval in profile, subcircular in cross section, composed of between 130 and 700 plates; primary plates with prominent radiating ridges, few diplopores. Secondary plates crowded with diplopores, surrounding primary plates. Pentaradial subvective system with exothecal pinnulate tribrachials; epithecal part with normal brachiole bases. Periproct in CD interray, covered by small irregular platelets. Hydropore-gonopore on aboral edge of posterior peristome plate.

EUMORPHOCYSTIS MULTIPORATA
Branson and Peck, 1940

Plates 35, 36; Figures 69-71

Eumorphocystis multiporata Branson and Peck, 1940, p. 89-92, pl. 13.

Regnellicystis typicalis Bassler, 1950, p. 276-277, p. 275, fig. 6-8.

Strimplecystis oklahomensis Bassler, 1950, p. 277, p. 275, fig. 19.

Diagnosis.—The diagnosis for this monotypic genus is the same as the generic diagnosis above.

Description.—Theca globular in immature specimens (Pl. 36, fig. 1, 2, 9, 11) to elongate oval in mature individuals (Pl. 35, fig. 2-5, 7), nearly circular in cross section (Pl. 35, fig. 9, 11; Pl. 36, fig. 1, 9), of approximately 130 to 700 irregularly polygonal plates. Known specimens ranging from 8 mm in thecal height (Pl. 36, fig. 10, 11) to 51 mm (holotype) (Pl. 35, fig. 4, 7). Only regularly arranged plates 4 large basals (Pl. 35, fig. 10, 11; Pl. 36, fig. 12) and 5 peristomals (Pl. 35, fig. 1, 9, 12; Pl. 36, fig. 21) (deltoids of Branson and Peck, 1940, p. 89, 90). Two or three "generations" of plates between basals and peristomals. Juvenile specimens showing 2 generations of plates, primaries and secondaries. (The theca in very early stages may be made up only of primaries.) Both primaries and secondaries added as thecae grow, each distinguished by ornament and position relative to other primaries.

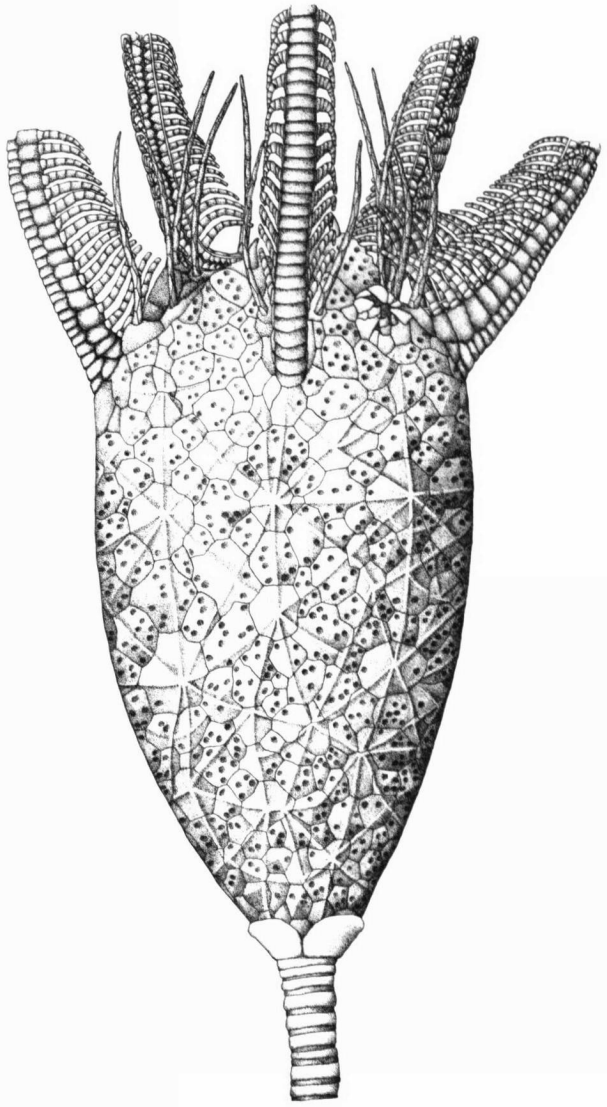
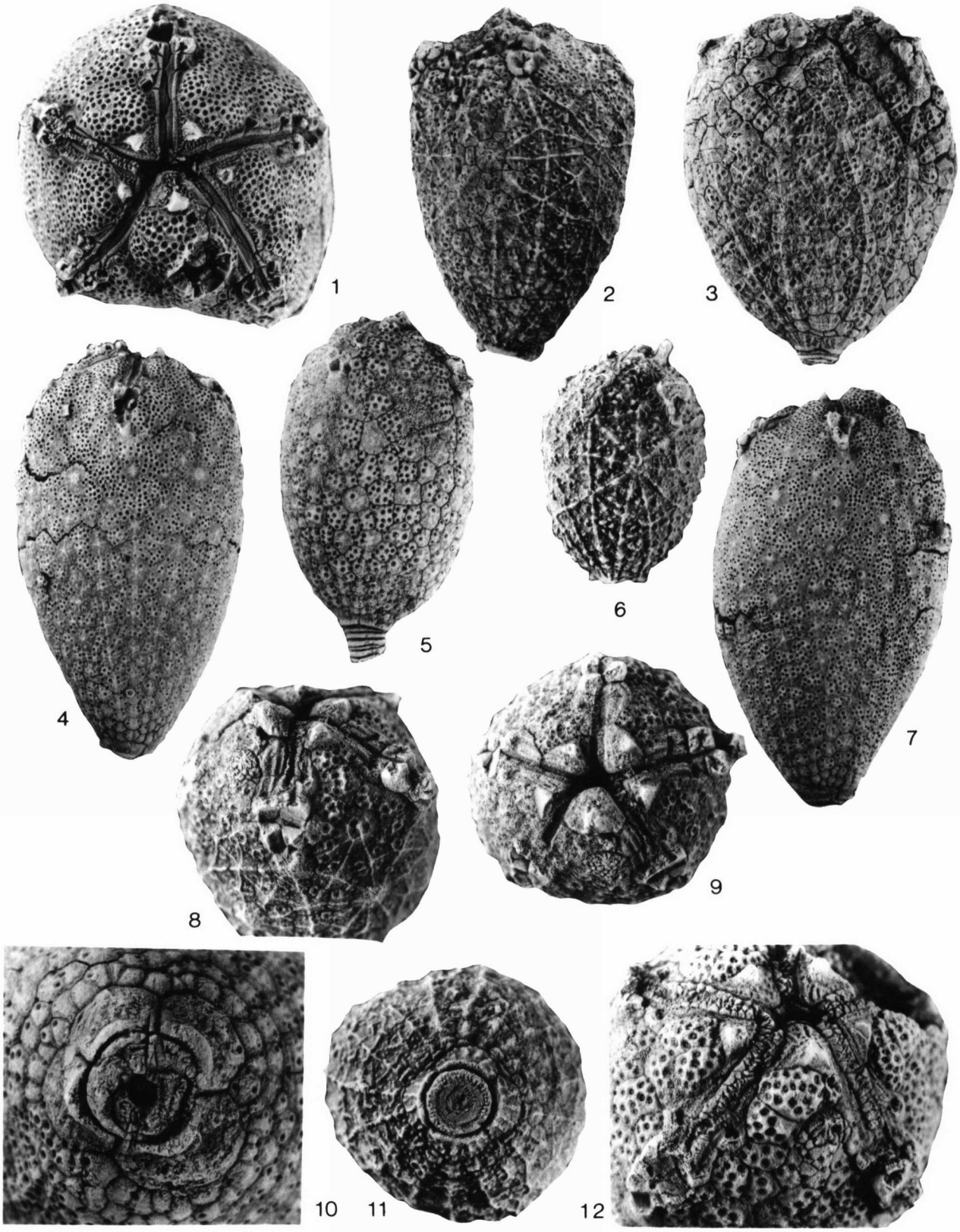


Fig. 69. Composite partial reconstruction of a mature *Eumorphocystis multiporata*, left posterior tribrachial toward the observer.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Early primary-secondary series apparently concentrated in upper theca as evidenced by large number of diplopores on secondary plates, which as suggested below, is indicative of an older thecal plate. In upper theca primary and secondary identities well defined. Close to basals, plates small, with few diplopores, often of uncertain "generation." (It is in this area that most new plates are added.)

Primary plates usually hexagonal or almost so, with central boss and ridges leading to plate corners. As primaries grow, boss becoming less prominent, diplopores forming near plate margins between radiating ridges. In large individuals, diplopores appearing near centers of primary plates, often opening through central boss and radiating ribs, thus requiring resorption of plate material and growth of new diplopore structure. Known specimens all more than 8 mm high, with secondary plates intercalated in circlets around primary plates (Pl. 35, fig. 2, 6, 8; Pl. 36, fig. 4, 19). (A theca 10 to 12 mm high has about 150 to 200 plates.)

Secondary plates lacking central boss, crossed by continuations of primary plate ridges, more irregularly polygonal, usually crowded with diplopores (from several to 20-odd in large secondary), large individuals with between 150 and 550 secondary plates. Intercalation of secondary plates resulting in random plate order between basals and peristomals. (In such large specimens as the holotype, small tertiary plates are intercalated between primary and secondary plates; Pl. 36, fig. 19.) Tertiary plates, if present, small, quadrate, usually bearing several diplopores.

Basals 4, large, equal-sized, usually unpored, adoral faces markedly convex (Pl. 35, fig. 10, 11). Attachment base formed by basals indented nearly half the height of series (Pl. 36, fig. 12). Aboral to indented attachment base, basals thickened by prosoponal ridge giving walls of attachment cup greater strength. Center of attachment base pierced by lumen forming approximately one-fourth total diameter (Pl. 36, fig. 7, 12).

Hump adjacent to posterior peristomal in larger specimens (thecal height about 25 mm), semi-hemispherical, composed of 4 (Pl. 35, fig. 12) to about 10 (holotype) interradial plates mostly crowded with diplopores. Larger specimens incorporating more plates in hump. (There is insufficient data to determine the rate at which plates are added.) Arcuate opening on right side of hump bounded by 3 to 5 plates, interpreted to be hydropore. Gonopore, usually closely associated with hydropore in diploporites, not discernible in *Eumorphocystis*. (Possibly the arcuate aperture is a combined hydropore-gonopore. The hump may have contained gonadal tissue or have been a storage area for sex products. The dense concentration of diplopores certainly suggests a high respiratory need inside the hump.)

Valvular (anal) pyramid, typical of many diploporites, not present. Periproct margin subcircular to pyriform, impinging slightly on aboral right side of hump. Periproctals variable in number and position, with few diplopores. Periproct plated with small irregularly shaped and arranged platelets (Pl. 35, fig. 12). In holotype periproct incorporated into hump.

Subvective system in 2 parts: epithecal part including modified thecal plates incorporated in system, and exothecal part encompassing pinnulate tribrachials.

Peristome of 5 thick, nonpored plates, each triangular except for broad quadrate posterior peristomal (Fig. 70; Pl. 35, fig. 1, 9, 12; Pl. 36, fig. 21). Large, slightly adoral-curving spine near aboral edge of each peristomal, spine suboval to quadrate in cross section. Thin, straight to sinuous prosoponal ridges radiating from base of each spine to margins of food grooves (Pl. 35, fig. 1; Fig. 70). Sutures between peristomals on floors of food grooves, grooves radiating from transversely elongated, pentagonal mouth opening. Supraoral covering plates or palate plates (Paul, 1971, p. 7) poorly preserved, prob-

PLATE 35.

Fig. 1-12. Thecal morphology of *Eumorphocystis multiporata* Branson and Peck, 1940; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. 1, 4, 7, 10. Apical, right lateral, left lateral, and proximal views of holotype UM 6757 from Fittstown Roadcut; X2, X1.5, X1.5, X3. 2. Left posterior lateral view; note well-developed unweathered ornament; 1121TX107 from Daube Ranch; X2. 3. Lateral view of somewhat compressed theca OU 9047 from Amis Ranch; X2. 5, 12. Right anterior view and detail of posterior ambulacral area; note in Fig. 12 the elevated "genital" hump, irregular plating over periproct, and 2 series of cover plates over epithecal food grooves; 1279TX126 from Fittstown Quarry; X2, X4. 6. Left lateral view; note well-developed ornament radiating from primary plates; OU 9049 from Amis Ranch; X2. 8, 9, 11. Oblique upper postero-right, apical, and proximal views of OU 9048 from Amis Ranch; note in Fig. 8 clearly defined primary-secondary plate arrangement and attachment base for postero-right exothecal tribrachial; X3.

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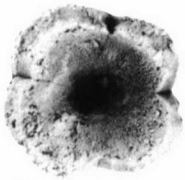
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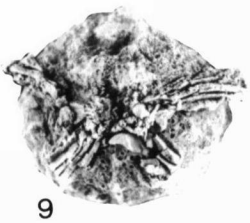
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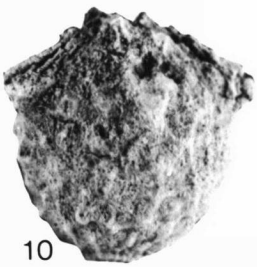
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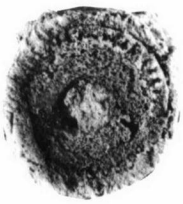
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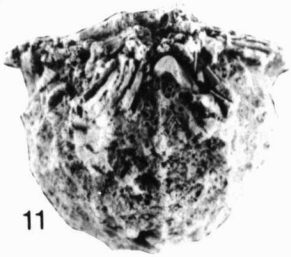
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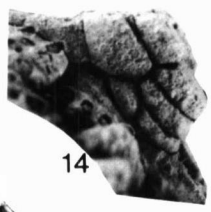
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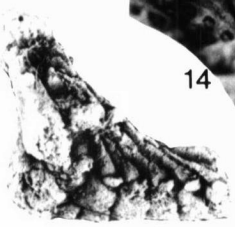
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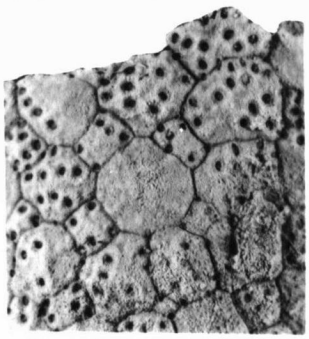
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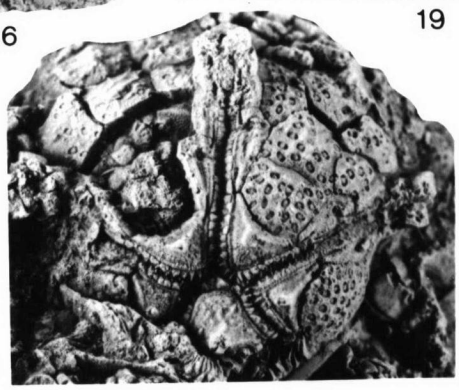
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ably floating loose in tissue over mouth opening.

Aboral to peristomals, food grooves carried on nonpored, paired but offset plates (Fig. 70, Pl. 35, fig. 1); first plates paired, elongate, each approximately heptagonal in outline with aboral end bulging into adjacent area of pored thecal plates. Aboral to paired heptagonal plates, 3 shorter alternating usually hexagonal plates, 2 on left side of food groove, 1 on right. Subvective plates aboral to this triad associated with exothecal part of system (discussed below). Straight axial trough or gutter (probably main conduit to mouth) extending length of epithecal main food grooves onto exothecal tribrachials (Pl. 35, fig. 1). Within main food grooves, plate sutures generally prominent. Low crenulate boundary ridges extending from mouth opening across epithecal subvective plates and onto exothecal tribrachials along edges of food grooves. Crenulations matching those on articulating seats of main covering plate series.

Food grooves (epithecal and apparently exothecal) covered by 2 series of plates (similar to those in many isorophid edrioasteroids; see Bell, 1976, p. 14-21). Wedge-shaped to pentagonal covering plates articulating against crenulated side ridges of food grooves, plates alternating to directly opposed in position. Small platelets comprising second irregular series of covering plates filling in medial spaces left by primary series, commonly rhomboid (diamond-shaped), but variable (Pl. 35, fig. 12).

(Most pentagonally arranged diploporites manifest a somewhat different epithecal subvective system, with narrow, short to long, main food grooves and short side branches that terminate in what appear to be brachiole seats. These seats typically have a pair of slightly elongate pits in the central part. Remnants of such a system are seen on *Eumorphocystis*.) Brachiole seats on each epithecal subvective plate except peristomals. Brachiole pits deeply incised, short side groove extending from between pits, through crenulated ridge at a 60 to 80° angle, into main food groove (Pl. 35, fig. 1, 9, 12). Minimally 20 exothecal brachioles, 4 for each subvective branch, extended from nonpored epithecal subvective plates. (Brachiole seats are found on normal diplopore-bearing thecal plates in many diploporite genera: *Glyptospharites*, *Protocrinites*, and *Fungocystites*.)

Brachioles biserial, thin, bladelike; apparently with food groove and covering plates. Brachioles capable of recumbency, forming protective tegmen over main food grooves. When recumbent, distal tips of brachioles lying between incurving spines of peristomals (Fig. 71B).

Base of attachment for exothecal tribrachials consisting of 5 thecal plates (Pl. 35, fig. 8) and a pair of pentagonal (in profile) wedge plates situated between tribrachial basals and paired ambulacral plates (hereafter abbreviated am, plural ams) of the exothecal tribrachial (Pl. 36, fig. 13, 14). Proximal 4 plates of tribrachial base roughly quadrangular, together tapering aborally toward pentagonal aborally rounded aboral base plate ("radial" plate of Branson and Peck, 1940, p. 90); these 5 plates forming a triangular area (Pl. 35, fig. 4, 8). In larger specimens thecal plates sometimes inserting slightly along sutures of tribrachial base. Quadrangular to pentagonal (in profile) plate over distal pair of tribrachial basals serving as a spacer (Pl. 36, fig. 13, 14)

PLATE 36.

Fig. 1-21. Morphology of the theca, column, and exothecal tribrachials of *Eumorphocystis multiporata* Branson and Peck, 1940; all specimens except 1, 2 from Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. 1, 2. Apical and lateral views of synonymous *Regnellicystis typicalis* Bassler, 1950, holotype USNM 113308, Benbolt Formation, Rye Cove, Scott County, Virginia; X2.5, X2. 3. Fragment of theca and pinnules of synonymous *Strimplecystis oklahomensis* Bassler, 1950, USNM 115193 from Fittstown Roadcut; X2. 4. Left lateral view; note well-defined ridges originating on primary plates and well-developed systems of encircling secondary plates; OU 9048 from Amis Ranch; X2. 5, 7, 8. Distal articulating face of a columnal, internal view of 4 basals with lumen, and proximal column with basals attached, respectively; 1279TX-134 from Fittstown Quarry; X8, X4, X3. 6. Proximal articulating face of a columnal; 1121TX107 from Daube Ranch; X6. 9-11. Apical, anterior, and oblique posterior views of smallest known theca (h = 8 mm); 1278TX12 from Cedar Village; X4. 12. Basals at aboral end of theca; note deeply indented column base, crenulated articulation area, and central lumen; 1121TX107 from Daube Ranch; X4. 13, 14. Oblique and lateral views of ambulacral and bracing plates at proximal end of exothecal tribrachial; 1107TX2 from Lick Creek; X5. 15, 16. Side views of tribrachial with attached uniserial pinnules; note flatness and squared outlines of pinnulars; 1279TX127 from Fittstown Quarry; X5. 17. Proximal end of tribrachial with pinnulars attached; 1279TX133 from Fittstown Quarry; X5. 18. Longest known fragment of a tribrachial; note attached pinnules; 1107TX2 from Lick Creek; X4. 19. Plate arrangement on holotype specimen; some primary plates are separated from secondaries by intercalated quadrate tertiaries; UM 6757 from Fittstown Roadcut; X4. 20. Small weathered theca 1221TX21 from Daube Ranch; X2.5. 21. Apical view of large incomplete specimen; primary covering plates of adoral epithecal ambulacra are well preserved; 1107TX2 from Lick Creek; X4.

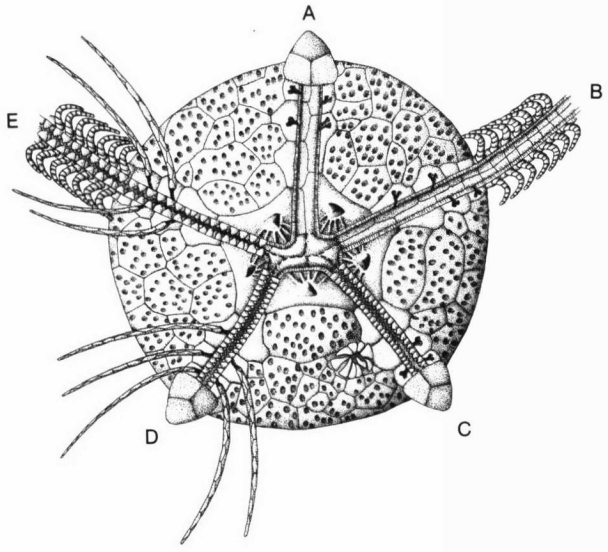

Fig. 70. Partial diagrammatic reconstruction of adoral surface of *Eumorphocystis multiporata*. Ambulacrum A, epithecal food groove without covering plates, brachioles, or attached tribrachial. Note brachiole bases and plate sutures in food groove. Ambulacrum B, same except with tribrachial and attached pinnules. Ambulacrum C, epithecal food groove with main series of covering plates. Ambulacrum D, same as C except with biserial brachioles attached in upright position. Ambulacrum E, same as D but with attached complete tribrachial.

between paired ams, and bracing plates (bracing plates apparently serial repetitions of distal tribrachial base plate or "radial"); spacer plate changing initial angle of exothecal tribrachials from horizontal to about 45° to axial plane. Exothecally, lumen formed equally by 3 plates making up tribrachial.

Exothecal tribrachials unique among Echinodermata. Paired ams each bearing a pinnule of uniserial, flattened pinnulars; third, bracing series of plates aboral to ams (Pl. 36, fig. 15-18). Ams about twice as high as long, bracing plates one-half to one-third as high as ams, becoming shorter compared to the ams in more mature specimens. An average of 2.5 bracing plates for each pair of ams at proximal ends of tribrachials, every other bracing plate inserting slightly into am series. Distally am to bracing plate ratio becoming uneven, 1.5 to 2 bracing plates per am pair common.

Food groove with central trough extending without interruption up tribrachials from epithecal plates, proximal width only slightly diminished (Pl. 36, fig. 21). Apparently covering plates also uninterrupted from theca to tribrachials as evidenced by crenulated lateral ridges of food grooves.

Pinnule seat on distal half of am plate adjacent to crenulated food groove ridge (Pl. 36, fig. 15-18). Seat an incised quarter-round facet canted outward into which short basal pinnular fits. Basal pinnular about one-half height of adjacent (second) pinnular. Second and more distal pinnulars rectangular, slightly longer than high, flattened starting with second pinnular, second pinnular sharply thinning distally. Complete pinnules unknown, estimated to be composed of about 15 pinnulars. A U-shaped food groove extending along aboral edge of pinnules. Some pinnules with suggestion of covering plates, the order of these plates not determined.

Total length of tribrachials unknown. Largest known segment (Pl. 36, fig. 18) 14 mm long with 15 pairs of ams. (Considering the slight taper of this segment, it probably is less than one-fourth of the whole. Tribrachials with 60 or more segments are expected. Presumably the pinnules formed a broad filtration fan similar to that of stalked articulate crinoids; certainly the subvective crown of *Eumorphocystis* with its large flat pinnules has more bulk and surface area than that of a comparable-sized crinoid.)

Only proximal end of column known; gently tapering distally, circular in cross section, proximally of alternating thick-thin holomerous columnals (Pl. 36, fig. 8). Distally, proximal column of thick columnals approximately twice as thick as thinner ones (Fig. 71A). Articulating surfaces of columnals with inset halo of approximately 40 radiating rounded crenulations or teeth (Pl. 36, fig. 5), corresponding sockets on articulating face of adjacent columnal (Pl. 36, fig. 6); relatively flat field between lumen and crenulations. Overall makeup of proximal column suggesting a straight, rather rigid structure; rounded nature of articulations suggesting that much strain could be applied, for example bending, before fracture.

Occurrence and material.—With the exception of the single specimen of *"Regnellicystis"* (USNM 113308) from the Benbolt Formation of Virginia, all specimens are from the Lower Echinoderm Zone, Mountain Lake Member of the Bromide Formation in southern Oklahoma. The holotype (UM 6757) and largest known specimen is from the Fittstown Roadcut, as is the fragmentary holotype of *"Strimplecystis oklahomensis"* (USNM 113308). About 25 other specimens, ranging from complete thecae to pieces of columns and tribrachials, are known: Fittstown Quarry (8 specimens, 1279TX126-131, 133-134); Daube Ranch (6 specimens, 1404TX6-7 [Watkins Coll.], 1221TX21-23, 1121TX107); Amis Ranch (6

specimens, OU 9047-9049, 1109TX1-2, 20); Lick Creek (2 specimens, 1107TX2, OU 9106); Cedar Village (2 specimens, 1278TX5, 12); and Cornell Ranch (1 specimen, OU 9107).

Discussion.—*Eumorphocystis* is noteworthy among primitive "pelmatozoan" echinoderms for the "evolutionary innovations" apparent in its unusual morphology. These include a possible genital bursa located in the semi-hemispherical hump in the CD interray. While genital bursae have not been observed in diploporites (or in other primitive echinoderms for that matter), this interpretation is reasonable because of the position of the hump in the CD interarea, the numerous diplopores on it for efficient internal oxygen diffusion, its presence only on larger presumed sexually mature specimens (thecal height about 25 mm), and the marginal inclusion of the hydropore-gonopore (see Paul, 1973, p. 17). The unique subvective system with its pinnulated tribrachials is like the subvective nets of crinoids. The large flat pinnules are also similar. With their large surface area, they "strained" the water as did the closely spaced tube feet on the thin pinnules of crinoids. Lastly, while most diploporites are thought to have had biserial brachioles as their principal subvective structures, in *Eumorphocystis* the biserial brachioles may have been vestigial and served primarily to form a "tegmen" over the epithecal food grooves.

The derivation of the unique tribrachials is enigmatic, for no intermediate forms are known and each tribrachial is fully triserial throughout. They may be modified brachioles, the third series derived from the aboral tribrachial basal or "radial" by serial repetition. This explanation requires a biserial brachiole at the distal end of the epithecal food groove and the incorporation of a third or bracing series through simple juxtaposition. The bracing series would strengthen the brachiole and allow for its (inferred) considerable length. Or tribrachials may be new exothecal extensions of the epithecal food grooves on newly evolved structures; tribrachials may be in no way homologous with biserial brachioles. In any case, tribrachials probably functioned both as brachioles (ciliary mucoid feeders probably devoid of subvective tube feet) and as arms, being similar to the tube-footed, pinnulated arms of crinoids.

Among the "pelmatozoan" echinoderms, pinnulated exothecal subvective appendages are known in at least five different classes. The term "pinnule" is used herein to indicate a side branch of an exothecal subvective structure; analogy not homology of these branches is suggested. 1) In crinoids pinnules are uniserial on uniserial arms (secondarily biserial in some) and are equipped with tube

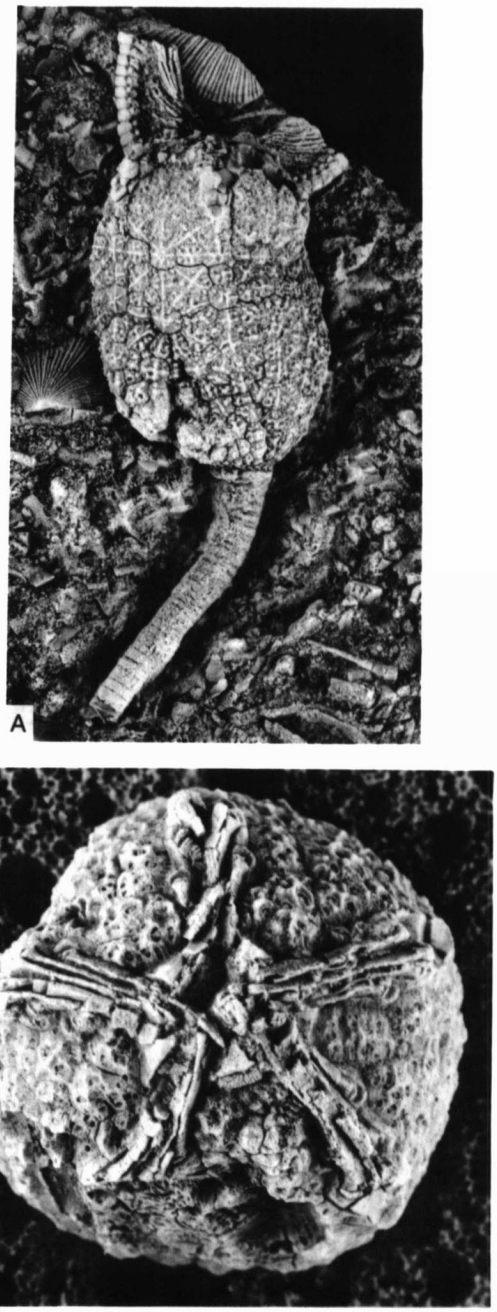

Fig. 71. Side and oral views of *Eumorphocystis multiporata*. A, Side view with column and 2 pinnulate tribrachials attached, 1109TX1 from Amis Ranch, X1.5. B, Oral view showing recumbently disposed brachioles forming a "tegmen" over each food groove. Brachiolar plates are held in place distally by incurving spines on peristome plates, 1404TX6 (Watkins Coll.) from Daube Ranch, X4.

feet. In mature rheophylic crinoids, a filtration net formed by the closely spaced pinnules and tube feet has proven a highly efficient subvective system as evidenced by its generally unchanged morphology from the Ordovician to the Holocene (see Macurda and Meyer, 1974; Lane and Breimer, 1974). 2) Paracrinoidea have uniserial, exothecal or epithecal, armlike structures with uniserial pinnules. There is no evidence for tube feet on the pinnules, and paracrinoid "arms" probably functioned like brachioles (see Parsley and Mintz, 1975, p. 11-14, 22-23). 3) In the rhombiferan superfamily Hemicosmitida, the genus *Caryocrinites* has biserial brachioles which served as pinnules. These pinnules branch off an erect ambulacrum with biserial ambulacral plates that are usually epithecal in other rhombiferans. This exothecal subvective extension gives a 5- to 10-fold increase in subvective area over a recumbent-armed condition (see Sprinkle, 1975, p. 1062-1073, and Brett, 1978, p. 724-726). 4) The probable eocrinoid *Trachelocrinus* exhibits branching biserial "arms" in which a biserial "pinnule" branches off approximately every third ambulacral pair on alternate sides of the main branch. This Late Cambrian genus is one of the earliest examples of branched exothecal brachia (see Sprinkle, 1973, p. 124-125, pl. 30). 5) Lastly, *Eumorphocystis* has exothecal triserial appendages with uniserial pinnular extensions. Of all of the mentioned examples, this last one is probably the most massive per unit length of subvective system. "Pinnulation" is clearly a method to increase subvective area per unit length of arm, brachiole, or tribrachial.

Stalked rheophylic crinoids form a broad filtration fan that opens like an umbrella, with the distal ends of the arms recurved up-current. The arms and pinnules form a baffle with the food grooves downstream (lee side) in the back eddies (Macurda and Meyer, 1974, p. 394-396). Presumably *Caryocrinites* and *Eumorphocystis* formed similar filtration fans. Crinoid pinnules are thin, and the sweeping of food from the water is done by closely spaced tube feet. In *Eumorphocystis* the fan was formed primarily by the closely spaced flat pinnulars. I suggest that these broad flat pinnulars were the primary sweepers of food because tribrachials, like biserial brachioles, were probably devoid of tube feet (see Sprinkle 1973, p. 21-27). *Caryocrinites* is similar, except that its "pinnular" brachioles are very similar to pinnules of crinoids. The pinnate appendages of paracrinoids, especially *Comarocystites* (see Parsley, 1978, p. 478), and the eocrinoid *Trachelocrinus* are more sparsely branched and not so easily compared with *Eumorphocystis*.

The short temporal span of Lower Paleozoic forms like *Caryocrinites* and *Eumorphocystis* bespeaks a lack of efficiency in "pinnulated brachioles." Certainly if the brachioles and tribrachials were devoid of tube feet, the efficiency of the water vascular system in filter feeding would be much less. The generally smaller food grooves in brachioles might also have reduced efficiency. Moreover, crinoid arms may well be more robust and less prone to damage than brachioles and tribrachials because of their seemingly better developed articulations.

The growth of the theca reflects an orderly increase in plate number by peripheral addition of secondary plates around the primary thecal plates. In early ontogenetic stages (theca less than 10 mm high), there are few diplopores. Most respiration in such small *Eumorphocystis* was through the plates by way of stromal tissues. If we take Paul's (1972a, p. 17-18) figures at face value, oxygen by diffusion alone will penetrate into an echinoderm to a depth of about 3 mm without special respiratory structures. Using these figures, a specimen of *Eumorphocystis* with a diameter of 6 mm would have a theca roughly 10 mm high and would marginally be able to respire without diplopores. Secondary plates are generally crowded with diplopores on thecae over 10 mm high. Specimens with thecae approximately 30 mm high and larger show clear examples of development of diplopores by resorption on primary plates; often these diplopores penetrate the central boss and radiating ribs. Insufficient numbers of specimens are on hand to determine a ratio of thecal volume to diplopore number. Because volume increases roughly by the cube as the surface area increases by the square, larger specimens will, as observed, have dramatically more diplopores than smaller specimens.

PALAEOCYSTITIDS

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Palaeocystitids are a fairly rare element in the Bromide echinoderm faunas, but a new genus (*Bromidocystis*) and two new species are present here. *Bromidocystis* is characterized by a large club-shaped or ovoid theca with numerous plates, five short recumbent ambulacra on the summit bearing long erect or recumbent brachioles, externally covered sutural pores and tangential canals between the thecal plates, and three basals. *Bromidocystis* is a rare form at most rich Lower Echinoderm Zone localities (about 0.4 percent of the calyx fauna), but its plates are fairly common at these localities and its inferred holdfast may make up 15 percent of the preserved holdfast fauna (Lewis, this volume). One complete theca is known from Cedar Village, where few other echinoderms have been found, and about 22 fragmentary thecae have been collected at Fittstown Quarry in the northeastern Arbuckles, where *Bromidocystis* plates are especially abundant. Plates of a second species of *Bromidocystis* are abundant at both localities of the *Bromidocystis* Bed and also occur in the Upper Echinoderm Zone and at one locality in the overlying lower Pooleville Member in the northeastern Arbuckles. Although no complete specimen is known yet, shape and ornament of the regular thecal plates plus four basals and a single ambulacral plate indicate that this form is most likely a second species of *Bromidocystis*. Because of their large size and numerous plates weakened by sutural pores, specimens of *Bromidocystis* probably fell apart easily after death unless buried quickly or overgrown by encrusting bryozoans. *Bromidocystis* may also have been an r-selection opportunist that became common only in marginal environments where other echinoderm were less abundant.

The taxonomic assignment of palaeocystitids is now in question. Broadhead and Breland (1980) have recently pointed out that the three previously known genera have been assigned to three different classes, *Palaeocystites* to the eocrinoids, *Ulrichocystis* to the rhombiferans, and *Schuchertocystis* to the paracrinoids. One obvious problem is the rarity of specimens and our incomplete knowledge of the morphology; until now no ambulacral structures, feeding appendages, or stems were known. Broadhead and Breland (1980, p. 172) proposed that palaeocystitids "may represent an evolutionary connection between the Eocrinoidea and Paracrinoidea," implying that they should be assigned to one of these two classes. Work on *Bromidocystis* indicates to me that palaeocystitids are probably not paracrinoids because they have symmetrical ambulacra and true brachioles; also, except perhaps for *Schuchertocystis*, the anus usually is not opposite the stem facet, and the theca is not bulged or lens-shaped as in many paracrinoids. The elongate thecal shape, numerous plates in columns, three unequal basals, externally covered sutural pores, and brachioles attached to recumbent ambulacra all agree with an assignment of this group to the eocrinoids, although none of these features is truly diagnostic. Palaeocystitids may well represent another relict group of eocrinoids that survived into the Middle Ordovician while other more advanced, suspension-feeding, echinoderm classes were diversifying and taking over many former eocrinoid niches. Other similar groups, such as the caryocystitids now classified in the Rhombifera but mentioned by Broadhead and Breland (1980), should also be carefully examined to see if they are truly rhombiferans or might also belong with the palaeocystitids in the Eocrinoidea.

Class EOCRINOIDEA Jaekel, 1918

Family PALAEOCYSTITIDAE Ubaghs, 1968

Genus BROMIDOCYSTIS Sprinkle, new

Type species.—*Bromidocystis bassleri* Sprinkle, n. sp.

Diagnosis.—Palaeocystitids with a large club-shaped or ovoid theca; 8 to 18 columns of plates, 3 unequal basals (2 larger, 1 smaller), plates 4- to 8-sided, slightly arched or domed, highly orna-

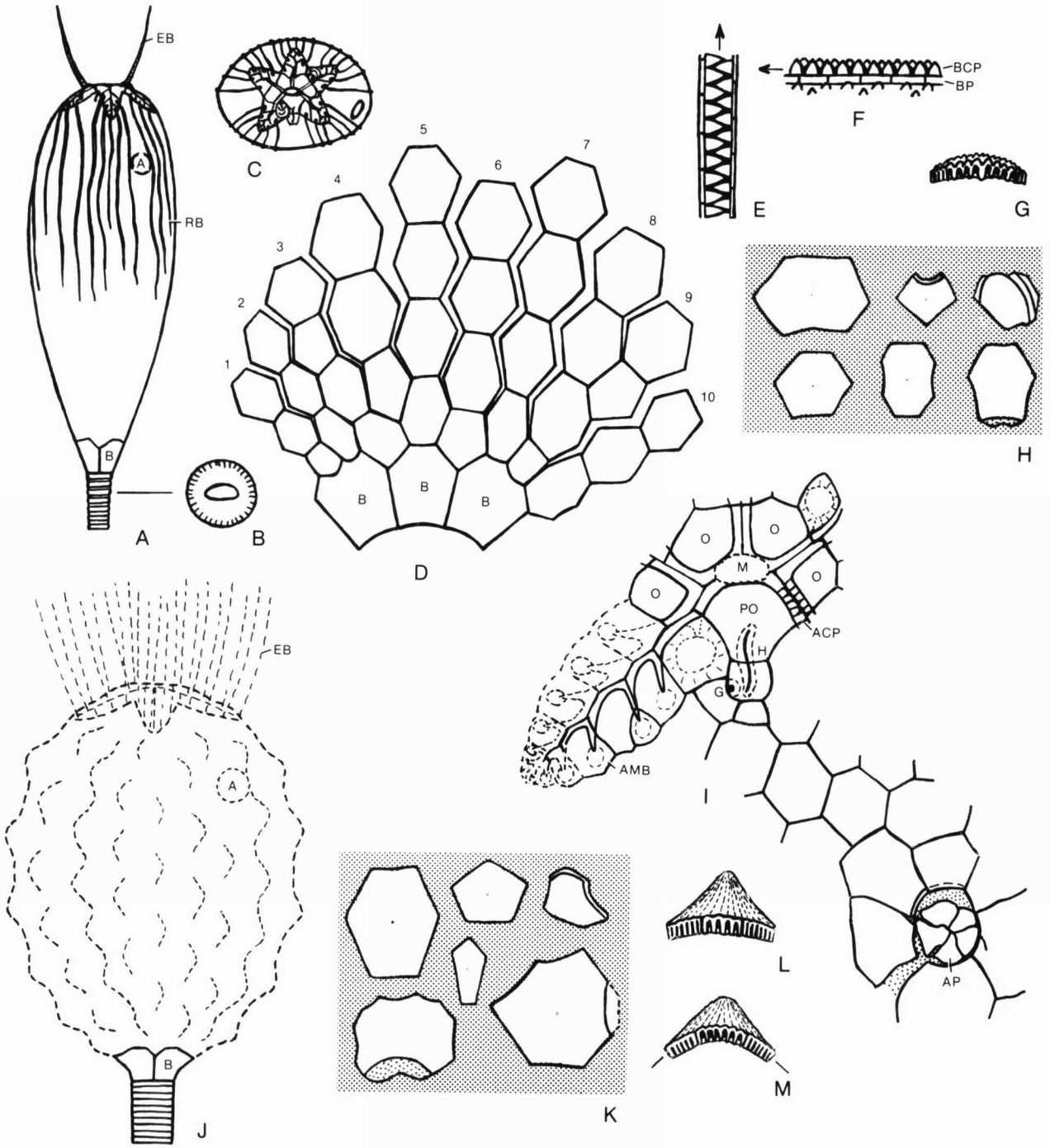

Fig. 72. *Bromidocystis* Sprinkle, n. gen.; morphology of *B. bassleri* Sprinkle, n. sp. (A-I) from the Lower Echinoderm Zone, and *B. Sinclairi* Sprinkle, n. sp. (J-M) from the *Bromidocystis* Bed, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma. A, Reconstructed side view of a complete *B. bassleri* theca showing thecal shape, narrow basals (B) with medium-sized stem, location of anus (A), short ambulacra mostly bearing recumbent brachioles (RB) and a few possibly erect brachioles (EB), slightly enlarged. B, Enlarged basal view of stem showing elliptical lumen. C, Top view of theca showing summit features, recumbent brachioles, and possible elliptical shape, slightly enlarged. D, Side-layout plating of small base 1279TX136; note 2 larger and 1 smaller basal (B) and 10 columns of thecal plates, including 2 (columns 4 and 9) inserted above basals, X4.8. E, F, Top, side views of a recumbent brachiole segment showing thin brachiolar plates (BP) and large, domed, brachiolar cover plates (BCP), much enlarged. G, Edge view of typical thecal plate showing slight curvature and sutural pores, X1.7. H, Typical plate shapes in *B. bass-*

mented; mouth central on summit, surrounded by 5 short recumbent ambulacra forming thecal wall, 2 to 10 biserial brachioles attached to each, brachioles long, either erect or recumbent down theca; anus on side of theca in BC interray, from 2 to 5 thecal plates below hydropore, surrounded by 5 to 6 thecal plates, protected by 5 periproctal cover plates; long slitlike (rarely branched) hydropore and adjacent small gonopore in CD interray below mouth, both may cross sutures; externally covered sutural pores present on edges of most thecal plates with simple tangential canals extending toward plate centers, 2 to 13 pores per suture; stem apparently long, circular, with medium to large diameter, lumen elliptical to rounded-triangular, stem apparently terminating in type 4 holdfast.

Occurrence.—Middle Ordovician, Oklahoma.

Discussion.—*Bromidocystis* differs in several features from the three other known palaeocystitid genera, *Palaeocystites*, *Ulrichocystis*, and *Schuchertocystis*. It is the only genus now known with five short recumbent ambulacra that form the thecal wall around the summit; it also has more plate columns than other genera, unusual recumbent brachioles in at least one species, more plates between the hydropore and anus, and a much more slitlike hydropore. *Bromidocystis* also differs from *Ulrichocystis* by having only a single tangential canal extending toward a plate center from each sutural pore; in this feature, it resembles *Palaeocystites* and *Schuchertocystis*. *Bromidocystis* differs from *Palaeocystites* and *Schuchertocystis* by also having a gonopore that touches a lateral suture (like *Ulrichocystis*) and a somewhat different thecal shape probably with more plates. *Bromidocystis* is about the same age as *Ulrichocystis* and *Schuchertocystis* but younger than *Palaeocystites*, from which it may have descended.

BROMIDOCYSTIS BASSLERI Sprinkle, n. sp.

Plate 37, figures 1-35; Figure 72A-I

Diagnosis.—Theca small to large, club-shaped with a conical base and rounded summit, circular to elliptical in cross section; basal expansion angle 25 to 40°; probably 8 to 11 columns of plates, plates mostly equal-sided, small to medium-sized, slightly arched but not domed, highly ornamented with coarse pustules on radiating ridges; sutural pores elongating into plate, 2 to 13 pores per suture, spacing averaging 0.65 mm/pore; ambulacra medium length, first flooring plate in B- and D-ray ambulacra domed; brachioles long, many flattened and apparently recumbent down theca in life; stem up to 5 mm in diameter proximally.

Description.—Four complete specimens, 3 overgrown by encrusting bryozoans; 9 other fragmentary specimens, including the large two-piece holotype; 19 smaller fragments; and nearly 2,000 separate plates available for study. Theca small to large, small nearly complete paratype 17 mm long (minus basals), large overgrown theca about 43 mm long, but many fragments indicating even larger specimens up to perhaps 80 mm long; theca club-shaped, circular to elliptical in cross section without sharp angles, small paratype diameter varying from 6 to 8 mm, large fragment at least 29 mm in diameter. Theca tapering slowly at base with a medium-sized, flat stem facet, basal expansion angle 25 to 40° in 5 specimens; summit rounded with depressed central mouth, much wider than base, nearly perpendicular to thecal axis.

At least 88 plates present in small paratype, probably more in large theca; plates arranged in approximately 8 to 11 nearly vertical columns over most of theca, small paratype with 10 slightly irregular columns (Pl. 37, fig. 14-17), well-preserved base with 10 columns (Fig. 72D), and overgrown fragment near middle of theca with 8 columns (Pl. 37, fig. 23). In addition to plate columns, 3 unequal basals around stem facet at base, 5 to 6 small thecal plates around anal opening, and 5 small orals and 10 to 50 ambulacral flooring plates present on summit.

Basals (BB) 3, curved, smaller than most regu-

leri including several thecal plates (left), anal edge plate (upper center), oral (upper right), and basal (lower right); paratypes 1279TX326-330 and 1404TX8 (Watkins Coll.), all X1.7. I, Composite summit and anal side of paratype 1279TX154 (D ambulacrum), paratype 1279TX135 (orals) and holotype 1279TX145A and B (lower summit and anus) showing brachiole facets on main or accessory ambulacral plates (AMB) that form thecal wall, enlarged first ambulacral plate with possible large facet in B and D ambulacra, orals (O) around central mouth (M), hydropore (H) and gonopore (G) just below mouth, and anal pyramid (AP) covering anus in BC interray, much enlarged. J, Hypothetical side view of complete *B. sinclairi* theca showing ovoid thecal shape with domed plates, inferred erect brachioles (EB) attached to ambulacra on summit, possible location of anus (A), and wide basals (BB) with large attached stem, natural size. K-M, Typical plate shapes in *B. sinclairi;* K, several thecal plates (upper left through lower right), oral or ambulacral plate (upper right), wide basal (lower left); edge views of 2 plates showing L, domed shape, and M, considerable curvature of some plates; holotype 1397TX12 (K, upper left, and L) and paratypes 1397TX13-17 and 1393TX4, all X1.3.

lar thecal plates but much larger than immediately adoral ones, slightly longer than wide with L to W ratio ranging from 1.08 to 1.18, relatively thick (2.0 mm or more). Two BB slightly wider adorally, with 2 directly overlying thecal plate columns, one B slightly narrower adorally, with only 1 plate column directly above (Fig. 72D). Orientation of BB unknown because of incomplete specimens. Largest stem facet about 5 mm in diameter.

Thecal plates in columns; in medium-sized base of theca, 8 starting right above BB, 2 more added immediately above this (Fig. 72D). In small paratype, probably 7 to 8 plates in each column; perhaps more in larger thecae. Plates becoming larger adorally until near ambulacra and summit, largest about 13 mm long and wide, slightly curved but usually not domed (constant thickness across width), about 1.2 mm thick. Most plates equidimensional, with from 4 to 8 sides, 6 to 7 sides most common, sides straight or slightly curved (Fig. 72H). Some plates with a ridge across interior, probably to attach mesentery holding organ in coelomic cavity (Pl. 37, fig. 25).

Summit rounded with depressed central mouth, perpendicular to thecal axis, relatively small. Mouth central, elliptical, surrounded by 5 orals

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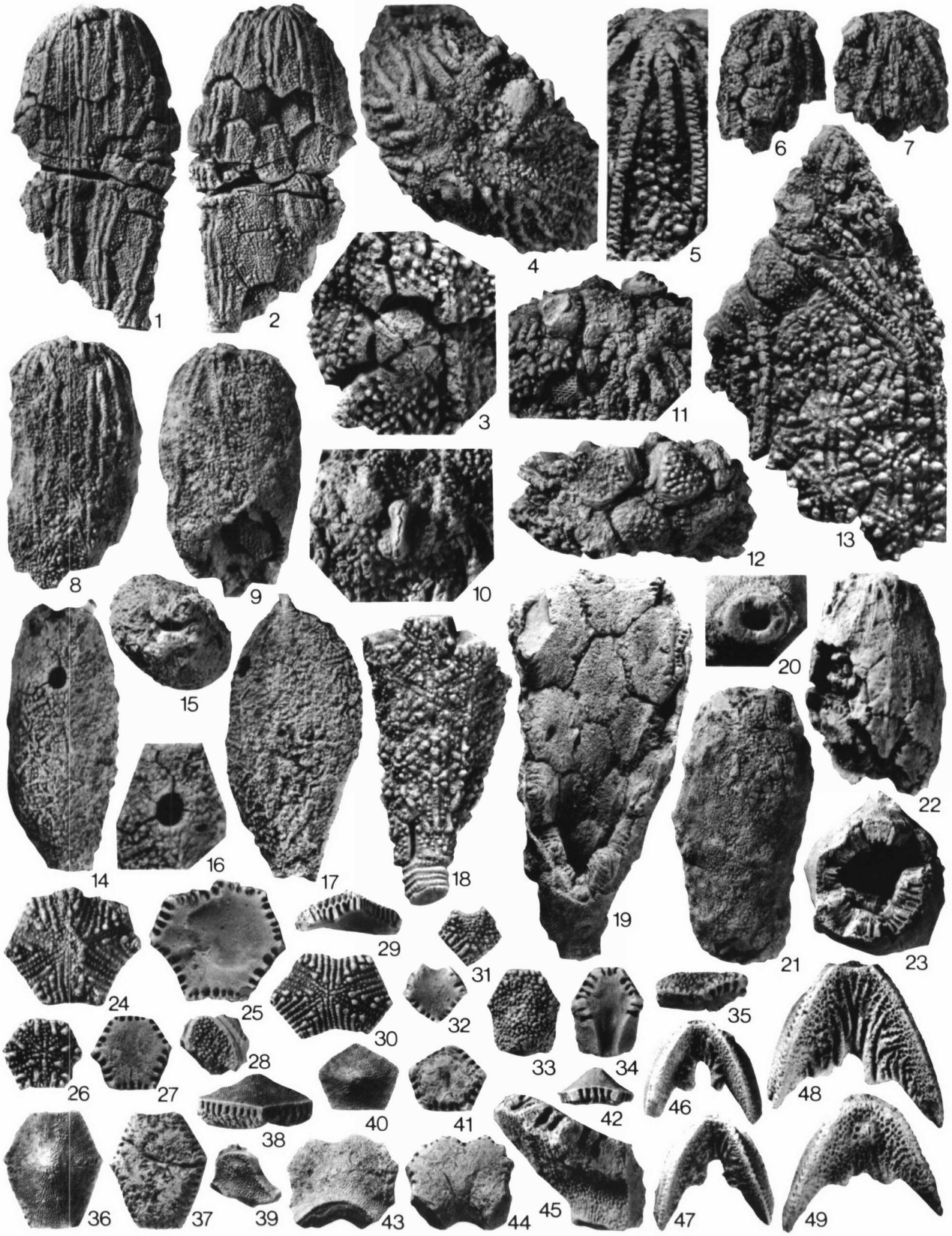
PLATE 37.

Fig. 1-35. *Bromidocystis bassleri* Sprinkle, n. gen., n. sp., Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1-13, 18-20, 23-32 from Fittstown Quarry, 14-17 from Lick Creek, 21 from Cedar Village, 22, 33-35 from Daube Ranch. 1-5. EA-interray and D-ray side views, enlarged anal pyramid in BC interray, summit, and recumbent brachioles attached to D ambulacrum, respectively, of large two-piece holotype 1279TX145A, B (C. Strimple Coll., Sprinkle Coll.); note 5 to 6 very long recumbent brachioles with biserial domed cover plates attached to each ambulacrum, and 6 plates around anus; X1.5 (1, 2), X4.5, X3, X5. 6, 7. E- and C-ray side views of very small paratype summit SUI 47230 (H. Strimple Coll.) showing only 2 recumbent brachioles attached to each very short ambulacrum and slitlike hydropore next to large, raised, first ambulacral plate in D ray (7); X3. 8-10. CD-interray and AB-interray side views and enlarged CD summit of medium-sized paratype SUI 47284 (H. Strimple Coll.); note near-cylindrical shape and highly raised slitlike hydropore with gonopore just to left (10); X2, X5. 11, 12. Enlarged CD interray and oral view of fairly large paratype summit 1279TX135 showing curved hydropore crossing suture, raised first ambulacral plate with apparent facet in D ray, slightly disarticulated orals around central mouth, and a few ambulacral cover plates still in place (12, lower right); X3. 13. Very large paratype fragment 1279TX154 showing right half of D-ray ambulacrum and adjacent CD interray; note shallow food grooves on 4 to 5 ambulacral (and accessory ambulacral) plates at left, recumbent brachioles, and branched hydropore covered with brachiole fragments at upper right; X3. 14-17. BC interray, summit, enlargement of anus, and AB interray of very small paratype OU 9552 (Fay Coll.) showing elliptical cross section (?slightly crushed), anus surrounded by 5 thecal plates, and missing basals; X3, X5. 18. Small paratype base 1279TX136 with attached stem; note narrow basals, low basal expansion angle, and medium-sized stem; X3. 19, 20. Side view of large paratype base 1279TX158 and enlarged end view of stem showing theca overgrown by encrusting bryozoan, epitaxial calcite on plate interiors, and large elliptical lumen in slightly elliptical stem; X1.5, X3. 21. Fairly small paratype 1278TX4 completely overgrown by an encrusting bryozoan and probably incomplete at the base; X2. 22. Medium-sized but abraded paratype 1121TX22 (Graffham Coll.); note plate columns and recumbent brachioles; X2. 23. Encrusted medium-sized paratype 1279TX155 showing 8 columns of plates near middle of theca; X2. 24, 25. Paratype thecal plate 1279TX325 showing external ornament, brachiole draped over surface, sutural pores, and ridges (for mesenteries) on interior; X2.2. 26, 27. Paratype thecal plate 1279TX326, a typical hexagonal plate with well-developed ornament; X2. 28. Paratype oral 1279TX327 showing slightly concave surface, lateral food grooves, and subdued pustular ornament; X2. 29, 30. Edge view and exterior of paratype thecal plate 1279TX328; note pustules lined up on ridges with a large pustule or spine absuturally and larger strut in middle of row of sutural pores (29, left); X2. 31, 32. Paratype anal edge plate 1279TX329 showing curved edge of anus and sutural pores dying out near this edge; X2. 33-35. Exterior, interior, and right edge views of paratype basal 1404TX8 (Watkins Coll.); note how narrow but thick plate is, large lumen to stem, and sutural pores dying out near stem facet, X2.

Fig. 36-45. *Bromidocystis sinclairi* Sprinkle, n. gen., n. sp.; *Bromidocystis* Bed, Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 36-42 from Daube Ranch, 43-45 from North-Central I-35. 36-38. Exterior, interior, and lateral edge views of holotype thecal plate 1397TX12 showing subdued ornament with tiny granules, elongate and domed plate shape, and epitaxial calcite covering plate interior; X1.5. 39. Paratype oral or ambulacral plate 1397TX13; note lateral food grooves and some similarity to 28 above; X1.5. 40-42. Exterior, interior, and lateral edge of paratype thecal plate 1397TX14 showing subdued ornament and sutural pores; X1.5. 43-45. Exterior, interior, and enlarged lateral edge of paratype basal 1393TX4; note great width of plate and sutures for 6 to 7 overlying small plates (compare 33, 34 above), thickness of plate near large stem facet, and wide expansion angle in 45; X1.5, X3.

Fig. 46, 47. *Astrocystites* sp. B; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, McLish Ranch, Arbuckle Mountains, southern Oklahoma. 46. Deltoid plate 1114TX53 showing thin limbs making up ambulacra and narrow aboral shelf with large central aboral notch; X3. 47. Deltoid plate 1114TX54; note pores for tube feet at edges of ambulacra; X3.

Fig. 48, 49. *Astrocystites* sp. A; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Buckhorn Ranch, Arbuckle Mountains, southern Oklahoma. 48. Large deltoid plate 1111TX21 showing wide limbs for ambulacra and pores for tube feet, wide aboral shelf ornamented with ridges, and beveled adoral edge of plate; X3. 49. Posterior deltoid plate 1111TX22; note raised slitlike hydropore with 2 gonopores alongside and almost no aboral notch; X3.



(OO). Five ambulacra extending from mouth off summit and a short distance down theca. Anus round, lateral, in BC interray, surrounded by 5 to 6 relatively small thecal plates, covered by pyramid of 5 triangular plates (Pl. 37, fig. 3). In small paratype, anus 1.2 mm in diameter and located about 4.0 mm below summit (Pl. 37, fig. 14, 16); in larger thecae, anus at least 4 mm in diameter. Hydropore and gonopore immediately below mouth in CD interray; hydropore an elongate slightly curved slit in an elevated ridge crossing suture between CD oral and peristomal plate directly below, hydropore ranging from 1.0 to 2.7 mm long, raised as much as 0.6 mm (Pl. 37, fig. 7, 10, 11). Large summit fragment with possible branched hydropore 2.2 mm long and 4.0 mm wide, partly covered by brachiole segments obscuring sutures (Pl. 37, fig. 13). Gonopore a slightly raised pore about 0.3 mm in diameter just to left of aboral end of hydropore, appearing to be on or adjacent to suture also (Pl. 37, fig. 10, 11).

Ambulacra relatively short, in small theca extending only to edge of summit; in large theca extending 12 to 15 mm down theca from summit (Pl. 37, fig. 4, 13). Ambulacral flooring plates (AFP) forming thecal wall, biserial, alternating across main food groove, 1 (rarely 2) sets present, each flooring plate supporting a long brachiole. Small thecae with only 1 to 2 flooring plates and 2 brachioles (Pl. 37, fig. 6, 7); largest ambulacral fragment with 4 to 5 flooring plates and brachioles on 1 side, implying as many as 9 to 10 flooring plates total (Pl. 37, fig. 13). Most flooring plates rhombic in shape, rapidly decreasing in size aborally, with shallow, wide main food groove and shallow side food grooves (Fig. 72I). Largest ambulacral fragment with smaller (perhaps added later), rounded, triangular flooring plate with attached brachiole inserted between larger rhombic ones at edge of ambulacrum (Pl. 37, fig. 13). First flooring plate on right sides of B and D ambulacra especially large and strongly humped (Pl. 37, fig. 4, 11); may have carried large erect brachiole (Fig. 72A). Main and side food grooves protected by single biserial set of small, triangular, intermeshing, ambulacral cover plates, plates continuing out onto brachioles; these becoming larger (0.5 to 0.7 mm) and rectangular (nonmeshing) on summit and over mouth (Pl. 37, fig. 4, 12).

Brachioles 1 per flooring plate, 10 total in small theca (Pl. 37, fig. 6, 7), perhaps 50 total (10 per ambulacrum) in largest ones, long and thin, extending down theca at least two-thirds distance to base, biserially plated. Many brachioles obviously flattened, attached to plate exteriors on many thecal fragments and even a few separate plates, appearing to have been recumbent in life. A few others not flattened (Pl. 37, fig. 13), probably erect in life. Longest brachiole segment 31+ mm long, most about 0.5 mm wide. Flattened brachioles with brachiolar plates (BP) only 0.3 to 0.4 mm high and 0.5 mm long, others about 0.5 mm high and 0.6 to 0.7 mm long; brachiolar cover plates (BCP) highly domed, perhaps slightly imbricate, about 0.25 to 0.3 mm long, 0.3 mm wide, and 0.3 mm high. BCP to BP ratio varying from 1.4 to 2.0, with low values for the few apparently erect brachioles. Some BCP's bearing a small spine.

Sutural pores numerous, elongate into plates, covered externally by thin (0.1 to 0.2 mm) plate material (epistereom), open internally, most plates having 2 to 13 pores per suture, pores diminishing aborally on BB, on plates near an ambulacrum, and on plates bordering anus (Pl. 37, fig. 32, 34). Pores in sutural view narrow, mostly vertical, few Y-shaped or inverted U-shaped, most about 1.0 mm high, 0.3 to 0.4 mm wide, and extending 0.6 to 0.8 mm deep into each plate. Pore spacing ranging from 0.54 to 0.78 mm/pore and averaging 0.65 mm/pore based on 10 measurements in 8 fragments and separate plates. On a long suture, partition between 2 pores closest to center of suture often wider than others and developed as strengthening strut (Pl. 37, fig. 29). Sutural pores leading to single tangential canal extending in toward plate center just under exterior surface; longest canal extending about 90 percent of distance in toward plate center; canal elliptical in cross section, about 0.3 to 0.4 mm wide and 0.6 to 0.7 mm high. Spine or large pustule on exterior usually marking absutural end of tangential canal (Pl. 37, fig. 30).

Thecal plates highly ornamented with medium to coarse pustules lined up on radiating ridges (which overlie internal tangential canals). Pustules usually conical, about 0.2 mm in diameter and 0.1 to 0.3 mm high; spines at inner end of row of pustules about 0.4 mm wide and 0.3 to 0.5 mm high.

Stem up to 5 mm in diameter, probably medium to long. Longest attached proximal segment only 2.3 mm long, 2.7 mm in diameter, containing 8 circular columnals showing a slight alternation in size, slight ridging, and a fairly large elliptical lumen (Pl. 37, fig. 18, 20). Proximal stem segments attached to 2 other thecae (both overgrown by

encrusting bryozoans); in 1, columnals elliptical (Pl. 37, fig. 20). Separate stem segments and one-piece columnals with elliptical or rounded-triangular lumens thought to belong to this form; also abundant type 4A and B holdfasts with same-shaped lumen.

Name.—The species is named for the late Ray S. Bassler, for many years at the U.S. National Museum, who studied and named many of the most common Bromide echinoderms in two important early papers.

Studied specimens.—Holotype 1279TX145A, B (C. Strimple and Sprinkle colls.); paratypes OU 9193-9195, 1121TX22 (Graffham Coll.), 1278TX4, 1279TX-146-165, 325-330, 1404TX8 (Watkins Coll.), and SUI 47230 and 47284 (H. Strimple Coll.); several dozen additional fragments in the TX collections and several thousand additional separate plates in the TX and OU collections.

Occurrence.—Known from the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation at Fittstown Quarry (18 partial specimens including the holotype, 13 smaller fragments, and over 2,000 separate plates), Lick Creek (3 complete specimens), Daube Ranch (1 partial specimen plus a basal and other plates), and Cedar Village (1 specimen); separate plates of this species are also known from Fittstown Roadcut, McLish Ranch, Amis Ranch, and Veterans Lake.

Discussion.—*Bromidocystis bassleri* is characterized by its club-shaped theca with a relatively narrow base and medium-sized proximal stem, 8 to 11 plate columns with slightly domed, nearly equant thecal plates having coarse pustular radiating ornament, sutural pores elongate into plates with an average pore spacing of 0.65 mm/pore, and many long brachioles apparently recumbent down over the theca in life. Another species from higher in the Bromide, *B. sinclairi*, n. sp., appears to belong to the same genus but differs in nearly all of the above features.

The recumbent brachioles found in *B. bassleri* are probably the species' most unusual feature. I first thought they were normal erect brachioles that had been draped over the theca when the specimen died and fell to the sea floor and were preserved in this position. However, attached brachioles are found on 26 of the 31 exposed specimens and fragments studied here, including fragments from near the base, and brachioles have also been found on a few separate thecal plates. Also, the holotype and several smaller paratypes have brachioles from all five ambulacra draped down over the theca, an unlikely occurrence if the brachioles were originally erect. Finally, many of these brachioles are quite flattened with very thin brachiolar plates and lie in recesses between ornamental ridges and spines; others have deeper and more rounded brachiolar plates and were probably erect. Recumbent brachioles are not unreasonable for a form that is most abundant in the northeastern Arbuckles with its shallow-water, storm-swept conditions; other forms living under similar conditions, such as the Chazyan paracrinoid *Malocystites*, have developed similar recumbent pinnules (Sprinkle, 1973, p. 185).

BROMIDOCYSTIS SINCLAIRI Sprinkle, n. sp.

Plate 37, figures 36-45; Figure 72J-M

Diagnosis.—Theca medium to very large, ovoid with protruding base, probably angular in cross section; basal expansion angle 90 to 100°; probably 12 to 18 plate columns, plates mostly elongate, up to 19 mm long, highly domed, very thick, others strongly curved; ornamented with fine pustules; sutural pores only slightly elongated into plate, 2 to 11 pores per suture, spacing averaging 0.89 mm/pore; most brachioles probably erect; stem up to 10 mm in diameter proximally.

Description.—Only separate plates available for this species, including about 180 thecal plates, 4 basals, and 1 oral or ambulacral flooring plate. Thecal size probably ranging from medium to very large based on plate sizes, largest specimens possibly up to 120 mm long. Theca apparently ovoid in shape with a protruding base, probably rectangular to pentagonal in cross section with sharp angles, based on some highly curved thecal plates (Fig. 72J). Stem facet large, flat; basal expansion angle probably 90 to 100° in large specimen. Shape of summit unknown.

Basals (BB) apparently 3, curved, medium-sized, much larger than immediately overlying small thecal plates, slightly to much wider than long with a L to W ratio ranging from 0.43 to 0.94, very thick (up to 3.5 mm in one B). Probably 2 larger and 1 smaller BB; larger BB (2 in present sample) with facets for 5 to 6 plate columns directly overlying, ?smaller B (2 also) with facets for 4 plate columns. Stem facet very large, estimated to be about 10 mm in diameter in largest basal (Pl. 37, fig. 43, 44).

Overlying thecal plates apparently in columns; based on number of facets on adoral edge of BB, probably 12 to 18 columns present. Unknown whether any new columns added above BB, or how many

plates present vertically in each column. Plates very small and thick just above BB (a possible example is 8 mm long by 5 mm wide, 2.0 mm thick on edge, and 3.0 mm thick in center), but becoming much larger and somewhat thinner on edge higher in theca. Holotype plate 15 mm long by 11.5 mm wide, 1.5 mm thick on edge, and perhaps as much as 3.0 mm thick in center (Pl. 37, fig. 36-38). Largest plates as much as 19 mm long, and 1 medium-sized plate 5.2 mm thick in center. Most plates slightly curved (through about 25 to 30°), but strongly domed with much thicker centers. However, some plates highly curved through 70 to 90° (Fig. 72M), probably forming "corners" on angular theca. Most plates longer than wide (extreme examples are over twice as long as wide), others nearly equidimensional. Thecal plates having 4 to 8 sides, with 5 to 7 sides most common, sides straight or slightly curved. No ridges observed on plate interiors, but many interiors covered with epitaxial calcite (Pl. 37, fig. 37, 38).

Ambulacral system known only from single oral or flooring plate (Pl. 37, fig. 39) which forms thecal wall. Plate rounded subtriangular, 6.6 mm long, 4.8 mm wide, with deep food grooves around one rounded end (?adoral) and lateral sutures converging ?aborally. (It resembles the CD oral in *B. bassleri*, but lacks a hydropore on its ?aboral margin, or a flooring plate to which an accessory flooring plate has been added.)

No brachioles present on surface of any thecal plate.

Sutural pores numerous, extending only slightly into each plate. Pores covered externally by thin plate material about 0.15 to 0.3 mm thick, open to interior, thecal plates with 2 to 11 pores per suture, pores only on adoral margins of BB (Pl. 37, fig. 45). Pores in sutural view fairly narrow, mostly vertical, few Y-shaped. Pores in holotype plate 1.3 mm high, 0.4 mm wide, extending about 0.4 mm into plate; in smaller plate with differently shaped pores, pores 0.9 to 1.0 mm high, 0.5 mm wide, extending 0.5 to 0.6 mm into plate. Pore spacing ranging from 0.70 to 1.04 mm/pore and averaging 0.89 mm/pore based on 12 measurements in 10 thecal plates. Sutural pores leading to single tangential canals extending in toward plate center just beneath exterior surface; longest (central) canal extending between 75 and 95 percent of distance in toward plate center; canal elliptical in cross section, about 0.4 mm wide, 0.6 mm high.

Thecal plates ornamented with fine to medium pustules, either randomly arranged or roughly lined up in radiating rows, but lacking any underlying radiating ridges. Pustules usually conical, about 0.15 to 0.25 mm in diameter and about 0.1 to 0.25 mm high. Almost no development of "spines" marking absutural ends of tangential canals; however, in few plates, groups of 2 to 3 pustules near top of domed center of plate coalescing to form low bump marking where tangential canal may end.

Stem unknown but probably long and at least 10 mm in diameter proximally. One-piece columnals with an elliptical lumen and type 4B holdfasts common in beds where these thecal plates occur.

Name.—This species is named for G. Winston Sinclair, recently retired from the Geological Survey of Canada, who studied and named several of the most common Bromide crinoids.

Studied specimens.—Holotype 1397TX12 (thecal plate); paratypes 1397TX13-50 (thecal plates plus 2 basals and 1 oral or flooring plate), 1393TX4-10 and 20-40 (thecal plates plus 1 basal), 1110TX4-5 and 9-19 (thecal plates), 1441TX2-4 (thecal plates), 1106TX17 (thecal plate), and OU 9176-9180 (thecal plates plus 1 basal).

Occurrence.—Known from the *Bromidocystis* Bed, named after the occurrence of this taxon at Daube Ranch (many plates and holotype) and North-Central I-35 (many plates) and from the Upper Echinoderm Zone at Sulphur (about a dozen plates), Lick Creek (5 plates), and North I-35 (1 plate), both in the upper Mountain Lake Member of the Bromide Formation, and about 3 m above the base of the overlying Pooleville Member of the Bromide Formation at Fittstown Roadcut (few plates).

Discussion.—*Bromidocystis sinclairi* differs from *B. bassleri* from lower in the Mountain Lake Member by apparently having a different thecal shape (ovoid instead of club-shaped), a wider base with a basal expansion angle of 90 to 100° (instead of 25 to 40°), larger, thicker, more elongate, and more highly domed thecal plates, some of which are strongly curved (implying an angular thecal shape), sutural pores that are less elongate into the plate and have a much higher average pore spacing (0.89 mm/pore vs. 0.65 mm/pore), finer pustular ornament that lacks the radiating ridges and has few of the larger spines marking the ends of the underlying tangential canals, and perhaps no recumbent brachioles. Because little is known about the summit region and ambulacral system, other differences may show up when a partial or complete theca is finally found. It may even become necessary to assign *B. sinclairi* to a new genus once it is better known, but this has not been done here because major differences between these two species are not yet evident.

EDRIOASTEROIDS

Bruce M. Bell

Stovall Museum, The University of Oklahoma

Bromide edrioasteroids include 378 specimens which belong to at least five species representing four genera, one an edrioasterid and three isorophids. Of the latter, one is a cyathocystid and two are lebetodiscids. Only the cyathocystids are at all common (338 specimens) and these still form only a minor component of the echinoderm fauna of the Bromide Formation in Oklahoma. Edrioasteroids are most common in the Lower Echinoderm Zone of the Mountain Lake Member, but do occur in the other two echinoderm zones. Of paleoecological interest is the concentration of the small pyrgocystid species that lived partially buried in loose substrate material in the Pooleville. All of the other edrioasteroids are attached forms, which were less common in this setting because of the reduced availability of suitable substrate attachment sites.

Most of the Bromide edrioasteroid material is fragmentary or too inadequately preserved to allow detailed analysis. Better specimens are needed to fully define this component of this Middle Ordovician echinoderm fauna.

Subphylum Indeterminate

Class EDRIOASTEROIDEA Billings, 1858

Order EDRIOASTERIDA Bell, 1976

Family EDRIOASTERIDAE Bather, 1899

Genus EDRIOPHUS Bell, 1976

EDRIOPHUS sp. cf. E. LAEVIS (Bather), 1914

Plate 39, figures 5-7

Only six fragmentary specimens represent the edrioasterid component of the Bromide fauna. All are from the Mountain Lake Member, with four from three localities in the Lower Echinoderm Zone and two from two sites in the Upper Echinoderm Zone. The most complete specimen, USNM 307369 (Pl. 39, fig. 5), includes the proximal parts of two adjacent ambulacra (probably II and III), the adjoining interambulacrals plus an interradial oral frame plate, and a number of other interambulacrals crushed against the lower side of the specimen. Other specimens include only short mesial or distal segments of ambulacra and associated interambulacral plates. These six specimens are clearly referable to the Edrioasteridae. They have: large thick tessellate interambulacrals; biserial ambulacral floorplates with sutural passageways connecting the ambulacral groove with the thecal cavity; large biserial coverplates that are centered directly over the floorplates and roof only the ambulacral tunnel by resting on the perradial two-thirds of the upper surfaces of the floorplates, thereby leaving the adradial ends of the floorplates exposed externally; large compound interadial oral frame plates; and plate dimensions consistent with those common to other Edrioasteridae. The fragmentary specimens suggest the ambulacra curved clockwise and, together with the lack of pronounced prosopon on the interambulacral plates, suggest the specimens most likely belong to a species of *Edriophus*. Plate and thecal size are consistent with those reported for *Edriophus laevis*, but confident assignment requires more complete material. Specimen 1279TX110 clearly preserves the floorplate sutural passageways and the accessory sutural grooves and basins typical of edrioasterids (Pl. 39, fig. 7).

Specimens.—USNM 307369 (Pl. 39, fig. 5); probably Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, west branch of Sycamore Creek, Daube Ranch; 20 mm "long" by 16 mm "wide." OU 9543 (Pl. 39, fig. 6); Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Sulphur; 14 mm "long" by 12 mm "wide." 1279TX110 (Pl. 39, fig. 7); 1 of 2 fragments from the Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Fittstown Quarry; 10.1 mm "long" by 4.4 mm "wide." 1279TX217; small fragment including part of an ambulacrum and a few adjacent interambulacrals; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Fittstown Quarry; 10.0 mm "long"

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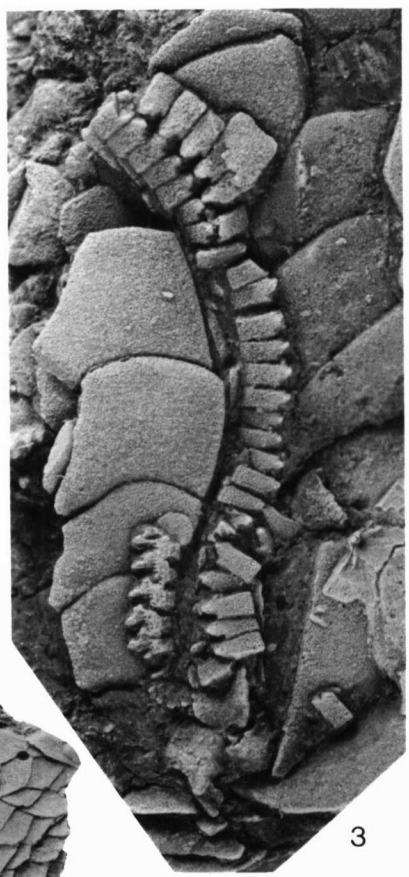

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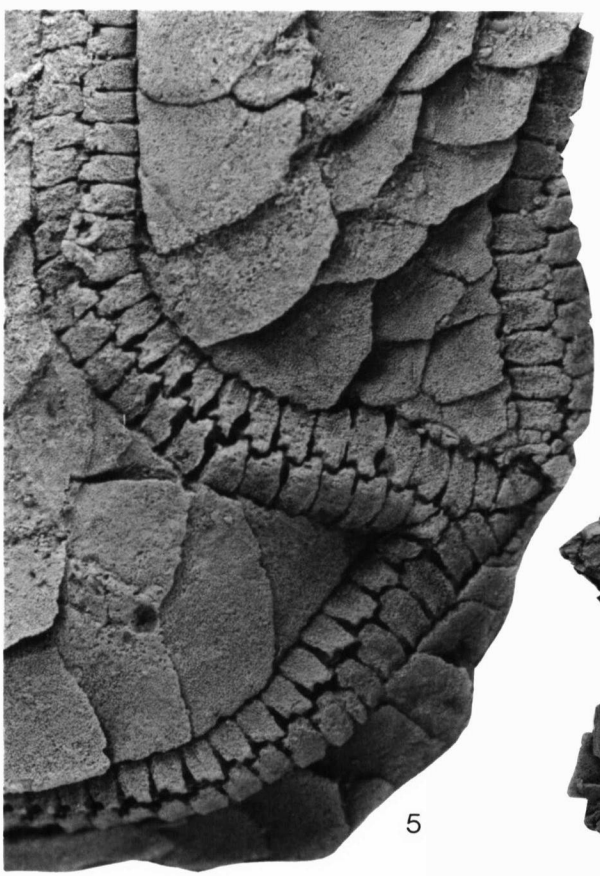

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by 7.5 mm "wide." 1221TX31; fragment including the distal tip of an ambulacrum and a few adjacent interambulacrals; Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, BC cut at North-Central I-35; 8.4 mm "long" by 7.4 mm "wide." 1278TX3; a completely jumbled cluster of plates; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Cedar Village; 21.5 mm "long" by 16.0 mm "wide."

Order ISOROPHIDA Bell, 1976

Suborder LEBETODISCINA Bell, 1976

Family LEBETODISCIDAE Bell, 1976

Genus FOERSTEDISCUS Bassler, 1935

FOERSTEDISCUS SPENDENS Bassler, 1936

Plate 38; Plate 39, figures 1-3

Foerstediscus splendens Bassler, 1936, p. 7, fig. 13.

Foerstediscus splendens Bassler, Bassler and Moodey, 1943, p. 202.

Foerstediscus splendens Bassler, Kesling, 1960, p. 162-163, text-fig. 8, pl. 7, fig. 1, 2.

Foerstediscus splendens Bassler, Regnéll, 1966, p. U165, text-fig. 115,1, 120,2b, 125,6, 126,5.

Foerstediscus splendens Bassler, Bell, 1976, p. 71-74, text-fig. 6, pl. 5, fig. 1-6.

The Bromide collections include seventeen lebetodiscid edrioasteroids from eight localities. Fifteen are from the Mountain Lake Member, four from three sites in the Lower Echinoderm Zone with six of these attached to a single bryozoan colony. The remaining two are each from a different site in the Pooleville. One specimen, UCMP 43291 (Pl. 38, fig. 1, 2, 6), is nearly complete although the distal margin of the oral surface, including the peripheral rim, has been folded in under the upper side and the right posterior third of the theca, including ambulacra IV and V and the oral area, has been crushed inward, distorting and obscuring the plate layout details in these areas. A second individual, OU 9537 (Pl. 38, fig. 4, 5), preserves about 40 percent of the theca, including ambulacrum I, most of II and the proximal part of III, plus interambulacra 1 and 2 and a small part of 5. Six individuals occur attached to a massive bryozoan colony (OU 9545A-F, Pl. 39, fig. 1-3). Five of these are reasonably complete, but all have been extensively etched and the smaller ones are distorted. The remaining specimens range from segments of the theca including ambulacra (Pl. 38, fig. 3, 7) to small clusters of plates which could belong to nearly any isorophid but are assigned here with some question to the Lebetodiscidae because of their association with the recognizable specimens.

This suite of specimens exhibits enough of the taxonomically significant features to permit assignment to *Foerstediscus splendens*, previously represented only by the holotype, USNM S-4079, "Black River (Decorah shale, Top of *Rhinidictya* bed), Ford plant, St. Paul, Minnesota" (Bassler, 1936, p. 10): highly convex domal theca (Pl. 38, fig. 1, 4, 6), oral area with several secondary oral plates (Pl. 38, fig. 2, 5), all ambulacra curving clockwise (Pl. 38, fig. 1, 4, Pl. 39, fig. 1), coverplate passageways large (Pl. 38, fig. 1-6), coverplates with lateral depression series (Pl. 38, fig. 7), and interambulacrals smooth (Pl. 38, fig. 1-7, Pl. 39, fig. 1-3). Specimens UCMP 43291 and OU 9538 (Pl. 38, fig. 1-3, 6) show that the perradial tips of the coverplates flex outward to form a large protuberance on the tip of each plate. Five of the coverplates along the lower left side of the ambulacrum in OU 9538 expose their ambulacral tunnel faces, showing the perradial ridges and lateral interlocking flanges. The lower side of specimen UCMP 43291 (Pl. 38, fig. 6) exposes four ambulacral floorplates, confirming the supposition (Bell, 1976) that these uniserial elements meet along oblique sutures so as to imbricate with one another. Two of the six individ-

PLATE 38.

Fig. 1-7. *Foerstediscus splendens* Bassler, 1936; Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 1, 2, 6 from Lower Echinoderm Zone at McLish Ranch; 3-5 from Lower Echinoderm Zone at Lick Creek; 7 from Upper Echinoderm Zone at Nebo. 1, 2, 6. Oral surface, enlarged oral area, and lower side of specimen UCMP 43291, showing in 6 disrupted interambulacrals, part of the peripheral rim, and thecal cavity view of short segment of one ambulacrum; X2, X4, X2. 3. Ambulacral segment with adjacent interambulacrals in OU 9538; note overturned coverplates at lower left; X4. 4, 5. Oral surface and enlarged oral area of OU 9537; X2, X7. 7. Ambulacral segment and adjacent interambulacrals in OU 9544; note coverplates with lateral depression series preserved in part; X10.

uals incrusting the bryozoan colony are juveniles (Pl. 39, fig. 2, 3), but mediocre preservation precludes detailed description.

Specimens.—UCMP 43291 (Pl. 38, fig. 1, 2, 6); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, McLish Ranch, presumably from along the access road; 31.8 mm axial diameter by 22.2 mm transverse diameter. OU 9537 (Pl. 38, fig. 4, 5); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Lick Creek; 28.2 mm axial diameter by 19 mm transverse diameter. OU 9538 (Pl. 38, fig. 3); same locality as OU 9537; 27.5 mm "long" by 21 mm "wide." OU 9544 (Pl. 38, fig. 7); 1 of 3 fragmentary specimens from Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Nebo; 18 mm "long" by 14.3 mm "wide." OU 9545A-F; 6 specimens incrusting a massive bryozoan; ?Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Rock Crossing: OU 9545A (Pl. 39, fig. 1), 15 mm greatest thecal diameter; OU 9545B (Pl. 39, fig. 2), 9.5 mm axial diameter; OU 9545C (Pl. 39, fig. 3), 5.5 mm transverse diameter; OU 9545D, 15 mm greatest diameter; OU 9545E, 15.5 mm greatest diameter; OU 9545F, 6.5 mm greatest diameter.

Five other specimens were examined: 2 are from the Pooleville Member, Bromide Formation, 1 from Rock Crossing, consisting of a small number of squamose plates on a brachiopod, the other from Culley Creek (Spring Creek), consisting of a small conglomeration of squamose plates; 3 are from the Mountain Lake Member, Bromide Formation, including specimens 1281TX6-7 on a bryozoan colony from the ?Upper Echinoderm Zone at Rock Crossing, and 1392-TX7, a fragment from the Lower Echinoderm Zone at Lowrance Springs. These 5 individuals are tentatively assigned to *F. splendens*, which is the only known isorophid that occurs in the fauna.

Genus PYRGOCYSTIS Bather, 1915a

Scalpellum Leach, Aurivillius, 1892, p. 1-24.

Pyrgocystis Bather, 1915a, p. 5-12, 49-60, pl. II, fig. 1-6, pl. III, fig. 1, 2, ?pl. III, fig. 3-15.

non Pyrgocystis Bather, Ruedemann, 1925, p. 39-40, pl. 13, fig. 2-5.

non Pyrgocystis Bather, Richter, 1930, p. 279-286, fig. 1a-h.

Pyrgocystis Bather, Bassler, 1935 (*partim*), p. 1-11.

Pyrgocystis Bather, Hecker, 1939, p. 241-246.

Pyrgocystis Bather, Regnéll, 1945 (*partim*), p. 203-214, ?pl. I, fig. 7, pl. II, fig. 1-8.

?non Pyrgocystis Bather, Rievers, 1961, p. 9-11.

?non Pyrgocystis Bather, Dehm, 1961, p. 13-17.

Pyrgocystis Bather, Regnéll, 1966 (*partim*), p. U165-U166, fig. 127, 2a-b.

Pyrgocystis Bather, Kesling, 1967 (*partim*), p. 197-202.

Type species.—*Pyrgocystis sardesoni* Bather, 1915a.

PLATE 39.

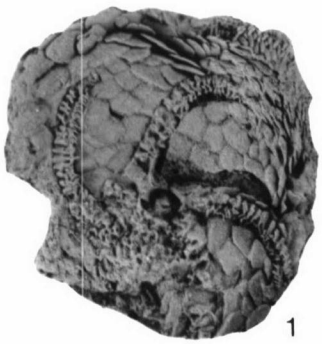
Fig. 1-3. *Foerstediscus splendens* Bassler, 1936; ?Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Rock Crossing, Criner Hills, southern Oklahoma. 1. Oral surface, extensively etched, of OU 9545A; note oral frame; X3. 2. Oral surface of "adolescent" OU 9545B; X3. 3. Oral surface of juvenile OU 9545C; X5.

Fig. 4. *Cyathocystis americanus* Bassler, 1936; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Lick Creek, Arbuckle Mountains, southern Oklahoma; cup 1107TX1 attached to bryozoan; note crinoid bases attached to basal surface of theca; X3.

Fig. 5-7. *Edriophus* sp. cf. *E. laevis* (Bather), 1914; Mountain Lake Member, Bromide Formation, Arbuckle Mountains, southern Oklahoma; 7 from Lower Echinoderm Zone at Fittstown Quarry, 5 probably from same zone at Daube Ranch, 6 from Upper Echinoderm Zone at Sulphur. 5. Oral surface view of USNM 307369; X3. 6. Fragment OU 9543 with parts of 2 ambulacra; X3. 7. Ambulacral floorplates and adjacent interambulacrals of 1279TX110; X6.

Fig. 8-10. *Pyrgocystis* sp. B; Pooleville Member, Bromide Formation, Rudd Quarry, Criner Hills, southern Oklahoma. 8. Lateral view of peduncular part of theca OU 9549; spines obscure plate detail except where theca disrupted; X5. 9. Lateral view of peduncular part of theca OU 9548; lower end intact with spines on imbricate plates; upper two-thirds disrupted, probably reworked by a sediment burrower, completely reorienting all plates; X5. 10. Lateral view of peduncular part of theca OU 9547; spines obscuring plate detail; X5.

Fig. 11-16. *Pyrgocystis* sp. A; Bromide Formation, Arbuckle Mountains, southern Oklahoma; 11, 12 from Lower Echinoderm Zone, Mountain Lake Member, Daube Ranch; 13 from same zone at Cornell Ranch; 14-16 from upper Pooleville Member, Johnston Ranch Roadcut. 11, 12. Lateral and oblique views of theca 1221TX30 showing large plates of peduncular region of theca and oral surface plates mostly obscured by spines; X5. 13. Oblique view of theca OU 9539 showing disrupted remnants of oral surface plates and edges of imbricate plates of peduncular part of theca; X4. 14-16. Oblique view, oral surface view, and lateral view, respectively, of theca OU 9550 showing margin of oral surface, spines obscuring most plates except for edges of coverplates of 2 ambulacra and a few adjacent nodose interambulacrals, and peduncular part of theca with large imbricate plates and small spines; X6.



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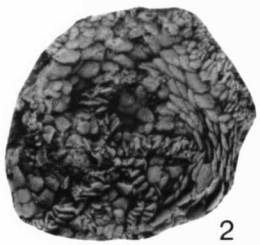

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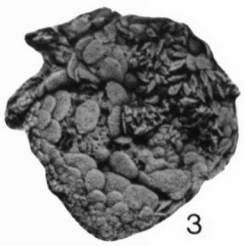

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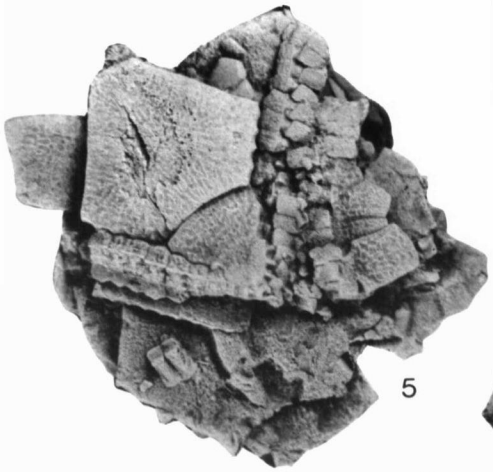

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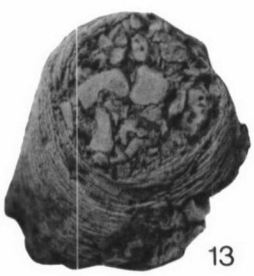

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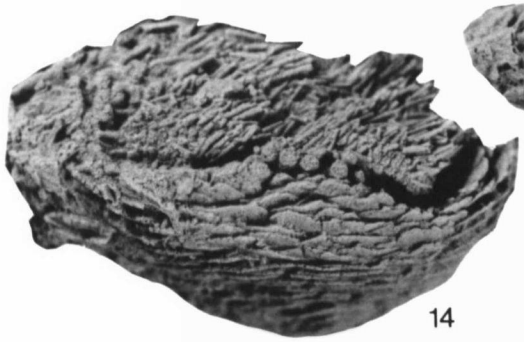

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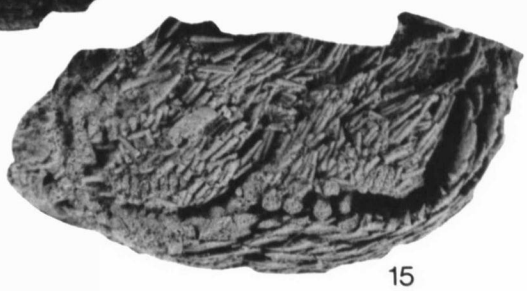

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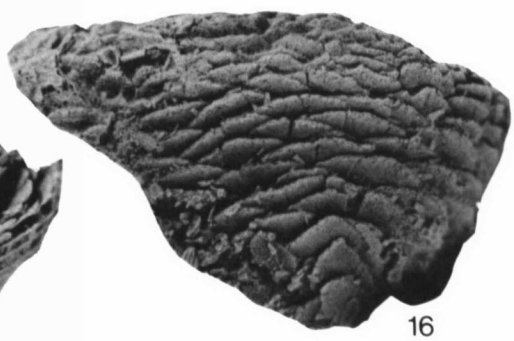

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Two groups of quite different edrioasteroids have been assigned to the genus *Pyrgocystis*. The sole taxobasis used to distinguish the genus has been the presence of an elongate, commonly cylindrical, peduncular structure made of numerous, imbricate, squamose plates that form rows or columns in some individuals. The oral face forms the flat to somewhat convex top of the theca. In most the peduncular zone tapers downward to a blunt, semi-conical base, without an attachment structure, although one Devonian specimen would seem to have a basal attachment disc made of minute granules. The elongate cylindrical theca was an adaptation that permitted these species to live in areas with soft or shifting substrates, where most edrioasteroids could not survive. This adaptation was developed at least twice. Therefore, the genus *Pyrgocystis* is here restricted to Ordovician and possibly some Silurian forms that share those oral face features which characterize the type species, *P. sardesoni*.

Only three of the approximately fourteen (depending upon synonym evaluation) described species are based on specimens that preserve the oral face: two of Bather's Ordovician forms and the Devonian form with the basal attachment disc described by Rievers. Others have been based solely on supposedly taxonomically distinctive features of the peduncular zone, such as ordering of plates into columns, columnar patterns, number of plates per given segment of column length, and cross-sectional shape of the column. Many if not all of these features are influenced by preservation and all are of dubious taxonomic value. Unfortunately, oral surface features are obscured by numerous spines in the Ordovician forms currently available for study. However, what can be seen of these features in the Bromide specimens, unpublished photographs of a missing specimen from the Ordovician in Minnesota, and in Bather's 1915a illustrations and descriptions suggest that the Ordovician species are lebetodiscids: three primary orals, single biseries of ambulacral coverplates with intrambulacral and intrathecal extensions, coverplate sutural passageways, and a periproct-type anal structure. The thickness and height of the coverplates suggest these species are Lebetodiscidae, but this assignment must remain in question until individuals clearly displaying the oral surface are located and studied.

Many hundreds of specimens have been collected from the type locality of Ruedemann's (1925) Devonian *Pyrgocystis batheri* and from surrounding equivalent horizons. Bather's report that his specimens are from the Silurian Bertie Formation is clearly in error as demonstrated by the lithology of the specimens, which is that of the overlying Middle Devonian Onondaga and not the distinctive Bertie "waterline," and by the occurrence of numerous topotypes in the Onondaga and lack thereof in the Bertie at the Bennett Quarry. Some of these topotypes include oral surface plates, although none is well preserved. These specimens clearly depict a much different edrioasteroid than the Ordovician species. These Devonian forms are thought to be cyathocystids in that most of the oral face is formed by five large deltoids. It is unclear whether these alone covered the oral-ambulacral area or whether medial coverplates roofed the five radii marked by the junctions of these plates. The anal area has not been identified because of the distorted condition of all available specimens. The peduncular parts of these specimens are similar in plate construction to those of the Ordovician *Pyrgocystis* species, but lack spines, as far as is known. The Devonian specimen from Germany described by Rievers (1961) as *P. coronaeformis* may be yet another homeomorph, unrelated to the New York species. Final determination must await examination of the unique specimen.

At least two species of pyrgocystids occur in Oklahoma in the Bromide Formation, one having a very large conical theca, the other a very elongate thin cylindrical theca. Unfortunately, neither is represented by specimens which adequately preserve oral surface features. Thus, formal naming is unwise and has been postponed until well-preserved specimens with the taxonomically critical areas intact become available.

PYRGOCYSTIS sp. A

Plate 39, figures 11-16

Six specimens with relatively large thecae from four sites, three in the Mountain Lake Member of the Bromide (two in the Lower Echinoderm Zone, one in the Upper Echinoderm Zone) and one in the Pooleville, were available for study. Three include oral surface plates, but these are obscured by spines in two and the third has only a few jumbled plates left. The Pooleville specimen is considerably larger than the others, both in size of individual elements and in overall size (Pl. 39, fig. 14-16). It may be unique, but not enough of the specimen is preserved to document this suggestion. Coverplates can be seen beneath the spines

along the edges of two of the ambulacra. The peduncular spines in this individual are much smaller than those on the oral face and are widely scattered, although this could be an artifact of preservation.

The other four specimens referred to as species A are from the Mountain Lake Member and are much larger than the Pooleville specimens referred to below as species B, but are more elongate and cylindrical than the Pooleville specimen of species A discussed above. The best of these four, from the Lower Echinoderm Zone, has oral face plates, but these are hidden beneath spines so that only faint outlines of the ambulacra are visible (Pl. 39, fig. 11, 12). None of the disrupted oral face plates seen in Plate 39, figure 13 appears particularly distinctive. The other three specimens are all from the Upper Echinoderm Zone at Sulphur and preserve only small parts of the cylindrical peduncular zone.

Specimens.—OU 9550 (Pl. 39, fig. 14-16); Pooleville Member, Bromide Formation, roadcut at Johnston Ranch; 12 mm "long" by 8 mm "high," 10 mm greatest preserved oral face diameter. 1221TX30 (Pl. 39, fig. 11, 12); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Daube Ranch; 5.5 mm oral face diameter, 8.5 mm vertical height, 11.6 mm "long." OU 9539 (Pl. 39, fig. 13); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Cornell Ranch; 7.5 mm oral face diameter, 11.6 mm "long." OU 9540, OU 9541, OU 9542; 3 large pyrgocystids; all from the Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, Sulphur; respectively 16.8 mm "long" by 15 mm diameter, 14.8 mm "long" by 10.5 mm diameter, and small fragment.

PYRGOCYSTIS sp. B

Plate 39, figures 8-10

Eleven specimens of a species referred to here as B were available for study, but at least eight others have been collected from the same horizon. None include oral face plates or basal terminations. Commonly, well-preserved specimens are covered with peduncular spines so numerous as to obscure the plates. Apparently sediment reworkers were attracted to these creatures upon burial and caused the complete jumbling of the plates in many cases, such as is seen in the upper half of the specimen in Plate 39, figure 9. Several specimens are in actuality "worm" trails filled with jumbled pyrgocystid plates. These are more irregular in shape than the nearly cylindrical thecae. The details of peduncular zone construction are probably of little taxonomic significance.

Specimens.—OU 9549 (Pl. 39, fig. 8), OU 9548 (Pl. 39, fig. 9), OU 9547 (Pl. 39, fig. 10); Pooleville Member, Bromide Formation, Rudd Quarry; respectively: 8.5 mm "long" and 2.5 mm diameter, 7.1 mm "long" and 2.1 mm diameter, and 9.2 mm "long," 3 mm diameter. Others: 9.8 mm "long," 2.9 mm diameter; 6.4 mm "long," 3.0 mm diameter; 1 small fragment.

Five other specimens were examined from the Pooleville Member, Bromide Formation, Dunn Quarry. All are similar to those illustrated from Rudd Quarry and are of varying lengths with diameters of 2 mm or less.

Suborder CYATHOCYSTINA Bell, 1975

Family CYATHOCYSTIDAE Bather, 1899

Genus CYATHOCYSTIS Schmidt, 1879

CYATHOCYSTIS AMERICANUS Bassler, 1936

Plate 39, figure 4; Plate 40

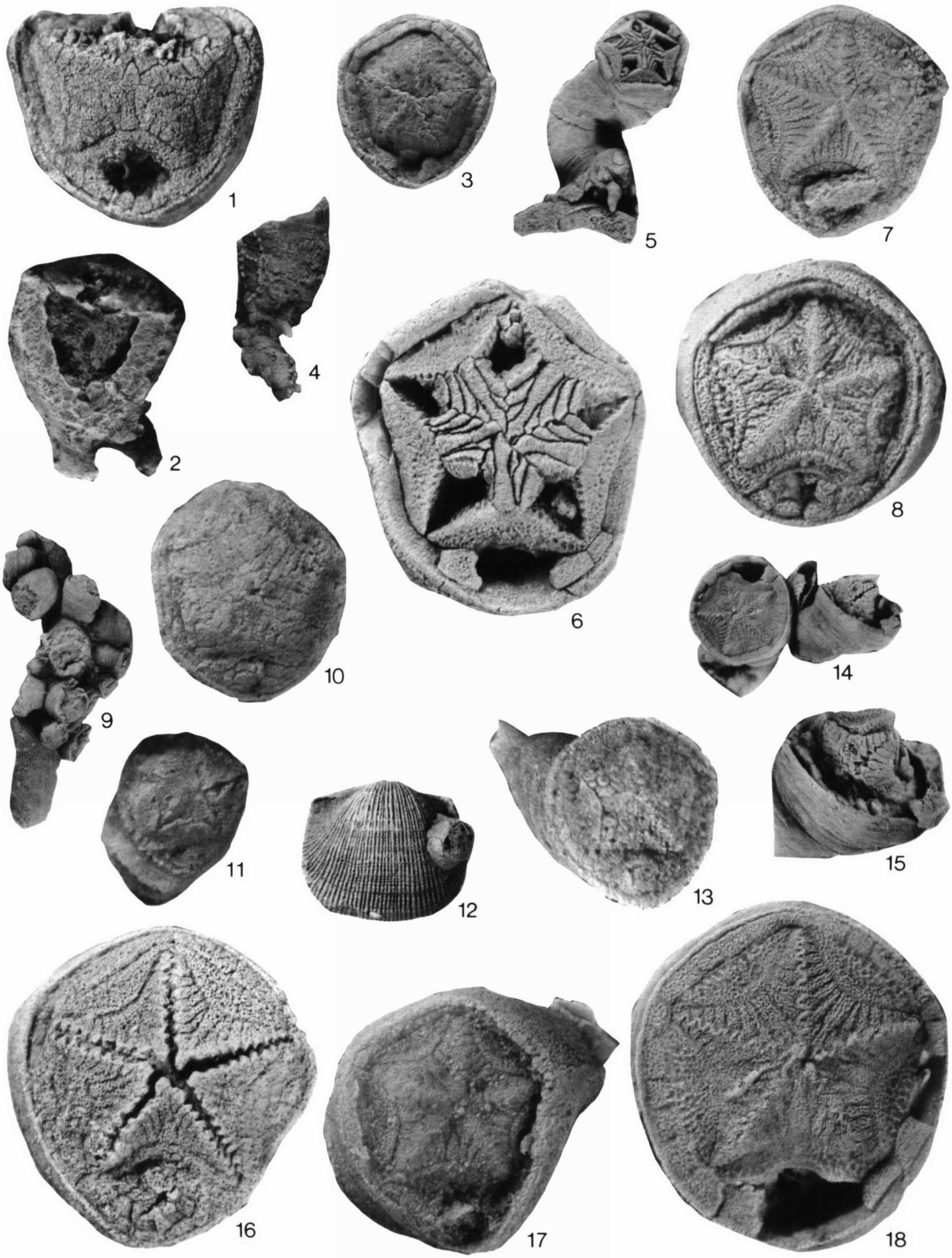
Cyathocystis americanus Bassler, 1936, p. 23, pl. 4, fig. 1, 2.

Cyathocystis oklahomae Strimple and Graffham, 1955, p. 353-355, fig. 3, 7, 8.

Cyathocystis americanus Bassler, Bell, 1975, p. 36, 49-50, pl. 5, fig. 6, 7; *C. oklahomae* Strimple and Graffham, *idem, ibid.*, p. 49-50.

Cyathocystis oklahomae Strimple and Graffham, Sprinkle and Bell, 1978, p. 82-83, 86-87, fig. 1C-D.

The cyathocystids remain among the most enigmatic of the edrioasteroids. Apparently they were specialized for shallow-water environments in a barnaclelike manner. Not only is the lower part of the theca fused into a massive cup firmly anchored to some hard surface, but even the oral surface elements are fused to a high degree. In species of *Cyathotheca*, the entire oral surface is reported to be formed by only five large triangular plates with a marginal anal vent. The Bromide specimens all belong to Bassler's *Cyathocystis americanus*, but unfortunately, specimens which retain oral face plates are uncommon and those that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do so are preserved in such a fashion as to obscure plate boundaries in all but a few. In *Cyathocystis americanus* most of the oral face is formed only by ambulacral coverplates, a single biseries for each ambulacrum, and by five massive deltoids, which form the interambulacra and extend under the coverplates, each abutting the two contiguous deltoids along the midline of the two adjacent ambulacra (Pl. 40, fig. 1, 3, 5-8, 14-18). Thus, the deltoids form the floor of the ambulacral troughs (Pl. 40, fig. 5, 6, 15). It is unclear whether or not these plates are modified ambulacral floorplates or are interambulacral in origin. If the former is the case, one could argue for the derivation of cyathocystids from the Edrioasterida. However, no evidence of ambulacral passageways has been seen, and thus it seems more likely these elements are modified interradial plates. If so, the floorplates apparently have been lost.

The deltoids have prominent grooves along the edges of the ambulacral tunnels into which the adradial edges of the coverplates fit tightly (Pl. 40, fig. 6, 15). The deltoids are surrounded by a single circlet of marginals varying in number from fifteen up to forty in larger specimens (Pl. 40, fig. 1, 3, 6, 8, 16-18). These separate the edges of the deltoids from the rim of the massive stereom thecal cup except posteriorly, where the anal periproct forms a prominent distal bulge, commonly making the outline of the cup rim oval. The periproct is formed by a single biseries of plates ranging in number from six to ten in those few specimens which preserve anals (Pl. 40, fig. 3, 8, 10, 11, 13, 16, 17). Even when the oral face is preserved, the anals are most often lost.

The cup is extremely variable, adapting to whatever surface it is attached to (Pl. 39, fig. 4; Pl. 40, fig. 5, 9, 12, 13). Some are twisted conspicuously, suggesting the individual had been knocked over and reoriented itself by changing its growth axis. Some are several times higher than wide, others the reverse. Cup shape has no taxonomic significance. They attach to any available hard object. Apparently, cups persisted in place even after an individual died, as shown by the specimen in Plate 39, figure 4 with crinoid bases attached to the inside of the cup base.

The oral ambulacral series is also simple. Three primary orals, two anterior and one posterior, combine with two large lateral bifurcation plates to form the center of the series (Pl. 40, fig. 1, 6-8, 10, 16, 18). These five plates are the largest coverplate elements and have a distinctive shape resulting from a pronounced perradial widening. It appears that the perradial end of the posterior oral consistently extends to the left of the two anterior orals, abutting the end of the left lateral bifurcation plate. The right anterior oral squarely abuts the tip of the posterior oral, limiting the contact of the left anterior oral with the posterior oral to a very narrow zone. Several small secondary orals which do not reach the adradial ambulacral suture fill the spaces between the orals and the first pair of ambulacral coverplates that extend fully across each ambulacrum (Pl. 40, fig. 6). Two such secondaries are found in each ambulacrum and not infrequently three are present. Adults have from six to eight or nine pairs of coverplates per ambulacrum. In well-preserved individuals the cover-

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PLATE 40.

Fig. 1-18. *Cyathocystis americanus* Bassler, 1936; 1, 2 from Cystid Zone, Ottosee Formation, Blount Group, Knoxville, Tennessee; all others from Bromide Formation, Arbuckle Mountains and Criner Hills, southern Oklahoma; 4, 7-13, 17 from Lower Echinoderm Zone of the Mountain Lake Member at Fittstown Quarry; 5, 6 from the same zone at Rhynes Ranch; 16 from the same zone at Daube Ranch; 3, 14, 15, 18 from upper Pooleville Member at Culley Creek. 1, 2. Oral surface and lateral views of holotype USNM 91846, showing broken side; X10, X6. 3. Oral surface of USNM 307367, type series specimen of *Cyathocystis oklahomae* Strimple and Graffham; X6. 4. Lateral view of cup 1279TX93 showing lateral protuberances and encrusting epizoan; X2. 5, 6. Lateral view and enlarged oral surface of specimen 1388TX1 attached by process to bryozoan; note in 6 etched proximal coverplates and junctions between adjacent deltoids in distal parts of ambulacra where coverplates are missing; X3, X8. 7. Oral surface of well-preserved individual 1279TX26; anal region obscured by matrix; X2. 8. Oral surface of small adult 1279TX53 with prosopon preserved on deltoid 1 and adjacent marginals; anal plates disrupted; X10. 9. Lateral view of small bryozoan covered with 18 cyathocystids (1279TX75-92) ranging from juvenile to adult; X2. 10. Oral surface of small adult 1279TX75; coverplates partially etched; X12. 11. Oral surface view of juvenile 1279TX76; X15. 12. Specimen OU 9536 attached to the brachiopod *Mimella;* X1.5. 13. Oral view of juvenile 1279TX55; X20. 14, 15, 18. Oblique view in 14 of 2 adults, OU 9546A-B, the smaller attached to the side of the larger, with a small brachiopod wedged in between; note small adult in 15 showing oral surface plates deflected almost 90° from original orientation, exposing lateral view of a large deltoid; enlarged oral surface of large adult in 18 shows prosopon preserved on coverplates, deltoids, and marginals, note perradial ridge and missing anal plates and adjacent marginals; X2.5, X5, X8. 16. Oral surface of large adult OU 9535 with all coverplates pulled apart perradially through postmortem disruption; anal plates also separated centrally; X8. 17. Oral view of small adult 1279TX54 with rapidly tapering theca; X10.

plates are found to form an elongated, zigzag ridge marking the perradial line (Pl. 40, fig. 16, 18).

Plate surfaces are generally etched smooth, but in better examples a scrobicular prosopon is apparent (Pl. 40, fig. 8, 18).

No evidence of a hydropore has been seen in any specimen and none of the ambulacral coverplates would seem to be modified for pore formation. This probably reflects the massive nature of the posterior deltoid, the development of which may have caused the migration of this pore to the only available open area, the periproct region. If these forms relied upon anal pumping as a respiratory device, this is not unreasonable. However, the rigidity of the theca suggests some type of compensatrix would have been necessary for pumping exchange. None of the specimens offers evidence to explain this dilemma.

Young individuals are included in the Bromide specimens (Pl. 40, fig. 11, 13, 17), but none permits evaluation of ontogenetic development.

Specimens are by far most common in the Lower Echinoderm Zone of the Mountain Lake Member, but individuals occur throughout the Bromide Formation. Three hundred and forty specimens from 23 different localities were examined, but a majority come from the Lower Echinoderm Zone at Fittstown Quarry, where this form is the most abundant echinoderm (59 percent of the echinoderm fauna).

Comparison of the Bromide specimens with the Tennessee type specimen of Bassler's *C. americanus* showed no significant differences. Those reported by Strimple and Graffham in describing their Bromide specimens as *C. oklahomae* are either preservational or within the normal range of intraspecific variation, i.e., cup shape, number of marginals, deltoid shape, etc. Strimple and Graffham reported that they would deposit the holotype and one paratype in the U. S. National Museum, Washington, D. C. Examination of the USNM specimens in comparison with Strimple and Graffham's 1955 illustrations and descriptions show that the USNM specimen illustrated in Plate 40, figure 3 is a paratype, the "second" specimen with oral face plates, and not the holotype, which has much more clearly defined coverplate sutures. A second paratype is also in the USNM, consisting only of the cup (which has been broken into several pieces). The present location of the holotype is unknown.

Specimens.—Supporting specimens are in the collections of the University of Texas at Austin and the Stovall Museum of Science and History, The University of Oklahoma. Those illustrated are: USNM 91846, holotype (Pl. 40, fig. 1, 2); Cystid Zone, Ottosee Formation, Blount Group, Knoxville, Tenn.; 4.6 mm oral face diameter, 6.3 mm high. USNM 307367, paratype of *Cyathocystis oklahomae* (Pl. 40, fig. 3); "Lower Bromide Formation,...exposure in the east bank of Spring Creek, a tributary of Hickory Creek, Criner Hills, some 7 miles southwest of Ardmore, Okla." (?Upper Pooleville at Cully Creek); 6 mm oral face diameter. 1107TX1 (Pl. 39, fig. 4); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Lick Creek; cup, 8 mm diameter. 1279TX26-110, 182-297, 205 specimens; Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Fittstown Quarry. Illustrated are: 1279TX26 (Pl. 40, fig. 7), 4.8 mm oral face diameter, 6 mm thecal diameter, 9.8 mm high; 1279TX53 (Pl. 40, fig. 8), 3.9 mm transverse oral diameter, 4.8 mm thecal diameter, 2.9 mm high; 1279TX54 (Pl. 40, fig. 17), 3.5 mm oral face diameter, 5.5 mm thecal diameter, 4.0 mm high; 1279TX55 (Pl. 40, fig. 13), 1.5 mm oral face diameter, 1.8 mm thecal diameter, 2.4 mm high; 1279TX75 (Pl. 40, fig. 10), 3.2 mm axial diameter; 1279TX76 (Pl. 40, fig. 11), 1.5 mm axial diameter; 1279TX93 (Pl. 40, fig. 4), 6.1 mm thecal diameter, 14.3 mm high. 1388TX1 (Pl. 40, fig. 5, 6); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Rhynes Ranch; also illustrated in Sprinkle and Bell, 1978, fig. 1C-1D; 5.3 mm transverse oral diameter, 6.0 mm axial diameter, 12.2 mm high. OU 9536 (Pl. 40, fig. 12); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Lick Creek; 4.0 mm transverse oral diameter, 4.2 mm thecal diameter, 3.8 mm high. OU 9546A-B; Pooleville Member, Bromide Formation, Culley Creek: OU 9546A (Pl. 40, fig. 14, 18), 6.4 mm transverse oral diameter, 7.5 mm thecal diameter, 10.2 mm high; OU 9546B (Pl. 40, fig. 14, 15), 5.4 mm transverse oral diameter, 6.0 mm thecal diameter, 8 mm high. OU 9535 (Pl. 40, fig. 16); Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, Daube Ranch; 5.9 mm transverse oral diameter, 7.5 mm thecal diameter, 13.5 mm high.

ASTROCYSTITES

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The rare edrioblastoid genus *Astrocystites* is represented in the Mountain Lake Member of the Bromide Formation only by distinctive parabolic deltoid plates. Two species appear to be present, one in the Upper Echinoderm Zone at Buckhorn Ranch, and a second in the Lower Echinoderm Zone at McLish Ranch and Pickens Ranch and in the *Bromidocystis* Bed at Daube Ranch. Neither species is named here because of the incomplete material. A species similar to the Bromide forms is also present as isolated deltoid plates in the Benbolt Formation of southwestern Virginia.

Subphylum ECHINOZOA Zittel, 1895

Class EDRIOBLASTOIDEA Fay, 1962

Order PENTACYSTIDA Jaekel, 1918

Family STEGANOBLASTIDAE Bather, 1900

Genus ASTROCYSTITES Whiteaves, 1897

Type species.—*Astrocystites ottawaensis* Whiteaves, 1897.

Diagnosis.—Echinozoans with bud-shaped theca having 5 basals, 5 radials, 5 parabolic deltoids, numerous interray plates below deltoids, and 5 small orals. Ambulacra elongate and U-shaped, extending down theca from central mouth on summit, bearing rows of pores for tube feet from closed water vascular system but no other plated appendages. Each ambulacrum formed by elongate limbs of two deltoid plates sutured together. Anus on side of theca below posterior deltoid, slit- or pore-like hydropore in posterior deltoid with 1 or more small gonopores nearby. Plates ornamented with small pits, with deep grooves crossing sutures but not penetrating to thecal interior. Stem divided into pentameres, tapering distally, probably short.

Occurrence.—Middle Ordovician, southern Canada, eastern, central, and southern United States, and southeastern Australia; Late Ordovician, Sweden.

ASTROCYSTITES sp. A

Plate 37, figures 48, 49

Description.—Deltoid plates parabolic in shape, relatively massive; smallest plate much wider than long, 3.5 mm long by 5.5 mm wide, largest plate more equidimensional, 10 mm long by 11 mm wide. Edges of adjacent ambulacra diverging at angle of 40 to 80°, angle gradually decreasing with increasing size. Aboral depressed shelf between diverging limbs fairly wide, with a small to medium-sized aboral notch; in posterior deltoids, shelf narrower and almost no aboral notch. Hydropore preserved in 3 posterior deltoids, a small, vertically oriented, nearly straight slit about 0.6 mm long; 1 or more raised gonopores alongside. Parabolic limbs ornamented with small pits alongside ambulacra and vertically oriented ridges on aboral shelf. Ambulacra moderately long and very deep, 2.5 mm deep in small deltoid, 3.3 mm deep in large one. Pores for tube feet developed as elongate slits on near-vertical side of ambulacrum, from 2.5 to 3.4 mm per 10 pores. Top of ambulacrum at adoral edge cut by oblique flat suture apparently for attachment of large oral cover plate.

Occurrence.—Upper Echinoderm Zone, top of Mountain Lake Member, Bromide Formation, fairly common at Buckhorn Ranch (22 deltoid plates and fragments).

Figured specimens.—1111TX21-22; other plates in collections 1111TX23 and OU 9122.

Discussion.—See combined discussion after *Astrocystites* sp. B.

ASTROCYSTITES sp. B

Plate 37, figures 46, 47

Description.—Deltoid plates parabolic in shape, limbs relatively thin; most plates equidimensional or slightly wider than long, large plate about 7 mm long by 7 mm wide. Ambulacral edges diverging at angle of 45 to 65° with little change during growth. Aboral shelf between diverging limbs narrow to medium in width, bearing a medium to large aboral notch. Hydropore unknown. Parabolic limbs ornamented with very small to small pits alongside ambulacra and a few vertically oriented ridges on narrow aboral shelf. Ambulacra relatively long and of moderate depth, from 1.9 to 2.3 mm deep in all specimens. Pores for tube feet developed as fairly elongate slits on near-vertical side of ambulacrum, from 2.5 to 3.1 mm per 10 pores.

Occurrence.—Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, McLish Ranch (4 deltoid plates) and Pickens Ranch (1 deltoid plate); also from the *Bromidocystis* Bed near the top of the Mountain Lake Member at Daube Ranch (1 broken deltoid plate).

Figured specimens.—1114TX53-54; other plates in collections 1114TX55, 1389TX2, and 1397TX57.

Discussion.—*Astrocystites* sp. A and B from different zones in the Bromide Formation appear to be fairly closely related, although they are very likely separate species. *Astrocystites* sp. B differs from sp. A by having somewhat smaller, less robust, narrower deltoids with a lower divergence angle, by having a narrower aboral shelf with a somewhat larger central notch and smaller pits laterally, and by having shallower ambulacra. Similar undescribed *Astrocystites* deltoid plates from the Benbolt Formation of southwestern Virginia (see Sprinkle, 1973, p. 188) differ from these Bromide species by being somewhat narrower with a lower divergence angle, by having a wider shelf with slightly larger pits, and perhaps by having a porelike (instead of slitlike) hydropore; otherwise, these three forms are relatively similar. *Astrocystites ottawaensis*, the somewhat younger type species, differs from these two Bromide species by having larger and much longer deltoids with a smaller aboral shelf and central notch, by having shallower ambulacral grooves with less vertical sides, and by having a much higher ambulacral pore spacing (4 to 5.9 mm per 10 pores; see Mintz, 1970, p. 875-876). *Astrocystites distans* from the Middle Ordovician of Australia differs from these Bromide species by having a porelike (instead of slitlike) hydropore, by having a more elongate deltoid shape, by having shallower ambulacral grooves with less vertical sides, and by having a somewhat higher ambulacral pore spacing of 3.3 to 4 mm per 10 pores (Webby, 1968, p. 515).

The Bromide deltoid plates of *Astrocystites* show that the ambulacral pores extend directly through the plate to the coelomic interior and form a "closed" water vascular system like that of other echinozoans, and that the grooves between ridges on the central part of the aboral shelf do not penetrate to the thecal interior, and therefore are not epispires such as those found in Cambrian eocrinoids and some other early echinoderms. *Astrocystites* appears to be a rare and archaic echinoderm of echinozoan (perhaps edrioasteroid) ancestry that has adopted an attached suspension-feeding way of life like most crinozoans and blastozoans. Many occurrences (including those in the Bromide and Benbolt formations) appear to be from the middle part of the Middle Ordovician, implying that *Astrocystites* may have been most common and geographically widespread at this time; however, other undescribed occurrences are also known from the Late Ordovician of Sweden (Paul, 1976, p. 570).

CYCLOCYSTOIDS

Dennis R. Kolata

Illinois State Geological Survey

Cyclocystoids are rare in the Bromide Formation. Only two specimens were available for study, neither of which reveals new information about the anatomy, functional morphology, or life mode of these enigmatic echinoderms.

Class CYCLOCYSTOIDEA Miller and Gurley, 1895

Family CYCLOCYSTOIDIDAE Miller, 1882

Genus CYCLOCYSTOIDES Salter and Billings, 1858

Type species.—*Cyclocystoides halli* Salter and Billings, 1858.

CYCLOCYSTOIDES sp.

Plate 4, figures 31-33

Description.—The two specimens available for study include a submarginal ring and a single submarginal ossicle. The submarginal ring (1222TX3) is approximately 12 mm in diameter and consists of about 25 poorly preserved submarginal ossicles (Pl. 4, fig. 33). The specimen is badly recrystallized and most of the fine surface detail has been destroyed. Neither the marginal ring nor the central discs are preserved. The radial dimension of each submarginal ossicle is greater than the width and approximately equal to the height. Each ossicle has 2 or, less commonly, 3 cupules that appear to lack facets.

The second specimen (1113TX15) is a well-preserved submarginal ossicle (Pl. 4, fig. 31, 32) that closely resembles ossicles from the Platteville Group of northern Illinois assigned to *Cyclocystoides* n. sp., aff. *halli* Billings by Kolata (1975, p. 57, pl. 11, fig. 1-8; pl. 13, fig. 1-4; text-fig. 17). The distal part of the ossicle has 3 cupules, each of which leads to a pore that passes through the ossicle. The cupules lack facets and thus are different from those of most species of *Cyclocystoides*. Each cupule is separated from adjacent cupules by a thin septum. The top of the ossicle (cupules oriented up) is evenly rounded and covered with small pustules, whereas the bottom is slightly convex, trapezoidal in outline, and pitted. The side of the ossicle that once faced the center of the disc has 1 or 2 circular indentations near the lower edge that apparently articulated with plates of the lower disc. A small vertical channel extends from the median circular indentation upward in line with the center submarginal pore. Directly below the submarginal pores is a row of closely spaced pits (Pl. 4, fig. 31). The sides of the submarginal ossicle have numerous fine striae that form an arc near the upper edge. Below the arc of striae are 2 rows each with 5 or 6 parallel ridges and grooves that mark the surface of articulation between submarginal ossicles. A small channel bounded by the ridges and the edge of the lower surface extends from the disc side along the lower edge of the ossicle up to an indentation in the septum between cupules of adjacent submarginals. This channel joins another channel beneath the overhanging edge of the ossicle above the cupules.

Discussion.—The Bromide cyclocystoids, like the Platteville specimens mentioned above, are most similar to *Cyclocystoides halli* Billings from the Trentonian Hull beds of the Ottawa Formation near Ottawa, Ontario, Canada. The lack of adequate study material, however, precludes assignment of the Bromide cyclocystoids to any species at this time.

Material and occurrence.—The submarginal ring (1222TX3) was found in the Upper Echinoderm Zone, Mountain Lake Member, North-Central I-35 Section, northern Arbuckle Mountains. The single submarginal ossicle (1113TX15) was found in the Lower Echinoderm Zone, Mountain Lake Member, C exposure at McLish Ranch, eastern Arbuckle Mountains, southern Oklahoma.

ECHINOIDS

Porter M. Kier

U.S. National Museum of Natural History

Only two specimens of echinoids have been collected in the Middle Ordovician Pooleville Member of the Bromide Formation of Oklahoma, but both are so distinct from any other echinoid that they warrant description. One of them is unlike all other echinoids in having only a single pore in each ambulacral plate and is referred to a new genus and species of the family Bothriocidaridae, *Unibothriocidaris bromidensis*. The other is a new species of *Bothriocidaris*, *B. kolatai*, easily distinguished by its numerous, highly elevated tubercles.

These two species were collected at the same locality and horizon within the Pooleville Member of the upper Bromide Formation. There is presently some uncertainty as to the age of the Bromide. Cooper (1956, p. 120-123) considered the upper Bromide to be Blackriveran on the basis of the brachiopods. Kolata (1975, p. 9) likewise considered the Bromide to be Blackriveran, but Decker (1952, p. 136-137) and Templeton and Willman (1963) placed it in the Trentonian. If these echinoids are Blackriveran, then they are approximately equivalent in age to the three species Kolata (1975) found in the Platteville Formation of Illinois: *Bothriocidaris solemi* Kolata, *Neobothriocidaris* sp., and "genus and species unknown." They are older than Kolata's *Neobothriocidaris templetoni* from the Trentonian Dunleith Formation. These species described by Kolata (1975) are the only other bothriocidarids known from North America. The Bromide *Unibothriocidaris bromidensis* has plates indistinguishable from plates referred by Kolata to "genus and species unknown," which may be further evidence that these Oklahoma and Illinois species are of the same age. These echinoids are among the oldest known. Three of the four species of *Bothriocidaris* from Estonia are definitely younger (Upper Ordovician), and the fourth, *B. pahleni* Schmidt, is from the Jöhvi (D1) stage, which may be as old but no older. The two species of *Neobothriocidaris* from Girvan described by Paul (1967a) are from the Upper Ordovician.

Class ECHINOIDEA Leske, 1778

Order BOTHRIOCIDAROIDA Zittel, 1879

Family BOTHRIOCIDARIDAE Klem, 1904

Genus UNIBOTHRIOCIDARIS Kier, new

Type species.—*Unibothriocidaris bromidensis* Kier, n. sp.

Diagnosis.—Test rigid with thick nonimbricating plates. Each ambulacral plate bearing a single pore passing straight through test. No plates possessing internal canals. Peripodium well developed around each ambulacral pore, each ambulacral plate bearing spines. Six columns present in each ambulacrum, 1 in each interambulacrum. Ambulacral plates arranged in chevra. No columns of nonperforate plates present in ambulacra.

Comparison with other genera.—This genus with its thick plates, rigid test, well-developed peripodia, and single column in each interambulacrum, clearly belongs to the Bothriocidaridae. It differs from the other two genera of this family, *Neobothriocidaris* and *Bothriocidaris*, in having a single pore in each ambulacral plate instead of pore pairs. It also differs from *Bothriocidaris* in having six columns instead of two in each ambulacrum and in having its ambulacral plates arranged in chevra. Although *Unibothriocidaris*, like *Neobothriocidaris*, has more than two columns in each ambulacrum, it lacks the column of imperforate plates dividing each ambulacrum and the enclosed water vascular system. These features are also lacking in *Bothriocidaris*. For this reason *Unibothriocidaris* seems to be more closely related to *Bothriocidaris* than to *Neobothriocidaris*.

Kolata (1975, p. 68, pl. 14, fig. 3-8) described and illustrated some isolated plates from the Middle Ordovician of Illinois which are indistinguishable from plates on this specimen. He has examined photographs of this specimen and consid-

ers (pers. commun., 1975) it to be very much like the plates he described. It is his opinion also that this Oklahoma specimen should be assigned to a new genus.

The plates studied by Kolata came from the Briton Member of the Mifflin Formation (Blackriveran Stage) and are the oldest of the bothriocidarids that he described. Therefore, the evidence suggests that his single-pored echinoid is the oldest of the bothriocidarids and that the single-pored condition is perhaps ancestral to the double-pored. Although Kolata (1975, p. 68) reported a slight constriction on the sides of the pores, which he suggested might show that the single pore was formed by a coalesced pore pair, it is just as reasonable to suggest that the reverse might be true. The constriction may have been producing a double pore from a single.

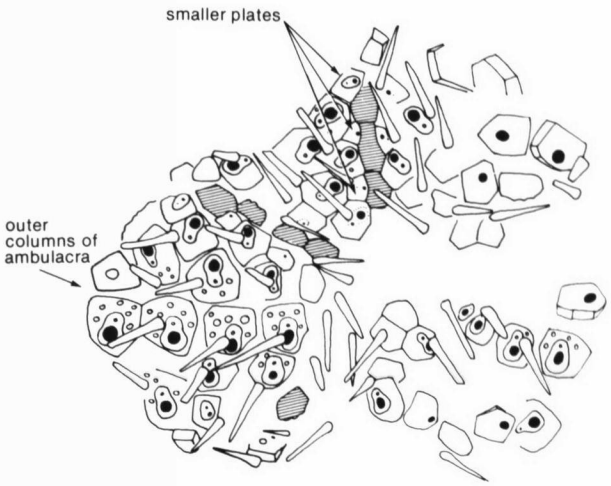


Fig. 73. *Unibothriocidaris bromidensis* Kier, n. gen., n. sp.; adapical view of holotype 1122TX1 (see Pl. 41, fig. 3), X5. Interambulacra are depicted by a pattern of parallel lines; outer columns of the ambulacra are discontinuous and are composed of smaller plates.

UNIBOTHRIOCIDARIS BROMIDENSIS Kier, n. sp.

Plate 41, figure 3; Figure 73

Material.—The holotype and only known specimen (1122TX1, Graffham Coll.) is flattened and distorted with many of the plates jumbled. It is 14 mm at its greatest width. The test was originally small—perhaps 10 mm in diameter. Most of the spines were still attached, but I have removed many of them to see the structure of the test. The upper side of the test appears to be adapical with the apical system near the center.

Apical system.—It is impossible to discern the plate arrangement except to note that there are many small plates. No genital plates are apparent.

Ambulacra.—Only 1 ambulacrum (left side of Fig. 73) has part of each of its columns preserved. It has 6 columns of pentagonal or hexagonal plates. The outermost column along the adradial suture is discontinuous and is composed of smaller plates alternating with the larger plates of the adjacent inner column. The better preserved smaller plates are indicated on Figure 73. Both the pore and peripodium are much smaller on these plates than on the plates of the inner columns. The plates of the 2 medial columns bordering the perradial suture are the largest. Each plate is perforated by a large, slightly elliptical pore situated eccentrically on each plate toward the adradial suture. This pore passes straight through the plate. There are no internal canals in any of the plates. A prominent peripodium (raised rim around the pore) is present on each plate. It is widest where it forms a raised rim around the pore and is more constricted where it bears a single perforated tubercle (on the opposite side of the pore from the adradial suture). Four to 6 nonperforate nodes are present on each ambulacral plate.

It is impossible to tell how many plates were in each column. There are 4 preserved in 1 column on the upper side of the specimen, so there were probably 8 to 10 in a complete column and 48 to 60 in a complete ambulacrum. One of the larger ambulacral plates is 1.4 mm wide and 1.3 mm high. The ambulacral plates are arranged in chevra.

Interambulacra.—A single column of plates is present in each interambulacrum. There were probably 8 to 10 plates in each column.

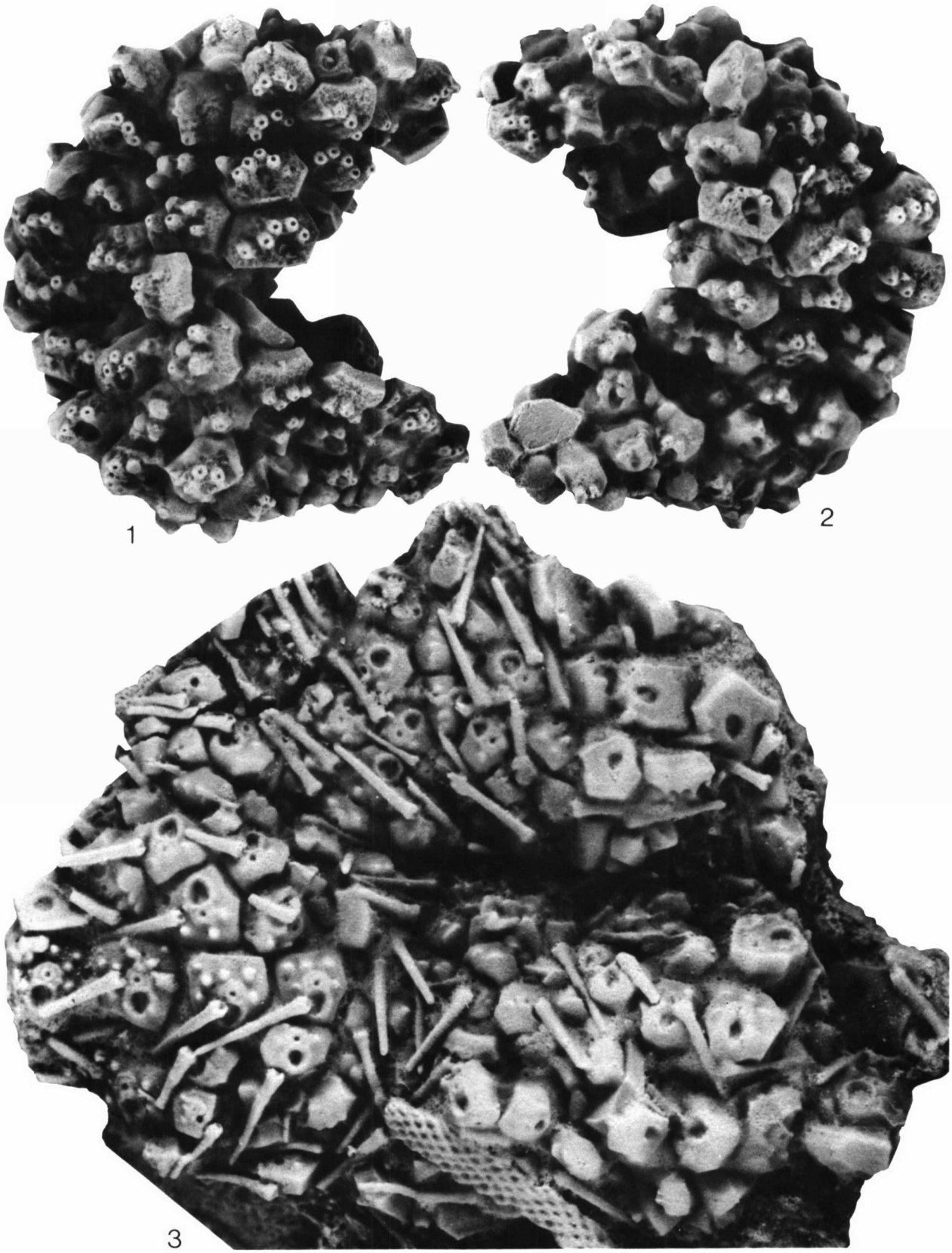
Spines.—The spines are all about the same length, 1.8 mm. They have widened, concave bases and taper to a point. The specimen is too badly weathered to determine if the spines are vertically striated.

Occurrence.—Middle Ordovician, Bromide Formation, Pooleville Member, zone 3, 9 to 10 m below the Viola Limestone, Culley Creek, Criner Hills, Carter County, southern Oklahoma.

Genus BOTHRIOCIDARIS Eichwald, 1859

BOTHRIOCIDARIS KOLATAI Kier, n. sp.

Plate 41, figures 1-2; Figures 74A-B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Diagnosis.—*Bothriocidaris* with 5 to 6 very highly elevated primary tubercles on each ambulacral plate, 4 to 5 on each interambulacral plate. Peripodia not surrounded by pronounced rim.

Material.—Only the holotype (1122TX57, Graffham Coll.) is known. Although the test is distorted, most of the plates are present. Because of the distortion, it is impossible to tell the shape or exact size of the test; but it was probably about 13 mm high. There were approximately 130 ambulacral and interambulacral plates in the entire test, most of which are preserved in this specimen. Eight of the original 10 basicoronal plates are preserved, but only 1 of the ocular plates is discernible. No parts of the lantern are present.

Apical system.—The apical region is badly distorted. The shifting of plates over each other makes it very difficult to identify particular plates. Only one ocular plate can be identified definitely, but it is partly covered by displaced adjacent plates that conceal its original size. Six small periproctal plates are present, but their shape and arrangement are obscured by displaced plates.

Ambulacra.—Each ambulacrum is composed of 2 columns of thick hexagonal plates with 9 or 10 plates in each column. A plate at the midzone (Pl. 41, fig. 1) is 2.3 mm wide, 1.5 mm high, and 1.0 mm thick including the height of the tubercles (0.43 mm). The pore pairs are in oblique peripodia with the outer pore of a pair more adapical than the inner. The peripodia occur nearer the medial perradial suture and the adoral horizonal suture. The pores of the same pore pair diverge in passing through the test, as shown by the fact that they are farther apart on the interior of the test than on the exterior. An elevated rim is absent around the pore pairs.

Most of the plates near the midzone have 5 highly elevated, perforated tubercles, 4 of which occur in an arc adapical to the peripodium (Pl. 41, fig. 1). The fifth tubercle occurs outside this arc, between it and the adradial suture. Several of the midzone plates have 6 tubercles with 5 in the arc. The tubercles rise 0.4 to 0.5 mm above the general surface of each plate. The most adapical plate has 2 tubercles; the next plate adoral to it has 4; and next, 5. The most adoral plate

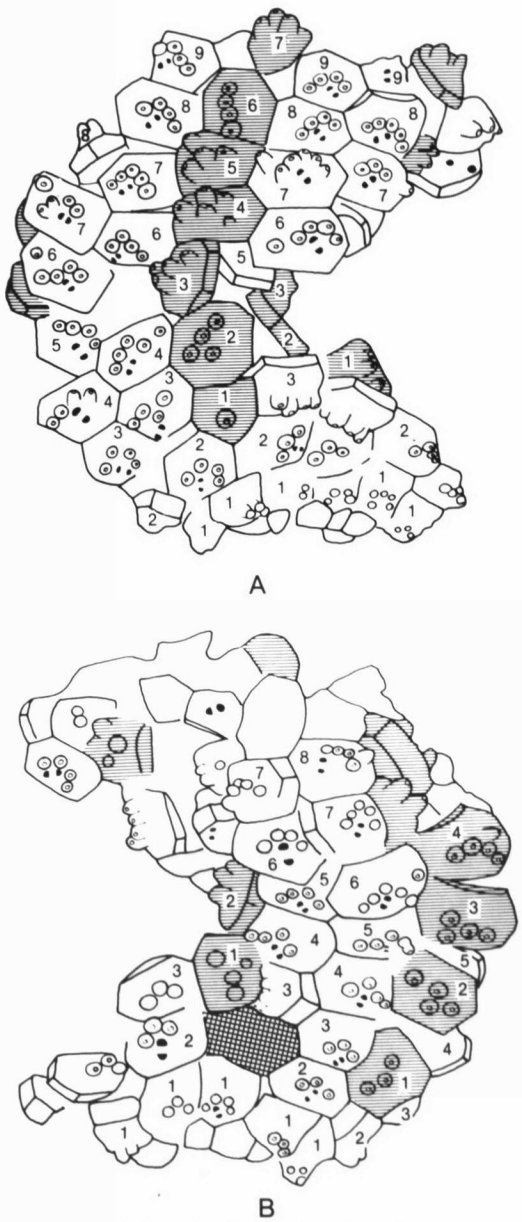

Fig. 74. *Bothriocidaris kolatai* Kier, n. sp.; A, B, Side views of holotype 1122TX57 (see Pl. 41, fig. 1, 2). Pattern of parallel lines indicates interambulacra; varying size of pore pairs, a factor of preservation, does not reflect original size of pores; X7.

PLATE 41.

Fig. 1-2. *Bothriocidaris kolatai* Kier, n. sp.; Zone 3, Pooleville Member, Bromide Formation, Culley Creek, Criner Hills, southern Oklahoma; side views of holotype 1122TX57 (Graffham Coll.) showing the numerous, highly elevated tubercles; X7.

Fig. 3. *Unibothriocidaris bromidensis* Kier, n. gen., n. sp.; Zone 3, Pooleville Member, Bromide Formation, Culley Creek, Criner Hills, southern Oklahoma; adapical view of holotype 1122TX1 (Graffham Coll.) showing the large single pore on each ambulacral plate; X12.

(adjacent to the basicoronal plates) has 4 tubercles. The pore pairs are situated at the adoral border of the plate.

Interambulacra.—Each interambulacrum is composed of a single column of 7 or 8 plates. The interambulacra do not extend to the peristome but are separated from this margin by 2 rows of ambulacral plates (Fig. 74A). The plates are of approximately the same size as the ambulacral plates—a plate at the midzone is 2.25 mm wide and 1.65 mm high. Most of the plates are hexagonal except for the adoral-most plate of each column, which may be pentagonal to heptagonal. The shape of the adapical-most plate in each column is not clear. Each plate has perforated tubercles that rise as high as those on the ambulacral plates. Most of the plates bear 4 or 5 of these tubercles, except for the most adoral plate in each column, which has 1 to 3. The more adapical plates each have 3 to 4 tubercles.

Basicoronal plates.—Ten imperforate plates lacking tubercles surround the peristome. The plates are far smaller than the ambulacral and interambulacral plates and consist of 5 larger plates each separated from the next by a smaller plate. The larger plates are roughly pentagonal, wider than high, with a width of 1.0 mm and a height of 0.75 mm. The smaller plates are narrower than high, 0.60 mm wide and 0.65 mm high. The larger plates occur perradially or medially between the 2 columns of the same ambulacrum, the smaller plates, between adjacent ambulacra, being interambulacral in position.

Occurrence.—Middle Ordovician, Bromide Formation, Pooleville Member, zone 3, 9 to 10 m below the Viola Limestone, Culley Creek, Criner Hills, Carter County, southern Oklahoma.

Name.—This species is named in honor of Dennis Kolata, who discovered and described the first bothriocidaroids from the Western Hemisphere.

Comparison with other species.—This species clearly belongs to the genus *Bothriocidaris*. It shares with the other species of this genus the following characters: 1) rigid test, 2) thick plates, 3) single column in each interambulacrum, 4) termination of the interambulacra at some distance from the peristome, 5) perforated tubercles, 6) pore pairs confined within the ambulacral plates, and 7) ten smaller basicoronal plates that lack pore pairs and tubercles. Five other species are known: four from the Middle and Upper Ordovician of Estonia and one from the Middle Ordovician of Illinois. The new species differs from *B. pahleni* Schmidt and *B. eichwaldi* Männil in having tubercles on its interambulacral plates, more tubercles on its ambulacral plates, and in lacking a pronounced rim around the peripodia. It differs from *B. parvus* Männil in having five or six perforate tubercles on each ambulacral plate instead of three and in having four to five perforate tubercles on the interambulacral plates instead of the single tubercle found in *B. parvus*. Of all the Estonian species, this new species most resembles *B. globulus* in having numerous tubercles on both interambulacral and ambulacral plates, but *B. kolatai* differs in having more tubercles on the interambulacra and in lacking the rim around the peripodia. It is easily distinguished from the only other species known from the Western Hemisphere, *B. solemi* Kolata, by its far more numerous primary tubercles and the absence of a rim around the peripodia. Finally, in none of the other species of *Bothriocidaris* are the tubercles as highly elevated and prominent as they are in *B. kolatai*.

HOLOTHURIANS

James Sprinkle

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Reso and Wegner (1964) described about 35 questionable holothurian sclerites, including the two new species *Thuroholia crinerensis* and *T. overbrookensis*, from the Pooleville Member, Bromide Formation, at Rock Crossing in the Criner Hills. The tentative assignment of these sclerites to the holothurians was provisionally accepted by Frizzell and Exline (1966, p. U658 and U664). Sievelike sclerites belonging to *Thuroholia croneisi* (which is the most common form occurring in the Bromide) were originally described by Gutschick (1954) from the similar-aged Platteville Group of Illinois. These were also provisionally accepted as holothurians by Frizzell and Exline (1966) and by Kolata (1975, p. 7-8), although all of these authors also condidered a possible origin from embryonic crinoids. Another possibility is suggested by the recent description of a Devonian ophiocistioid having nearly the entire skeleton composed of microscopic sclerites, including sievelike sclerites plating the large tube feet (Haude and Langenstrassen, 1976). However, although ophiocistioids occur in the Ordovician, no specimens have been found either in the Bromide Formation or in the Platteville Group.

The index map in Reso and Wegner (1964) indicates that they collected their sclerites from shaly interbeds in the upper Pooleville Member about 7.5 to 11 m below the Viola Limestone contact. No attempt was made to collect additional sclerites from this interval at Rock Crossing, and no other possible holothurian sclerites were found in shale residues from other Bromide localities or zones during this project.

ASTEROIDS

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Only about fifteen fragmented fossil asteroid individuals are known from the Bromide Formation in Oklahoma. Their identification is difficult because of their fragmented state and the general lack of information on asteroid ontogeny. Most Bromide asteroids have come from the upper Pooleville Member in the Criner Hills; most of these specimens may be assigned to *Urasterella* sp., but the unit has also produced two juvenile *Promopalaeaster* specimens. Localities in the Mountain Lake Member at Fittstown, Lick Creek, and North-Central I-35 have also produced a few specimens, including *Petraster wigleyi*, n. sp., *Protopalaeaster narrawayi* Hudson, *Hudsonaster* sp., *Promopalaeaster* sp., and *Urasterella* sp.

Such sparse occurrence of specimens is not unusual for fossil asteroids. As benthic opportunistic scavengers, gleaners, and predators, modern asteroids rarely occur in great densities where preservational potential is high. The poor fossil record of asteroids in part reflects the commonly low natural densities of the living animals. Skeletal anatomy is another probable factor. Asteroid ossicles are not rigidly fused into tests as are the plates of representatives of the more preservable echinoderm classes. Rather, they are relatively loosely joined by interossicular muscles or by common investment in an integument of connective tissue. Any postmortem organic decomposition of a specimen increases the probability of skeletal element separation and disarrangement. Blake (1967) documented that modern asteroids may lose superficial skeletal elements by abrasion before natural burial. Under unfavorable conditions modern asteroids commonly autonomize arms or ossicle-invested portions of their body walls. Such disarticulation of skeletal elements makes fossil asteroid material difficult to recognize, and fragmented specimens can be overlooked as "crinoid-" or "echinoderm-hash."

Even when recognized, fossil asteroid material remains difficult to identify further because nearly all taxa are presently described on the basis of "ideal" ossicle arrangement, rather than ossicle morphology. Such arrangement is impossible to perceive for highly fragmented specimens. Furthermore, ossicle arrangement and complement commonly change throughout ontogeny, and the scarcity of specimens makes it difficult to assemble growth series for most fossil species.

Morphology and terminology.—This report utilizes the morphological terminology of Spencer and Wright (1966) and the ossicle abbreviations of Blake (1973) with the following emendations and additions. Dorsal and ventral refer respectively to the aboral (or abactinal) and the oral (or actinal) surfaces of the asteroid theca. The arms join at the disc, or central portion of the body. The primary skeleton is composed of ossicles commonly present in a young post-larval asteroid: primary circlet and mouthframe ossicles, centrale, carinals, primary axillaries, ambulacrals (Ambb), adambulacrals (Adambb), superomarginals (SupMM), inferomarginals (InfMM), and terminals. Secondary skeletal ossicles develop between ossicles of the primary skeleton. Directional parameters additional to those listed in Spencer and Wright are as illustrated in Figure 75. Primary measurements include the major radius (R), the mean length from the center of the disc to the tip of all normally developed and measurable arms, the minor radius (r), the mean shortest possible lengths between the center of the disc and the thecal margin in each interbrachial area, and the arm width (Rw) taken across the base of each arm from one margin to the other. Because fossil specimens are usually fragmental or distorted from their living condition and proportions, values for these parameters only approximate those of the living animal and should be used only to establish relative size. As recommended by Blake (1973, p. 3), length, height, and width of individual ossibles are taken relative to thecal orientation rather than ossicular axial length. Thecal and ossicle lengths lie horizontally along hypothetical vertical planes which would radiate from the center of the disc. Heights are measured vertically on these planes and widths are taken normal to the planes.

The arrangement of taxonomic units adopted here follows Spencer and Wright (1966). Diagnoses uti-

lize characteristics usually visible on both modern and fossil material.

Subphylum ASTEROZOA Zittel, 1895

Class STELLEROIDEA Lamarck, 1816

Subclass ASTEROIDEA de Blainville, 1830

Order PAXILLOSIDA Perrier, 1884

Suborder HEMIZONINA Spencer, 1951

Family PETRASTERIDAE Spencer, 1951

Diagnosis.—Pentaradial Hemizonina with well-developed InfMM forming the marginal frame. Ventral axillary area ossified with small, sometimes granular, axillary interbrachials in columns, columns in some extending distally to intercalate between InfM and Adamb columns.

Occurrence.—Early Ordovician to Silurian.

Genus PETRASTER Billings, 1858

Type species.—*Palasterina rigidus* Billings, 1857, p. 291; by original designation. From Trenton Limestone at Ottawa, Ontario, Canada.

Diagnosis.—Characteristics of family.

Discussion.—Only one specimen of the type species is known; it shows the ventral surface only. Schuchert (1915) and Spencer (1951) included other previously described species in the genus and used them to determine the nature of the *Petraster* dorsal surface. Using *Palaeasterina speciosa* Miller and Dyer, 1878 as his model *Petraster*, Schuchert (1915, p. 140) concluded that members of the genus did not possess "prominent basal radial [proximal carinal] and supramarginal [SupMM] plates" on their dorsal surfaces. Spencer (1918, p. 111) erroneously listed *Palaeasterina rugosus* Billings as the type species of the genus, but correctly noted that useful comparisons of *Petraster* with other genera awaited better knowledge of the type species. Spencer (1950, p. 405) reassigned some species he earlier (1916, p. 105; 1918, p. 109) assigned to *Uranaster* Gregory, 1899, to *Petraster*. His diagnoses and figures of these species indicate conspicious SupMM on dorsal surfaces. There is such morphologic diversity among these "Uranasters" and *Palaeasterina speciosa* that all cannot be accommodated in *Petraster*. No new specimens of the type species have been recognized, but a new species of *Petraster* with a ventral surface very similar to that of *Petraster rigidus* is described below (Fig. 76). Its dorsal surface is composed of small, pustulose ossicles, and prominent brachial SupMM are absent. On this basis it seems advisable to recognize the American species as generically distinct from the European species examined by Spencer, and to reerect *Uranaster* to accommodate the species Spencer placed in that genus in 1916 and 1918.

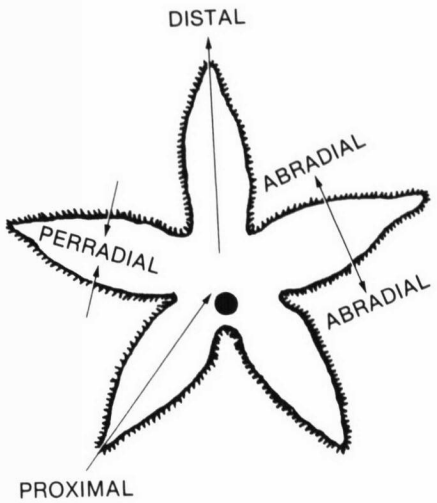


Fig. 75. General orientation terminology of asteroid theca.

PETRASTER WIGLEYI Branstrator, n. sp.

Plate 42, figures 1-3; Figure 76B

Diagnosis.—*Petraster* similar to *P. rigidus* (Billings) except for greater Adamb to InfM ratio (about 3:2) in new species. Each ventral axil carrying a single and distinctively large accessory interbrachial orad of each axillary InfM.

Description.—In the single known specimen, R = 20 mm; r = 5 mm; wR = 5 mm. Small asteroid with gradually tapering arms margined by prominent InfMM, InfMM becoming widest proximally (Pl. 42, fig. 1). Adambb wider than long, in numeric ratio of 3:2 with adjacent InfMM. Proximal axillary interbrachials larger than more distal ones; largest one in each axil unpaired (Fig. 76B). Ventral ossicles armored on exterior surfaces with small nonpaxillate spines articulated on pustules or, in the case of the Adambb, in spine pits.

Dorsal surface of spinose, nonpaxillate ossi-

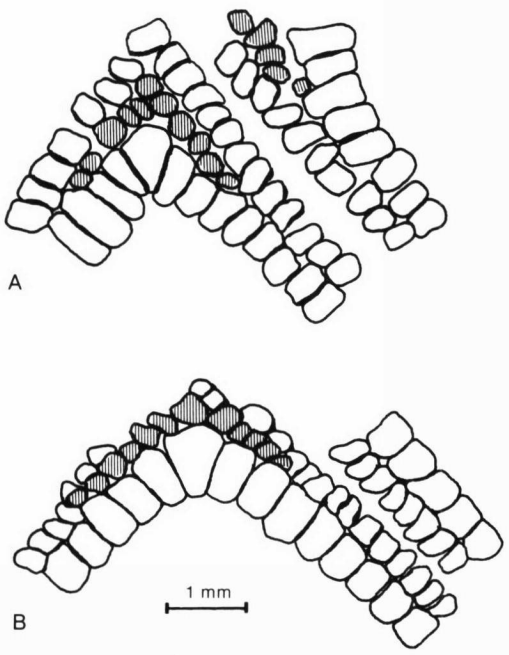


Fig. 76. Two species of *Petraster* with axillary interbrachial series of each shaded. A, Holotype of type species, *P. rigidus* (Billings). B, Holotype of *P. wigleyi* Branstrator, n. sp.

cles arranged in diagonally transverse rows and longitudinal columns (Pl. 42, fig. 2). Ossicles morphologically similar; carinals similar to other dorsal ossicles, recognized by position. SupMM, if present, indistinguishable from other dorsal ossicles. Ossicles in dorsal columns more numerous then InfMM in adjacent column, but slightly fewer than corresponding Adambb. New dorsal ossicles generated in zone along dorsal margin of InfM column, hence perradial dorsals larger than abradial ones (Pl. 42, fig. 3).

Details of dorsal disc, oral frame, and Ambb not available from the type material.

Type material and nomenclature.—The holotype 1279TX24 was found in 2 fragments by James Sprinkle in the Lower Echinoderm Zone at Fittstown Quarry in the northeastern Arbuckles. The species is named for the late W. C. Wigley, who owned the ranch on which the C & L Wigley Quarry at Fittstown is now located.

Order VALVATIDA Perrier, 1884

Suborder PUSTULOSINA Spencer, 1951

Family HUDSONASTERIDAE Schuchert, 1914

Diagnosis.—Pustulosina with a relatively large, single axillary InfM in each axil throughout ontogeny, and primary ossicles dominating skeletal framework. Secondary skeleton usually superficial and nonintercalating. Podial basins biserial throughout ontogeny.

Occurrence.—Early to Late Ordovician.

Discussion.—Species in such other pustulosine families as the Mesopalaeasteridae and Promopalaeasteridae seem to pass through a *Hudsonaster*-like stage in their early post-larval development (Schuchert, 1915, p. 34). In true *Hudsonaster*, however, the enlarged axillary InfMM remain marginal throughout life, and the skeleton is composed exclusively of primary ossicles and articulating superficial spines and granules. Major radii may reach 20 mm or longer without the development of intercalating secondary ossicles. Other Pustulosina show development of secondary thecal ossicles before attaining this size. Until they develop characteristic secondary ossicles, juvenile Pustulosina are extremely difficult to identify to family and lower categories.

Genus PROTOPALAEASTER Hudson, 1912

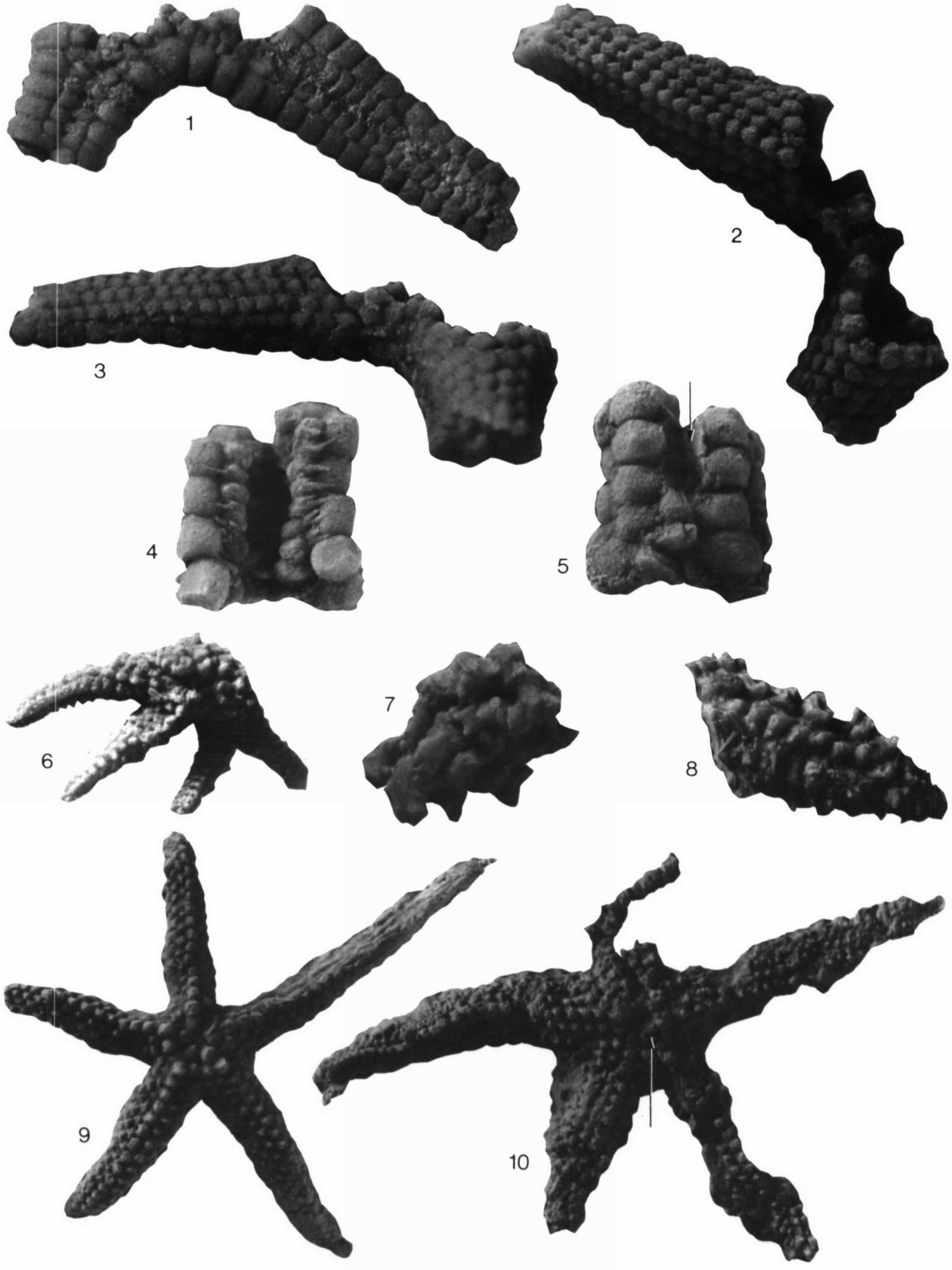
Diagnosis.—Hudsonasteridae with blocky, nonoverlapping, compressed Ambb without proximal or distal flanges for articulation with successive

PLATE 42.

Fig. 1-3. *Petraster wigleyi* Branstrator, n. sp.; holotype 1279TX24, from the Lower Echinoderm Zone, Mountain Lake Member of the Bromide Formation, Fittstown Quarry; ventral, dorsal, and dorsolateral views; X10.

Fig. 4, 5. *Protopalaeaster narrawayi* Hudson, 1912; OU 9237 from the Lower Echinoderm Zone, Mountain Lake Member of the Bromide Formation, Lick Creek; ventral and dorsal views (arrow on Amb); X5.

Fig. 6-10. *Urasterella* sp.; from the Pooleville Member of the Bromide Formation in the Criner Hills. 6. Dorsal aspect of OU 9244, small (R = 6 mm) specimen from 3 m below the Viola-Bromide contact at Rudd Quarry; X6. 7. Dorsal aspect of one of 15 fragments in OU 9243 from 12 to 13 m below the Viola (Zone 5 of Fay), Culley Creek; X7. 8. Ventral surface of 1122TX58 from 9 to 10 m below the Viola (Zone 3), Culley Creek (Graffham Coll.); X5. 9. Dorsal aspect of OU 9241 from 13 m below the Viola (Zone 4), Culley Creek; X3. 10. Dorsal surface of OU 9240 from about 3 m below the Viola, Dunn Quarry (arrow points to location of madreporite); X3.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Ambb. Arms tapering gradually in adult individuals.

Occurrence.—Middle Ordovician, Ontario, Minnesota, and Oklahoma.

PROTOPALAEASTER NARRAWAYI Hudson, 1912

Plate 42, figures 4, 5

Diagnosis.—Characteristics of monotypic genus.

Material.—Holotype ROM 18881 was found in the "Black River Formation" at Ottawa, Ontario, Canada. Additional specimens are known from the Decorah Shale at Minneapolis, Minnesota (Sardeson, 1928b), and the Platteville Formation at Minneapolis (USNM 96231). Schuchert (1915, p. 60) reported other occurrences of the species, but the specimens appear to be of young individuals of other Pustulosina. A single Bromide specimen (OU 9237) is known from the Lower Echinoderm Zone at Lick Creek.

Description.—Adambb and InfMM in 2:1 ratio (Pl. 42, fig. 4). Large, perradial, paired Adamb spines and smaller, abradial and more numerous Adamb spines well preserved on Bromide specimen. InfM spines lost; spine-base pustules numerous, with central pits.

Several small, terete spines still in place on dorsal surface of several SupMM (Pl. 42, fig. 5). As in other hudsonasterids, SubMM and InfMM of adjacent columns aligning alternately.

Ambb in adjacent columns in opposite arrangement (Pl. 42, fig. 5, arrow). Ambb not greatly compressed.

Discussion.—Although a small arm fragment, the Bromide specimen is easily identified as a *Protopalaeaster*. No morphologic data suggest that the Bromide specimen represents a new species, but not all characters are available from it.

Genus HUDSONASTER Stürtz, 1900

Diagnosis.—Hudsonasteridae with blocky, nonoverlapping, compressed Ambb without longitudinal flanges for articulation with successive Ambb. Arms tapering rapidly from wide bases.

Occurrence.—Middle to Late Ordovician, Quebec, Illinois, Ohio, Indiana, Kentucky, and Oklahoma.

HUDSONASTER sp.

Material.—Two fragments (1279TX25A-B) from the Lower Echinoderm Zone at Fittstown Quarry show the rapidly tapering arms and ossicle complement typical of the genus. The material is not sufficiently well preserved for identification to species.

Family PROMOPALAEASTERIDAE Schuchert, 1914

Diagnosis.—Pustulosina developing intercalating secondary ossicles between InfM, SupM, and carinal columns; few secondary columns in juveniles, many in adults. Podial basins biserial in small individuals, becoming quadriserial in larger individuals.

Occurrence.—Middle to Late Ordovician, North America, Scotland, and Australia.

Genus PROMOPALAEASTER Schuchert, 1914

Diagnosis.—Promopalaeasteridae with primary and secondary skeletal ossicles massive, abutting. Papular pores present, not numerous; at junctions of dorsal and lateral ossicles, ossicles not greatly modified to accommodate pores.

Occurrence.—Early to Late Ordovician, Scotland, Ontario, Ohio, Indiana, Kentucky, and Oklahoma.

PROMOPALAEASTER sp.

Material.—Four small fragments (1279TX298A-B and 299A-B) from the Lower Echinoderm Zone at Fittstown Quarry in the northeastern Arbuckles show the characteristic primary and secondary skeletal arrangement of the genus. Two juvenile specimens (OU 9239A-B) came from 11 to 13 m below the Viola Limestone in the Pooleville Member at Culley Creek in the Criner Hills.

Discussion.—Enough of each Bromide *Promopalaeaster* specimen is present for identification to genus, but no further. No morphologic datum suggests that specimens from the different localities (and zones) are different species.

Order FORCIPULATIDA Perrier, 1884

Suborder URACTININA Spencer and Wright, 1966

Family URASTERELLIDAE Schuchert, 1914

Diagnosis.—Uractinina with broad, short Adambb

most prominent ossicles on arms. InfMM and SupMM, if present, indistinguishable from other dorsal ossicles in prominence. Arms round in section.

Occurrence.—Early Ordovician to Late Carboniferous. United States, Canada, Russia, Northern and Central Europe, and Australia.

Discussion.—Spencer (1950, p. 406) provided a useful key to the generic differentiation of the "urasterellids." Bromide material from the Mountain Lake and Pooleville members, although fragmental and usually distorted, keys easily to *Urasterella*.

Genus URASTERELLA McCoy, 1851

Diagnosis.—Urasterellidae with a single column of prominent carinals on each arm, and dorsal ossicles differentiated as to size and paxillar development between carinal column and ambitus.

Occurrence.—Middle Ordovician to Late Carboniferous. Geographic range of family.

URASTERELLA sp.

Plate 42, figures 6-10

Material.—Most known Bromide asteroid specimens are *Urasterella*. The oldest known Bromide specimen (1276TX7) from the *Carabocrinus* Beds in the middle Mountain Lake Member at North-Central I-35 in the northern Arbuckles is a dorsal aspect of a disc with portions of four arms. Fragmental Pooleville specimens from Criner Hills localities range in size from R = 6 mm (OU 9244; Pl. 42, fig. 6) to R = 24 mm (OU 9240; Pl. 42, fig. 10). A Culley Creek specimen (1122TX58) has pectinate columns of Adamb spines (Pl. 42, fig. 8). Fifteen jumbled fragments from Culley Creek (OU 9243) show details of Amb, Adamb, and paxillar structure (Pl. 42, fig. 7). A more complete specimen from Culley Creek (OU 9241) has disc and brachial ossicular arrangements typical of the genus.

Description.—Carinals quadrate with sturdy paxillar columns; largest on disc. Other dorsals decreasing in size toward ambitus. Brachial dorsals arranged in longitudinal columns and diagonally transverse rows. Median 3 columns, including quadrate carinals, more massive with more erect paxillar columns than more lateral dorsals, these dorsals apparently reniform with abradially resupinate paxillar columns. Ambitus formed of finely paxillate dorsals. Dorsal disc ossified with a centrale surrounded by a circlet of 6 prominent ossicles, in turn surrounded by a circlet of 15 smaller more differentiated ossicles, 5 of these basal carinals. Entire dorsal wall perforated with papular pores at ossicle junctions. (OU 9240 retains a small, dorsal madreporite; Pl. 42, fig. 10, arrow.)

Adambb short, high and broad, each with a transverse pectinate series of large spines. Ambb in adjacent columns opposite, not greatly compressed, abradially excavated along their proximal and distal margins to accommodate ampullae of water-vascular system (see Branstrator, 1975b, p. 65, pl. 2, fig. 4).

Discussion.—The literature is of no practical use in distinguishing Bromide urasterellid species from one another or from other related species. Although *Urasterella* was long-lived and had a wide range, established taxobases within the genus are scientifically untenable. Nearly all species have been distinguished on the bases of geological or geographical occurrence, size, degree of distortion, or characteristics that change during ontogeny and hence are of dubious use in describing species represented by single or few specimens (Branstrator, 1975a, p. 72-89). The stratigraphic separation between urasterellid occurrences in the Bromide suggests that several species are probably represented, but a revision of the taxonomic literature on *Urasterella* is necessary before this can be determined.

HOMALOZOANS

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Homalozoans or "carpoids," as they are sometimes called, are fairly rare and have low diversity in the Bromide Formation. Specimens of the two previously described genera (*Anatiferocystis* and *Myeinocystites*) and a probable anomalocystitid (*Enoploura?*) were found only in scattered localities in the Pooleville Member.

The class Homoiostelea is represented by a few specimens of the belemnocystitid genus *Myeinocystites* Strimple. All of the examples are incomplete to complete thecae; proxisteles and proximal parts of the arm are present on some specimens.

The class Stylophora is represented not only by the anomalocystitid fragment but also by the lagynocystitid mitrate *Anatiferocystis* Chauvel (=*Kirkocystis*? Bassler). All of the material consists of small thecae, many with the proximal aulacophore attached. None of the Bromide material preserves the aboral articulated spine or the distal aulacophore. Some problems exist with the comparison of *Anatiferocystis* with *Kirkocystis*. *Kirkocystis*, as it is commonly called in the Bromide, is preserved with its plates intact. *Anatiferocystis* is usually preserved as an internal or external mold, making actual plate discrimination, especially of the plastron or ventral thecal surface, difficult. The plastron plating pattern of *Kirkocystis* is very unusual for a mitrate, and may be different from that of its European homologue *Anatiferocystis*. Whether the differences, if any, are at the generic or specific level will hopefully be resolved by work now in progress on North American mitrates (Parsley and Caster, in prep.).

Subphylum HOMALOZOA Whitehouse, 1941

Class HOMOIOSTELEA Gill and Caster, 1960

Order SOLUTA Jaekel, 1901

Family BELEMNOCYSTITIDAE Parsley, 1968

Genus MYEINOCYSTITES Strimple, 1953b

MYEINOCYSTITES NATUS Strimple, 1953b

Morphological analysis of this species has recently been published by Parsley (1972) and by Kolata, Strimple, and Levorson (1977) and need not be elaborated on here.

Material and occurrence.—In addition to the holotype (USNM 4657, Springer Coll.) from Rock Crossing in the Criner Hills, 4 other specimens are known: a topotype from Rock Crossing (OU 9183), a specimen from the south end of Dunn Quarry (1119TX2), one from zone 3 at Culley Creek (OU 9184), and one from 9 m below the top at Dunn Quarry (OU 9185). All specimens are from the upper Pooleville.

Discussion.—*Myeinocystites* is a rare form but has a fairly wide geographic distribution. Specimens are also known from the Benbolt Formation in Tennessee, the Dunleith Formation of northern Illinois (*M. crossmani*), and the Platteville Formation of Minnesota (undescribed specimen).

Kolata and others (1977) have in my opinion incorrectly oriented *Myeinocystites* and related forms (*Iowacystis*, *Belemnocystites*, and *Scalenocystites*) with the arm-bearing surface in a ventral position. This orientation places the putative hydropore also facing into the substrate. Parsley (1972), Caster (1968), and others have maintained that the arm and hydropore faced away from the substrate, where they were less likely to be fouled by the substrate.

Class STYLOPHORA Gill and Caster, 1960

Order MITRATA Jaekel, 1918

Suborder LAGYNOCYSTIDA Caster, 1952

Family KIRKOCYSTIDAE Caster, 1952

Genus ANATIFEROCYSTIS Chauvel, 1941

ANATIFEROCYSTIS PAPILLATA (Bassler), 1943

Enoploura? papillata Bassler, 1943, p. 695, pl. 1, fig. 3-5.

Kirkocystis papillata (Bassler), Bassler, 1950, p. 277, fig. 15, 16.

Anatiferocystis papillata (Bassler), Ubaghs, 1968a, p. S555, fig. 355, 3a-e.

A detailed morphological analysis is in preparation by Parsley and Caster and the subject will not be dealt with here.

Material and occurrence.—In addition to the 3 cotypes (USNM 113105) from Rock Crossing in the Criner Hills, the following specimens are available: Culley Creek, 22 (1122TX5-26), Rudd Quarry, 26 (OU 9186), and Rock Crossing, 26 topotypes (1281TX1-3 and OU 9551, 23 specimens). All specimens are from the upper Pooleville in the Criner Hills.

Discussion.—The imbricate nature of the thecal plates is unusual in the Mitrata and seems to be an effective way to increase thecal strength without increasing plate thickness. When viewed dorsally the overlap between the two large plates that comprise the doral and lateral surfaces can be in either direction.

The theca of *Anatiferocystis*—except for the short dorsal and lateral spines, which are inclined adorally—exhibits a high degree of streamlining in the aboral direction. Ubaghs (1979) has shown that *A. spinosa* from the Letná Formation (Lower Caradocian) of Czechoslovakia, a species closely related to *A. papillata*, has a long whiplike distal aulacophore. This combination of thecal streamlining and long distal aulacophore (coupled with the large slip planes of the proximal aulacophore) suggests that this genus was highly mobile. Presumably movement was akin to that of a tadpole, by undulations of the subvective appendage. Also, the single hooklike styloid flange is rather small, indicating less anchoring ability and probably need than in such other mitrates as *Enoploura*.

Suborder ANOMALOCYSTITIDA Caster, 1952

Family ANOMALOCYSTITIDAE Bassler, 1938

Genus ENOPLOURA Caster, 1952

ENOPLOURA? sp.

A single fragment of the adoral end of a small *Enoploura*-like mitrate with part of the proximal aulacophore attached is the only evidence of an anomalocystitid in the Bromide. The specimen (1395TX3) is from the upper Pooleville at the Johnson Ranch roadside strip quarry in the southwestern Arbuckle Mountains.

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APPENDIX

MEASURED SECTIONS AND COLLECTING LOCALITIES

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Oklahoma Geological Survey, Geological
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INTRODUCTION

Sixteen relatively complete sections of the Bromide Formation in the Arbuckle Mountains and Criner Hills of south-central Oklahoma (Fig. 77) were measured for information on the location of echinoderm zones and the thickness and lithology of members. Fifteen of these sections are included on the correlation diagrams in Figure 78 (see pocket inside back cover). Eight other collecting localities for echinoderms (see Fig. 77) are also included at the end of this Appendix but were not measured. Thickness is indicated in meters (m) throughout the descriptions. "Thin-bedded" means beds 2.5 cm thick or less; "medium-bedded" means beds 2.5 to 30 cm thick and "thick-bedded to massive" refers to beds more than 30 cm thick. "Medium-granular" means with from 1- to 4-mm grains and refers mostly to echinoderm remains. The limestones of the Pooleville Member are highly argillaceous and may grade into very fine-grained to lithographic calcitic mudstones. Many of the lime-

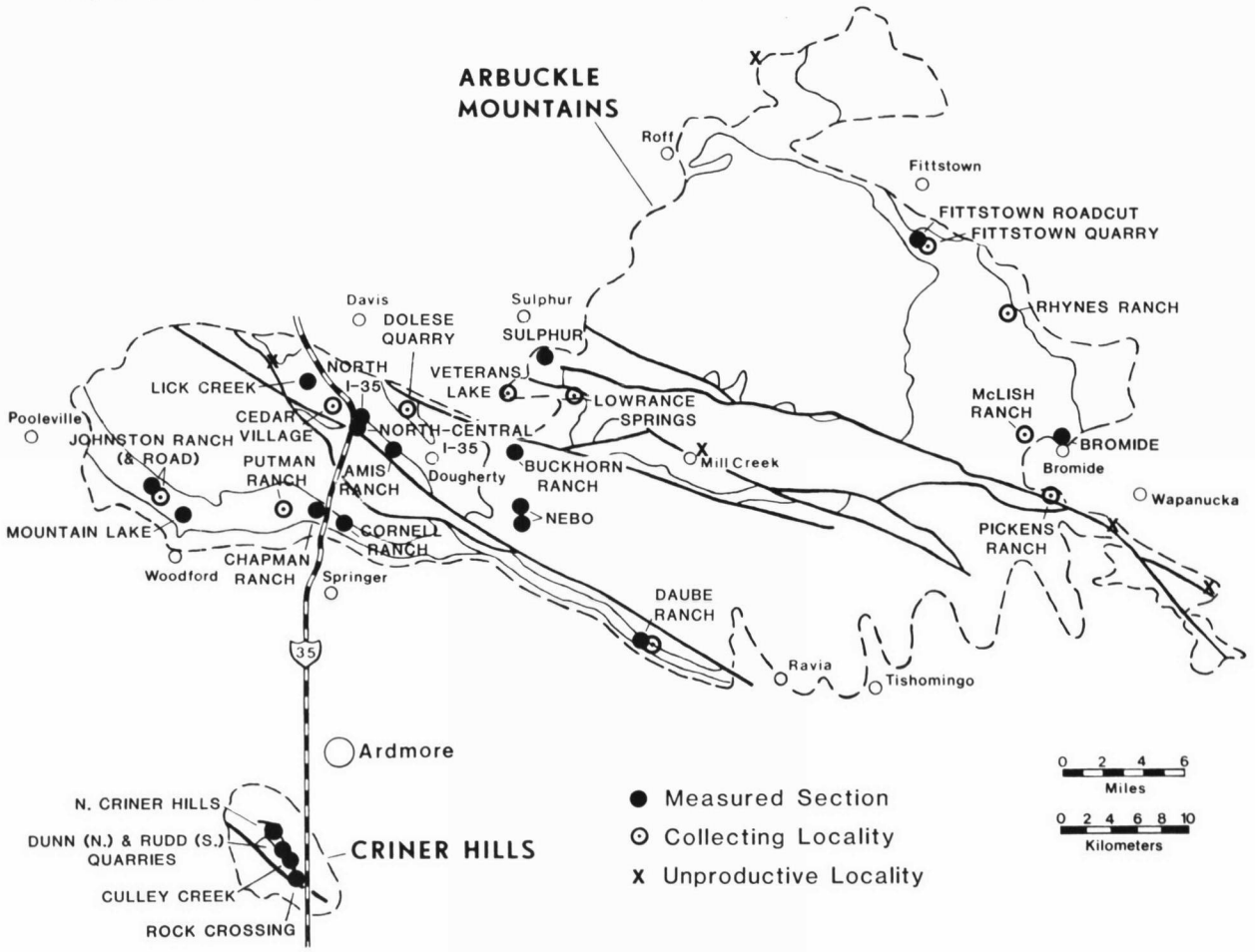


Fig. 77. Names and locations of measured sections and collecting localities in the Arbuckle Mountains and Criner Hills of southern Oklahoma. Unproductive localities visited during this project are also indicated. Base map from Lewis (1981b), redrawn from Ham (1969, fig. 13).

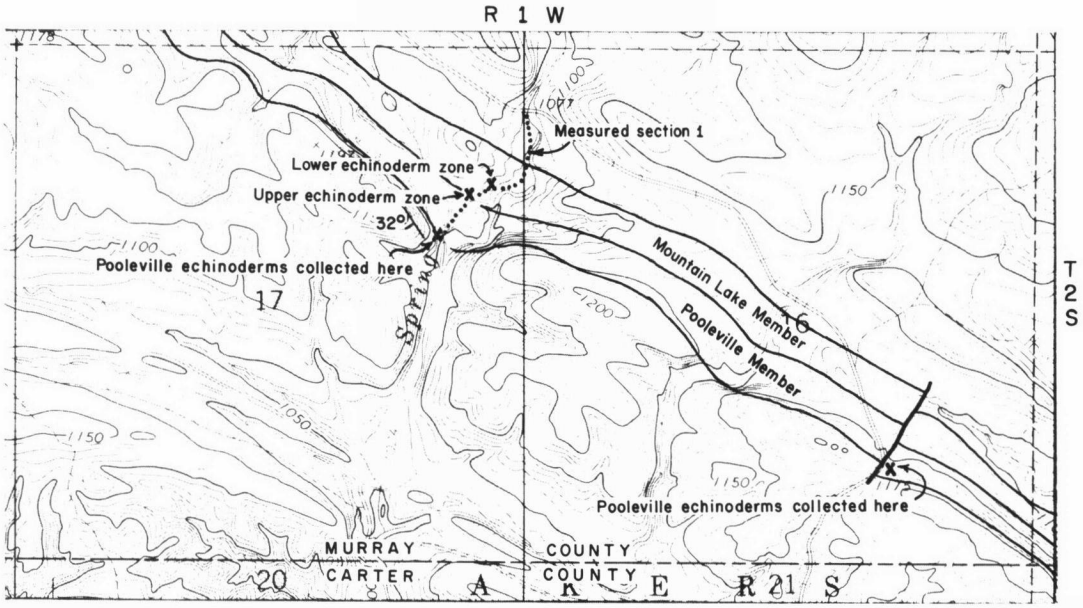


Fig. 79. Geologic map showing Bromide Formation and location of Measured Section 1 at Johnston Ranch.

stones of the Mountain Lake Member are echinodermal and medium-granular, with much interbedded greenish-gray shale. The basal third of the Mountain Lake contains much sandstone, siltstone, and shale, and these units are described by conventional standards.

The base maps used in the preparation of most locality maps were U.S.G.S. topographic quadrangles, seven-and-a-half-minute series, at a scale of 1:24,000. All outcrops and excavations were photographed between 1965 and 1967.

Measured Section 1

JOHNSTON RANCH, MURRAY COUNTY

Beginning at top in Viola Limestone and proceeding downsection through the Bromide Formation, below dam of upper Humble Lake, and along Spring Creek (see Fig. 79), in the N½SE¼NE¼ sec. 17, T. 2 S., R. 1 W., Murray County, Oklahoma. This is the type locality and the type section for the Pooleville Member (above) and the Mountain Lake Member (below). Pooleville is a small town (formerly Elk) about 8 km northwest of Humble Lake, and Mountain Lake is a reservoir about 4 km southeast of the area. A few echinoderms were also found in the upper Pooleville Member about 11 m below the Viola Limestone in a small stripped exposure where the Johnston Ranch access road cuts through the Pooleville-Viola ridge about 1.6 km southeast of Spring Creek (see Fig. 79). Mr. Virgil Johnston and Mr. Bill Johnston run the ranch. Strike N 45° W, dip 32° SW.

ORDOVICIAN SYSTEM — Thickness (m)
SIMPSON GROUP
BROMIDE FORMATION (total thickness 147.2 m)
Top in contact with Viola Limestone, which is dark-gray, very fine-grained, lithographic, cherty, thin-bedded, with a pyritic iron-stained contact with the Pooleville, eroding into a grassy hill above the massive Bromide ledges.
Pooleville Member (total thickness 71.3 m)

1. Limestone, brown, fine-grained, dense, medium-bedded to massive, fossiliferous, eroding into prominent massive bluff.....4.1
2. Limestone, gray to tan, fine-grained to medium-granular, thin-bedded, very fossiliferous, with many brachiopods, bryozoans, and echinoderm remains, with a *Platycystites* found 3.6 m below the top.....5.2
3. Limestone, light-gray to tan, fine-grained, dense, well-indurated, thin-bedded, stained yellow in many places, extremely fossiliferous, with many brachiopods, bryozoans, and echinoderm parts, alternating with many 15- to 7-cm, tan shale seams, with much shale in upper 4.8 m, partly covered.....26.8
4. Limestone, gray, fine-grained, dense, fossiliferous, thick-bedded.....3.6
5. Limestone, gray, fine-grained, dense, massive, fossiliferous, eroding into prominent ridge on north end of dam.....0.3
6. Limestone, tan, fine-grained, dense, moderately to weakly indurated, fossiliferous, with some alternating tan shale.....0.91
7. Limestone, gray, fine-grained, dense, massive, well-indurated, fossiliferous, eroding into ledge.....0.61
8. Limestone, light-gray, fine-grained, dense, thin- to medium-bedded, well-indurated, fossiliferous, with some interbedded tan shale.....5.8
9. Shale, tan, platy, weakly indurated, fossiliferous, with some interbedded fine-grained gray dense limestone, with *Vogdesia bromidensis* zone about 0.9 m below the top.....2.13
10. Limestone, gray to tan, fine-grained, dense, well-indurated, thin-bedded, fossiliferous, eroding into ridge.....0.3
11. Shale, tan, platy, thin-bedded, weakly indurated, with some interbedded fine-grained limestone.....1.22
12. Limestone, light-gray to tan, fine-grained, dense, well-indurated, thin-bedded, fossiliferous, with many bryozoans and brachiopods, eroding into ridge.....0.23
13. Shale, tan, platy, weakly indurated, fossiliferous, with many 2.5- to 5.0-cm tan fossiliferous limestone beds, with *Vogdesia bromidensis* zone 0.61 to 0.76 m below the top.....1.67
14. Limestone, light-gray to tan, fine-grained, argillaceous, dense, platy, thin-bedded, with some alternating thin shale seams, stained lemon-yellow, very fossiliferous, with many bryozoans, brachiopods, and some large cephalopods, eroding into ridge.....4.3
15. Shale, tan, platy, weakly indurated, with interbedded thin limestone, as above, with *Vogdesia bromidensis* zone 1.52 m below top.....1.83
16. Limestone, gray to tan, fine-grained, dense, argillaceous, well-indurated, thin-bedded, with some alternating tan shale seams, eroding into ridge.....2.44
17. Shale, tan, platy, weakly indurated, very fossiliferous, with many bryozoans.....1.06
18. Limestone, tan to gray, fine-grained, argil-

laceous, massive, well-indurated, eroding into ridge.....0.15
19. Shale, tan, platy, weakly indurated, with many 2.5- to 5.0-cm gray dense limestone beds, fossiliferous in upper 3.05 m, with many bryozoans...8.5
Mountain Lake Member (total thickness 75.9 m)
Upper Mountain Lake (total thickness 2.48 m)
20. Limestone, light-gray to tan, fine-grained, dense, massive, fossiliferous, eroding into ledge.....0.09
21. Shale, tan, platy, thin-bedded, with some interbedded tan thin-bedded fossiliferous dense limestone.....0.76
22. Limestone, tan, fine-grained, dense argillaceous, rubbly, medium-bedded, well-indurated, highly jointed, fossiliferous with many straight cephalopods, eroding into ledge.....0.23
23. Shale, greenish-gray, mottled tan, thin-bedded, platy, weakly indurated, fossiliferous, with some interbedded brown limestone.....0.46
24. Limestone, brown, fine-grained, argillaceous, dense, fossiliferous, moderately indurated, eroding into ledge.....0.18
25. Shale, greenish-gray, mottled tan, thin-bedded, platy, with some interbedded tan argillaceous limestone, fossiliferous, with many brachiopods, bryozoans, and cephalopods.....0.76
Upper Echinoderm Zone (total thickness 1.98 m)
26. Shale, greenish-gray, mottled tan, as above, fossiliferous, with *Platycystites* found near top 1.07
27. Limestone, orange-brown, fine- to medium-grained, argillaceous, alternating with greenish-gray shale, fossiliferous, with many bryozoans, brachiopods, and cephalopods, with 4 *Oklahomacystis* and 2 *Platycystites* found 0.15 to 0.30 m above the base. (Base of the Upper Echinoderm Zone, this limestone erodes into a ridge above the drainage ditch to the upper lake; see Fig. 80, 81.).....0.91
Middle Mountain Lake (total thickness 30.3 m)
28. Shale, greenish-gray to blue-gray, fissile, platy, weakly indurated.....4.9
29. Limestone, blue-gray, argillaceous, fine-grained, platy, moderately indurated, fossiliferous.....0.09
30. Shale, greenish-gray to blue-gray, fissile, platy, weakly indurated.....4.9
31. Limestone, tan, medium-grained, well-indurated, medium-bedded, fossiliferous, echinodermal, eroding into prominent ridge north of spillway cut.....2.28
32. Shale, greenish-gray, mostly covered.....13.1
33. Limestone, light-gray, medium-grained, thin-bedded, well-indurated, fossiliferous, echinodermal, eroding into ledge.....0.61
34. Shale, greenish-gray to tan, platy, weakly indurated.....1.52
35. Limestone, tan, medium-grained, well-indurated, fossiliferous, eroding into ledge.....0.09
36. Shale, greenish-gray, platy, weakly indurated..0.53
37. Limestone, tan, medium-grained, massive, well-indurated, fossiliferous, echinodermal, eroding into ledge.....0.23
38. Shale, greenish-gray to tan, platy, with some interbedded thin tan limestone beds, fossilifer-

Fig. 80. Spring Creek exposure, Murray County. View looking west where strike is N 45° W, and dip 32° SW, of Upper Echinoderm Zone of Mountain Lake Member (type section), 75.4 m below Viola Limestone, and 4.3 m below the Pooleville Limestone Member, just below broken dam of Upper Humble Lake, in the SW¼NE¼SE¼NE¼ sec. 17, T. 2 S., R. 1 W., Measured Section 1. Allen Graffham is pointing to the lower 0.3-m tan limestone and shale bed from which a few *Oklahomacystis* specimens were collected. The upper 0.6 m of this ledge did not produce any echinoderms. Many *Platycystites* were found about 0.6 m above the nonproductive zone. The ditch is underlain with greenish-gray shale.

ous, with echinoderms, especially *Hybocrinus*, in lower 0.3 m.....1.98
39. Limestone, gray to tan, medium-grained, platy, well-indurated, very fossiliferous, with many brachiopods.....0.09
Lower Echinoderm Zone (total thickness 1.67 m)
40. Shale, greenish-gray, mottled tan, platy, with some thin tan limestone beds, very fossiliferous, with many bryozoans, brachiopods, and echinoderms, with *Hybocrinus*, *Palaeocrinus*, and *Platycystites* mainly in upper 0.3 m.....1.67
Lower Mountain Lake (total thickness 9.4 m)
41. Limestone, tan, fine-grained, argillaceous, well-indurated, thin-bedded, fossiliferous, with alternating tan shale seams, eroding into a ledge.....0.91
42. Shale, tan, platy, weakly indurated, with some thin nodular limestone beds.....0.91
43. Limestone, gray to tan, fine- to medium-grained, massive, fossiliferous, eroding into ledge...0.46
44. Shale, greenish-gray to tan, platy, weakly indurated, mostly covered.....7.2
Basal sandstone sequence (total thickness 30.1 m)
45. Limestone, gray, arenaceous, fine- to medium-grained, thin-bedded, eroding into ledge.....0.76
46. Shale, greenish-gray to tan, mostly covered.....7.6
47. Limestone, brown, arenaceous, fine- to medium-grained, well-indurated, eroding into ledge.....0.09
48. Shale, greenish-gray to tan, with some interbedded brown sandstone, partly covered.....8.2
49. Sandstone, brown, fine- to medium-grained, quartzose, massive, moderately indurated, eroding into ledge.....0.91
50. Shale, greenish-gray, with interbedded sandstone, partly covered.....7.0
51. Sandstone, brown, fine- to medium-grained, quartzose, thin- to medium-bedded, moderately indurated, eroding into ledge.....5.5
TULIP CREEK FORMATION (upper 56.4 m measured)
52. Shale, greenish-gray, partly covered.....12.8
53. Sandstone, brown, fine- to medium-grained, quartzose, medium-bedded, moderately indurated...0.76
54. Shale, greenish-gray, partly covered.....8.8
55. Limestone, tan, arenaceous, fine-grained, massive, gradational into sandstone.....0.3
56. Shale, greenish-gray to tan, mostly covered.....7.3
57. Limestone, tan, arenaceous, fine-grained, thin-bedded, extremely fossiliferous, with many brachiopods.....0.09
58. Shale, greenish-gray, partly covered.....10.4
59. Limestone, tan, arenaceous, fine-grained, massive, eroding into ledge.....0.23
60. Shale, greenish-gray, partly covered.....6.7
61. Limestone, brown, arenaceous, fine-grained, massive, well-indurated, eroding into ledge.....0.15
62. Shale, greenish-gray, platy, weakly indurated, partly covered.....6.1
63. Limestone, brown, arenaceous, medium-grained, medium-bedded, fossiliferous, eroding into ridge 2.74

Measured Section 2

MOUNTAIN LAKE, CARTER COUNTY

Mountain Lake is formed by a dam built in 1922 across Hickory Creek to supply water for Ardmore. Beginning at the top in the Viola Limestone at the northwest end of the dam, and proceeding downsection through the Pooleville Member, section measured in the NW¼NE¼SE¼ sec. 22, T. 2 S., R. 1 W., Carter County, Oklahoma (see Fig. 82). Strike N 40° W, dip 25° SW.

Fig. 81. Spring Creek exposure, Murray County. Close-up view of Upper Echinoderm Zone seen in Figure 80. The tan argillaceous limestone contains much interbedded shale at the base (hammer), resting upon greenish-gray shale. Most of the echinoderms were collected about 0.2 m above the base.

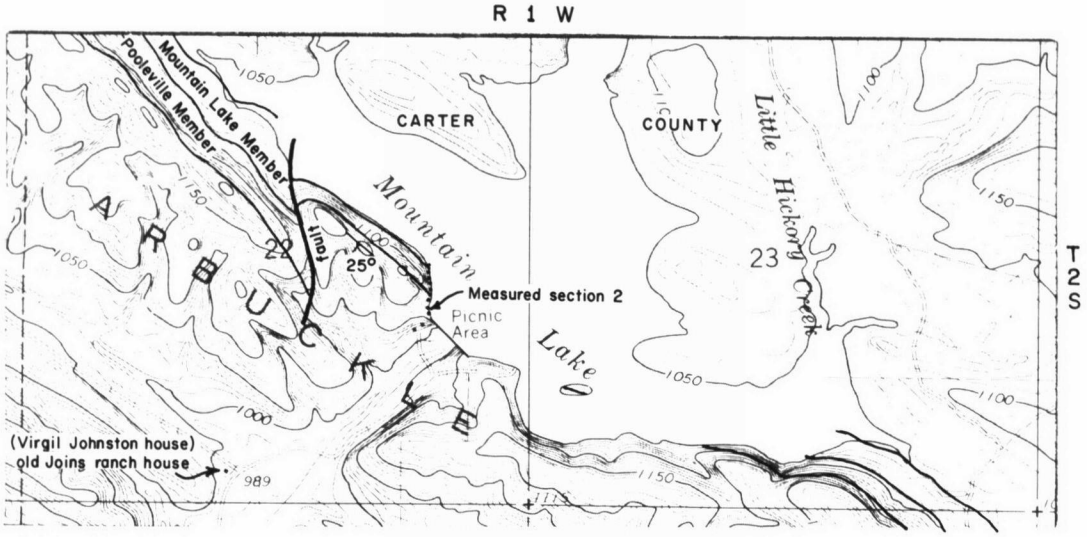


Fig. 82. Geologic map showing Bromide Formation and location of Measured Section 2 at Mountain Lake.

ORDOVICIAN SYSTEM — Thickness (m)
VIOLA LIMESTONE
1. Limestone, gray, lithographic, thin-bedded, well-indurated, with gray to yellow-brown chert, immediately exposed.....15.2
SIMPSON GROUP
BROMIDE FORMATION (upper 59.1 m exposed)
Pooleville Member (total thickness 51.4 m)
2. Limestone, gray, fine-grained, well-indurated, medium-bedded to massive, fossiliferous, with some *Ischadites*, eroding into ledge.....7.9
3. Shale and limestone, tan to gray, fine-grained, thin-bedded, weakly indurated, sparsely fossiliferous.....4.6
4. Shale, yellow-brown, limy, with some interbedded gray fine-grained limestone, moderately fossiliferous, with some brachiopods and bryozoans.....0.3
5. Shale and limestone, tan to gray, as above, with some fossiliferous zones of brachiopods and bryozoans.....2.13
6. Shale and limestone, as above, extremely fossiliferous, with many brachiopods and bryozoans..0.91
7. Shale, gray, mottled tan, with some thin-bedded gray fine-grained limestone, weakly indurated, sparsely fossiliferous.....14.0
8. Limestone, gray, fine-grained, thin-bedded, well-indurated, fossiliferous.....2.89
9. Limestone, gray, fine-grained, dense, massive, well-indurated, thin-bedded, fossiliferous in middle 0.61 m, eroding into ledge.....2.13
10. Shale, tan to greenish-gray, thin-bedded, weakly indurated, with interbedded thin-bedded gray limestone, extremely fossiliferous, with bryozoans, brachiopods, and cephalopods in upper 1.22 m.....3.8
11. Limestone, gray, fine-grained, dense, thin-bedded, well-indurated, fossiliferous, eroding into ledge.....2.28
12. Shale, gray to tan, with interbedded gray fine-grained limestone, thin-bedded, weakly indurated.....10.3
Mountain Lake Member (upper 7.7 m exposed)
13. Limestone, gray, fine-grained, dense, thin-bedded, well-indurated, fossiliferous, with many *Ischadites* in lower part, eroding into ledge.....1.37
14. Shale, tan to yellow-brown, limy, weakly indurated, thin-bedded, with some 2.5- to 5.0-cm limestone beds, partly covered, with a *Sowerbyella* limestone near base.....3.3
15. Shale, greenish-gray, thin-bedded, platy, unfossiliferous, exposed to lake level.....3.05

Measured Section 3

TULIP CREEK, CARTER COUNTY
(Chapman Ranch and Cornell Ranch)

Beginning at top of section in Viola Limestone on the old J. A. Chapman Ranch (now Fred Chapman Ranch of Ardmore) in the W½NW¼NE¼ sec. 25, T. 2 S., R. 1 E., west of Tulip Creek and west of Interstate Highway 35, and proceeding downsection, section measured northward to Tulip Creek Formation along county road (see Fig. 83). Strike N 52° W, dip 58° SW.

The section was then measured again on the nearby Phil Cornell Ranch, east of old U.S. Highway 77, where the Lower Echinoderm Zone is well developed (Fig. 84). Only the lower part of the Mountain Lake was measured here.

Chapman Ranch

ORDOVICIAN SYSTEM — Thickness (m)
VIOLA LIMESTONE
1. Limestone, gray to dark-brown, fine-grained, thin-bedded to laminated, with much brown chert, eroding into ledge, with thin pyritic iron-stained zone at lower contact.....2.44+
SIMPSON GROUP
BROMIDE FORMATION (total thickness 130.7 m)
Pooleville Member (total thickness 39.0 m)
2. Limestone, gray, fine-grained, dense, well-indurated, massive, eroding into ledge.....4.3
3. Limestone, gray to tan, fine-grained, dense, thin-bedded, well-indurated, fossiliferous, eroding into ledge.....4.9
4. Limestone, gray, fine-grained, dense, medium-bedded, well-indurated, fossiliferous, eroding into ledge.....2.89
5. Limestone, light-gray to tan, medium-grained, medium-bedded, well-indurated, very fossiliferous, echinodermal, with many brachiopods, partly covered.....2.13
6. Limestone, light-gray, mottled tan, medium-grained, thin-bedded, moderately indurated, with interbedded shale, very fossiliferous, with brachiopods, bryozoans, and echinoderm remains, mostly covered.....6.7
7. Limestone, light-gray, fine-grained, dense, massive, fossiliferous, eroding into escarpment...0.3
8. Limestone, gray to tan, medium-grained, argillaceous, thin-bedded, moderately indurated, flaggy, with interbedded shale, very fossiliferous, with many brachiopods, eroding into a recess, partly covered.....3.9
9. Limestone, gray, fine-grained to medium-grain-

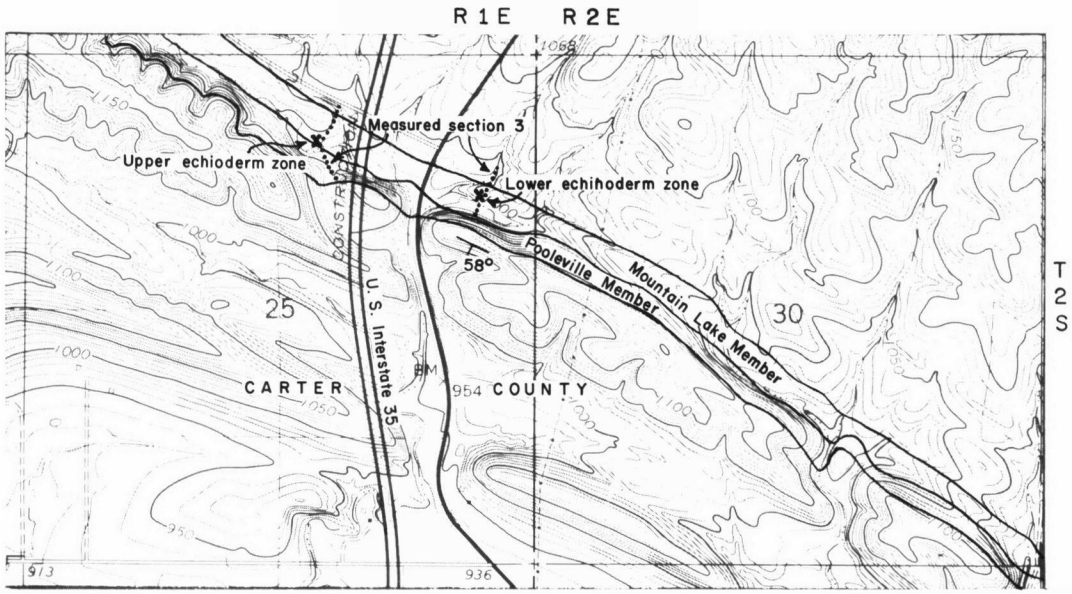


Fig. 83. Geologic map showing Bromide Formation and location of Measured Section 3 at Tulip Creek.

ed, well-indurated, medium-bedded, fossiliferous, eroding into escarpment.....0.61
10. Limestone, gray, mottled tan, fine-grained, argillaceous, fossiliferous, with interbedded shale, eroding into recess.....1.83
11. Limestone, gray, mottled tan, fine-grained, thin- to medium-bedded, well-indurated, fossiliferous, eroding into ridge.....1.83
12. Limestone, tan, fine-grained, argillaceous, moderately to weakly indurated, thin-bedded, fossiliferous, with interbedded shale, eroding into recess.....2.74
13. Limestone, gray, fine-grained, dense, well-indurated, thin- to medium-bedded, cherty, fossiliferous, with some interbedded weakly indurated argillaceous brown limestone, eroding into prominent ridge.....4.1
14. Shale and limestone, tan, fine-grained, argillacous, moderately to weakly indurated, thin-bedded, fossiliferous, with many bryozoans and brachiopods.....2.06
15. Limestone, tan, medium-grained, moderately to weakly indurated, thin-bedded, with some interbedded brown shale, extremely fossiliferous, echinodermal, with many bryozoans and brachiopods, eroding into low ridge.....1.22

Mountain Lake Member (total thickness 91.1 m)

Upper Mountain Lake (total thickness 0.3 m)

16. Shale, tan, thin-bedded, weakly indurated, with interbedded tan limestone, extremely fossiliferous, with many bryozoans and brachiopods...0.3

Upper Echinoderm Zone (total thickness 3.28 m)

17. Shale, tan, thin-bedded, weakly-indurated, with interbedded tan limestone, extremely fossiliferous, with many bryozoans and brachiopods; with *Oklahomacystis* in top 0.3 m. (The upper 0.3 m is termed the upper part of the Upper Echinoderm Zone, where 15 specimens of *Oklahomacystis* were found in 0.6 cubic m of rock.).....0.91
18. Limestone, tan, fine-grained, well-indurated, massive, fossiliferous, eroding into prominent escarpment.....0.37
19. Shale, tan, thin-bedded, fossiliferous, with many bryozoans and brachiopods, with some interbedded brown limestone, with rhombiferan cystoid found 0.3 m below top.....0.76
20. Limestone, brown, fine- to medium-grained, argillaceous, moderately indurated, thin-bedded, with some interbedded brown shale, eroding into low ledge.....0.3
21. Shale, tan, thin-bedded, weakly indurated, fossiliferous, with interbedded medium-grained gray limestone, with 6 specimens of *Oklahomacystis* found 0.3 m above base. (This 0.91-m zone is termed the lower part of the Upper Echinoderm Zone; 10 echinoderms were found in 1.4 cubic m of rock.).....0.91

Middle Mountain Lake (total thickness 49.8 m, including Lower Echinoderm Zone, which is covered)

22. Limestone, gray, fine-grained, dense, well-indurated, eroding into low ledge... .....0.15
23. Shale, greenish-gray, thin-bedded, weakly indurated, with interbedded argillaceous limestone.....0.46
24. Shale, greenish-gray, blocky, weakly indurated, eroding into deep recess, mostly covered...3.9
25. Limestone, brown, medium-grained, well-indurated, thin-bedded, fossiliferous, with much interbedded weakly indurated brown shale, eroding into slope, mostly covered.....4.9
26. Limestone, gray to tan, fine- to medium-grained, thin-bedded, well-indurated, fossiliferous, eroding into prominent ridge.....1.98
27. Shale, greenish-gray, blocky, weakly indurated, with some 2.5- to 5.0-cm beds of fossiliferous brown limestone.....6.1
28. Limestone, brown, medium-grained, well-indurated, massive, fossiliferous, with many small brachiopods like *Sowerbyella*, eroding into low ridge.....0.23
29. Shale, greenish-gray, blocky, weakly indurated 15.2
30. Limestone, tan, fine-grained, thin-bedded, well-indurated, eroding into prominent ridge.....1.52
31. Shale, greenish-gray, as above.....0.61
32. Limestone, tan to gray, medium-grained, thin-bedded, moderately indurated, fossiliferous.....0.23
33. Shale, greenish-gray, as above.....0.61
34. Limestone, brown, medium-grained, well-indurated, massive, fossiliferous, eroding into ledge.....0.24
35. Shale, greenish-gray, blocky, weakly indurated..5.9
36. Limestone, gray to tan, fine- to medium-grained, thin-bedded, well-indurated, eroding into ledge.....0.46
37. Shale, greenish-gray, as above, mostly covered 1.83
38. Limestone, tan, fine-grained, thin-bedded to massive, fossiliferous, eroding into ledge.....0.23
39. Shale, brown to greenish-gray, weakly indurated, partly covered.....1.83
40. Limestone, brown, fine- to medium-grained, thin-bedded, moderately indurated, fossiliferous, with many bryozoans and brachiopods, with interbedded greenish-gray to brown shale, eroding into several low ridges (probably includes Lower Echinoderm Zone in lower part but deeply

eroded and partly covered).....3.3
Lower Mountain Lake (total thickness 6.8 m)
41. Shale, greenish-gray to brown, weakly indurated, with some interbedded brown limestone.....3.3
42. Limestone, brown, fine- to medium-grained, thin-bedded, moderately indurated, fossiliferous, with many bryozoans and brachiopods, with interbedded yellow-brown shale.....1.67
43. Shale, greenish-gray, blocky, weakly indurated 1.83
Basal sandstone sequence (total thickness 31.0 m)
44. Limestone, gray to brown, medium-grained, arenaceous, well-indurated, echinodermal, massive, gradational into a medium-grained sandstone, eroding into ledge.....0.46
45. Shale, greenish-gray, as above, with some interbedded medium-grained limestone and fine- to medium-grained quartzose sandstone, mostly covered.....21.3
46. Sandstone, brown, fine- to medium-grained, quartzose, massive, well-indurated, eroding into ledge.....1.22
47. Shale, greenish-gray, blocky, weakly indurated 3.6
48. Sandstone, light-tan, fine- to medium-grained, thin- to medium-bedded, quartzose, well-indurated, eroding into prominent ledge.....4.3
TULIP CREEK FORMATION (upper 26.2 m measured)
49. Shale, greenish-gray, as above, with some interbedded thin limestone and sandstone beds.....23.1
50. Sandstone, brown, fine- to medium-grained, quartzose, medium-bedded, well-indurated, eroding into ledge just south of road on north side of a branch of Tulip Creek; exposed.....3.05

Cornell Ranch

Beginning in creek just south of the Lower Echinoderm Zone, about 79.3 m below Viola Limestone or 39.6 m below top of Mountain Lake Member in the NE¼NW¼SE¼NE¼ sec. 25, T. 2 S., R. 1 E., about 152 m east of U.S. Highway 77 (see Fig. 83), and proceeding downsection northward through the lower Mountain Lake Member, section measured into the Tulip Creek Formation. This ranch was owned by Phil Cornell of Dallas, Texas.

BROMIDE FORMATION
Pooleville Member (not measured)
Mountain Lake Member (upper part not measured; measurement beginning about 39.6 m below top in middle part)
Middle Mountain Lake (lower 12 m measured)
1. Limestone, brown, fine-grained, thin-bedded, well-indurated, eroding into ledge.....1.07
2. Shale, greenish-gray, blocky, weakly indurated..1.83
3. Limestone, brown, fine-grained, argillaceous, well-indurated, massive, fossiliferous, with bryozoans and a cephalopod, eroding into ledge in creek.....0.3
4. Shale, greenish-gray, platy, weakly indurated...0.91
5. Limestone, brown, medium-grained, platy, thin-bedded, moderately indurated, fossiliferous, with brachiopods, with interbedded greenish-gray shale.....2.28
6. Shale, greenish-gray, blocky to platy, weakly indurated.....2.74
7. Limestone, brown, fine-grained, quartzose, medium-bedded to massive, well-indurated, eroding into ledge.....0.23

Fig. 84. Cornell Ranch exposure, Carter County. View looking northwest along strike N 52° W, with dip 58° SW, of Lower Echinoderm Zone of Mountain Lake Member, 91 m below Viola Limestone, on north side of a branch of Tulip Creek about 152 m east of U.S. Highway 77, in the NE¼NW¼SE¼NE¼ sec. 25, T. 2 S., R. 1 E., Measured Section 3. The zone of greenish-gray and light-brown shale is about 0.9 m thick, and approximately 300 specimens of echinoderms were collected from about 6.7 cubic m of rock.

8. Shale, greenish-gray, blocky, weakly indurated, with large brachiopods in basal 0.07 m.....4.6
9. Limestone, gray, fine-grained, massive, well-indurated, mottled by burrowing, eroding into ledge (see Fig. 84).....0.15

Lower Echinoderm Zone (total thickness 0.91 m)

10. Shale, greenish-gray to light-brown, thin-bedded, weakly indurated, with some interbedded brown siltstone at base, extremely fossiliferous, with many bryozoans, brachiopods, and echinoderms, especially *Hybocrinus* and *Platycystites*, with some *Palaeocrinus*, *Carabocrinus*, and one *Eumorphocystis*. (About 6.7 cubic m of rock was removed from an excavation about 7.0 m long and 0.91 to 1.22 m deep, and as wide as the zone, 0.91 m; see Fig. 84.).....0.91

Lower Mountain Lake (total thickness 6.3 m)

11. Shale, as above, fossiliferous.....0.3
12. Shale, greenish-gray, blocky, weakly indurated 1.14
13. Shale, brown, platy, weakly indurated, with many brachiopods.....0.46
14. Limestone, brown, fine-grained, thin-bedded to massive, mottled by burrowing, fossiliferous, with many *Ischadites* at top, eroding into ledge...0.3
15. Shale, brown to greenish-gray, blocky, weakly indurated, with some thin interbedded limestone...3.9
16. Limestone, gray to brown, medium-grained, thin-bedded, well-indurated, eroding into ledge..0.07
17. Shale, greenish-gray, as above, covered.....0.07

Basal sandstone sequence (total thickness 32.4 m)

18. Limestone, brown, fine-grained, arenaceous, massive, well-indurated, eroding into ledge.....0.15
19. Shale, greenish-gray, as above, partly covered 3.05
20. Sandstone, brown, fine- to medium-grained, quartzose, calcitic, thin-bedded, well-indurated, eroding into ledge.....0.23
21. Shale, greenish-gray, as above, with some interbedded thin limestones and sandstones, mostly covered.....10.3
22. Sandstone, brown, fine- to medium-grained, quartzose, medium-bedded, well-indurated, eroding into prominent ridge.....0.61
23. Shale, as above, with much sandstone, partly covered.....6.4
24. Sandstone, brown, fine- to medium-grained, quartzose, medium-bedded, well-indurated, eroding into ledge.....1.52
25. Shale, greenish-gray, as above, partly covered..7.6
26. Sandstone, brown, fine- to medium-grained, quartzose, well-indurated, medium-bedded, eroding into ledge.....2.44

TULIP CREEK FORMATION (upper 49.8 m measured)

27. Shale, greenish-gray, as above, with some interbedded sandstone, partly covered.....13.1
28. Limestone, dark-gray to brown, medium-grained, arenaceous, well-indurated, thin- to medium-bedded, weathering red-brown, eroding into ledge 1.22
29. Shale, greenish-gray, blocky, weakly indurated, partly covered.....5.5
30. Sandstone, brown, fine- to medium-grained, quartzose, massive, well-indurated, eroding into ledge.....1.07
31. Shale, greenish-gray, blocky, weakly indurated, with some interbedded brown sandstone beds...11.5
32. Limestone, gray to brown, medium-grained, well-indurated, thin-bedded, fossiliferous, with some interbedded greenish-gray shale, eroding into ledge.....1.67
33. Shale, greenish-gray, blocky, weakly indurated, partly covered.....14.0
34. Limestone, gray, medium-grained, thin-bedded, well-indurated, echinodermal, with some interbedded shale, eroding into ledge.....1.67

Measured Section 4

DAUBE RANCH, JOHNSTON COUNTY

Beginning at top in Viola Limestone and proceeding downsection northward along west branch of Sycamore Creek (see Fig. 85), section measured in the SW¼SE¼NW¼ sec. 27, T. 3 S., R. 4 E., on the Sam Daube Ranch (of Ardmore), Johnston County, Oklahoma. Strike N 50° W, dip 74° SW.

ORDOVICIAN SYSTEM — Thickness (m)

VIOLA LIMESTONE (basal 1.52 m measured)

1. Limestone, dark-gray, fine-grained, lithographic, thin-bedded, cherty, well-indurated.....1.52

SIMPSON GROUP

BROMIDE FORMATION (total thickness 95.1 m)

Pooleville Member (total thickness 26.2 m)

2. Limestone, gray, fine-grained, medium-bedded, well-indurated.....2.28
3. Limestone, light-gray, fine-grained, thick-bedded, fossiliferous, eroding into series of massive ledges, forming prominent escarpment.....6.4
4. Limestone, light-gray, fine-grained, thin-bedded, well-indurated.....1.67
5. Limestone, light-gray, fine-grained, thick-bedded to massive, well-indurated, eroding into ledge.....3.3
6. Limestone, light-gray, fine-grained, medium-bedded, well-indurated.....3.9
7. Limestone, light-gray to tan, fine-grained, well-indurated, thick-bedded to massive, eroding into ledge.....3.7
8. Limestone, brown, medium- to coarse-grained, thin-bedded, moderately indurated, fossiliferous, echinodermal, eroding into escarpment.....4.0
9. Limestone, light-gray, medium-grained, well-indurated, echinodermal, eroding into ledge...0.67

Mountain Lake Member (total thickness 68.9 m)

Upper Mountain Lake (total thickness 5.8, including Upper Echinoderm Zone)

10. Limestone, brown, medium- to coarse-grained, thin-bedded, moderately indurated, extremely fossiliferous, echinodermal.....5.8

Middle Mountain Lake (total thickness 40.4 m)

11. Shale, greenish-gray to tan, platy, weakly indurated.....3.9
12. Limestone, gray, medium-grained, well-indurated, fossiliferous, echinodermal, eroding into ledge.....0.15
13. Shale, greenish-gray to tan, platy, weakly indurated.....3.2
14. Limestone, tan to gray, medium- to coarse-grained, thin- to medium-bedded, well-indurated, with some interbedded tan shale, with much tan to gray chert in lower 0.3 m, eroding into several ledges.....1.83
15. Limestone, gray, fine-grained, thin- to medium-bedded, mottled tan, well-indurated, with some tan to gray chert, with some interbedded tan shale, eroding into several ledges.....4.3
16. Shale, tan to greenish-gray, platy, weakly indurated, partly covered.....1.98
17. Limestone, gray to light-tan, medium- to coarse-grained, well-indurated, thin-bedded to massive, fossiliferous, echinodermal, eroding into ledge.....2.28
18. Shale, greenish-gray, platy, weakly indurated, alternating with some 15- to 20-cm fine- to medium-grained gray limestone beds, fossiliferous, with many brachiopods like *Sowerbyella* and many crinoid stems, echinoderm plates, and root systems, along with bryozoans; most fossiliferous shale now called *Bromidocystis* Bed.....0.58
19. Shale, greenish-gray, platy, weakly indurated, extremely fossiliferous, with interbedded greenish-gray argillaceous coarse-grained limestone...3.05
20. Limestone, gray to tan, fine- to medium-grained, thin-bedded to massive, well-indurated, with some 5- to 7-cm greenish-gray shale seams, eroding into ledge, covered in lower 1.83 m.....7.0
21. Limestone, tan, arenaceous, quartzose, well-indurated, massive, eroding into ledge.....0.61
22. Limestone, gray, fine-grained, well-indurated, thin-bedded, eroding into recess.....2.74
23. Limestone, gray, fine-grained, well-indurated, medium-bedded to massive, eroding into ledge.....0.49
24. Shale, greenish-gray, limy, blocky, weakly indurated, with some 2.5-cm light-gray limestone layers, eroding into recess.....1.37
25. Limestone, light-gray to tan, fine-grained, thin-bedded to massive, well-indurated, eroding into ledge.....0.61
26. Shale, tan to greenish-gray, limy, platy, rubbly, weakly indurated, extremely fossiliferous, with many bryozoans, with some 2.5- to 20-cm interbedded brown crystalline limestone.....5.8
27. Limestone, gray to tan, coarse-grained, thin-bedded to massive, well-indurated, echinodermal, with some whole echinoderms, eroding into ledge..0.46

Lower Echinoderm Zone (total thickness 1.07 m)

28. Shale, greenish-gray to tan, limy, platy,

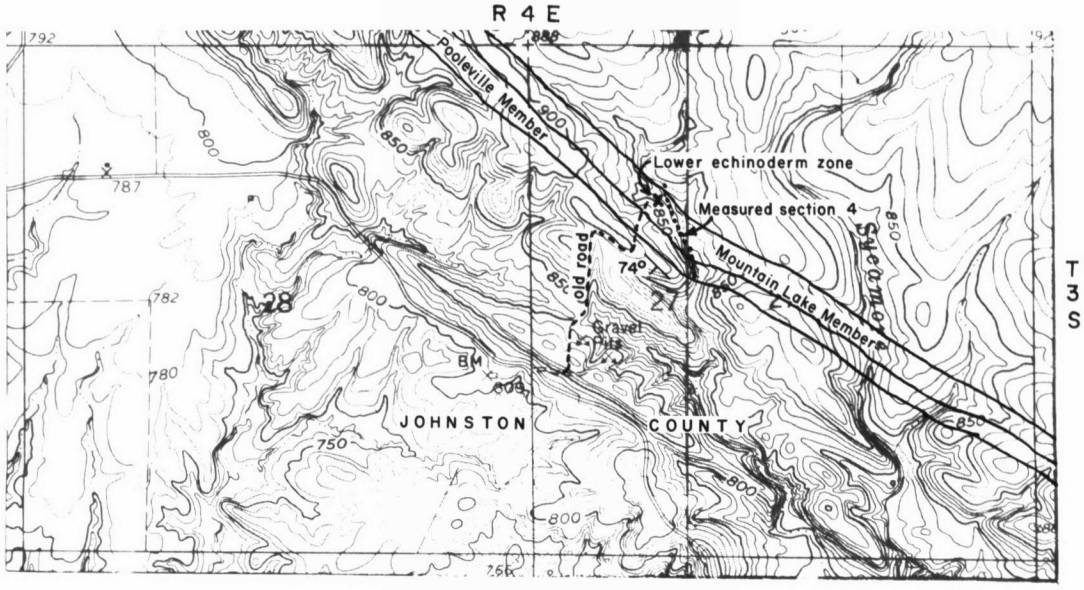


Fig. 85. Geologic map showing Bromide Formation and location of Measured Section 4 at Daube Ranch.

thin-bedded, with many coarsely crystalline tan limestone lenses, extremely fossiliferous, with many bryozoans and brachiopods, and many hundreds of complete echinoderms including *Hybocrinus, Platycystites, Carabocrinus, Palaeocrinus, Eumorphocystis,* rhombiferan cystoids, edrioasteroids, and crinoids from a 15-cm zone about 30 cm above base. (The zone is in the hill west of the creek in the NW¼SW¼SE¼NW¼ sec. 27, and has been bulldozed along strike for about 91.5 m; see Fig. 86. About 11.2 cubic m of rock has been dug from the zone for this study.).....1.07

Lower Mountain Lake (total thickness 7.7 m)

29. Limestone, gray to tan, fine- to coarse-grained, thin-bedded, well-indurated, with some greenish-gray shale at top, fossiliferous.....0.46
30. Limestone, gray to tan, fine-grained, well-indurated, massive, mottled by burrowing, fossiliferous, eroding into prominent ledge (see Fig. 86).....0.39
31. Shale, greenish-gray, limy, platy, weakly indurated, fossiliferous, eroding into recess....1.61
32. Limestone, tan to greenish-gray, fine-grained, thin-bedded, moderately indurated, with some interbedded shale.....0.39
33. Shale, greenish-gray to tan, platy, weakly indurated, fossiliferous.....0.7
34. Limestone, tan to gray, medium-grained, silty, well-indurated, fossiliferous, thin-bedded, eroding into ledge.....0.3
35. Shale, greenish-gray to tan, platy, weakly indurated.....2.13
36. Limestone, tan, coarse-grained, moderately indurated, echinodermal, eroding into ledge.....0.15
37. Shale, greenish-gray to tan, platy, weakly indurated.....0.91
38. Limestone, tan to gray, fine- to medium-grained, well-indurated, thin-bedded, alternating with some greenish-gray to tan shale.....0.61

Basal sandstone sequence (total thickness 13.8 m)

39. Shale, greenish-gray to tan, arenaceous, weakly indurated, with some tan quartzose sandstone beds 2.5 to 5.0 cm thick, mostly covered.....10.0
40. Sandstone, tan to brown, fine- to medium-grained, quartzose, massive, moderately indurated, eroding into ledge.....3.7

TULIP CREEK FORMATION (upper 26.7 m measured)

41. Shale, greenish-gray, mostly covered in slope...6.7
42. Limestone, tan to brown, arenaceous, well-indurated, massive, eroding into ledge.....0.55
43. Shale, greenish-gray, mostly covered in slope...3.9
44. Sandstone, brown, fine- to medium-grained, moderately indurated, thin-bedded to massive, eroding into ledge.....1.07
45. Limestone, brown, fine-grained, arenaceous, thin-bedded, moderately indurated, gradational into fine-grained sandstone.....3.6
46. Sandstone, brown, fine-grained, quartzose, calcitic, massive, well-indurated, gradational into fine-grained arenaceous limestone, eroding into ledge.....0.91
47. Limestone, brown, fine-grained, silty, platy, moderately to weakly indurated.....8.5
48. Limestone, gray to tan, fine- to medium-grained, medium-bedded, well-induratd, fossiliferous, eroding into series of ledges.....1.37

Measured Section 5

BROMIDE AND McLISH RANCH, COAL COUNTY

Beginning at top in Viola Limestone and proceeding downsection through the type locality for the Bromide Formation, section measured along old road about 152 to 305 m north of the old Galbreath Hotel in Bromide, Coal County, Oklahoma (see Fig. 87), in the SE¼NW¼SW¼ sec. 32, and the E½SW¼SW¼ sec. 32, T. 1 S., R. 8 E. Strike N 35° W, dip 14° NE at top of hill and 14° SW at bottom of hill. At top of section in field to north is brown chert and soil, presumed to mark the basal Viola Limestone, but basal contact is covered. The old McLish Ranch is to the west in sec. 36, T. 1 S., R. 7 E., and the Lower Echinoderm Zone is well exposed in the NW¼SE¼ alongside the road, in adjacent fields, and on the east side of the hill about 290 m east of the road (see Fig. 87), where complete *Platycystites* and *Hesperocystis* plates were collected.

ORDOVICIAN SYSTEM — Thickness (m)

SIMPSON GROUP

BROMIDE FORMATION (total thickness 69.2 m)

Pooleville Member (total thickness 10.3 m)

1. Limestone, gray to light-tan, fine-grained, medium-bedded, well-indurated, cherty, with some silicified fossils.....0.3
2. Limestone, as above, with much soil and chert colluvium, mostly covered.....3.9
3. Limestone, tan, fine-grained, well-indurated, medium-bedded, fossiliferous, partly covered.....4.9
4. Limestone, tan, fine-grained, massive, well-indurated, eroding into ledge.....0.61
5. Limestone, as above, with some shale, mostly covered.....0.61

Mountain Lake Member (total thickness 58.9 m)

Upper Mountain Lake (total thickness 2.74 m)

6. Limestone, tan, fine- to coarse-grained, medium-bedded, echinodermal, with some shale, partly covered.....2.74

Upper Echinoderm Zone (total thickness 1.06 m)

7. Limestone, tan, coarse-grained, well-indurated, massive, fossiliferous, with *Oklahomacystis*, *Cleiocrinus*, and *Hybocrinus*, eroding into ledge 0.3
8. Limestone, as above, with some brown chert, partly covered.....0.76

Middle Mountain Lake (total thickness 44.8 m)

9. Limestone, tan, fine-grained, well-indurated, thin- to medium-bedded, fossiliferous, eroding into ledge.....1.52
10. Limestone, tan, fine-grained, well-indurated, massive, eroding into ledge.....0.46
11. Limestone, as above, with some shale, thin-bedded, mostly covered.....1.52
12. Limestone, light-tan, fine-grained, well-indurated, thin-bedded, eroding into several ledges..2.44
13. Limestone, as above, mostly covered.....4.6
14. Limestone, tan, fine-grained, well-indurated, thin-bedded, fossiliferous, eroding into ledge...1.83
15. Limestone, with some shale, as above, mostly covered.....3.05
16. Limestone, tan, fine-grained, thin- to medium-bedded, well-indurated, eroding into ledge....0.91
17. Limestone, as above, mostly covered.....1.22
18. Limestone, tan, fine-grained, well-indurated, thin- to medium-bedded, eroding into ledge.....0.61
19. Limestone and shale, as above, mostly covered..0.91
20. Limestone, tan, very fine-grained, medium-bedded, well-indurated, vuggy, with yellow limestone in vugs, eroding into ledge.....0.46
21. Limestone, light-tan, fine-grained, thin-bedded, cherty, fossiliferous, partly covered.....4.6
22. Limestone, tan, fine- to medium-grained, well-indurated, thin-bedded, eroding into ledge.....0.91
23. Limestone, tan, fine-grained, silty, well-indurated, thin-bedded, cherty, partly covered.....4.3
24. Limestone, gray to light-tan, fine-grained, well-indurated, thin-bedded, cherty, fossiliferous, mottled pink, eroding into ledge.....1.22
25. Limestone, tan, fine- to medium-grained, well-indurated, medium- to thin-bedded, cherty, mostly covered.....4.9
26. Limestone, tan, coarse-grained, echinodermal, medium-bedded, well-indurated, alternating with shale, eroding into ledges.....2.74
27. Limestone, tan to gray, coarse-grained, thin-bedded, well-indurated, fossiliferous, eroding into ledge.....0.76
28. Shale, greenish-gray, blocky, weakly indurated 0.15
29. Limestone, tan, fine- to medium-grained, thin-bedded, well-indurated, echinodermal, alternating with light-tan shale.....1.07
30. Limestone, tan, medium-grained, well-indurated, thin-bedded, fossiliferous, echinodermal, eroding into ledge.....0.3
31. Shale, light-tan, blocky, weakly indurated, fossiliferous, with many fossils such as crinoid stems and cephalopods near top, eroding into slope.....2.44
32. Limestone, tan, fine-grained, massive, well-indurated, fossiliferous, with many massive bryozoans, eroding into ledge.....0.15
33. Shale, tan to greenish-gray, blocky, weakly indurated, fossiliferous, with some 2.5- to 5.0-cm tan limestone beds, eroding into slope....1.52

Fig. 86. Daube Ranch exposure, Johnston County. View looking northwest along strike N 50° W, with dip 74° SW, of Lower Echinoderm Zone of the Mountain Lake Member, 73 m below Viola Limestone, on hillside west of west branch of Sycamore Creek, in the NE¼NE¼SW¼NW¼ sec. 27, T. 3 S., R. 4 E., Measured Section 4. The main zone of greenish-gray to tan shale and interbedded limestone is on the left side, about 1.1 m thick, where many hundreds of echinoderms were collected from about 11.2 cubic m of rock.

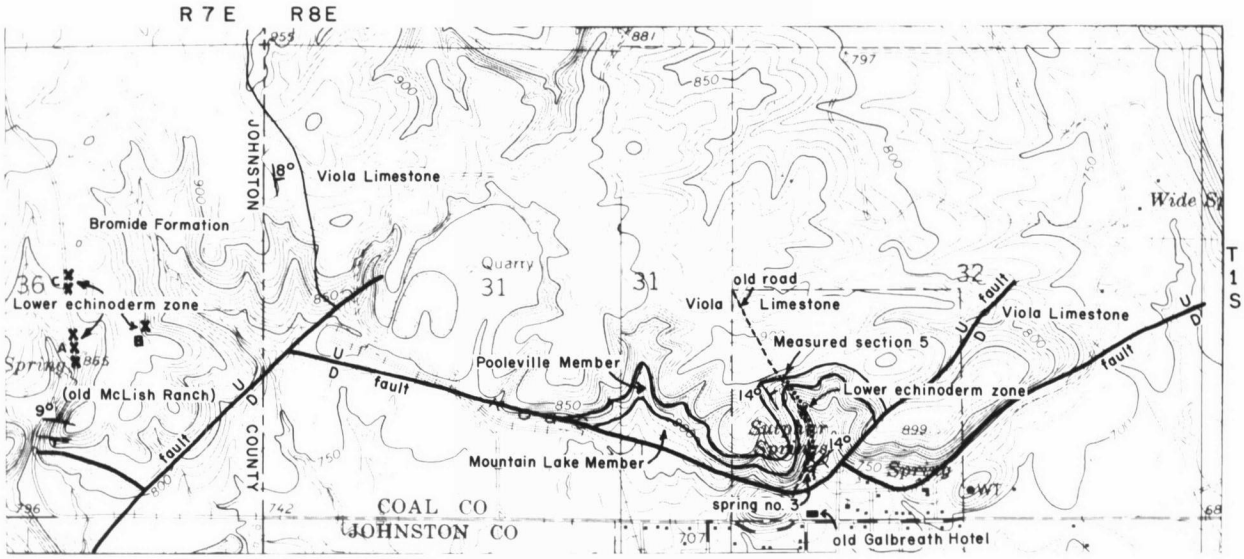


Fig. 87. Geologic map showing Bromide Formation, location of Measured Section 5 at Bromide, and collecting localities to west on McLish Ranch.

Fig. 88. Bromide exposure, Coal County. View looking northwest, of Lower Echinoderm Zone of Mountain Lake Member, 58.9 m below Viola Limestone, along old road about 305 m north of the old Galbreath Hotel, in the SE¼NW¼SW¼ sec. 32, T. 1 S., R. 8 E., Measured Section 5. The tan shale directly below the limestone contains some small *Hybocrinus* specimens.

Lower Echinoderm Zone (total thickness 1.52 m)
34. Limestone, tan, medium- to coarse-grained, medium-bedded, well-indurated, extremely fossiliferous, with many brachiopods and echinoderm fragments, with small *Hybocrinus* zone at base, with many pentagonal echinoderm stems, eroding into ledge.....0.3
35. Shale, tan, limy, blocky, weakly indurated, fossiliferous, with many bryozoans, echinoderm stems, and small *Hybocrinus* at top (see Fig. 88).....1.22
Lower Mountain Lake (total thickness 7.6 m)
36. Limestone, gray to tan, coarse-grained, medium-bedded, well-indurated, echinodermal, eroding into ledge.....1.07
37. Shale, brown, limy, blocky, weakly indurated, with some interbedded echinodermal limestone.....0.61
38. Limestone, tan, medium-grained, medium-bedded, well-indurated, fossiliferous, echinodermal, eroding into ledge.....3.05
39. Limestone and shale, as above, covered to top of old artesian well #3.....1.67
40. Limestone and shale, mostly covered, as above..1.22
Basal sandstone sequence (total thickness 1.52 m)
41. Sandstone, tan, quartzose, medium-grained, thin-bedded, calcitic, well-indurated, gradational into limestone, with some interbedded gray shale, eroding into ledge. (The spring from well #3 flows eastward down hill over the ledge; this is the basal sandstone of the Bromide.).....1.52
TULIP CREEK FORMATION (upper 4.6 m exposed)
42. Shale and limestone, gray, medium-grained, thin-bedded, fossiliferous, eroding into slope below top of well #3, exposed.....4.6

Measured Section 6

LICK CREEK, MURRAY COUNTY

Beginning at top in Viola Limestone and proceeding downsection, section measured along Lick Creek, in the NW¼SW¼NW¼ sec. 24, T. 1 S., R. 1 E., for Pooleville and upper Mountain Lake portion, and NE¼SE¼NE¼NE¼ sec. 23, T. 1 S., R. 1 E., for lower Mountain Lake portion (see Fig. 89). Strike N 30° W, dip 69° NE on Upper Echinoderm Zone of the Mountain Lake, and strike N 27° W, dip 84° NE on Lower Echinoderm Zone of Mountain Lake Member. The area is part of Camp Classen, a field camp for the Y.M.C.A. and Y.W.C.A. of Oklahoma City, Oklahoma.

ORDOVICIAN SYSTEM Thickness (m)
VIOLA LIMESTONE (basal 0.61 m measured)
1. Limestone, gray-brown, dense, thin- to medium-bedded, well-indurated, cherty, eroding into ledge; lower contact obscured by rubble, but apparently composed of rock as above.....0.61
SIMPSON GROUP
BROMIDE FORMATION (total thickness 132.0 m)
Pooleville Member (total thickness 34.4 m)
2. Limestone, light-gray, mottled light-brown, fine-grained, massive, well-indurated, rubbly, eroding into ledge.....0.76
3. Limestone, light-gray, argillaceous, thin-bedded, moderately indurated, weathering into recess.....1.28
4. Limestone, light-brown, fine-grained, well-indurated, massive, eroding into ledge.....0.67
5. Limestone, light-gray, argillaceous, fine-grained, thin-bedded, moderately to weakly indurated, wavy-bedded in middle 15 cm, fossiliferous, with *Tetradium*.....1.52
6. Limestone, light-gray, fine-grained, argillaceous, medium-bedded, moderately indurated, fossiliferous, mottled light-brown, eroding into ledge.....0.91
7. Limestone, tan to light-gray, fine-grained, thin-bedded, moderately indurated, eroding into recess.....0.61
8. Limestone, light-gray to tan, fine-grained, thin-bedded, moderately indurated, fossiliferous, eroding into recess.....1.22
9. Limestone, tan, fine-grained, well-indurated, massive, eroding into ledge.....0.43
10. Limestone, light-gray, fine-grained, argillaceous, thin-bedded, weakly indurated, eroding into recess.....1.52
11. Limestone, tan to light-gray, fine-grained, massive, fossiliferous, eroding into ledge.....2.13
12. Limestone, light-gray, mottled tan, fine-grained, thin-bedded, moderately indurated, fucoidal?, eroding into recess.....1.07
13. Limestone, light-gray to tan, fine-grained, medium-bedded to massive, well-indurated, fossiliferous, eroding into prominent ledge.....7.6
14. Limestone, tan to light-gray, fine-grained, argillaceous, thin-bedded, weakly indurated, with some interbedded shale.....0.79
15. Limestone, light-gray, fine-grained, massive, well-indurated, eroding into ledge.....0.24
16. Limestone and shale, light-gray, as above, weakly indurated, partly covered.....1.83
17. Limestone, light-gray to tan, fine-grained, massive, well-indurated, eroding into ledge.....1.52
18. Limestone, tan to light-gray, fine-grained, argillaceous, thin-bedded, moderately to weakly indurated, with interbedded tan shale, fossiliferous, with large flat brachiopods in upper 15 cm, bryozoans and gastropods in lower part....2.89
19. Limestone, tan to light-gray, fine-grained, medium-bedded to massive, well-indurated, fossiliferous, with many flat brachiopods at base, eroding into ledge.....3.6
20. Shale, light-gray, and limestone, light-gray, fine-grained, dense, thin-bedded, weakly indurated.....1.52
21. Limestone, light-gray to tan, fine-grained, argillaceous, thin-bedded, weakly indurated, fossiliferous.....1.12
22. Shale, light-gray to brown, calcitic, thin-bedded, weakly indurated, fossiliferous, with some interbedded light-gray limestone.....1.07
Mountain Lake Member (total thickness 97.6 m)
Upper Echinoderm Zone (total thickness 3.14 m)
23. Limestone, light greenish-gray to tan, medium-grained, echinodermal, massive, well-indurated, with some *Oklahomacystis*.....0.61
24. Shale, tan, calcitic, clayey, thin-bedded, fossiliferous.....0.46
25. Limestone, tan to light-brown, medium-grained, thin-bedded, platy, well-indurated, with interbedded yellow-brown shale, echinodermal, with many bryozoans, eroding into a ledge in middle part; subdivided into two main zones (see Fig. 90). (The upper zone is 0.3 to 0.46 m below the top, where 0.6 cubic m of rock was removed and 170 *Oklahomacystis*, 20 *Sinclairocystis*, 18 crinoids, and 1 rhombiferan cystoid were collected. The lower zone is 0.82 to 0.91 m above the base, where 0.2 cubic m of rock were removed and 35 *Oklahomacystis* and 1 crinoid were collected. The outcrop is north of a sharp bend in Lick Creek.).....2.07
Middle Mountain Lake (total thickness 44.9 m)
26. Shale, greenish-gray, mottled yellow-brown, flaky, weakly indurated.....0.3
27. Limestone, tan to light-brown, fine- to medium-grained, well-indurated, fossiliferous, in 5- to 10-cm beds with some interbedded yellow-brown shale.....1.07
28. Shale, greenish-gray, platy, plastic, weakly indurated, weathering yellow-brown.....3.3
29. Limestone, light-gray to yellow-brown, medium-grained, well-indurated, medium- to thick-bedded, fossiliferous, echinodermal, with some interbedded yellow-brown shale, eroding into ledge.....2.53
30. Limestone, light-gray, fine-grained, thin-bedded, weakly to moderately indurated, with some medium-grained echinodermal beds, and some greenish-gray shale partings, with brown chert in upper 0.61 m.....2.74
31. Limestone, light greenish-gray, fine-grained, well-indurated, thin-bedded, with much tan platy shale.....3.9
32. Limestone, light-gray, fine-grained, medium-bedded, well-indurated, eroding into ledge.....4.4
33. Limestone and shale, light-gray, fine-grained, thin-bedded, well- to weakly indurated, eroding into recess.....3.6
34. Limestone, light-gray, fine- to medium-grained, well-indurated, massive, fossiliferous, with many bryozoans, and echinoderm fragments.....1.52
35. Shale, yellow-brown, platy, weakly indurated, thinly laminated, with some bryozoans, covered in part.....2.59
36. Limestone, tan to light-gray, fine-grained, well-indurated, thin-bedded, with some interbedded yellow-brown shale, eroding into ledge.....1.67

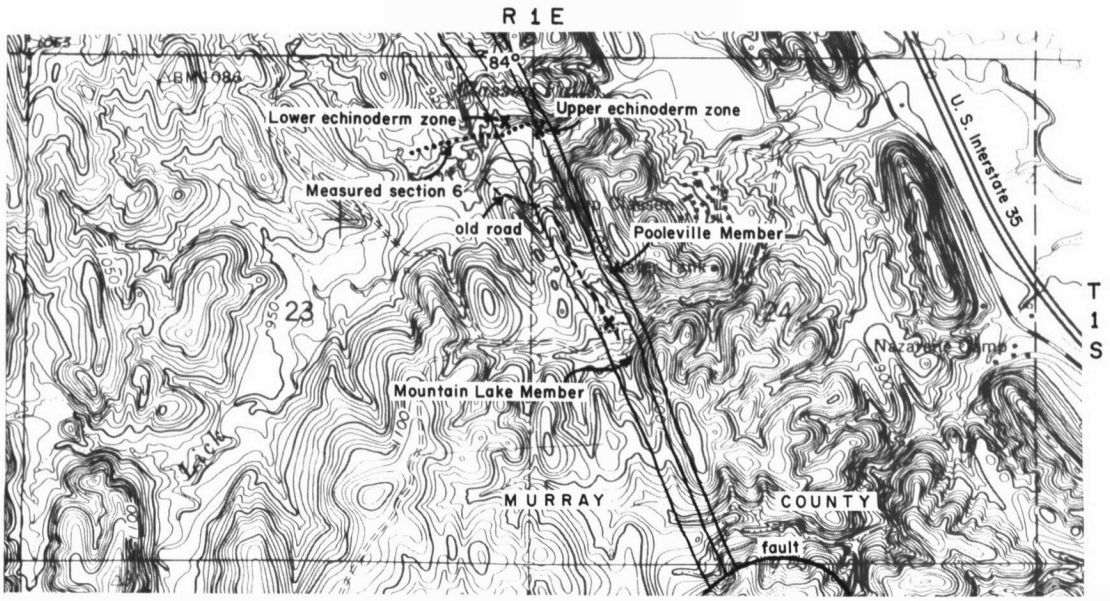


Fig. 89. Geologic map showing Bromide Formation and location of Measured Section 6 at Lick Creek.

Fig. 90. Lick Creek exposure, Murray County. Close-up view, looking north, of Upper Echinoderm Zone of Mountain Lake Member, about 36 m below Viola Limestone, on northwest side of creek in the NW¼NW¼NW¼ sec. 24, T. 1 S., R. 1 E., Measured Section 6. Approximately 200 echinoderms were collected from about 0.6 cubic m of tan shale directly above the limestone. Some echinoderms were collected below the limestone and in shale interbedded with the limestone.

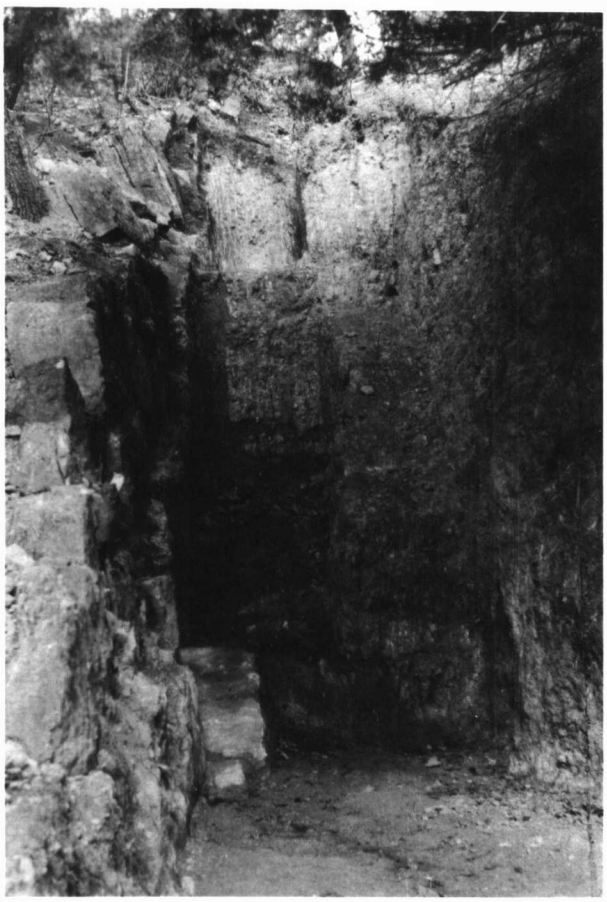


Fig. 91. Lick Creek exposure, Murray County. View looking northwest along strike N 27° W, with dip 84° NE, of Lower Echinoderm Zone of the Mountain Lake Member, 82.9 to 83.2 m below Viola Limestone, on northeast side of creek, in the NE¼NE¼NE¼ sec. 23, T. 1 S., R. 1 E., Measured Section 6. The main zone of greenish-gray shale and interbedded limestone is on the left, where many hundreds of echinoderms were collected along the fringes of a bryozoan-rich biostrome, from about 5.6 cubic m of rock. The overlying 0.9 m of beds yielded several hundred specimens of echinoderms from 8.4 cubic m of rock.

37. Shale and limestone, yellow-brown, fine-grained, weakly to well-indurated, thin-bedded, fossiliferous, with some bryozoans.....3.3
38. Limestone, light-tan, fine-grained, well-indurated, medium-bedded, with some interbedded yellow-brown shale, fossiliferous, with many brachiopods, especially *Sowerbyella* in middle, and large planoconvex brachiopods in upper 0.3 m.....2.13
39. Sandstone, gray, medium-grained, quartzose, calcitic, moderately indurated, eroding into ledge.....0.67
40. Siltstone, yellow-brown, calcitic, fine-grained, well-indurated, massive.....0.3
41. Shale, yellow-brown, plastic, with some interbedded medium-grained tan fossiliferous limestone.....2.44
42. Limestone, tan to gray, medium- to fine-grained, well-indurated, thin-bedded, fossiliferous, with some interbedded tan shale, eroding into 3 ledges. (The top 0.8 m shale has produced a few complete echinoderms as well as plates and stems and is now called the *Carabocrinus* Beds.).....2.74
43. Shale, greenish-gray, flaky, weakly indurated..1.07
44. Limestone, gray, fine- to medium-grained, thin-bedded, well-indurated, rubbly, with much shale in lower part, eroding into ledge.....1.07
45. Shale, greenish-gray, platy, weakly indurated..1.83
46. Shale, greenish-gray to yellow-brown, thin-bedded, weakly indurated, extremely fossiliferous, with many bryozoans and echinoderms.....1.22

Lower Echinoderm Zone (total thickness 1.37 m)

47. Shale, greenish-gray to yellow-brown, thin-bedded, weakly indurated, extremely fossiliferous, with many bryozoans, brachiopods, and echinoderms, subdivided into two zones. (The upper zone is 0.76 to 1.37 m above the base, where 8 cubic m of rock was removed, containing mainly *Hybocrinus*—75 specimens—and some *Platycystites*, crinoids, rhombiferan cystoids, and 1 *Bromidocystis*. The lower zone is 0.46 to 0.76 m above the base, where 6 cubic m of rock was removed, containing almost 1,000 *Platycystites*, 700 *Hybocrinus*, 75 rhombiferan cystoids, 50 *Palaeocrinus*, 20 *Carabocrinus*, and some crinoids, a starfish, edrioasteroids, paracrinoids, and *Eumorphocystis*, along with 300 or more holdfasts; see Fig. 91.).....1.37

Lower Mountain Lake (total thickness 6.7 m)

48. Limestone, tan, fine-grained, massive, well-indurated, mottled with burrows, eroding into prominent ledge (see Fig. 90).....0.61
49. Shale, yellow-brown, weakly indurated, fossiliferous, with many bryozoans and brachiopods.....3.2
50. Limestone, yellow-brown, fine-grained, thin-bedded, well-indurated, eroding into ledge.....0.46
51. Shale, yellow-brown, weakly indurated, fossiliferous, with many bryozoans, brachiopods, and echinoderm remains.....2.44

Basal sandstone sequence (total thickness 41.7 m)

52. Sandstone, tan, fine-grained, quartzose, calcitic, thin-bedded, well-indurated, eroding into ledge.....2.28
53. Shale, yellow-brown, plastic.....0.46
54. Shale, greenish-gray, platy, weakly indurated, with some thin-bedded fossiliferous limestone in middle, and large bryozoans, brachiopods, and echinoderm remains in lower 0.91 m.....3.05
55. Sandstone, brown, fine-grained, quartzose, moderately indurated.....0.21
56. Shale, greenish-gray, platy, weakly indurated..1.07
57. Sandstone, white, fine-grained, quartzose, well-indurated, eroding into ledge.....0.76
58. Sandstone, tan, fine-grained, quartzose, weakly indurated.....0.3
59. Shale, greenish-gray, platy, weakly indurated..3.05
60. Sandstone, white to brown, fine-grained, quartzose, well-indurated, with some interbedded brown shale, eroding into ledge.....2.13
61. Shale, yellow-brown, weakly indurated, with some interbedded sandstone at base.....1.83
62. Shale, greenish-gray, platy, weakly indurated..1.07
63. Sandstone, yellow-brown, fine-grained, quartzose, massive, well-indurated, eroding into ledge.....2.74
64. Shale, greenish-gray, and interbedded yellow-brown sandstone.....2.44
65. Sandstone, yellow-brown, fine-grained, quartzose, thin-bedded, with some interbedded shale...0.61
66. Shale, greenish-gray, platy, weakly indurated..2.13
67. Sandstone, yellow-brown, as above, with some interbedded shale in middle, eroding into ledge...4.6
68. Shale, greenish-gray, arenaceous, with some interbedded sandstone.....1.22
69. Sandstone, yellow-brown, as above, with some interbedded shale, eroding into ledge.....5.2
70. Shale, greenish-gray, arenaceous, platy, weakly indurated.....1.22
71. Sandstone, yellow-brown, as above, eroding into ledge.....1.07
72. Sandstone, yellow-brown, fine-grained, quartzose, weakly indurated.....2.44
73. Sandstone, white to yellow-brown, fine-grained, quartzose, thin-bedded, moderately to well-indurated, eroding into ledge.....1.83

TULIP CREEK FORMATION (upper 7.0 m measured)

74. Shale, yellow-brown, weakly indurated, fossiliferous, with some interbedded fine-grained limestone.....3.3
75. Limestone, tan, fine-grained, arenaceous, medium-bedded, well-indurated, fossiliferous, with cephalopods and echinoderm remains in lower part, eroding into ledge.....1.83
76. Shale, greenish-gray, moderately to weakly indurated, with interbedded thin-bedded gray to tan limestone, eroding into recess.....1.83

Measured Section 7

AMIS RANCH, MURRAY COUNTY

Beginning at top in Viola Limestone and proceeding downsection, section measured on ridge south of private lake in the SE¼NW¼SW¼ sec. 3, T. 2 S., R. 2 E., for Pooleville Member and Upper Echinoderm Zone of Mountain Lake Member, ending in the SE¼NW¼SE¼SW¼ sec. 3, T. 2 S., R. 2 E., for Lower Echinoderm Zone of Mountain Lake Member, to Tulip Creek Formation (see Fig. 92). The beds are slightly overturned on the northeast flank of the Arbuckle anticline, with strike N 42° W, dip 80° SW. The owner is Amis Construction Company of Oklahoma City. A private road enters the area about 1.6 km southeast of the measured section.

ORDOVICIAN SYSTEM — Thickness (m)

VIOLA LIMESTONE (lower 3.05 m measured)

1. Limestone, gray, lithographic, well-indurated, cherty, thin-bedded.....3.05

SIMPSON GROUP

BROMIDE FORMATION (total thickness 93.0 m)

Pooleville Member (total thickness 25.9 m)

2. Limestone, light-gray, fine-grained, dense, thin- to medium-bedded, moderately to weakly indurated, fossiliferous, with ostracods such as *Leperditia* and brachiopods, eroding into recess...5.3
3. Limestone, gray to tan, fine-grained, well-indurated, medium-bedded to massive, fossiliferous, eroding into 2 ledges.....3.7
4. Limestone, light-gray to tan, fine-grained, argillaceous, thin-bedded, moderately indurated, fossiliferous, with some gray shale, eroding into recess.....3.3
5. Limestone, gray, fine-grained, dense, well-indurated, massive, fossiliferous, eroding into ridge.....2.59
6. Shale, gray, limy, weakly indurated, fossiliferous, with bryozoans, cephalopods, and echinoderm remains.....0.91
7. Limestone, gray, fine-grained, dense, well-indurated, thin-bedded, fossiliferous.....0.15
8. Shale, gray, limy, weakly indurated, with some interbedded thin-bedded light-gray fine-grained limestone, very fossiliferous, with many brachiopods and bryozoans.....4.4
9. Limestone, gray to tan, fine-grained, dense, medium-bedded, well-indurated, with many brachiopods such as *Hesperorthis* and *Oepikina*, eroding into ledge.....1.75
10. Shale, light-gray, limy, thin-bedded, moderately indurated, fossiliferous, eroding into slope.....1.22
11. Limestone, light-gray, fine-grained, dense, well-indurated, eroding into ledge.....0.46
12. Shale, tan, limy, weakly indurated, with some thin-bedded gray fine-grained limestone beds, partly covered.....1.83

Mountain Lake Member (total thickness 67.0 m)

Upper Mountain Lake (total thickness 2.13 m)

13. Limestone, tan, fine-grained, thin-bedded, with some interbedded greenish-gray shale, partly covered.....0.76
14. Shale, greenish-gray, platy, weakly indurated, with some interbedded brown limestone, with many *Oxoplecia*.....1.37

Upper Echinoderm Zone (total thickness 1.37 m)

15. Shale, greenish-gray, platy, weakly indurated, with interbedded brown limestone, partly covered, with *Oxoplecia* in upper 0.76 m, and 50 *Oklahomacystis* in upper part and 1 *Sinclairocystis* in lower part, with some *Platycystites*, crinoid, and cystoid fragments.....1.37

Middle Mountain Lake (total thickness 34.5 m)

16. Shale, greenish-gray, platy, weakly indurated, with interbedded brown limestone, becoming tan in lower 1.37 m, with *Ischadites* and bryozoans, partly covered.....4.9
17. Limestone, tan, fine-grained, well-indurated, thin-bedded, very cherty, eroding into ledge.....6.4
18. Shale, tan to greenish-gray, weakly indurated, fossiliferous, with some interbedded fine-grained gray limestone, eroding into slope.....5.8
19. Limestone, tan, fine-grained, dense, cherty, well-indurated, massive, fossiliferous, eroding into ledge.....1.67
20. Shale, tan, weakly indurated, with many medium-bedded tan fossiliferous limestone beds, very fossiliferous, with many bryozoans and brachiopods, eroding into slope.....10.6
21. Limestone, tan, fine- to medium-grained, fossiliferous, echinodermal, thin- to medium-bedded, moderately indurated, eroding into several ledges.....4.3

Lower Echinoderm Zone (total thickness 0.91 m)

22. Shale and limestone, tan, thin-bedded, moderately to weakly indurated, extremely fossiliferous, with many bryozoans, brachiopods (especially *Mimella*), and many echinoderms, including 600 *Hybocrinus*, 100 *Platycystites*, 118 *Palaeocrinus*, 30 *Carabocrinus*, 2 *Eumorphocystis*, and many crinoids, cystoids, and edrioasteroids (About 5 cubic m of rock was removed just west of the private road south of the lake; see Fig. 93.).....0.91

Lower Mountain Lake (total thickness 13.0 m)

23. Limestone, tan, echinodermal, thin-bedded, moderately indurated, mottled by burrowing, eroding into ledge.....0.46
24. Shale, tan to greenish-gray, with some thin-bedded limestone, fossiliferous, with many bryozoans and echinoderm remains.....3.05
25. Limestone, tan, coarse-grained, moderately indurated, echinodermal.....0.3

(Section extrapolated to next hill south, next to road)

26. Shale, tan, weakly indurated, fossiliferous....1.67
27. Limestone, tan, fine- to medium-grained, thin-bedded, fossiliferous, with some interbedded greenish-gray shale.....3.4
28. Shale, greenish-gray, weakly indurated, fossiliferous.....2.74
29. Limestone, tan, medium-grained, platy, fossiliferous, echinodermal.....0.46
30. Shale, greenish-gray, platy, weakly indurated..0.91

Basal sandstone sequence (total thickness 15.8 m)

31. Sandstone, tan, fine- to medium-grained, quartzose, thin-bedded, moderately indurated, eroding into ledge.....0.37
32. Shale, greenish-gray, as above, with some sandstone.....3.05
33. Sandstone, tan, as above.....0.46
34. Shale, greenish-gray, as above.....1.22
35. Sandstone, brown, as above.....1.07
36. Shale, greenish-gray, weakly indurated, with some interbedded fine- to medium-grained brown sandstone, eroding into slope.....5.5
37. Sandstone, brown, as above, eroding into ledge..4.3

TULIP CREEK FORMATION (upper 24 m measured)

38. Shale, greenish-gray to tan, arenaceous, platy, weakly indurated, eroding into slope.....6.1
39. Limestone, tan, medium-grained, well-indurat-

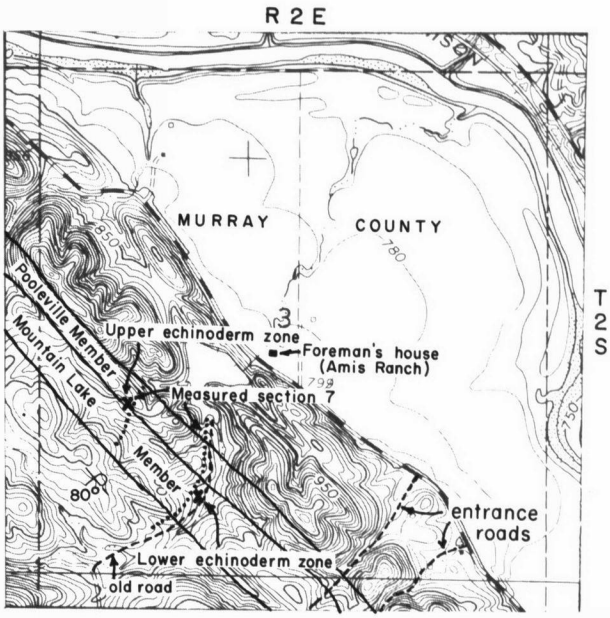


Fig. 92. Geologic map showing Bromide Formation and location of Measured Section 7 at Amis Ranch.

ed, platy, echinodermal, eroding into ledge.....0.3
40. Shale, tan to greenish-gray, weakly indurated..1.83
41. Limestone, tan, as above, alternating with greenish-gray shale, eroding into slope.....1.83
42. Shale, greenish-gray, platy, weakly indurated...3.6
43. Limestone, tan, as above, eroding into ledge...0.91
44. Shale, tan to greenish-gray, as above, with some thin-bedded echinodermal limestone.....8.2
45. Sandstone, brown, fine- to medium-grained, quartzose, moderately indurated, eroding into ledge.....1.22

Measured Section 8

NEBO, MURRAY COUNTY

Beginning at top in Viola Limestone and proceeding downsection, section measured along road 2.6 to 2.9 km west of Nebo Store, west of U.S. Highway 177, on north side of section-line road in the S½SE¼SW¼ sec. 22, T. 2 S., R. 3 E. (see Fig. 94), on property of Mrs. Corda Mann. The Lower Echinoderm Zone of the Mountain Lake Member yielded some fossils in the NW¼SE¼ sec. 27, T. 2 S., R. 3 E., on the east side of the creek about 0.8 km south of the section-line road (see Fig. 94). Strike N 20° W, dip 13° SW. Mrs. Mann lives in the first house east of the outcrop.

ORDOVICIAN SYSTEM Thickness (m)
VIOLA LIMESTONE (lower 1.22 m measured)
1. Limestone, dense, lithographic, thin-bedded, cherty, contact covered.....1.22
SIMPSON GROUP
BROMIDE FORMATION (total thickness 66.2 m)
Pooleville Member (total thickness 18.6 m)
2. Limestone, tan, fine-grained, dense, well-indurated, medium-bedded to massive, fossiliferous, with some interbedded argillaceous limestone, eroding into several ledges near top of hill, partly covered.....10.3
3. Limestone, tan, fine-grained, dense, well-indurated, thin-bedded, fossiliferous, with much interbedded weakly indurated argillaceous tan limestone and shale, eroding into slope.....3.3
4. Limestone, tan, fine-grained, dense, well-indurated, thin- to medium-bedded, fossiliferous, eroding into ledge.....2.89
5. Shale, tan, limy, thin-bedded, weakly indurated, fossiliferous, with alternating thin-bedded gray to tan limestone.....0.91
6. Limestone, gray to tan, fine-grained, dense, well-indurated, thin-bedded, fossiliferous, eroding into escarpment.....0.91
7. Shale, tan, limy, thin-bedded, weakly indurated 0.15
Mountain Lake Member (total thickness 47.5 m)
Upper Mountain Lake (total thickness 1.98 m)
8. Limestone, gray to tan, fine-grained, dense, well-indurated, massive, eroding into escarpment 0.15
9. Shale, tan, limy, thin-bedded, weakly indurated, fossiliferous, with some interbedded tan to gray dense limestone, eroding into slope.....1.83
Upper Echinoderm Zone (total thickness 1.07 m)
10. Limestone, gray to tan, medium-grained, well-indurated, thinly-laminated, fossiliferous, echinodermal, with rhombiferan cystoids, bryozoans, and brachiopods, especially *Sowerbyella*.....0.15
11. Shale, tan, limy, thin-bedded, weakly indurated, with interbedded fine-grained limestone, fossiliferous, with many brachiopods, bryozoans, echinoderms, especially *Oklahomacystis*, and some edrioasteroids and crinoids, with *Sinclairocystis* about 0.15 m above base, eroding into slope along old wagon road trending northward.....0.91
Middle Mountain Lake (total thickness 37.2 m)
12. Shale, tan to light greenish-gray, limy, weakly indurated, eroding into slope, partly covered 2.44
13. Limestone, tan, medium-grained, well-indurated, thin- to medium-bedded, echinodermal, with some interbedded limy shale, eroding into ledge 3.6
14. Shale, greenish-gray, weakly indurated, with

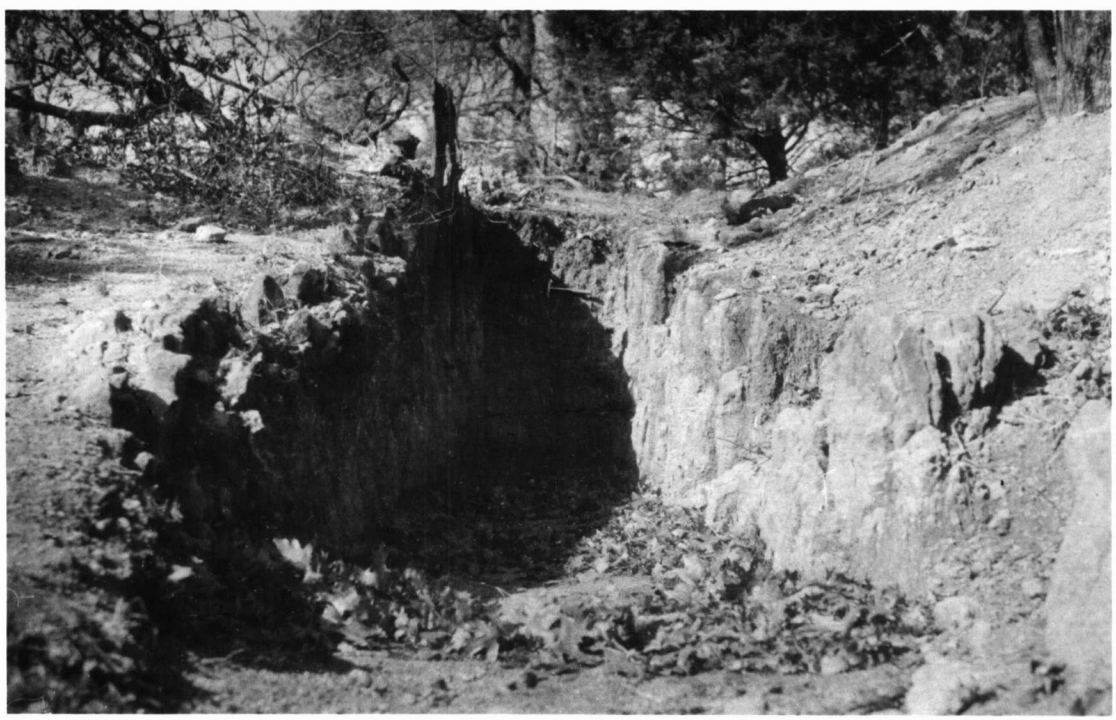


Fig. 93. Amis Ranch exposure, Murray County. View looking northwest along strike N 42° W, with dip 80° SW, of Lower Echinoderm Zone of Mountain Lake Member, 63.4 m below Viola Limestone, on northwest side of road in the SE¼NW¼SE¼SW¼ sec. 3, T. 2 S., R. 2 E., Measured Section 7. The main echinoderm zone is 0.46 m of greenish-gray shale and limestone lenses on the right side, where approximately 5 cubic m of rock was removed and almost 1,000 echinoderms were collected.

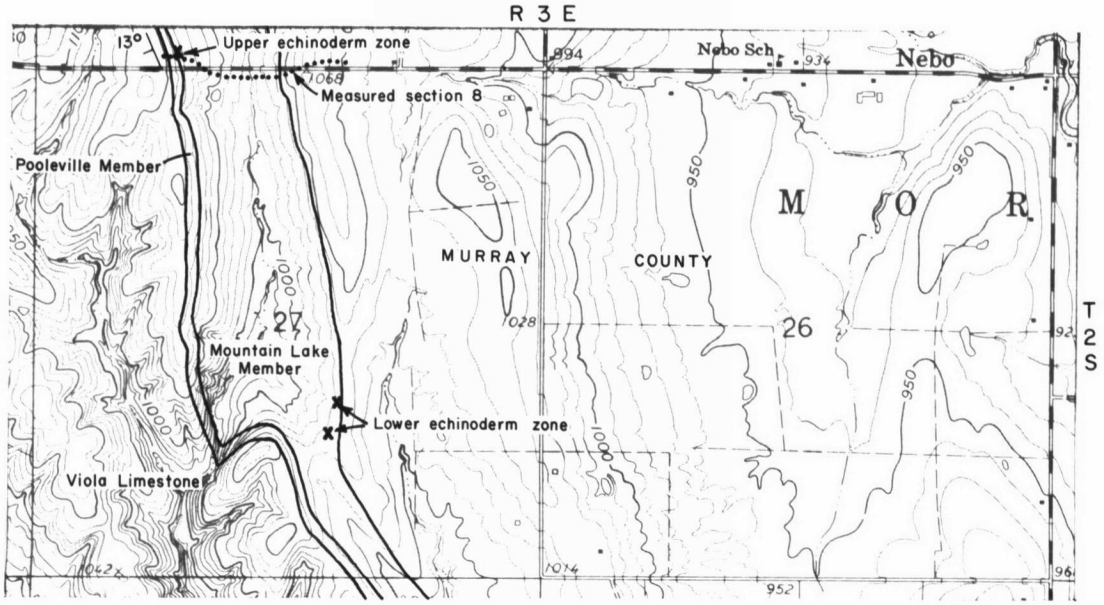


Fig. 94. Geologic map showing Bromide Formation and location of Measured Section 8 at Nebo.

some interbedded brown limestone, eroding into low slope, mostly covered.....8.5
15. Limestone, gray to tan, medium-grained, well-indurated, fossiliferous, echinodermal, eroding into ledge.....0.27
16. Shale, tan to gray, limy, weakly indurated, fossiliferous, with some interbedded fine-grained limestone, eroding into slope, mostly covered 5.2
17. Limestone, gray to tan, medium-grained, thin-bedded, platy, well-indurated, fossiliferous, echinodermal, with interbedded moderately indurated limy tan shale, eroding into series of ledges.....3.05
18. Shale, tan, limy, thin-bedded, weakly indurated, fossiliferous, eroding into slope.....1.83
19. Limestone, gray, fine-grained, massive, well-indurated, fossiliferous, eroding into ledge.....0.12
20. Shale, gray to tan, limy, thin-bedded, moderately indurated, fossiliferous, with much interbedded fine-grained limestone, eroding into slope.....1.22
21. Shale, gray, weakly indurated, eroding into slope, mostly covered.....1.52
22. Limestone, tan, medium-grained, thin-bedded, well-indurated, echinodermal, eroding into prominent ledge.....0.73
23. Shale, tan, limy, thin-bedded, moderately indurated, fossiliferous, with many bryozoans, and with many 2.5- to 5.0-cm beds of tan echinodermal limestone, eroding into slope.....2.89
24. Limestone, tan, medium-grained, argillaceous, thin-bedded, platy, fossiliferous, echinodermal, with some interbedded shale, eroding into ledge..1.07
25. Shale, tan, limy, thin-bedded, fossiliferous, with some interbedded echinodermal limestone, eroding into slope.....4.6
Lower Echinoderm Zone (total thickness 0.3 m)
26. Shale, tan, limy, fossiliferous, thin-bedded, with interbedded echinodermal limestone, with *Hybocrinus*, crinoids, and many holdfasts found about 0.8 km south of road, east of creek, in NW¼SE¼ sec. 27, T. 2 S., R. 3 E.....0.3
Lower Mountain Lake (total thickness 6.2 m)
27. Limestone, tan, medium-grained, thin-bedded, well-indurated, fossiliferous, echinodermal, eroding into prominent ledge a few feet west of creek; section extrapolated south of section line road along creek and east of creek.....1.07
28. Shale, tan, limy, weakly indurated, fossiliferous, eroding into slope, mostly covered.....3.3
29. Limestone, tan, medium-grained, thin-bedded, well-indurated, fossiliferous, echinodermal, occurring in bed of creek.....0.3
30. Shale, tan to gray, weakly indurated, eroding into slope, mostly covered.....1.52
Basal sandstone sequence (total thickness 0.91 m)
31. Sandstone, brown, fine- to medium-grained, quartzose, well-indurated, eroding into ledge....0.61
32. Shale, gray, weakly indurated, with some interbedded brown fine- to medium-grained sandstone, eroding into slope, mostly covered.....0.3
TULIP CREEK FORMATION (upper 15.8 m measured)
33. Shale, gray, weakly indurated, eroding into slope, mostly covered.....2.44
34. Limestone, tan, medium-grained, argillaceous, thin-bedded, well-indurated, fossiliferous, echinodermal, with some interbedded brown shale, eroding into escarpment.....1.83
35. Shale, brown, weakly indurated, eroding into slope, mostly covered.....2.44
36. Sandstone, brown, fine-grained, quartzose, silty, well-indurated, gradational into a fine-grained limestone, eroding into ledge.....0.76
37. Shale, tan, weakly indurated, fossiliferous, with prominent brachiopod *(Valcourea)* zone at base on north side of road, eroding into slope, mostly covered.....0.91
38. Limestone, gray to tan, medium-grained, thin-bedded, well-indurated, fossiliferous, echinodermal, eroding into ledge.....4.6
39. Shale, greenish-gray, weakly indurated, mostly covered at top of hill.....3.05

Measured Section 9

BUCKHORN RANCH, MURRAY COUNTY

Beginning at top in Viola Limestone on east-facing escarpment and proceeding downsection, section measured in the NE¼SW¼SW¼ sec. 3, T. 2 S., R. 3 E., on the Buckhorn (Tom Jack) Ranch, about 0.8 km east of the ranch house (see Fig. 95). Strike N 40° W, dip 20° SW. The Upper Echinoderm Zone of the Mountain Lake Member is about 23 m west of the road to the ranch house, where the road turns northward for a short distance.

ORDOVICIAN SYSTEM	Thickness (m)
VIOLA LIMESTONE (lower 0.3 m measured)	
1. Limestone, light-gray, fine-grained, lithographic, very dense, thin-bedded, well-indurated, rubbly, contact partly covered	0.3
SIMPSON GROUP	
BROMIDE FORMATION (upper 25.9 m measured, basal part	

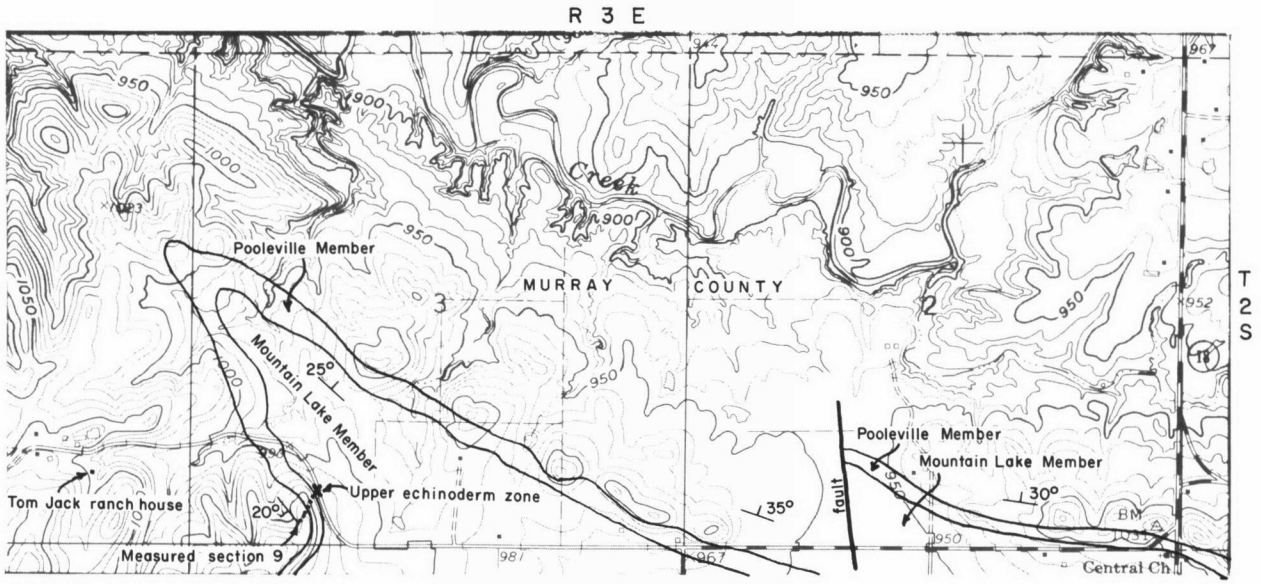


Fig. 95. Geologic map showing Bromide Formation and location of Measured Section 9 at Buckhorn Ranch.

Fig. 96. Buckhorn Ranch exposure, Murray County. View looking northwest along strike N 40° W, with dip 20° SW, of Upper Echinoderm Zone of Mountain Lake Member, 21.3 m below Viola Limestone, about 30.5 m west of road, in the NE¼SW¼SW¼ sec. 3, T. 2 S., R. 3 E., Measured Section 9. Several thousand echinoderms were collected from a 0.3-m layer of gray shale and limestone at the bottom of the pit, where approximately 4.7 cubic m of rock was removed. The Pooleville contact is at top of limestone on rim of pit.

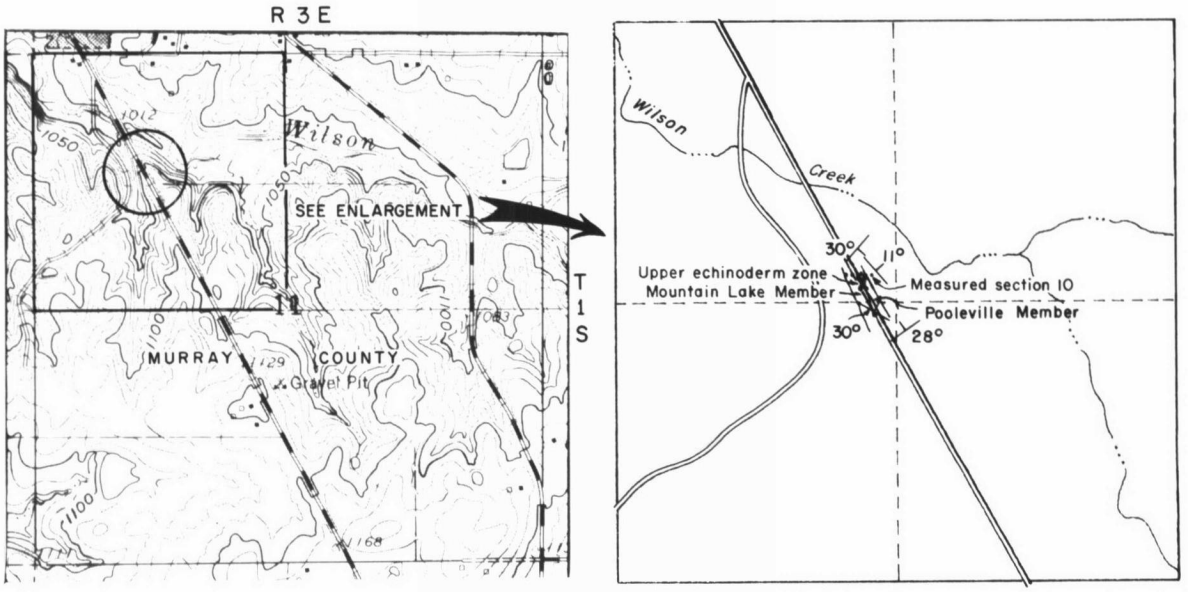


Fig. 97. Geologic map showing Bromide Formation and location of Measured Section 10 at Sulphur.

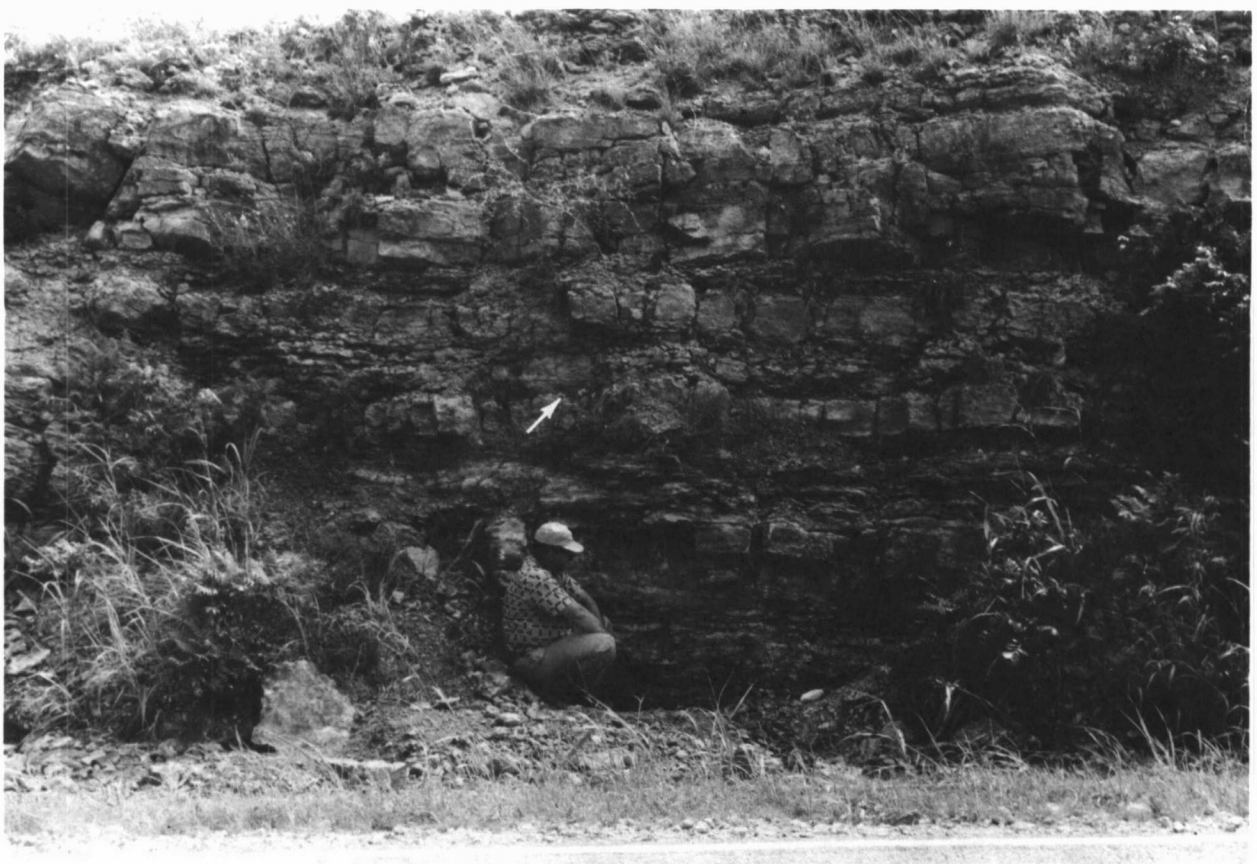


Fig. 98. Sulphur exposure, Murray County. View looking east where strike is N 22° W and dip 11° NE, of Upper Echinoderm Zone of Mountain Lake Member (at hammer), 23.7 to 24.4 m below Viola Limestone, on east side of U.S. Highway 177, about 1.4 miles southeast of Sulphur, near the center NW¼ sec. 11, T. 1 S., R. 3 E., Measured Section 10. About 150 echinoderms were collected from this reddish-brown limestone and shale, where about 1.1 cubic m of rock was removed. The Pooleville contact (arrow) is about 0.76 m above the head of Allen Graffham.

covered)
Pooleville Member (total thickness 19.8 m)
2. Limestone and shale, light-gray, fine-grained, dense, eroding into slope, mostly covered.....3.9
3. Limestone, light-gray, fine-grained, dense, well-indurated, eroding into ledge.....0.06
4. Shale, gray, and interbedded blocky weakly indurated very fossiliferous limestone, eroding into glade with many brachiopods and bryozoans...3.05
5. Limestone, light-gray, fine-grained, dense, medium-bedded, well-indurated, eroding into ledge..0.46
6. Shale, light-gray, weakly indurated, with interbedded dense limestone, eroding into slope, partly covered.....1.22
7. Limestone, light-gray, fine-grained, dense, medium-bedded, well-indurated, eroding into ledge..2.13
8. Shale, light-gray, weakly indurated, with interbedded light-gray limestone, eroding into slope, partly covered.....4.6
9. Limestone, light-gray to tan, fine-grained, dense, well-indurated, medium-bedded, fossiliferous, eroding into prominent ledge.....0.67
10. Shale, gray, calcitic, weakly indurated, with some interbedded gray limestone, eroding into slope, partly covered.....3.6
Mountain Lake Member (upper 6.1 m measured, lower part covered)
Upper Mountain Lake (total thickness 1.31 m)
11. Limestone, gray, medium-grained, well-indurated, echinodermal, eroding into ledge.....0.09
12. Shale, light greenish-gray, calcitic, platy to blocky, thin-bedded, fossiliferous, eroding into slope.....1.22
Upper Echinoderm Zone (total thickness 3.39 m)
13. Shale and limestone, gray, calcitic, platy, moderately indurated, with many cephalopods near base, *Sinclairocystis* just above base, *Oklahomacystis* mainly in upper 15 cm. (About 5 cubic m of rock was removed; see Fig. 96. It yielded 2,850 or more *Oklahomacystis*, 40 *Sinclairocystis*, 25 or more crinoids, 2 edrioasteroids, 1 *Platycystites*, plates of *Astrocystites* and many other echinoderm plates, along with many bryozoans and brachiopods.).....0.3
14. Limestone, gray, fine-grained, argillaceous, blocky to platy, moderately to well-indurated, fossiliferous, eroding into ledge (see Fig. 96)..0.12
15. Shale, tan to light greenish-gray, calcitic, blocky, weakly indurated, fossiliferous.....1.52
16. Limestone, tan, medium-grained, well-indurated, medium-bedded, echinodermal, eroding into ledge.....0.36
17. Shale, greenish-gray, blocky, weakly indurated, partly covered.....0.91
18. Limestone, tan, medium-grained, well-indurated, echinodermal, with 6 rhombiferan cystoids, a few *Oklahomacystis*, and a crinoid, eroding into ledge.....0.18
Middle Mountain Lake (upper 1.37 m exposed)
19. Shale, greenish-gray, blocky, weakly indurated, covered below in road and field except for few isolated limestone ledges.....1.37

Measured Section 10

SULPHUR, MURRAY COUNTY

Beginning at top in Viola Limestone and proceeding

Fig. 99. Sulphur exposure, Murray County. Close-up view of Figure 98, showing interbedded lenticular limestone on the right, with reddish-brown shale on the left. Most of the echinoderms came from the interfingered zone, or from the bryozoan-rich biostromal limestone, but a few came from the shale farther away. Almost all *Sinclairocystis* specimens came from the basal 7.6 cm.

downsection, section measured about 2.2 km southeast of Sulphur on U.S. Highway 177, on east side of highway, near center NW¼ sec. 11, T. 1 S., R. 3 E., ending in the Tulip Creek Formation on the west side of the highway (see Fig. 97). The area is faulted, and the Upper Echinoderm Zone of the Mountain Lake Member occurs in a down-dropped fault block on the east side of the road in the ditch (see Fig. 98, 99), with strike N 22° W, and dip 11° NE.

ORDOVICIAN SYSTEM — Thickness (m)
VIOLA LIMESTONE (not measured)
Occurs in quarry to east.
SIMPSON GROUP
BROMIDE FORMATION (total thickness 51.2 m)
Pooleville Member (total thickness 22.2 m)
1. Upper 18.6 m mostly covered (The section begins at the top of the cliff face along the east side of the highway.).....18.6
2. Limestone, tan to greenish-gray, medium-grained, well-indurated, medium-bedded, platy, fossiliferous, echinodermal, with some interbedded tan to greenish-gray shale.....0.91
3. Shale, tan to reddish-brown, limy, thin-bedded, weakly indurated, fossiliferous, with many bryozoans.....0.27
4. Shale, tan to reddish-brown, as above, moderately indurated, with interbedded tan to greenish-gray fossiliferous limestone.....0.21
5. Limestone, tan to greenish-gray, medium-grained, medium-bedded, well-indurated, fossiliferous, echinodermal, eroding into ledge.....0.18
6. Shale, tan to red-brown, thin-bedded, weakly indurated, echinodermal.....0.15
7. Limestone, gray to tan, medium-grained, well-indurated, medium-bedded, echinodermal, eroding into massive ledge.....0.97
8. Shale, tan, mottled greenish-gray to red-brown, weakly indurated, fossiliferous, with many bryozoans.....0.15
9. Limestone, tan, fine-grained, well-indurated, medium-bedded, echinodermal, eroding into massive ledge.....0.27
10. Limestone, gray to tan, mottled greenish-gray to red-brown, medium-grained, moderately indurated, echinodermal, with some interbedded tan to red-brown shale, eroding into recess at base..0.39
Mountain Lake Member (total thickness 28.9 m)
Upper Mountain Lake (total thickness 1.52 m)
11. Limestone, gray to tan, fine-grained, well-indurated, massive, echinodermal, eroding into ledge.....0.24
12. Shale, red-brown, thin-bedded, weakly indurated, fossiliferous, eroding into recess.....0.21
13. Limestone, tan, medium-grained, thin-bedded, wavy-bedded, well-indurated, with interbedded tan shale, fossiliferous, echinodermal, with many bryozoans.....0.39
14. Limestone, tan to greenish-gray, medium-grained, well-indurated, medium-bedded to massive, echinodermal, with many bryozoans, eroding into prominent ledge.....0.67
Upper Echinoderm Zone (total thickness 0.7 m)
15. Shale, maroon to red-brown, mottled greenish-gray at base, moderately to weakly indurated, with many 5- to 7-cm tan limestone layers (see Fig. 98, 99), fossiliferous, with many bryozoans, brachiopods, and echinoderms. (About 90 *Oklahomacystis* were found in the upper 30 cm and about 40 *Sinclairocystis* in the basal 7 cm. About 1 cubic m of rock was removed, and about 9 crinoids, several rhombiferan cystoids, and 40 holdfasts were collected in addition to the listed paracrinoids.).....0.7
Middle Mountain Lake (total thickness 23.4 m, including lower Mountain Lake to top of basal sandstone sequence)
16. Shale, red-brown, mottled greenish-gray, platy, weakly indurated, fossiliferous, with many bryozoans, in ditch at bottom of dig. (Section extrapolated to next fault block to north, where this zone is at the top of the exposure; strike N 25° E, dip 22° SE.).....1.46
17. Limestone, tan, fine-grained, well-indurated, medium-bedded to massive, echinodermal, with many bryozoans, and such brachiopods as *Oepikina* and *Sowerbyella* on upper surface, eroding into prominent ledge.....0.36
18. Shale, tan to greenish-gray, platy, weakly indurated, fossiliferous.....0.27
19. Limestone, tan, fine-grained, as above, medium-bedded, eroding into ledge.....0.12
20. Shale, tan, as above, fossiliferous.....0.24
21. Limestone, tan, as above, eroding into ledge...0.09
22. Shale, tan, as above, fossiliferous, with many bryozoans.....0.09
23. Limestone, tan to light greenish-gray, fine- to medium-grained, medium-bedded, well-indurated, echinodermal, eroding into ledge, base covered by talus slope. (Section extrapolated to next fault block to north; strike N 25° W, dip 17° NE.).....1.64
24. Limestone, gray, fine-grained, thin-bedded, well-indurated, fossiliferous, echinodermal, eroding into ledge.....1.37
25. Limestone, gray to tan, fine- to medium-grained, medium-bedded to massive, wavy-bedded, with some red-brown shale at top, eroding into massive ledge.....0.91
26. Shale, red-brown to tan, thin-bedded, with some interbedded thin-bedded tan to gray fine-grained fossiliferous limestone, eroding into recess.....0.15
27. Limestone, gray to greenish-gray, fine-grained, well-indurated, massive, eroding into ledge 0.49
28. Limestone, tan, fine-grained, argillaceous, silty, medium-bedded, moderately indurated, eroding into ledge.....0.3
29. Siltstone, red-brown to tan, calcitic, thin-bedded, weakly indurated, with interbedded tan limestone, mottled greenish-gray to north, eroding into recess.....0.52
30. Limestone, greenish-gray, fine-grained, well-indurated, medium-bedded, fossiliferous, with some echinoderms, eroding into ledge to base of fault block.....0.91
31. Limestone, as above, mostly covered by Highway 177; strike N 20° W, dip 24° NE, on west side of highway.....3.6
32. Limestone, gray, medium-grained, well-indurated, massive, fossiliferous, echinodermal, with many bryozoans, eroding into ledge.....0.61
33. Limestone, tan to light-gray, fine-grained, thin- to medium-bedded, well-indurated, fossiliferous, eroding into ledge.....0.61
34. Limestone, gray, coarse-grained, echinodermal, mostly covered, probably with some interbedded shale.....7.9
35. Shale, tan, limy, thin-bedded, covered at top, greenish-gray at base, with echinoderm plates and bryozoans.....1.22
Basal sandstone sequence (total thickness 3.3 m)
36. Sandstone, brown, fine- to coarse-grained, quartzose, medium-bedded to massive, well-indurated, eroding into ledge.....3.3
TULIP CREEK FORMATION (upper 2.13 m exposed)
37. Limestone, tan, medium-grained, well-indurated, medium-bedded, fossiliferous.....0.61
38. Shale and limestone, interbedded, in several ledges, with limestone, as above, partly covered 1.52

Measured Section 11A

FITTSTOWN ROADCUT, PONTOTOC COUNTY

Beginning at top in Viola Limestone and proceeding downsection, section measured on west side of U.S. Highway 99, in the NW¼SW¼ sec. 12, T. 1 N., R. 6 E., about 4.8 km south of Fittstown, and 1.9 to 2.4 km north of Oklahoma Highway 31 junction, Pontotoc County, Oklahoma (see Fig. 100). The upper 5.8 m of the Pooleville is the type section for the Corbin Ranch Formation of Harris (1957), here recognized as part of the Pooleville Member. Strike N 35° W, dip 18° NE. A new quarry (C & L Wigley Quarry of Fittstown) was opened about 1972 near the NW¼NW¼ sec. 13, about 0.8 km to the southeast, where the Lower Echinoderm Zone is well exposed and where Sprinkle and others have recently collected echinoderms (see Measured Section 11B).

ORDOVICIAN SYSTEM — Thickness (m)
VIOLA LIMESTONE (lower 9.1 m measured)
1. Limestone, light-gray to buff, very fine-grained, medium-bedded, cherty, well-indurated, with calcite veins, eroding into bluff.....7.6
2. Limestone, light-gray, very fine-grained, ar-

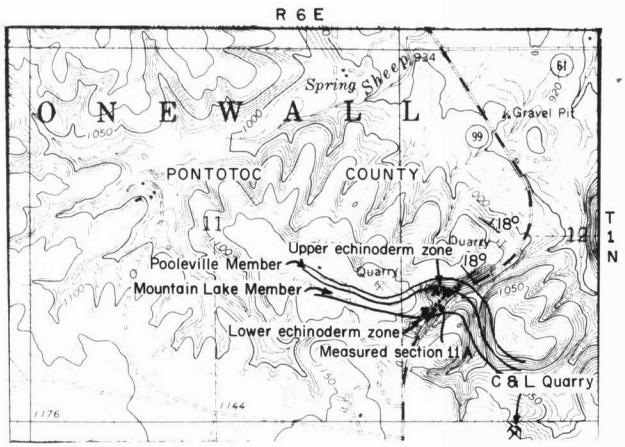


Fig. 100. Geologic map showing Bromide Formation and location of Measured Section 11A at Fittstown Roadcut.

gillaceous, cherty, thinly laminated, well-indurated, with light-tan chert, eroding into bluff..1.22
3. Limestone, gray, mottled greenish-gray, fine-grained, argillaceous, cherty, weakly to well-indurated, with some interbedded greenish-gray limy shale.....0.12

SIMPSON GROUP

BROMIDE FORMATION (total thickness 51.8 m)

Pooleville Member (total thickness 17.6 m)

4. Limestone, gray, fine-grained, well-indurated, fossiliferous, eroding into ledge.....0.06
5. Limestone, white to light-gray, very fine-grained, lithographic, well-indurated, medium-bedded, fossiliferous, eroding into ledge.....0.43
6. Shale, tan, limy, weakly indurated, thinly laminated to thin-bedded, with some rubbly white limestone.....0.21
7. Limestone, white, very fine-grained, well-indurated, fossiliferous, with many calcite specks, eroding into ledge.....0.09
8. Shale, gray, thinly-laminated, weakly indurated 0.03
9. Limestone, light-gray, very fine-grained, as above, moderately indurated, thin-bedded, with interbedded gray shale.....0.3
10. Limestone, light-gray, as above.....0.15
11. Limestone, light-gray, mottled pink and tan, very fine-grained, thin-bedded, moderately to weakly indurated, fossiliferous, with some thin shale seams.....0.21
12. Limestone, light-gray, very fine-grained, massive, well-indurated, fossiliferous, eroding into ledge.....0.39
13. Shale, gray, thinly-laminated, weakly indurated.....0.03
14. Limestone, light-gray, as above, eroding into ledge.....0.12
15. Shale, light-gray, thinly laminated, weakly indurated.....0.27
16. Limestone, light-gray, mottled tan, very fine-grained, well-indurated, massive, fossiliferous, eroding into ledge.....0.18
17. Shale, gray, limy, platy, weakly indurated.....0.06
18. Limestone, light-gray to white, mottled pink, very fine-grained, medium-bedded, fossiliferous, with calcite veins, eroding into ledge.....0.46
19. Limestone, light-gray to pink, very fine-grained, thin-bedded, moderately to well-indurated, fossiliferous, with many light-gray shale seams, eroding into ledge.....1.28
20. Limestone, gray to tan, very fine-grained, dense, massive, well-indurated, fossiliferous, eroding into ledge.....0.33
21. Limestone, light-gray to tan, mottled pink, very fine-grained, thin-bedded, fossiliferous, with some thin shale seams.....0.46
22. Shale, light greenish-gray to tan, platy, weakly indurated.....0.03
23. Limestone, tan, very fine-grained, massive, well-indurated, fossiliferous, with calcite veins, eroding into ledge.....0.21
24. Shale, light-gray, mottled pink, thinly laminated, weakly indurated.....0.03
25. Limestone, gray, mottled tan, very fine-grained, massive, fossiliferous, with calcite veins, eroding into ledge.....0.36
26. Shale, greenish-gray, limy, platy, weakly indurated (base of the type Corbin Ranch of Harris, 1957).....0.06
27. Limestone, light-tan, fine-grained, well-indurated, medium-bedded to massive, fossiliferous, with some calcite veins, eroding into ledge.....2.44
28. Limestone, light-tan, fine-grained, thin- to medium-bedded, vuggy, well-indurated, cross-bedded, very fossiliferous, eroding into ledge.....2.89
29. Limestone, light-tan, fine-grained, vuggy, thinly laminated, well-indurated, even-bedded, fossiliferous, eroding into ledge.....0.49
30. Limestone, light-gray, fine-grained, silty, thin-bedded, well-indurated, extremely fossiliferous, eroding into ledge.....0.49
31. Limestone, light-gray, fine-grained, silty, medium-bedded to massive, well-indurated, fossiliferous, eroding into ledge.....0.94
32. Limestone, light-tan to light-gray, very fine-grained, well-indurated, massive, fossiliferous, with calcite specks, eroding into ledge.....0.64
33. Limestone, tan, mottled light-gray, very fine-grained, argillaceous, moderately to weakly indurated, thin-bedded, fossiliferous, with some tan shale seams, eroding into recess.....0.39
34. Limestone, light-gray to light-tan, fine- to medium-grained, medium-bedded to massive, fossiliferous, echinodermal, eroding into ledge.....1.07
35. Limestone, light-gray to tan, fine-grained, thin-bedded, moderately indurated, extremely fossiliferous, with many 2.5- to 5.0-cm gray to tan shale seams, eroding into recess.....1.52
36. Limestone, light-tan, fine-grained, medium-bedded, fossiliferous, with some 5- to 7-cm shale seams, eroding into 4 ledges.....1.13

Mountain Lake Member (total thickness 34.1 m)

Upper Mountain Lake (total thickness 1.15 m)

37. Shale, greenish-gray, argillaceous, limy, platy, weakly indurated, fossiliferous, with some interbedded greenish-gray limestone.....0.52
38. Limestone, light-tan to gray, medium-grained, massive, well-indurated, echinodermal, eroding into ledge.....0.64

Upper Echinoderm Zone (total thickness 0.3 m)

39. Shale, tan to greenish-gray, platy, fossiliferous, echinodermal, with many 2.5- to 5.0-cm tan to greenish-gray medium-grained limestone beds. (Many holdfasts and stems, 3 *Oklahomacystis*, and 1 *Cleiocrinus* were collected about 137.2 m northwest of State Highway 99 in a glade, and along the old quarry road entrance about 6.1 m west of the highway, 1.52 m above road level.).....0.3

Middle Mountain Lake (total thickness 21.7 m)

40. Limestone, gray, mottled tan, fine-grained, well-indurated, thin- to medium-bedded, fossiliferous, eroding into ledge.....0.46
41. Shale, greenish-gray, mostly covered, eroding into slope.....0.91
42. Limestone, light-gray, very fine-grained, massive, well-indurated, fossiliferous, eroding into ledge at road level. (The section was measured west along the old road.).....0.46
43. Shale, greenish-gray, mostly covered.....0.61
44. Limestone, gray, very fine-grained, thin- to medium-bedded, well-indurated, fossiliferous, eroding into ledge.....0.55
45. Shale, greenish-gray, alternating with fine-grained limestone beds, mostly covered across ravine.....6.4
46. Sandstone, gray to tan, coarse-grained, calcitic, well-indurated, cross-bedded, thin- to medium-bedded, fossiliferous, gradational into a limestone, eroding into ledge.....3.05
47. Limestone, tan, coarse-grained, quartzose, well-indurated, even-bedded, medium-bedded, fossiliferous, gradational into a coarse-grained sandstone, eroding into ledge.....0.46
48. Limestone, gray, mottled tan, coarse-grained, quartzose, even-bedded, moderately indurated, fossiliferous, gradational into shale, eroding into recess.....0.3
49. Limestone, tan, coarse-grained, arenaceous, thin-bedded, wavy-bedded, cross-bedded, fossiliferous, eroding into ledge.....1.22
50. Limestone, tan, fine-grained, silty, massive, fossiliferous, gradational into a siltstone,

eroding into ledge.....0.91
51. Limestone, gray to tan, fine- to medium-grained, thin- to medium-bedded, wavy-bedded, well-indurated, fossiliferous, echinodermal, eroding into ledge.....1.52
52. Siltstone, tan, argillaceous, limy, thin-bedded to medium-bedded, weakly indurated.....1.52
53. Shale, tan, silty, thin-bedded, weakly indurated, with some interbedded 2.5- to 5.0-cm siltstone beds.....1.22
54. Siltstone, tan, thin-bedded, limonitic, moderately indurated, gradational into fine-grained limestone, eroding into ledge.....0.3
55. Shale, greenish-gray, thin-bedded, weakly indurated, fossiliferous, with light-gray limestone nodules and beds 2.5 to 5.0 cm thick.....1.83

Lower Echinoderm Zone (total thickness 1.07 m)

56. Shale, greenish-gray, calcitic, thin-bedded, weakly indurated, with some 2.5- to 5.0-cm limestone beds, eroding into recess in cliff face, with many bryozoans, brachiopods, and some echinoderms (Most echinoderms were collected in the basal 0.15 m, where 0.8 cubic m of rock was removed; see Fig. 101. Many plates and stems, 3 *Platycystites*, 2 *Cyathocystis*, 2 crinoids, 2 rhombiferan cystoids, many holdfasts, and the holotype of *Eumorphocystis* were collected here.) 1.07

Lower Mountain Lake (total thickness 0.58 m)

57. Limestone, gray to tan, fine- to medium-grained, thin-bedded, wavy-bedded, well-indurated, eroding into ledge.....0.28
58. Shale, greenish-gray, blocky, weakly indurated 0.3

Basal sandstone sequence (total thickness 9.2 m)

59. Limestone, brown, coarse-grained, arenaceous, well-indurated, massive, fossiliferous, gradational into coarse-grained sandstone, eroding into ledge.....0.15
60. Shale, greenish-gray, blocky, weakly indurated 0.15
61. Limestone, gray, mottled tan, fine-grained, medium-bedded, well-indurated, eroding into ledge.....0.46
62. Limestone, tan, fine- to medium-grained, arenaceous, thin-bedded, well-indurated, gradational into sandstone and quartzite, eroding into ledge.....0.61
63. Shale, greenish-gray, blocky, weakly indurated 0.3
64. Limestone, tan, fine-grained, silty, thin-bedded, well-indurated, eroding into ledge.....0.91
65. Limestone, gray, mottled tan, arenaceous, well-indurated, medium-bedded, gradational into fine- to medium-grained quartzose sandstone and siltstone, eroding into ledge.....1.64
66. Siltstone, tan, argillaceous, massive, weakly indurated.....0.15
67. Siltstone, tan, argillaceous, calcitic, thin- to medium-bedded, cross-bedded, well-indurated, gradational into limestone, eroding into ledge...2.44
68. Shale, greenish-gray, blocky, weakly indurated, with some 2.5- to 5.0-cm tan siltstone beds...0.3
69. Sandstone, tan, very fine-grained, quartzose, thin-bedded, cross-bedded, well-indurated, gradational into siltstone, eroding into ledge at

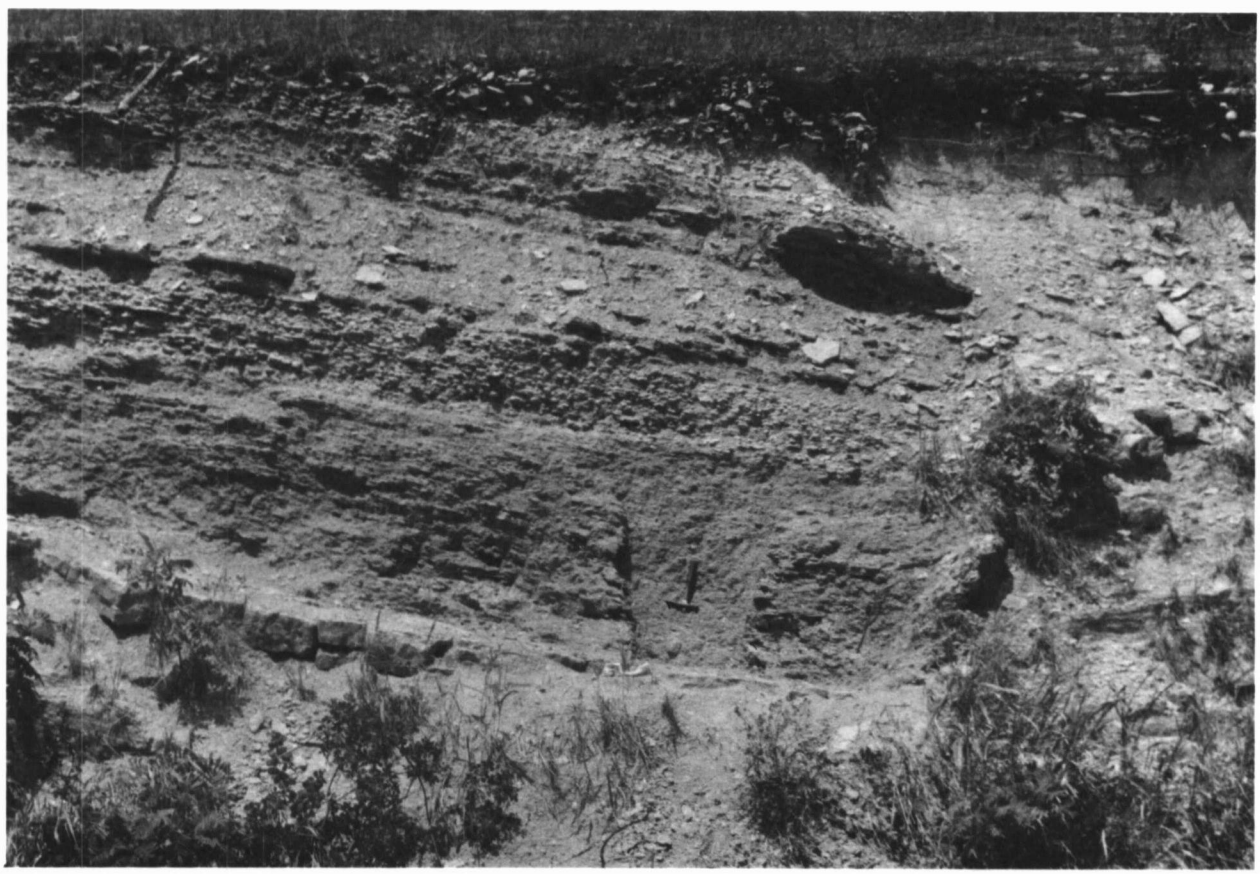


Fig. 101. Fittstown Roadcut exposure, Pontotoc County. View looking northwest along strike N 35° W, with dip 18° NE, of Lower Echinoderm Zone of Mountain Lake Member, 41.4 m below Viola Limestone, on northwest side of Oklahoma Highway 99, in the NW¼SW¼ sec. 12, T. 1 N., R. 6 E., Measured Section 11. The main zone is 0.15 m of greenish-gray shale and siltstone, about 0.3 m below hammer, where a few echinoderms were collected from 0.8 cubic m of rock. The overlying 0.9 m of greenish-gray shale contains many loose plates of *Bromidocystis* and other echinoderms and is probably the bed from which the type specimen of *Eumorphocystis* was collected.

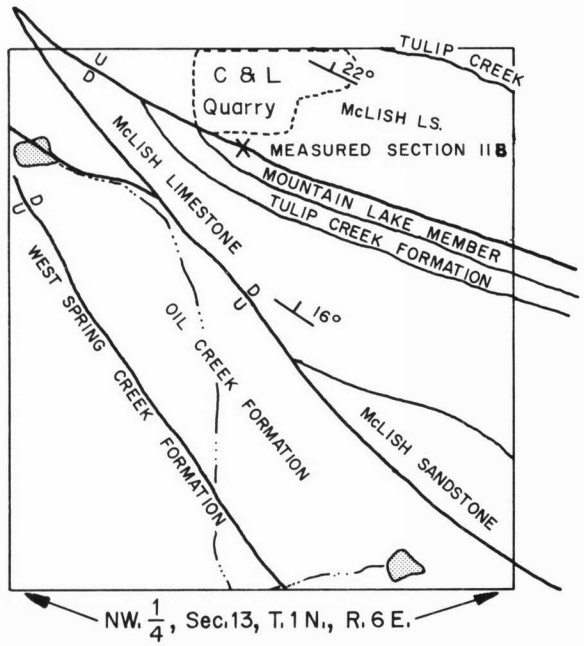


Fig. 102. Geologic map showing Bromide Formation and location of Measured Section 11B at Fittstown Quarry.

second ravine south of old quarry road.....2.13
TULIP CREEK FORMATION (not measured)
70. Probably shale but mostly covered.....9.1

Measured Section 11B

FITTSTOWN QUARRY, PONTOTOC COUNTY

Beginning at top in down-dropped block of lower Mountain Lake Member of Bromide Formation, on south side of C & L Wigley Quarry, section meaured at collecting locality of Lower Echinoderm Zone in SE¼NE¼NW¼NW¼ sec. 13, T. 1 N., R. 6 E., about 0.8 km southeast of Measured Section 11A (see Fig. 102). Section measured by Roger Burkhalter, October, 1978; revised by James Sprinkle, November, 1978. Strike N 62° W, dip 22° NE.

ORDOVICIAN SYSTEM	Thickness (m)
SIMPSON GROUP	
McLISH FORMATION (to north of Measured Section)	
Fault (south side downthrown)	
BROMIDE FORMATION	
Mountain Lake Member (only lower 7.15 m measured)	
1. Limestone, tan to buff, arenaceous, cross-bedded, thin-bedded, fossiliferous, burrowed	0.97
2. Limestone, tan to buff, arenaceous, thin-bedded, fossiliferous, interbedded with irregular masses and vertical interfingerings of gray arenaceous limestone	2.13
Lower Echinoderm Zone (total thickness 1.3 m)	
3. Shale, greenish-gray, slightly arenaceous, with some thin-bedded limestones, fossiliferous, mostly bryozoans but also *Cyathocystis*, *Bromidocystis*, *Hybocrinus*, rhombiferan cystoids, and other complete echinoderms, stems and plates	0.97
4. Limestone and shale, gray to green arenaceous, biosparrudite, echinodermal, a few complete specimens, many plates and stems	0.3
Lower Mountain Lake (upper 2.74 m measured)	
5. Limestone, gray, arenaceous, medium-bedded, fossiliferous	1.07
6. Shale, gray, weakly indurated	0.15
7. Limestone, gray, arenaceous, medium-bedded	0.46
8. Shale, gray, weakly indurated	0.15
9. Limestone, gray, arenaceous, medium-bedded	0.91

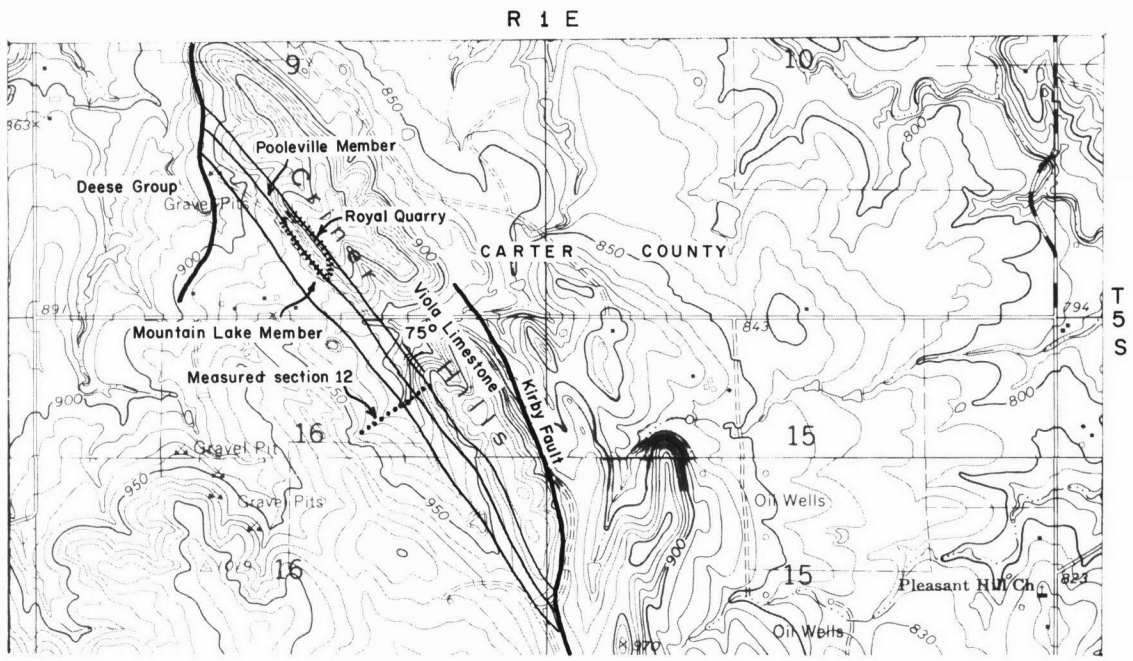


Fig. 103. Geologic map showing Bromide Formation and location of Measured Section 12 at North Criner Hills.

Measured Section 12

NORTH CRINER HILLS, CARTER COUNTY

Beginning at top in Viola Limestone and proceeding downsection, section measured in the NE¼ sec. 16, T. 5 S., R. 1 E. (see Fig. 103). Strike N 30° W, dip 75° E. It is about 253 m between the base of the Viola Limestone and the top of the McLish massive limestone.

ORDOVICIAN SYSTEM	Thickness (m)
VIOLA LIMESTONE (basal 3.05 m measured)	
1. Limestone, gray, very fine-grained, dense, well-indurated, thinly-laminated, with much light-tan chert	3.05
SIMPSON GROUP	
BROMIDE FORMATION (total thickness 96.4 m)	
Pooleville Member (total thickness 39.6 m)	
2. Limestone, gray, fine- to medium-grained, well-indurated, medium-bedded to massive, echinodermal, eroding into ledge	2.74
3. Limestone, gray, fine-grained, argillaceous, thin-bedded, well-indurated, fossiliferous, with some shale partings, eroding into slope, mostly covered	28.3
4. Limestone, gray, fine- to medium-grained, well-indurated, thin- to medium-bedded, fossiliferous, with some shale partings, eroding into ledge	9.1
Mountain Lake Member (total thickness 56.8 m)	
5. Shale, greenish-gray, blocky, weakly indurated, with some coarse-grained thin-bedded moderately indurated echinodermal limestone beds, mostly covered	16.7
6. Shale, greenish-gray, as above, with some coarse-grained limestone beds, and with some tan sandstone beds near base, mostly covered	37.8
7. Sandstone, tan, fine-grained, quartzose, thinly-laminated, well-indurated, eroding into low ridge	1.52
TULIP CREEK FORMATION (upper 15.2 m measured)	
8. Shale, greenish-gray, as above, mostly covered	13.7
9. Limestone, gray, coarse-grained, medium-bedded, well-indurated, echinodermal, eroding into ledge	1.52

Measured Section 13A

RUDD QUARRY, CARTER COUNTY

Beginning at top in Viola Limestone near north end of quarry, and proceeding downsection, section measured in the NW¼SE¼SE¼ sec. 22, T. 5 S., R. 1 E., in quarry owned by Mr. Harold Rudd, about 183 m north of the road (see Fig. 104). This is also termed the lower quarry or south quarry, because it is lower than another (Dunn) quarry directly to the north. At the Viola-Bromide contact, strike N, dip 60° W. At the east end of quarry, strike N 5° W, dip 34° W. The lower part of the section is faulted.

ORDOVICIAN SYSTEM	Thickness (m)
VIOLA LIMESTONE (lower 8.2 m measured)	
1. Limestone, light-gray, very fine-grained, medium-bedded to massive, well-indurated, with light-brown chert	7.6
2. Limestone, light-tan, fine-grained, cherty, thinly laminated, moderately indurated, brecciated	0.61
SIMPSON GROUP	
BROMIDE FORMATION (upper 23.4 m measured)	
Pooleville Member (upper 23.4 m measured)	
3. Limestone, gray, medium-grained, massive, well-indurated, cherty, eroding into ledge	0.61
4. Limestone, light-gray, very fine-grained, argillaceous, dense, thin-bedded, wavy-bedded, moderately indurated, with many 5- to 7-cm greenish-gray to tan shale partings, with many brachiopods, bryozoans, and echinoderms, especially a crinoid colony about 1.83 m below top (see Fig. 105), with 34 crinoids, 26 *Kirkocystis*, some rhombiferan cystoids, 4 edrioasteroids, and many stems, with 2 starfish 2.44 m below top, and a *Diabolocrinus* zone at base	3.9
5. Limestone, tan to light-gray, fine-grained, argillaceous, medium-bedded, well-indurated, with some shale partings, fossiliferous, with many brachiopods, some *Kirkocystis*	3.6
6. Limestone, tan to light-gray, fine-grained, argillaceous, thin- to medium-bedded, with some shale partings, fossiliferous, with many brachiopods and *Oxoplecia* in upper 1.52 m	3.05
7. Limestone, light-gray, mottled tan, very fine-grained, argillaceous, medium-bedded, sparingly fossiliferous, with some shale partings, with *Archaeocrinus* near base	4.6
8. Limestone, light-gray to tan, fine-grained, argillaceous, thin-bedded, moderately to weakly indurated, fossiliferous, with several trilobites such as *Lonchodomus* near base, deeply eroded, mostly covered	7.6

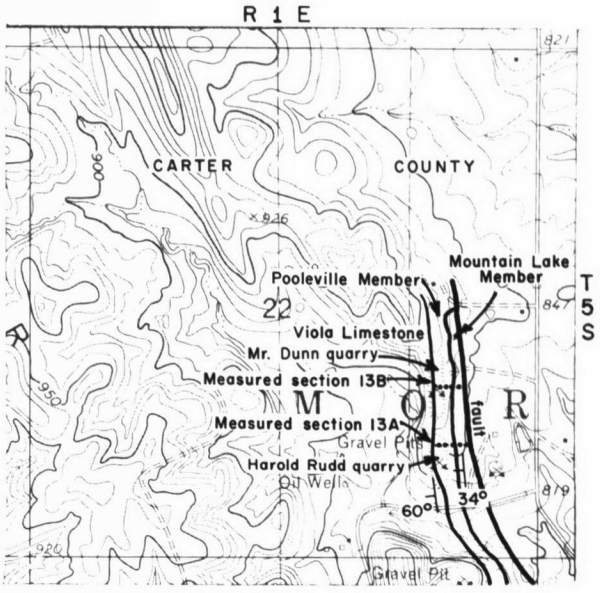


Fig. 104. Geologic map showing Bromide Formation and location of Measured Section 13A and 13B at Rudd (south) and Dunn (north) Quarries.

Measured Section 13B

DUNN QUARRY, CARTER COUNTY

Beginning at top in Viola Limestone and proceeding downsection, section measured in quarry on property leased by Mr. Dunn in the W½NE¼SE¼ sec. 22, T. 5 S., R. 1 E., just north of the Rudd Quarry, in the Criner Hills (see Fig. 104). This is also known as the upper quarry or north quarry. Strike N 5° E, dip 40° W.

ORDOVICIAN SYSTEM	Thickness(m)
VIOLA LIMESTONE (lower 3.05 m measured)	
1. Limestone, gray, very fine-grained, cherty, with tan chert, thin-bedded, well-indurated, lower contact covered	3.05
SIMPSON GROUP	
BROMIDE FORMATION (upper 38.1 m measured)	
Pooleville Member (upper 38.1 m measured)	
2. Limestone, gray, medium-grained, brecciated, massive, well-indurated, echinodermal, 3 crinoids collected, eroding into massive ledge	0.46
3. Limestone, light-gray, very fine-grained, argillaceous, well-indurated, thin-bedded, with some shale seams, fossiliferous, echinodermal, 14 *Pleurocystites* 1.52 to 2.44 m below top, 5 crinoids 1.52 m below top, 2 *Porocrinus* 1.83 m below top, 1 starfish 2.44 m below top, 4 edrioasteroids 3.05 m below top, many stems and plates (see Fig. 106)	3.9

Fig. 105. Rudd Quarry exposure, Carter County. View looking west, of upper part of Pooleville Member, with strike N 5° W, dip 60° W, about 3.05 m below Viola Limestone, in the NW¼SE¼SE¼ sec 22, T. 5 S., R. 1 E., Measured Section 13. *Kirkocystis* occurs about 1.5 to 3.9 m below the Viola, the main zone being near the base of the quarry face.

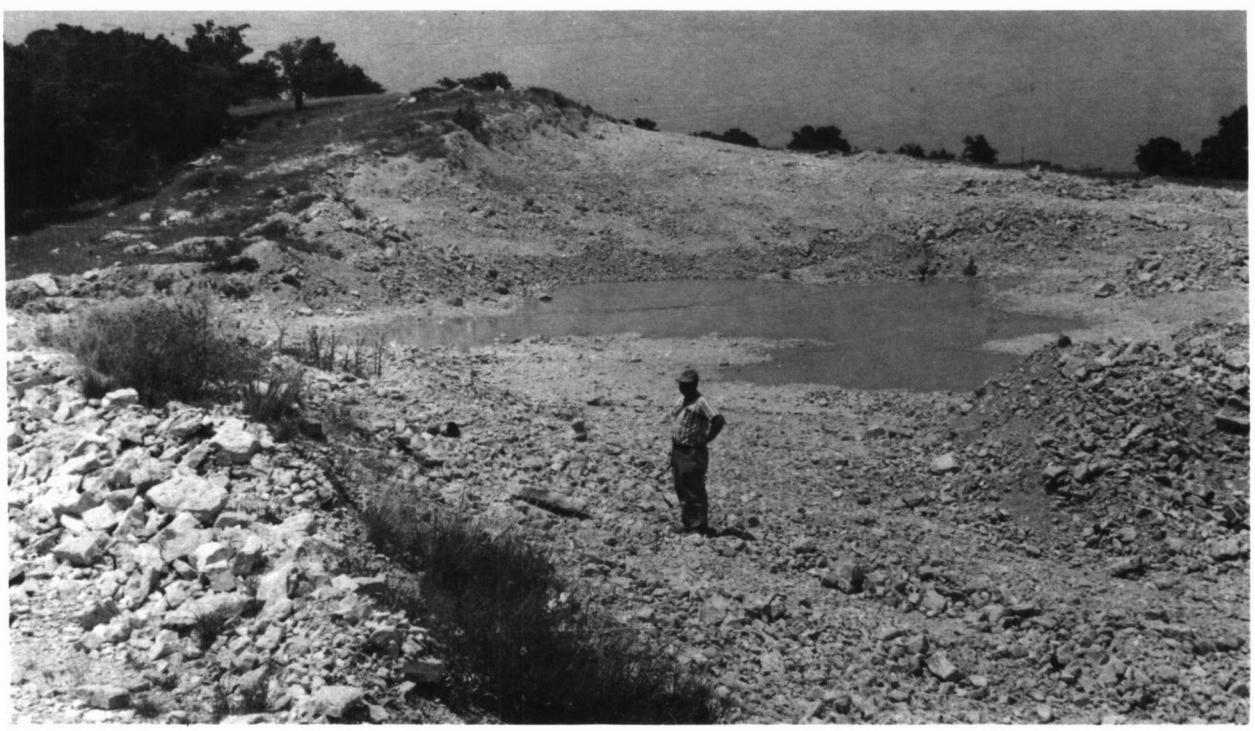


Fig. 106. Dunn Quarry exposure, Carter County. View looking north, with Viola Limestone on ridge, striking N 5° E, with dip 40° W, of Pooleville Member, in the W½NE¼SE¼ sec. 22, T. 5 S., R. 1 E., Measured Section 13. A *Hybocrinus* zone occurs 3.1 to 6.1 m below Viola Limestone, where Allen Graffham is standing. An *Archaeocrinus* zone is about 11.2 m below the Viola Limestone, about where Allen's hat touches the water in the background. *Vogdesia bromidensis* occurs about 29.5 m below the Viola, to the right of the water, about 3.05 m west of a well casing.

4. Limestone, light-gray, very fine-grained, argillaceous, well-indurated, medium-bedded, fossiliferous, with some shale seams, *Oxoplecia*, 4 crinoids, 3 edrioasteroids, and *Myeinocystites* 3.05 to 4.6 m below top, 6 rhombiferan cystoids, 4 crinoids, *Acolocrinus*, and *Archaeocrinus* 4.6 to 7.6 m below top, an *Archaeocrinus* zone 6.4 m below top (see Fig. 106).....7.0
5. Limestone, light-gray to tan, very fine-grained, argillaceous, medium- to thick-bedded, well-indurated, fossiliferous, some cystoids and crinoids in upper 0.61 m, 1 crinoid 3.6 m below top, *Vogdesia* zone about 18.3 m below top, basal part covered.....27.4

Measured Section 14

CULLEY CREEK, CARTER COUNTY

Beginning at top in Bromide Formation just below Viola Limestone and proceeding downsection, section measured in the SW¼NW¼NW¼ sec. 26, T. 5 S., R. 1 E., on east side of Culley Creek (formerly Spring Creek) near a pipeline crossing, on property of Mrs. George Hollingsworth of Ardmore (see Fig. 107). Mr. Grant Adams, Jr., has leased the surface rights. The outcrop is reached by an old road that enters sec. 26 at the north quarter corner, trending southward a short distance, then westward to an old oil well, then west-southwest to the outcrop. The name Culley Creek is new and is for Mr. Bill Culley, who lived near the east quarter corner of sec. 26. Mr. Ewing Dunlap of Ardmore has the oil rights and production in the area. Strike N 75° E, dip 45° NW.

ORDOVICIAN SYSTEM — Thickness (m)
VIOLA LIMESTONE (broken rubbly zone)
1. Limestone, gray, cherty, in large blocks at base of a conglomerate section (Pennsylvanian?), dipping with the underlying Bromide section.....0.91
SIMPSON GROUP
BROMIDE FORMATION (upper 36.3 m measured)
Pooleville Member (upper 36.3 m measured)
2. Limestone, tan, fine-grained, argillaceous, well-indurated, blocky, medium-bedded, with some 1.3- to 2.5-cm shale seams, fossiliferous, some brachiopods, 130 or more *Archaeocrinus* from a 0.3 m zone 0.91 to 1.22 m below top; this entire unit designated Zone 1.....7.6
3. Limestone, tan, fine-grained, argillaceous, well-indurated, blocky, even-bedded, medium-bedded, with some 1.3- to 2.5-cm shale seams, fossiliferous, some brachiopods and echinoderms, 13 *Archaeocrinus*, 1 *Hybocrinus;* designated Zone 2.....1.15
4. Limestone, light-tan, fine-grained, argillaceous, well-indurated, blocky, with many 0.6- to 1.3-cm tan shale seams, medium-bedded, fossiliferous, with many echinoderms, including 61 *Archaeocrinus* and *Pararchaeocrinus*, *Hybocrinus*, starfish, cystoids, other echinoderms; designated main upper echinoderm zone or Zone 3.....0.91
5. Limestone, tan, fine-grained, dense, argillaceous, well-indurated, medium-bedded, with many 2.5- to 5.0-cm shale seams, massive 0.3 m limestone bed at base, fossiliferous, many brachiopods, some echinoderms such as 2 *Cyathocystis*, 3 crinoids, 1 complete starfish; designated Zone 4 .....1.46
6. Limestone, tan to gray, fine-grained, argillaceous, dense, blocky, well-indurated to moderately indurated, medium-bedded, with many 1.3- to 2.5-cm shale seams, extremely fossiliferous, echinodermal, *Diabolocrinus* colony in upper 5 to 7 cm, *Parachaeocrinus* colony in lower 15 cm, *Vogdesia bromidensis* zone at base with many *Archaeocrinus*, some cystoids, and 2 small starfish; designated main lower echinoderm zone or Zone 5 (see Fig. 108).....2.13
7. Limestone, tan to gray, fine-grained, dense, argillaceous, well-indurated, medium-bedded, with thin shale seams, fossiliferous, with *Lonchodomus;* designated Zone 6.....3.3
8. Limestone, tan to gray, fine-grained, dense, medium-bedded, with some shale seams, mostly covered.....10.9
9. Shale and limestone, tan, as above, with much shale, relatively unfossiliferous, mostly covered.....6.4
10. Shale, tan, limy, moderately to weakly indurated, with some interbedded tan argillaceous limestone, relatively unfossiliferous.....2.13

The remainder of the section may belong to the McLish Formation and may be faulted.

11. Limestone, gray to tan, fine- to medium-grained, medium-bedded, well-indurated, with some shale, echinodermal, with some rhombiferan cystoid plates, with *Ischadites* near base, eroding into series of ledges.....36.6

Immediately to the south is a sandstone, with gray shale below with much ironstone, striking northeast with vertical dip; probably Pennsylvanian.

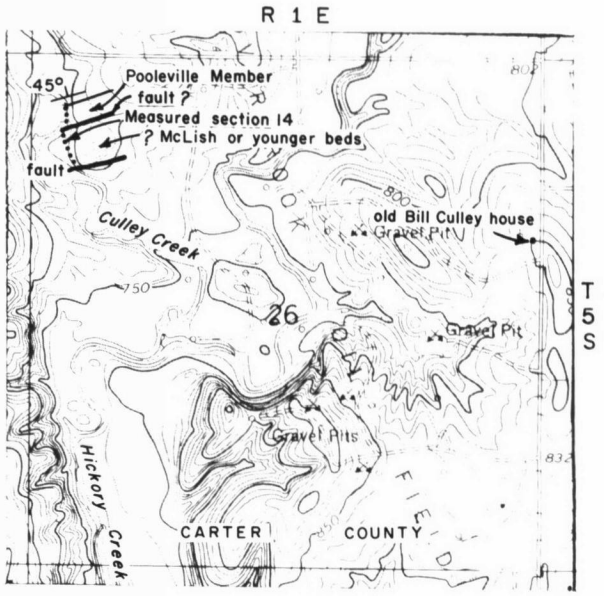


Fig. 107. Geologic map showing Bromide Formation and location of Measured Section 14 at Culley Creek.

Measured Section 15A

ROCK CROSSING, CARTER COUNTY

Beginning at top of section in Viola Limestone and proceeding downsection, west of road crossing Hickory Creek, in the SE¼NE¼NE¼SW¼ sec. 35, T. 5 S., R. 1 E., section measured through Pooleville Member to Mountain Lake Member east of road in the SW¼NW¼NW¼SE¼ sec. 35, in the Criner Hills (see Fig. 109). Strike N, dip 40° W. The road crosses through the Pooleville outcrop, and this place is designated Rock Crossing. It is possible that this was also called Hickory Gap in the early 1900's (see Bassler, 1943), but we have been unable to verify this usage.

ORDOVICIAN SYSTEM — Thickness(m)
VIOLA LIMESTONE (lower 7.6 m measured)
1. Limestone, dark-brown, very fine-grained, lithographic, thinly laminated, well-indurated, cherty, graptolitic, fossiliferous, eroding into low ridges, contact covered.....7.6
SIMPSON GROUP
BROMIDE FORMATION (total thickness 80.5 m)
Pooleville Member (total thickness 40.2 m)
2. Limestone, gray to light-tan, fine-grained, argillaceous, medium-bedded, well-indurated, fossiliferous, eroding into a few ledges, partly covered.....5.5
3. Limestone, gray, fine-grained, argillaceous, thin- to medium-bedded, well-indurated, fossiliferous, with many brachiopods, especially *Sowerbyella* and *Oxoplecia* near top.....1.52
4. Limestone, light-gray, fine-grained, well-indu-

rated, fossiliferous, with many brachiopods such as *Sowerbyella* and *Hesperorthis*, and some trilobites such as Lichenaria near top.....2.28
5. Limestone, light-gray, fine-grained, well-indurated, thin- to medium-bedded, as above, mostly covered.....4.6
6. Limestone, light-gray to light-tan, mottled bluish-gray, very fine-grained, well-indurated, thin- to medium-bedded, with some paper-thin shale seams, sparingly fossiliferous, eroding into ledges below bridge.....7.3
7. Limestone, light-gray, as above, mostly covered 7.6
8. Limestone, light-gray, very fine-grained, argillaceous, dense, well-indurated, thin-bedded, with many shale seams, sparingly fossiliferous, eroding into ledges.....4.3
9. Limestone, light-gray to light-tan, very fine-grained, argillaceous, well-indurated, dense, wavy-bedded, thin- to medium-bedded, with some tan shale seams, sparingly fossiliferous, weathering rubbly, eroding into ledge at top of waterfalls.....1.52
10. Limestone, light-gray, mottled tan, very fine-grained, argillaceous, thin-bedded, even-bedded, fossiliferous, eroding into recess.....1.52
11. Limestone, light-tan to light-gray, fine- to medium-grained, medium-bedded, wavy-bedded, well-indurated, fossiliferous, with *Vogdesia* near top, eroding into ledge.....0.61
12. Limestone, light-tan to gray, medium-grained, argillaceous, medium-bedded to massive, well-indurated, echinodermal, eroding into prominent ledge.....1.07
13. Limestone, gray to tan, medium-grained, argillaceous, thin-bedded, wavy-bedded, fossiliferous, with many shale seams eroding into recess...1.67
14. Limestone, tan to gray, medium-grained, argillaceous, massive, well-indurated, echinodermal, eroding into prominent ledge.....0.3
15. Limestone, light-gray, very fine-grained, argillaceous, thin-bedded, wavy-bedded, fossiliferous, with many tan shale seams, eroding into recess.....0.46

Mountain Lake Member (total thickness 40.2 m)

Upper Mountain Lake (total thickness 3.5 m)

16. Limestone, gray, medium-grained, argillaceous, massive, well-indurated, fossiliferous, echinodermal, eroding into ledge (The main waterfall flows over this ledge.).....0.3
17. Limestone, gray, mottled red-brown at base, medium-grained, with some greenish-gray shale, fossiliferous, echinodermal, with *Multicostella*, 1 edrioasteroid, many holdfasts and stems, eroding into recess (see Fig. 110).....0.37
18. Shale, tan to greenish-gray, limy, platy, weakly indurated, with many rubbly limestone ledges, with *Multicostella*.....0.3
19. Limestone, gray, medium-grained, massive, fossiliferous, echinodermal, weathering tan, eroding into ledge.....0.37
20. Shale, greenish-gray, platy, weakly indurated, with many branching bryozoans.....0.15
21. Limestone, gray, medium-grained, argillaceous, thin-bedded, well-indurated, thin-bedded, fossiliferous, weathering tan, eroding into ledge...0.37
22. Shale, greenish-gray, as above, with many bryozoans, eroding into recess.....0.15
23. Limestone, gray, medium-grained, thin-bedded, well-indurated, echinodermal, eroding into ledge, weathering tan, with many echinoderm stems and plates collected 0.98 m below top.....1.52

Fig. 108. Culley Creek exposure, Carter County. View looking along strike N 75° E, with dip 45° NW, of middle part of Pooleville Member, about 14.3 m below Viola Limestone, on east side of Culley Creek (formerly Spring Creek), in the SW¼NW¼NW¼ sec. 26, T. 5 S., R. 1 E., Measured Section 14. Allen Graffham is pointing to the *Diabolocrinus* layer at top of Zone 5, about 1.83 m above the *Vogdesia bromidensis* zone.

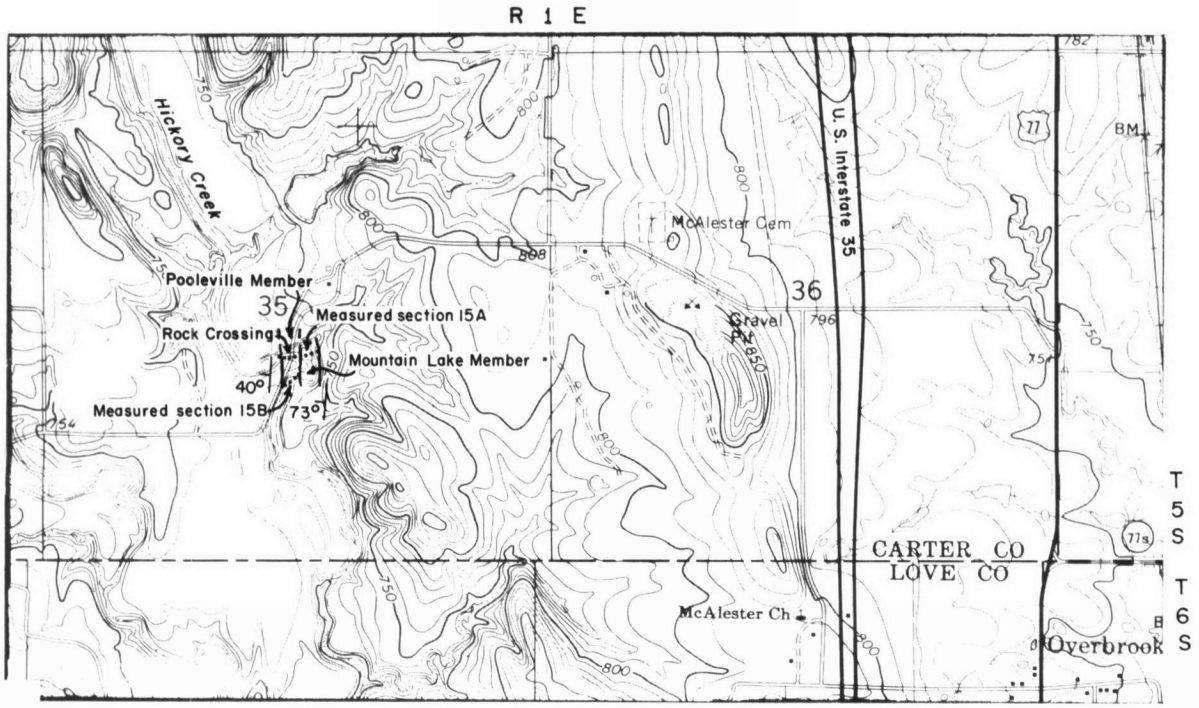


Fig. 109. Geologic map showing Bromide Formation and location of Measured Sections 15A and 15B at Rock Crossing.

Section extrapolated to southeast side of creek.
?Upper Echinoderm Zone (total thickness 0.61 m)
24. Shale, greenish-gray, limy, platy, with many 2.5- to 5.0-cm gray to tan limestone layers, extremely fossiliferous, echinodermal, with many echinoderm plates, holdfasts, and branching bryozoans, eroding into recess.....0.61
Middle and Lower Mountain Lake (total thickness 18.9 m)
25. Limestone, gray to tan, medium-grained, well-indurated, medium-bedded, wavy-bedded, with some greenish-gray shale, fossiliferous, echinodermal, eroding into ledge.....0.76
26. Shale, greenish-gray, platy, weakly indurated, partly covered.....4.6
27. Limestone, tan, medium-grained, conglomeratic, thick-bedded to massive, well-indurated, fossiliferous, echinodermal with *Receptaculites* at top, eroding into prominent ledge.....0.76
28. Shale, greenish-gray, platy, weakly indurated, fossiliferous, with many bryozoans.....0.15
29. Limestone, tan, as above (total thickness 0.03 m)
30. Shale, greenish-gray to tan, platy, weakly indurated, fossiliferous, with many bryozoans and echinoderms, especially 0.76 to 1.07 m below the top, where 5 edrioasteroids collected.....1.40
31. Shale, greenish-gray, platy, weakly indurated, mostly covered.....1.83
32. Limestone, gray, fine- to medium-grained, weathering tan, eroding into ledge.....0.23
33. Shale, greenish-gray, platy, weakly indurated, with some interbedded tan echinodermal limestone beds, mostly covered.....9.1
Basal sandstone sequence (total thickness 17.1 m)
34. Sandstone, tan, fine-grained, silty, limy, thin-bedded, well-indurated, gradational into limestone, fossiliferous, some brachiopods, bryozoans, and echinoderm remains, eroding into hogback on north side of creek, dipping 73° westward.....1.83
35. Sandstone, tan, mottled gray, fine-grained, silty, limy, medium- to thick-bedded, well-indurated, fossiliferous, eroding into ledge.....2.28
36. Sandstone, tan, fine-grained, silty, thin-bedded, moderately to weakly indurated, eroding into ledge.....2.13
37. Shale, greenish-gray, blocky, weakly indurated 1.83
38. Siltstone, tan to greenish-gray, argillaceous, limy, fucoidal, thin-bedded, moderately indurated.....0.91
39. Limestone, dark-gray, medium-grained, silty, thin-bedded, well-indurated, echinodermal, gradational into tan siltstone, eroding into ledge..1.52
40. Siltstone, tan, limy, thin-bedded, platy, weakly indurated, partly covered.....3.05
41. Shale, greenish-gray, blocky, weakly indurated 1.83
42. Sandstone, tan, silty, thin- to medium-bedded, well-indurated, eroding into hogback.....1.83
TULIP CREEK FORMATION (upper 22.5 m measured)
43. Shale, tan to greenish-gray, thin-bedded, weakly indurated, with some interbedded tan siltstone and fine-grained sandstone.....1.52
44. Shale, greenish-gray, as above, mostly covered, may be faulted.....3.9
45. Limestone, brown to gray, medium-grained, thin-bedded, well-indurated, fossiliferous, echinodermal, many bryozoans, eroding into ledge, beds slightly overturned, dipping 76° eastward.....0.76
46. Shale, greenish-gray, blocky, weakly indurated 0.3
47. Shale, tan, platy, thin-bedded, weakly indurated, fossiliferous, with interbedded tan to gray limestone.....0.61
48. Limestone, gray, mottled tan, fine-grained, argillaceous, massive, well-indurated, eroding into ledge.....0.23
49. Siltstone, tan, limy, thinly laminated, weakly indurated, fossiliferous, with interbedded 5- to 7-cm tan limestone beds, eroding into recess..2.28
50. Shale, greenish-gray, blocky, weakly indurated 1.22
51. Siltstone, tan, limy, fine-grained, well-indurated, medium-bedded, with some interbedded shale, gradational into echinodermal limestone, eroding into ledge.....1.22
52. Shale and siltstone, greenish-gray to tan, thin-bedded, weakly indurated, with some interbedded tan fossiliferous limestone, mostly covered.....9.1
53. Limestone, tan, medium-grained, thin-bedded to massive, well-indurated, echinodermal, with some interbedded greenish-gray shale, weathering dark-gray, eroding into ledge.....1.52
The remainder of the section is cut out unconform-

ably by overlying younger Pennsylvanian sandstone and shale beds.

Measured Section 15B

SOUTHEAST ROCK CROSSING, CARTER COUNTY

Beginning at top about 1.5 m below base of Viola Limestone, and proceeding downsection, section measured in bend of Hickory Creek east of road and south of Rock Crossing in the NE¼SE¼NE¼SW¼ sec. 35, T. 5 S., R. 1 E., Carter County, Oklahoma (see Fig. 109). Near the top of the section on the west side of the creek is a conglomeratic rubble with some Bromide and some Viola Limestone, about 0.9 m thick, which may not be in place. Almost all echinoderms collected at Rock Crossing came from the upper 19.5 m of this section. Strike N, dip 40° W.

ORDOVICIAN SYSTEM — Thickness (m)
SIMPSON GROUP
BROMIDE FORMATION (measured thickness 38.8 m)
Upper 1.37 m eroded.
Pooleville Member (measured thickness 38.8 m)
Upper 1.37 m eroded.

1. Limestone, light-gray, very fine-grained, argillaceous, thin-bedded, wavy-bedded, with many 2.5-cm greenish-gray shale seams, fossiliferous, with many brachiopods, some harpid trilobites, some *Kirkocystis*. (Many small normal faults occur, downdropped on the south side.).....3.6
2. Limestone, light-gray, as above, medium-bedded, with many 2.5- to 5.0-cm greenish-gray fossiliferous shale seams, *Hybocrinus* 1.22 m above base, *Kirkocystis* and 3 *Pleurocystites* 1.83 m above base, other crinoids and cystoids in lower 1.22 m (see Fig. 111).....3.6
3. Limestone, light-gray, argillaceous, as above, medium-bedded, with a few thin shale partings, fossiliferous, with *Kirkocystis*, crinoids, and cystoids, especially rhombiferan cystoids, about 2.74 m below top.....6.7
4. Limestone, light-gray, very fine-grained, argillaceous, medium- to thick-bedded, well-indurated, fossiliferous, with some 1.3-cm shale partings, with *Kirkocystis* in upper 1.22 m, some rhombiferan cystoids in upper 5.5 m (see Fig. 112).....6.1
5. Limestone, light-gray, very fine-grained, argillaceous, thin- to medium-bedded, with many 1.3- to 2.5-cm shale seams, fossiliferous, with a *Vogdesia bromidensis* zone 2.74 m above base.....6.4
6. Limestone, light-gray, fine-grained, argillaceous, thin-bedded, fossiliferous, with many 2.5-cm shale seams and some medium-grained limestone beds, partly covered.....2.44
7. Limestone, light-gray, very fine-grained, dense, thin- to medium-bedded, with many 7- to 10-cm shale partings, sparingly fossiliferous, partly covered.....5.8
8. Limestone, light-tan to light-gray, very fine- to medium-grained, medium- to thick-bedded, well-indurated, echinodermal, eroding into hogback.....3.6
9. Limestone, light-gray, medium-grained, thin-bedded, wavy-bedded, well-indurated, fossilif-

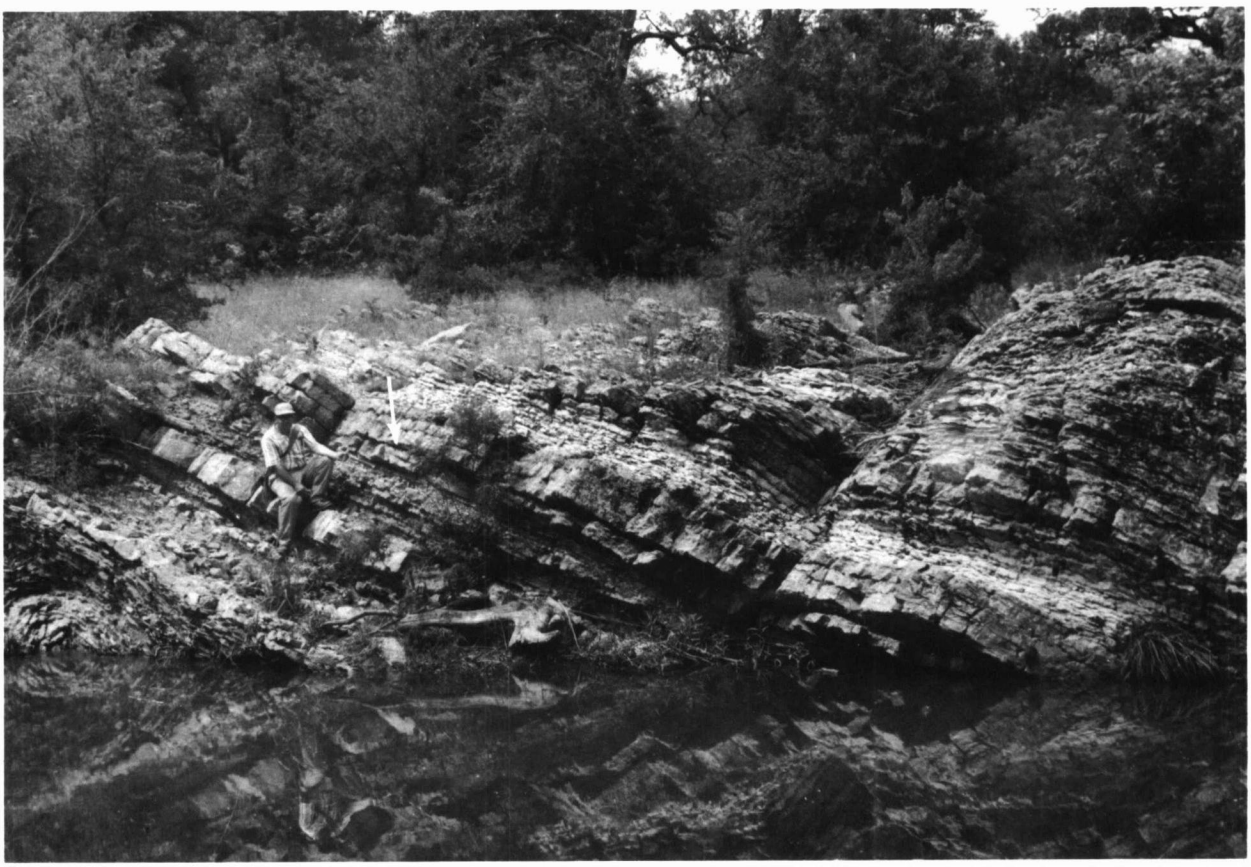


Fig. 110. Rock Crossing exposure, Carter County. View looking south along strike N, with dip 40° W, of contact (arrow) between Pooleville Member and Mountain Lake Member (below), about 38.4 m below Viola Limestone, on southeast side of Hickory Creek, east of bridge, in the SW¼NW¼NW¼SE¼ sec. 35, T. 5 S., R. 1 E., Measured Section 15A. Allen Graffham is pointing to the top of the *Multicostella* zone of greenish-gray shale and gray echinodermal limestone, at top of Mountain Lake Member.

erous, with some thin shale partings, eroding into recess.....0.46
Mountain Lake Member
Same as that described in Measured Section 15A.

Measured Section 16A

NORTH INTERSTATE 35 SECTION, MURRAY COUNTY

Beginning at top of section in Viola Limestone and proceeding downsection and southward along the east side (A cut) of Interstate 35, in the center W½NE¼SE¼ sec. 30, T. 1 S., R. 2 E., Murray County (see Fig. 113), section measured through the Bromide Formation into the Tulip Creek Formation. The beds are slightly overturned southward, with strike N 60° W, dip 70° SW.

ORDOVICIAN SYSTEM — Thickness (m)
VIOLA LIMESTONE (total thickness 216 m; only lower part described)
1. Limestone, gray to dark-gray, fine-grained, argillaceous, laminated, medium- to thick-bedded, well-indurated, nodular, with dark-gray chert, alternating with dark-gray fine-grained limestone, graptolitic, with 5-cm pyritic-ironstone stained zone at base, eroding into prominent grass-covered ridge.....29.5
SIMPSON GROUP
BROMIDE FORMATION (total thickness 105 m, with station 2658+60' on top, east side of east lane)
Pooleville Member (total thickness 24.4 m)
2. Limestone, light-gray, fine-grained, fossiliferous, thick-bedded to massive, even-bedded, well-indurated, with some greenish-gray argillaceous laminae, weathering tan, eroding into escarpment.....2.13
3. Limestone, light-gray, fine-grained, thin- to medium-bedded, crinkly-bedded, well-indurated, fossiliferous, with many light greenish-gray argillaceous laminae, weathering tan, eroding into escarpment.....1.83
4. Limestone, light-gray to tan, fine-grained, fossiliferous, massive, well-indurated, eroding into escarpment.....2.13
5. Limestone, light-gray to tan, fine-grained, fossiliferous, medium- to thick-bedded, well-indurated, with some argillaceous laminae in lower 3.9 m, eroding into escarpment.....7.0
6. Limestone, tan, fine-grained, medium-bedded, well-indurated, fossiliferous, with many light greenish-gray argillaceous laminae, with some tan to bluish-gray to greenish-gray medium- to coarse-grained echinodermal limestones, eroding into escarpment. (Station 2657+40' is at the base on the east side of the east lane.).....11.2
Mountain Lake Member (total thickness 81.1 m)
Upper Mountain Lake, including Upper Echinoderm Zone (total thickness 9.4 m)
7. Shale, bluish-gray, calcitic, platy, laminated, weakly indurated, fossiliferous, alternating with tan to bluish-gray medium-bedded coarsely crystalline echinodermal limestone, with a brecciated bed of tan, fine-grained, dense, cabbage-

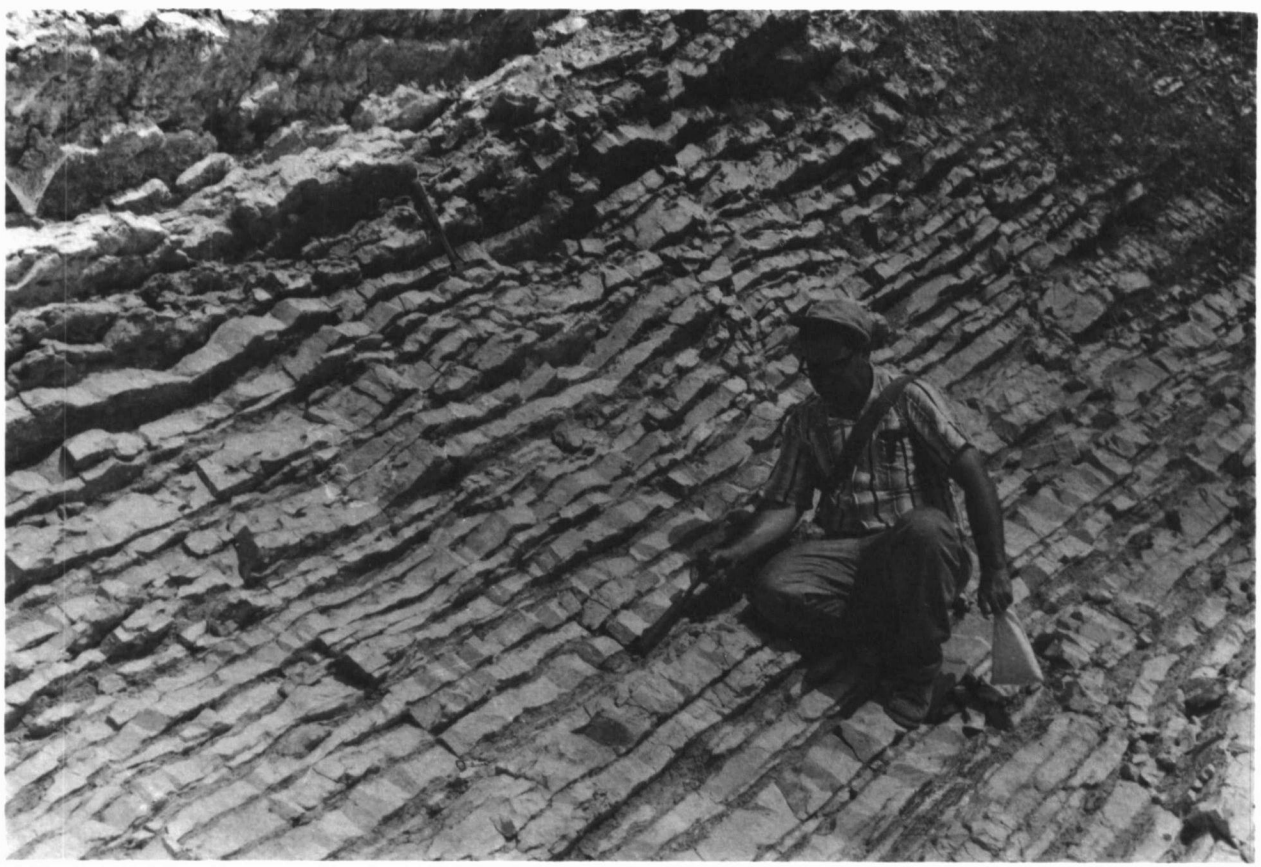


Fig. 111. Rock Crossing exposure, Carter County. View looking north, of upper part of Pooleville Member, 5.5 m below Viola Limestone (Allen Graffham pointing with hammer), where the type specimen of *Pleurocystites watkinsi* was collected, on west side of Hickory Creek, in the NE¼SE¼NE¼SW¼ sec. 35, T. 5 S., R. 1 E., Measured Section 15B. Many plates of *Pleurocystites* were found 0.46 m below the main zone and up to 1.52 m above the zone. The top of the *Kirkocystis* zone is at the base of the hammer. *Strophomena crinerensis* occurs between beds indicated by hammers.

shaped stromatoporoids 1.83 to 2.44 m below top, *Platycystites* found 0.61 m and 7.6 to 7.9 m below top, *Oklahomacystis* found at top and 0.3, 1.52, 3.3, 4.9, and 6.7 m below top, eroding into slope, with lower 2.44 m formed into slide area.....9.4

Middle Mountain Lake (total thickness 44.5 m)

8. Limestone, gray, fine- to medium-grained, massive, well-indurated, fossiliferous, weathering tan, eroding into massive ledge.....1.22
9. Limestone, gray, fine-grained, argillaceous, nodular, fossiliferous, thin- to medium-bedded, well-indurated, alternating with bluish-gray to tan calcitic shale beds, weathering tan, eroding into slope.....15.2
10. Limestone, gray, fine- to coarse-grained, fossiliferous, echinodermal, well-indurated, massive, weathering tan, eroding into escarpment....2.44
11. Shale, bluish-gray to tan, calcitic, platy, weakly indurated, many bryozoans.....1.22
12. Limestone, gray, fine- to medium-grained, fossiliferous, massive, well-indurated, with thin-bedded nodular argillaceous crinkly bedded limestone and shale in the middle 0.5 m, eroding into escarpment.....1.52
13. Limestone, gray, fine-grained, argillaceous, nodular, thin-bedded, crinkly bedded, well-indurated, with some tan shale laminae, eroding into slope. (Station 2655+85' is at the base on the east side of the east lane.).....0.91
14. Limestone, gray to tan, fine- to coarse-grained, fossiliferous, echinodermal, alternating with laminated to thin-bedded to medium-bedded shales, eroding into slope.....3.05
15. Interval covered, probably same as above, eroding into slope (includes Lower Echinoderm Zone and lower Mountain Lake member).....18.6

Basal sandstone sequence (total thickness 27.4 m)

16. Sandstone, yellow-brown, fine- to medium-grained, quartzose, moderately indurated, interbedded with greenish-gray platy shale, with a 3.3-m massive sandstone at base, mostly covered. (Base of section is about at station 2654+60' on west fence of west lane or station 2653+25' on east fence line of east lane.).....27.4

TULIP CREEK FORMATION (total thickness 100.5 m)

17. Shale, greenish-gray, calcitic, platy, fossiliferous, weakly indurated, with some medium-bedded, bluish-gray to tan, coarse-grained, well-indurated echinodermal limestone beds, weathering tan, eroding into slope. Remaining section exposed but not described.....29.8

Measured Section 16B

NORTH-CENTRAL INTERSTATE 35 SECTION, MURRAY COUNTY

Beginning at exposed base in basal sandstone of the Mountain Lake Member and proceeding southward along the west side (D cut), center section (BC cut), and east side (A cut) of Interstate 35, in the SW¼SE¼SE¼ sec. 30, T. 1 S., R. 2 E., Murray County (see Fig. 113), strike N 60° W, dip 32° SW. Section measured by James Sprinkle in August, 1976; written up by Robert O. Fay.

Fig. 112. Rock Crossing exposure, Carter County. View looking north along strike N, with dip 40° W, of Pooleville Member of Bromide Formation, 15.2 m below Viola Limestone, on west side of Hickory Creek, east of road, in the NE¼SE¼NE¼SW¼ sec. 35, T. 5 S., R. 1 E., Measured Section 15B. The hammer rests upon a zone from which *Hybocrinus* was collected about 23.7 m above the base of the Pooleville and marks the lowest position of beds from which echinoderms were collected in this section of the Pooleville.

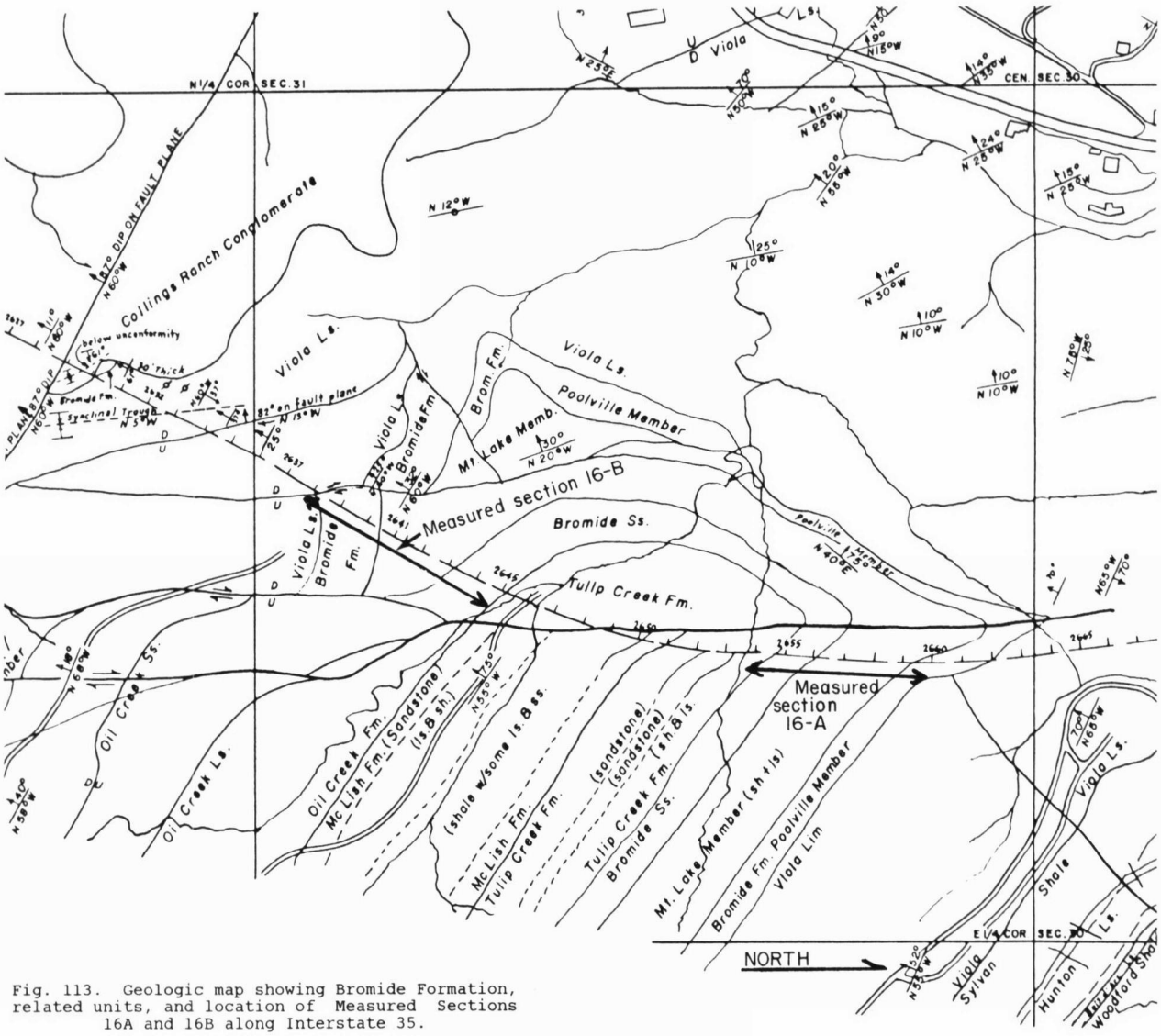


Fig. 113. Geologic map showing Bromide Formation, related units, and location of Measured Sections 16A and 16B along Interstate 35.

ORDOVICIAN SYSTEM — Thickness (m)

VIOLA LIMESTONE

1. Limestone, white to buff, micritic, alternating with thin shale beds, lenticular, with some chert, measured in A cut.....3.05

SIMPSON GROUP

BROMIDE FORMATION (measured thickness 95.9 m)
Base not seen.

Pooleville Member (measured thickness 21.3 m)

2. Limestone, micritic, birdseye, white, with upper contact pyritic, 7 to 10 cm of relief, weathering red-brown to yellow-brown, limonitic..0.61
3. Limestone, grayish-white to tan, very fine-grained, micritic, burrowed, medium-bedded.....3.05
4. Limestone, as above, thin-bedded, with *Tetradium* colonies.....0.61
5. Limestone, grayish-white to tan, micritic, burrowed, medium-bedded.....2.44
6. Limestone, white, massive, relatively unfossiliferous.....1.83
7. Limestone, grayish-white to tan, very fine-grained, micritic, burrowed, medium-bedded.....3.05
8. Limestone, as above, with much brown chert.....0.3
9. Limestone, gray to tan to grayish-white, massive to medium-bedded, very fossiliferous below in lower 3.05 m, decreasing upward, with *Tetradium* colonies beginning about 7.6 m above base, lowest 6.1 m faulted out in A cut, transferred to BC cut below.....9.4

Mountain Lake Member (measured thickness 75 m; base not seen)

Upper Echinoderm Zone (total thickness 6.0 m)

10. Limestone, gray to light-tan to brown, coarsely granular, massive to medium-bedded, with some gray micritic beds, with many brachiopods, bryozoans, and trilobites in upper part, *Oklahomacystis* 0.76 m above base.....1.83
11. Limestone, calcarenitic, gray to tan, weathering brown, with some shale, fossiliferous, medium-bedded, with many bryozoans and echinoderms, with *Oklahomacystis* 1.83 to 2.44 m above base, *Cyclocystoides* 1.67 m above base, *Cleiocrinus* 1.83 m above base.....2.89
12. Limestone, gray, calcarenitic, interbedded with shale, thin-bedded, with much echinoderm debris, bryozoans, brachiopods, and some trilobites, *Oklahomacystis* 0.46 m above base.....1.28

Middle Mountain Lake (total thickness 41.1 m)

13. Limestone, gray, calcarenitic, medium-bedded in 4 beds, alternating with shale, weathering brown.....1.07
14. Shale, greenish-gray, mottled brown, relatively unfossiliferous, with interbedded limestones in upper 0.61 m with brachiopods, trilobites,

and echinoderms, some limestones with reddish-brown tops (?hardgrounds).....2.59
15. Limestone, gray, calcarenitic, medium-bedded, in 6 beds, alternating with greenish-gray shales, silty, with white chert nodules in lower part with some possible hardgrounds, with large echinoderm plates in lower part.....1.83
16. Limestone, light grayish-white, thin-bedded, nodular, with medium-brown chert nodules and some pyrite, alternating with thin shales, cyclic at top.....1.98
17. Limestone and shale, gray to greenish-gray, more limy in middle part, cyclic, moderately fossiliferous in lower 1.52 m, less fossiliferous above, with hardgrounds about 3.05 m above base, faulted near top in D cut, so remaining section from here up was measured along the median (BC cut), from here down, in D cut.....9.1
18. Limestone, gray, massive, medium-bedded, fossiliferous, with bryozoans and trilobites, and several hardgrounds at top and 15 and 46 cm below top, with burrows, pyrite lumps, and cracks.....3.05
19. Shale and limestone, gray to greenish-gray, with many bryozoans, echinoderm plates, 1 *Sinclairocystis*, and holotype of *Arbucklecystis*; now called *Bromidocystis* Bed.....0.98
20. Limestone, gray, calcarenitic, massive ledge, with large bryozoan colonies.....0.61
21. Limestone and shale, gray to greenish-gray, with some bryozoans and trilobites.....0.53
22. Limestone, gray, calcarenitic, massive ledge, with few fossils but extensively burrowed, pyritic hardground at top.....0.76
23. Limestone and shale, alternating in cycles, gray to greenish-gray, burrowed, with some trilobites, with a very fossiliferous calcarenite 1.83 m above base with 2 hardgrounds.....3.6
24. Limestone, gray, thin- to medium-bedded, massive-bedded in middle, with cyclic shales at base and top, fossiliferous near top, with pyritic hardgrounds at top and 0.53 m below top....3.05
25. Limestone and shale, gray to greenish-gray, alternating cyclic, in small recess at base of prominent ledge, with trilobites, with an 0.3-m limestone bed in middle with pyrite at top.....1.14
26. Limestone and shale, gray to greenish-gray, alternating, cyclic, moderately fossiliferous, with many bryozoans and echinoderms, with 1 *Platycystites* and 1 *Ectenocrinus* 0.3 to 0.46 m below the top, called the upper *Carabocrinus* Beds.....2.74
27. Limestone, gray, massive, with hardground in middle, with trilobite hash filling cavities, nodular above.....0.37
28. Limestone and shale, gray to greenish-gray, alternating, cyclic, very fossiliferous, with many bryozoans, brachiopods, trilobites, and echinoderms, with some whole echinoderms collected 15 to 20 cm below top, with *Carabocrinus*, *Platycystites*, *Diabolocrinus*, starfish, and other echinoderm plates throughout, called the main *Carabocrinus* Beds.....0.91
29. Limestone, gray, massive, with some trilobite hash.....0.46
30. Limestone and shale, gray, alternating, cyclic, relatively unfossiliferous below, with trilobites above, with a 15-cm trilobite hash about 22 cm below top.....1.07
31. Limestone, gray, calcarenitic, medium- to thick-bedded, with some shale near base, and a trilobite hash near top, with 2 hardground layers in top 0.46 m.....1.67
32. Limestone and shale, gray to greenish-gray, with bryozoans and echinoderms, with more limestone at base, 1 *Hybocrinus* 0.39 m above base, pyritic layer 0.3 m below top, and large bryozoan colonies at top, much shale at top.....1.07
33. Shale, greenish-gray, with bryozoans near base, a thin limestone in middle, and an iron-stained zone in upper 0.3 m.....3.05

Lower Echinoderm Zone (total thickness 3.6 m)

34. Shale and limestone, gray to greenish-gray, biosparitic to calcarenitic, thin-bedded, more limy near base, with many bryozoans, brachiopods, and echinoderms, with a bryozoan buildup 0.61 to 1.52 m above the base, with 1 *Hybocrinus* 1.07 m above base, and 1 *Cyathocystis* 1.22 m above base.....3.6

Lower Mountain Lake (total thickness 8.0 m)

35. Limestone, gray to tan, mottled by burrowing, biosparite, massive, weathering brown.....0.53
36. Shale and interbedded limestone, gray to greenish-gray, with bryozoans and echinoderms....0.98
37. Limestone, gray to tan, as above, weathering brown.....0.27
38. Shale, greenish-gray, with thin limestone stringers and bryozoans.....0.3
39. Limestone, gray, as above, lenticular, with bryozoans, weathering brown.....0.15
40. Shale and interbedded limestone, gray to greenish-gray, as above, with 1 thick limestone 0.46 m below top, with bryozoan buildups, attached echinoderm bases.....1.52
41. Limestone, gray to tan, calcarenitic, silty, with bryozoan buildups.....1.07
42. Siltstone and shale, greenish-gray to tan, limy, thin-bedded, with many bryozoans.....2.44
43. Siltstone and shale, greenish-gray and tan, eroding into recess.....0.76

Basal sandstone sequence (measured thickness 15.7 m, base covered)

44. Sandstone, brown, quartzose, fine- to medium-grained, limy, thin-bedded eroding into ledge....0.68
45. Siltstone and sandstone, brown, quartzose, fine- to medium-grained, with some gray shale....1.83
46. Sandstone, brown, as above, thin- to medium-bedded, eroding into cliff.....3.9
47. Siltstone and sandstone, brown, as above, eroding into recess.....1.52
48. Sandstone, brown, as above.....0.84
49. Shale, greenish-gray to tan, silty, weakly indurated, mostly covered.....1.37
50. Sandstone, brown, as above.....0.84
51. Shale, siltstone, and some sandstone, as above, covered at north end of D cut.....4.6

OTHER COLLECTING LOCALITIES

Rhynes Ranch. Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, bulldozed strip along north side of new fence at base line about 190 m west of 342-m hilltop, center of south edge, SE¼SE¼ sec. 35, T. 1 N., R. 7 E., Harden City 7½ minute Quadrangle, in the northeastern Arbuckle Mountains, Pontotoc County, southern Oklahoma. Sparse fauna including numerous plates, 2 *Hybocrinus*, and 2 *Cyathocystis*, one of which is figured in Sprinkle and Bell (1978, fig. 1C-D). Entrance to area is at gate on county line road; permission to enter is obtained from Rhynes Ranch about 2.8 km to north.

Cedar Village. Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, steeply dipping beds 6.5 to 8.5 m above basal sandstone on west edge of bulldozed drillsite at end of dirt road, NW¼SW¼NW¼ sec. 30, T. 1 S., R. 2 E., about 0.8 km west of U.S. route 77 at Cedar Village, Turner Falls 7½ minute Quadrangle, northern Arbuckle Mountains, Murray County, southern Oklahoma. Small but unusual fauna from several shaly beds (4 *Cyathocystis*, 3 *Platycystites*, 2 *Hybocrinus*, 1 *Bromidocystis*, 1 *Eumorphocystis*, 1 *Carabocrinus*, and 1 edrioasteroid); permission to visit area is obtained from Mr. Robert Howe at Cedarvale Gardens or house nearby.

Pickens Ranch. Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, 3 exposures on flat and in small drainage cuts 60 m east and 60 and 150 m west of recently laid north-south pipeline, center of south edge, SW¼, and SE¼SW¼ SW¼ sec. 18, T. 2 S., R. 8 E., 1.6 km north of Oklahoma route 7 on Pickens Ranch, Connerville NE 7½ minute Quadrangle, eastern Arbuckle Mountains, Johnston County, southern Oklahoma. Sparse fauna, with a *Cyathocystis*, an *Astrocystites* plate, and other plates; permission to visit area is obtained from Mr. Elmer Pickens at house on Oklahoma route 7, 1.6 km west of place where pipeline crosses main road.

Lowrance Springs. Lower Echinoderm Zone, Mountain Lake Member, Bromide Formation, weathered debris from telephone cable ditch on west side of section line road on north side of Viola hill, center of east edge, SE¼SE¼ sec. 24, T. 1 S., R. 3 E., 1.6 km east of U.S. route 177, about 6.4 km south of Sulphur, Sulphur South 7½ minute Quadrangle, northern Arbuckle Mountains, Murray County, southern Oklahoma. Small fauna with 5 *Cyathocystis*, 2 *Platycystites*, 1 *Diabol-*

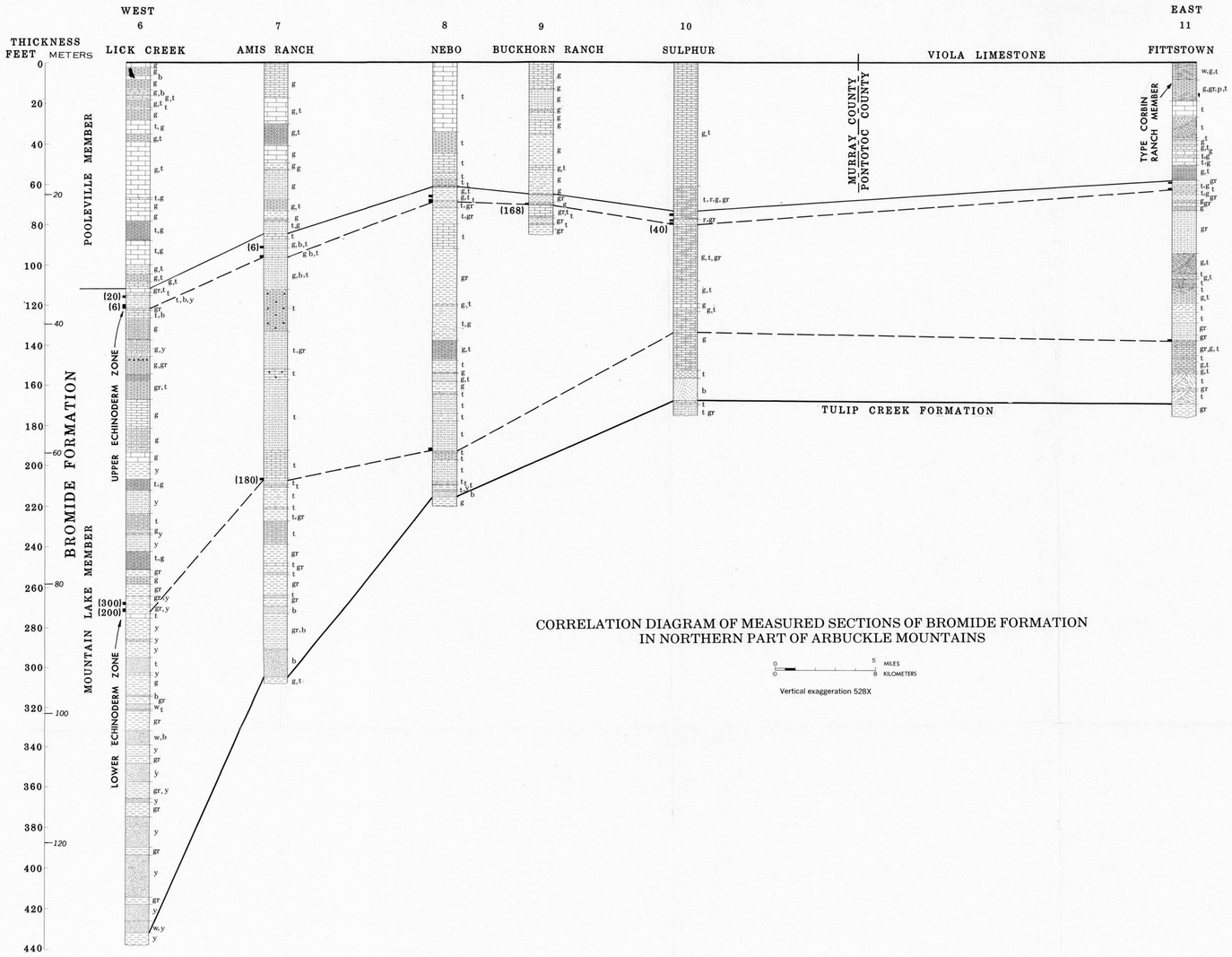
ocrinus, 1 edrioasteroid, and plates.

Veterans Lake. Lower Echinoderm Zone?, Mountain Lake Member, Bromide Formation, steep rubbly southeast bank of small stream, NW¼SW¼NE¼SE¼ sec. 21, T. 1 S., R. 3 E., about 4 km south of Veterans Lake, Sulphur South 7½ minute Quadrangle, northern Arbuckle Mountains, Murray County, southern Oklahoma. A *Platycystites*, a *Cyathocystis*, and numerous plates from possible zone.

Putman Ranch. Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, small shale bank on south side of dirt road opposite house, SE¼NW¼SW¼SE¼ sec. 22, T. 2 S., R. 1 E., on Putman Ranch about 3.2 km west of Interstate 35, Springer 7½ minute Quadrangle, southern Arbuckle Mountains, Carter County, southern Oklahoma. A *Platycystites* plus fragments and plates in float. Mrs. Hershel Putman lives in house at end of this dirt road.

Lick Creek Road. Lower Echinoderm Zone (and shale bed immediately below), Mountain Lake Member, Bromide Formation, shale banks alongside old dirt road up hill off main dirt road, 0.8 km southwest of Camp Classen headquarters building (see Fig. 89), NE¼NW¼SW¼ sec. 24, T. 1 S., R. 1 E., Turner Falls 7½ minute Quadrangle, northern Arbuckle Mountains, Murray County, southern Oklahoma. Small fauna with 3 *Platycystites*, 2 *Cyathocystis*, 1 *Doliocrinus*, 1 *Pirocystella*, and 1 *Archaeocrinus*.

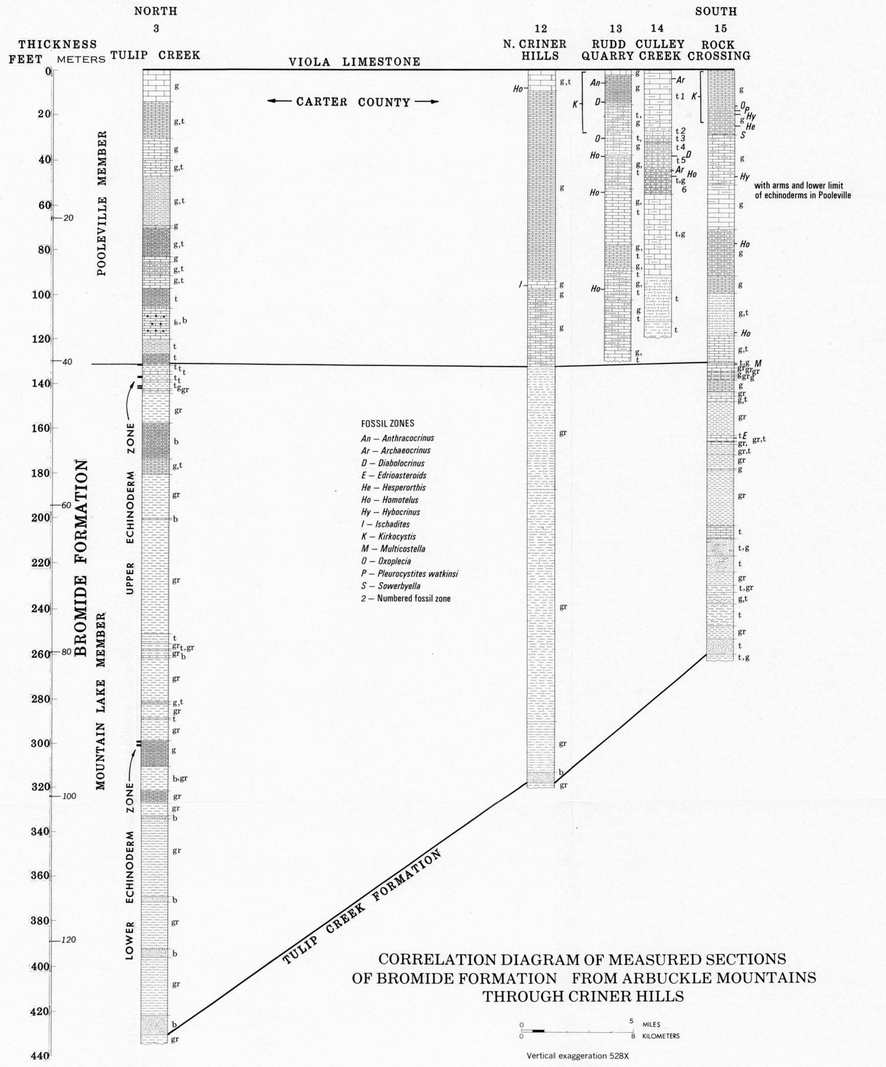
Dolese Quarry. Upper Echinoderm Zone, Mountain Lake Member, Bromide Formation, small exposure about 15 m off road just inside woods on north side of ridge made up of Pooleville and Viola Limestone, SW¼SE¼NW¼ sec. 27, T. 1 S., R. 2 E., about 0.4 km south of entrance to Dolese Quarry (inactive), Dougherty 7½ minute Quadrangle, in the northern Arbuckle Mountains, Murray County, southern Oklahoma. Sparse fauna with 1 *Oklahomacystis* and a partial *Cleiocrinus*.



CORRELATION DIAGRAM OF MEASURED SECTIONS OF BROMIDE FORMATION
IN NORTHERN PART OF ARBUCKLE MOUNTAINS

0 5 MILES
0 8 KILOMETERS

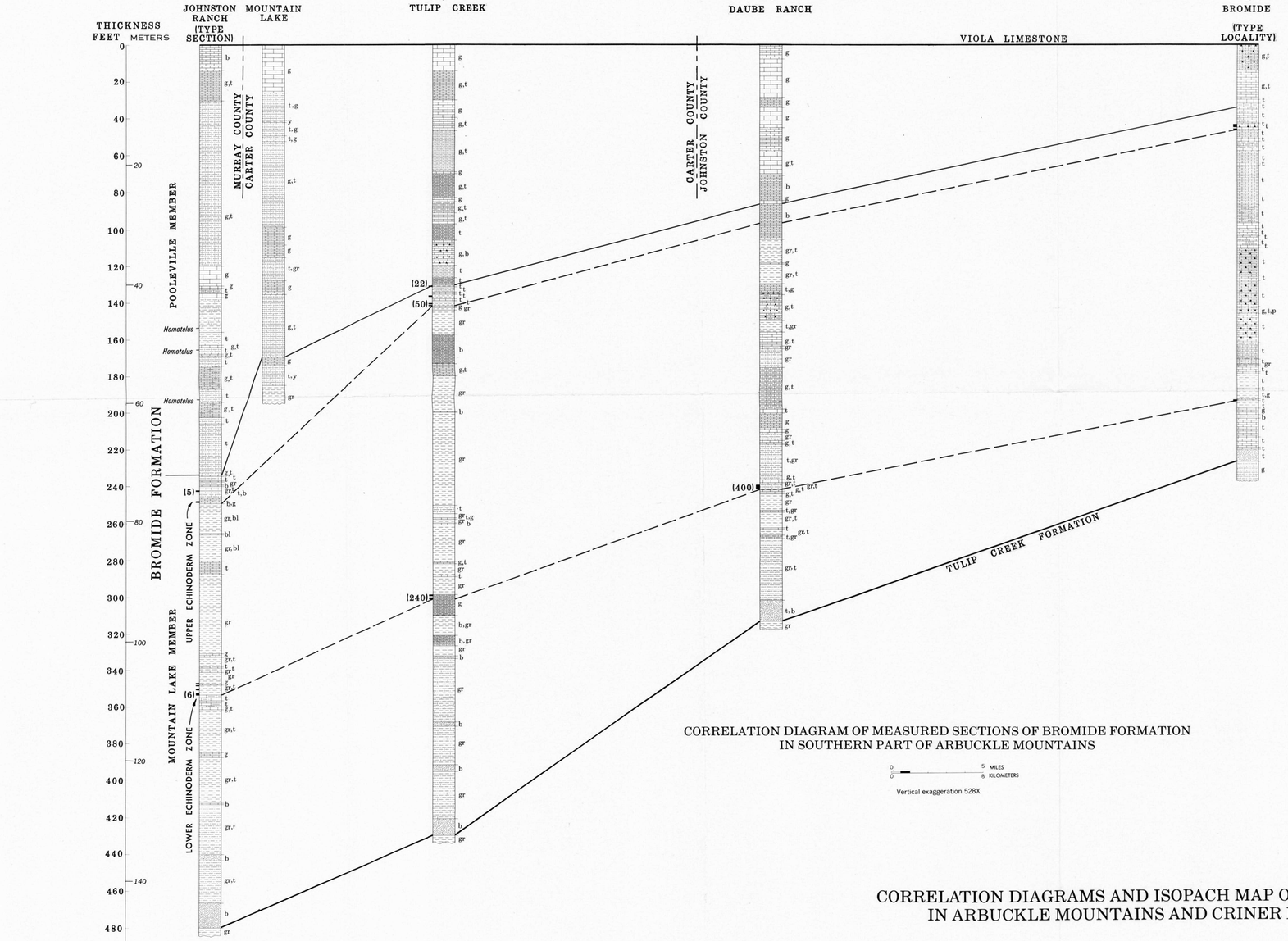
Vertical exaggeration 528X



CORRELATION DIAGRAM OF MEASURED SECTIONS
OF BROMIDE FORMATION FROM ARBUCKLE MOUNTAINS
THROUGH CRINER HILLS

0 5 MILES
0 8 KILOMETERS

Vertical exaggeration 528X



CORRELATION DIAGRAM OF MEASURED SECTIONS OF BROMIDE FORMATION
IN SOUTHERN PART OF ARBUCKLE MOUNTAINS

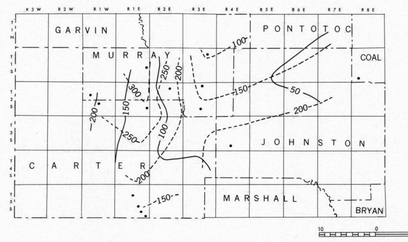
0 5 MILES
0 8 KILOMETERS

Vertical exaggeration 528X

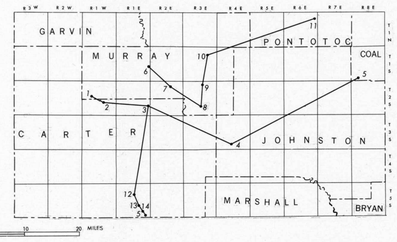
EXPLANATION

- Limestone
- Limestone with interbedded shale
- Cross-bedded limestone
- Interbedded limestone and shale
- Interbedded limestone and siltstone
- Interbedded limestone and sandstone
- Shale
- Shale with some interbedded sandstone
- Interbedded shale and sandstone
- Siltstone
- Cross-bedded siltstone
- Sandstone
- Cross-bedded sandstone
- Sandstone with some interbedded shale
- Chert
- (50) Echinoderm zone; number represents cubic feet of rock removed
- Correlation line at base of echinoderm zone

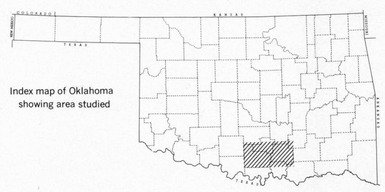
Color symbols: b, brown; bl, blue-gray; g, gray; gr, greenish-gray; p, pink; r, red-brown; t, tan; w, white; y, yellow-brown.



Isopach map of Pooleville Member (solid line) and Mountain Lake Member (dashed line) in Arbuckle Mountains and Criner Hills; isopach interval, 50 feet



Index map showing locations of measured sections and correlation diagrams of Bromide Formation in Arbuckle Mountains and Criner Hills



Index map of Oklahoma showing area studied

CORRELATION DIAGRAMS AND ISOPACH MAP OF BROMIDE FORMATION
IN ARBUCKLE MOUNTAINS AND CRINER HILLS, OKLAHOMA