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# TEXTURES AND CONDITIONS OF FORMATION OF MIDDLE PENNSYLVANIAN COAL BALLS, CENTRAL UNITED STATES[1]

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## ABSTRACT

Calcareous, fossiliferous nodules occasionally occur within coal seams of Middle Pennsylvanian age and may contain a wide variety of remarkably well-preserved plant taxa and sometimes marine animal shells. Textural variability within these nodules, termed coal balls, suggests that the energy of transport of organic constituents varied from mild current activity to turbid wave or perhaps tidal movements. The environment of coal ball deposition may have been in coastal marshes similar to the southwest Florida mangroves, where repeated influxes of marine sediment-bearing water provide both the energy source for agitation and mixing of organic detritus and the proper geochemical conditions for carbonate diagenesis.

## INTRODUCTION

Carbonate nodules containing petrified plant fossils and sometimes marine bioclastic mud occur within some coal seams of Middle Pennsylvanian age from the central U.S.A., New Brunswick, Canada, various parts of Europe, and the Donets Basin, U.S.S.R. (see Andrews, 1951; Baxter, 1960; and Snigirevskaya, 1972). These coal balls have been studied for over 100 years by paleobotanists for their contained plant fossils, which are often so well preserved as to allow detailed analysis of their cellular structures (see Andrews, 1951, and Baxter, 1965). Two mechanisms have been proposed for their origin. The theory of *in situ* formation, first proposed by Hooker & Binney (1855), holds that the organic matter in coal balls accumulated by gentle settling near growth positions in a peat bog and was permineralized soon after burial. Mamay & Yochelson (1953, 1962) proposed a second mechanism to explain the origin of coal balls consisting of marine bioclastic mud and petrified peat. They suggested that marine carbonate mud rollers and slurries were occasionally cast over beach barriers and carried into adjacent swamps during storm activity, where they mixed with peat and lithified into coal balls.

The coal ball textures examined during this study suggest that a whole range of energy conditions, from the very low energy *in situ* type to the

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very high energy "storm transport" conditions, were involved in the accumulation of organic matter within coal balls, and that coal balls may have formed within coastal marshes where marine waters repeatedly invaded the bogs, perhaps as tidal or seasonal influxes. Eight types of coal balls, which vary in their fossil content and mode of origin, can be defined on the basis of texture.

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# METHODS

Coal balls were collected systematically from localities in southeastern Kansas and northeastern Oklahoma (Fig. 1). All specimens are from coal seams of Middle Pennsylvanian age. The stratigraphic positions of the specimens from the localities in Oklahoma and Kansas are described in the columnar sections Figures 2 and 3. In addition, coal balls from localities in Indiana, Illinois, Iowa, and Missouri were used in this study. A list of localities and respective stratigraphic coal ball zones is given in Table 1.

TABLE 1.—*List of Localities Sampled.*

[Locations shown in Figure 1.]

| LOCALITY NO. | ZONE AND DESCRIPTION |
|---|---|
| 1 | Welch Locality 1 (Mineral Coal); NW¼ SW¼ sec. 27, R. 20 E., T. 28 N., Craig Co., Okla.; 4.5 mi (6 km) west of Welch near Okla. Hwy. 10. Bill's Coal Co. washing platform. |
| 2 | Welch Locality 2 (Iron Post Coal); sec. 11, R. 19 E., T. 27 N., Craig Co., Okla.; 9 mi (15 km) southwest of Welch. Abandoned strip pit. |
| 3 | Welch Locality 3 (Mineral Coal); NW¼ SE¼ sec. 2, R. 20 E., T. 28 N., Craig Co., Okla.; 5 mi (7 km) northwest of Welch. Active strip pit. |
| 4 | Vinita Locality (Iron Post Coal), Peabody Coal Company.<br>Tipple area: sec. 5, R. 18 E., T. 25 N., Craig Co., Okla.<br>Strip pits: sec. 31, R. 18 E., T. 26 N., Craig Co., Okla., 13 mi (22 km) west northwest of Vinita near U.S. Hwy. 60. |
| 5 | West Mineral Locality (Mineral and Fleming Coals), Pittsburg and Midway No. 19 Mine.<br>Tipple area: sec. 6, R. 22 E., T. 33 S., Cherokee Co., Ks., 9 mi (14 km) southwest of West Mineral.<br>Strip pit: sec. 29, R. 23 E., T. 32 S., Cherokee Co., Ks., 4 mi (6 km) south of West Mineral. |
| 6 | Garland Locality (Bevier Coal); sec. 25, R. 25 E., T. 26 S., Bourbon Co., Ks.; 2 mi (3.5 km) northwest of Garland. Washing and loading platform. |
| 7 | Berryville Locality (Calhoun Coal); SW¼ NE¼ NW¼ sec. 7, R. 13 W., T. 2 N., Lawrence Co., Ill. |
| 8 | Cayuga Locality (Murphysboro-equivalent Coal); sec. 34, R. 9 W., T. 18 N., Fountain Co., Ind. |
| 9 | Rich Hill Locality (Rich Hill Coal); sec. 21, R. 31 W., T. 38 N., Bates Co., Mo. |
| 10 | Oskaloosa Locality (Unnamed Cherokee Group Coal), Lost Creek Coal Company; sec. 36, R. 16 W., T. 75 N., Mahaska Co., Iowa; 6 mi (9 km) south of Oskaloosa near Hwy. 137. |
| 11 | What Cheer Locality (unnamed Cherokee Group Coal), What Cheer Clay Products Co.; sec. 9, R. 13 W., T. 76 N., Keokuk Co., Iowa; 0.5 mi (1 km) south of What Cheer. |

Coal balls from each locality were serially sectioned, and acetate peels were prepared from acid-etched, sawn surfaces by the technique described by Joy, Willis, & Lacey (1956). Selected specimens containing marine animal fossils were dissolved in dilute solutions of formic acid to free the pyritic and phosphatic shells from the carbonate cement. A total of 271 coal balls were examined in this study. Representative specimens described in this paper are stored in the paleobotanical collections of the University of Kansas, Lawrence, Kansas.

## COMPOSITION OF THE COAL BALL FLORAS AND FAUNAS

Coal balls from southeastern Kansas and northeastern Oklahoma contain a large diversity of both nonmarine plant and marine animal taxa. The qualitative aspects of the floral assemblages

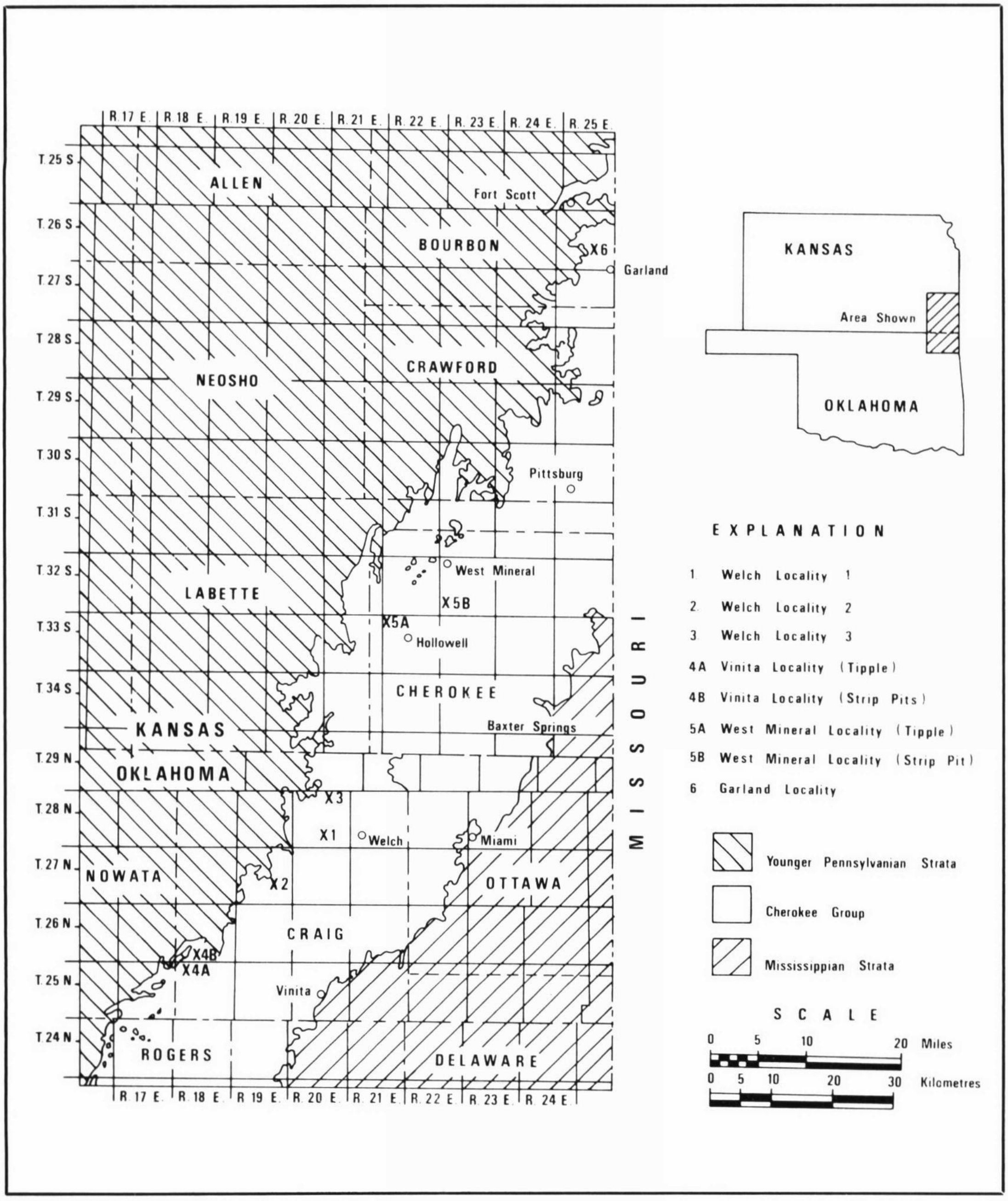


FIG. 1. Geologic map showing localities visited and the outcrop of the Desmoinesian Cherokee Group in southeastern Kansas and northeastern Oklahoma (adapted from Jewett, 1969, and Miser, 1954).

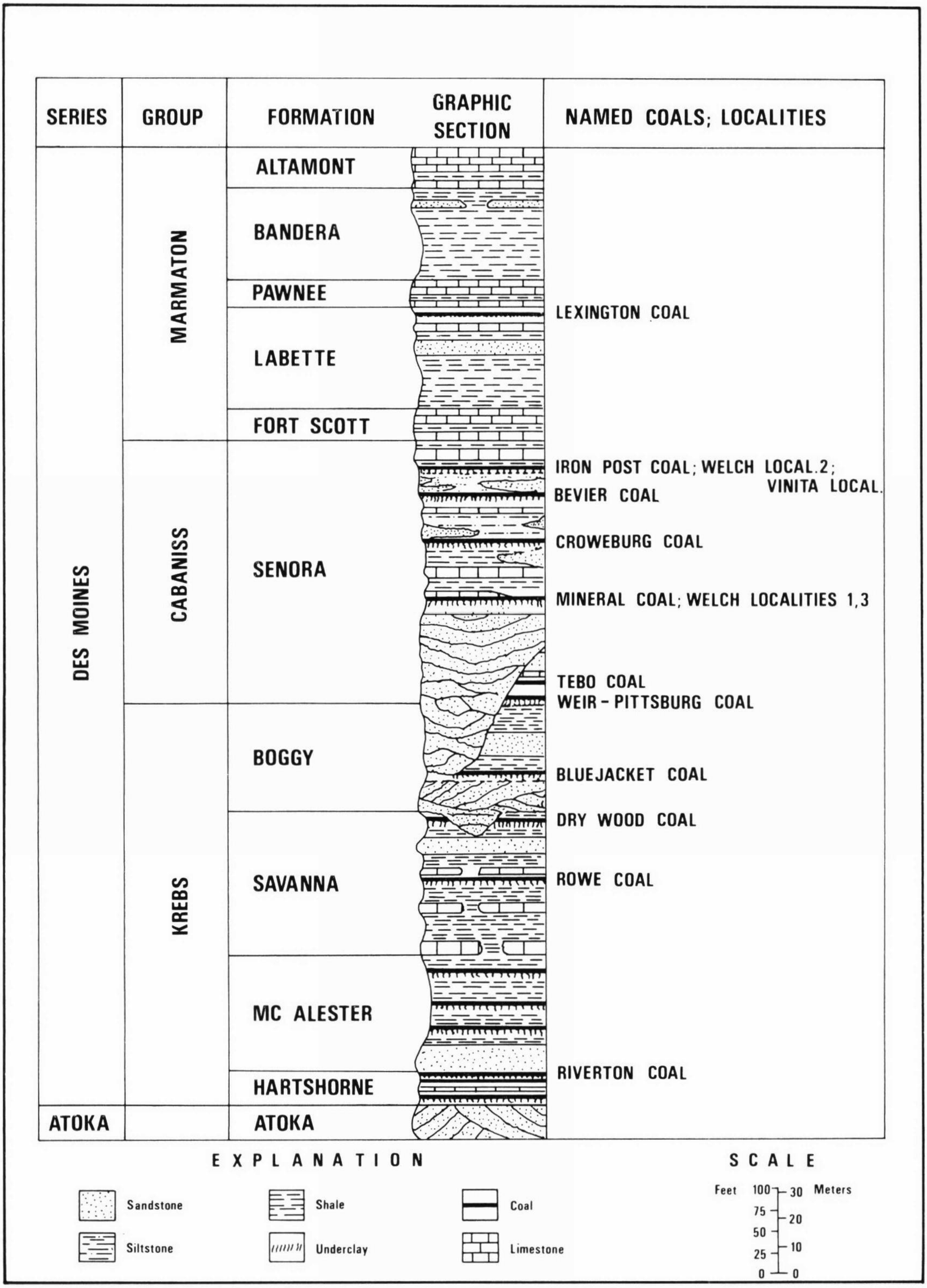


FIG. 2. Stratigraphic succession of Desmoinesian coals in Craig County, Oklahoma (adapted from Branson & Huffman, 1965).

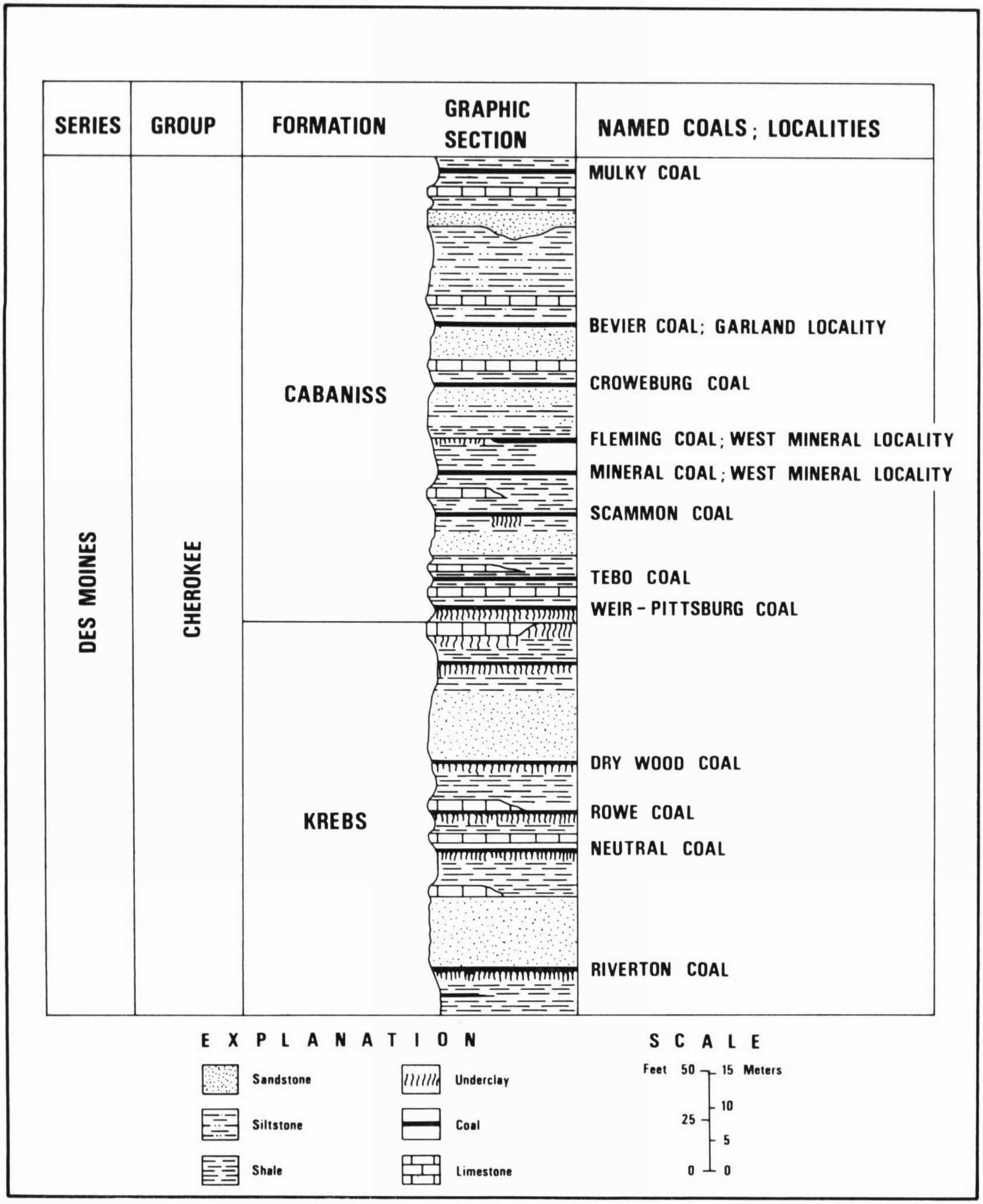


FIG. 3. Stratigraphic succession of coals in the Cherokee Group of southeastern Kansas (adapted from Zeller, 1968).

are usually similar in coal balls from the same coal seam, even in widely separated localities, while coal balls from different seams may show consistent differences in floral content; i.e., to a limited extent, the coal ball floras are useful as index fossils to specific coals. Differences in the faunas of coal balls from different localities and in different coals depend less on the relative abundances of the taxa than on the presence or absence of particular genera. As such, the faunas probably contain more definitive index fossils to given localities and coals than do the floras of coal balls. Tables 2 and 3 summarize the relative

TABLE 2.—*Relative Abundance of Plant Megafossils in Coal Balls from Welch Localities 1 and 2, the Vinita Locality, and the West Mineral Locality.* [Explanation.—*A,* abundant (present in nearly every coal ball examined); *C,* common (present in at least one-third of coal balls examined); *R,* rare (present in less than one-third of coal balls examined); *O,* absent.]

| TAXON | LOCALITY | | | |
|---|---|---|---|---|
| | Welch 1 | West Mineral | Welch 2 | Vinita |
| Lycopodophyta | | | | |
| Lepidocarpon | C | C | A | A |
| Lepidodendron | C | C | A | A |
| Lepidophloios | O | C | O | O |
| Lepidophylloides | C | C | A | A |
| Lepidostrobus | R | R | R | R |
| Paurodendron | R | R | R | R |
| Stigmaria | C | C | A | A |
| Arthrophyta | | | | |
| Asterophyllites | R | R | R | R |
| Astromyelon | R | R | C | C |
| Bowmanites | R | R | O | O |
| Calamites | C | R | C | C |
| Calamocarpon | O | R | C | C |
| Peltastrobus | O | O | O | R |
| Sphenophyllum | C | C | A | A |
| Marattiales | | | | |
| Cyathotrachus | O | R | R | O |
| Psaronius | C | C | A | C |
| Scolecopteris | R | C | C | C |
| Stipitopteris | R | C | C | C |
| Coenopteridales | | | | |
| Anachoropteris | O | C | R | R |
| Ankyropteris | O | R | O | O |
| Botryopteris | C | C | O | O |
| Etapteris | O | C | O | R |
| Pteridospermae | | | | |
| Alethopteris | C | C | A | C |
| Callistophyton | O | R | O | O |
| Conostoma | O | R | R | R |
| Dolerotheca | O | R | O | O |
| Heterangium | O | C | R | R |
| Medullosa | C | C | R | R |
| Microspermatopteris | O | R | O | O |
| Myeloxylon | C | C | A | C |
| Pachytesta | O | C | R | C |
| Tyliosperma | O | R | R | O |
| Cordaitales | | | | |
| Amyelon | C | C | R | R |
| Cardiocarpus | A | A | O | O |
| Cordaianthus | C | A | O | O |
| Cordaioxylon | A | A | O | O |
| Cordaites | A | A | R | O |

The relative abundances of individual organ genera in coal balls is a result not only of the abundance of the plants themselves but also of their habit and deciduous parts. Accordingly, it is not incongruous to have an abundance of the deciduous *Cordaites* leaves but perhaps few of the *Cordaioxylon* stems in a sample. Even more so, in the Coenopteridales, the leaf pinna may be numerous while the stem specimens are very rare. The abundance of any one part of the plant is therefore sufficient to establish the plant as a dominant element of the flora. Rare members of the floras listed above may not have been detected due to small sample sizes.

TABLE 3.—*Relative Abundances of Animal Taxa in Coal Balls from Welch Localities 1 and 2, the Vinita Locality, the West Mineral Locality, the Garland Locality, and the Berryville Locality.* [Explanation.—*A,* abundant (over 25 individuals counted in each residue); *C,* common (over 10 individuals counted in each residue); *R,* rare (at least one individual counted); *O,* absent.]

| TAXON | LOCALITY | | | | | |
|---|---|---|---|---|---|---|
| | Welch 1 | West Mineral | Garland | Welch 2 | Vinita | Berryville |
| Protozoa | | | | | | |
| Apterrinella | O | O | O | O | O | A |
| Undet. fusulinids | O | O | A | O | O | O |
| Porifera | | | | | | |
| Hexactinellid spicules | O | O | O | O | O | R |
| Coelenterata | | | | | | |
| Lophophyllid corals | O | O | O | R | R | O |
| Brachiopoda | | | | | | |
| Undet. linguloids | R | R | O | R | R | O |
| Undet. orbiculoids | R | R | O | A | C | O |
| Composita | O | O | O | O | R | O |
| Marginifera | O | O | C | A | A | O |
| Mesolobus | O | O | O | C | A | O |
| Undet. productids | C | C | O | O | O | C |
| Wellerella | O | O | O | A | A | O |
| Bryozoa | | | | | | |
| Penniretepora | O | O | O | O | O | A |
| Rhombopora | O | O | A | O | R | A |
| Mollusca | | | | | | |
| Bulimorpha | O | A | O | O | O | O |
| Donaldina | O | O | O | A | O | A |
| Eucochlis | O | C | O | O | O | O |

| TAXON | LOCALITY | | | | | |
|---|---|---|---|---|---|---|
| | Welch 1 | West Mineral | Garland | Welch 2 | Vinita | Berryville |
| Girtyspira | O | C | O | O | O | O |
| Glabrocingulum | A | O | O | O | O | O |
| Pseudozygopleura | O | A | O | O | O | O |
| Shansiella | O | O | O | C | O | C |
| Undet. low-spired gastropods | C | C | O | O | O | O |
| Undet. high-spired gastropods | C | C | O | O | R | O |
| Aviculopecten | O | O | O | R | R | O |
| Undet. pelecypods | O | O | O | R | R | O |
| Annelida | | | | | | |
| Spirorbis | C | O | O | R | O | O |
| Arthropoda | | | | | | |
| Bairdia | C | A | O | R | C | C |
| Bairdiacypris | C | A | O | R | A | O |
| Echinodermata | | | | | | |
| Crinoid columnals | C | C | R | A | A | A |
| Vertebrate fragments | R | R | O | R | R | R |

abundances of floral and faunal assemblages, respectively, at all localities where enough data were obtained for reasonable tabulations. The lists of taxa in these charts are probably incomplete due to small sample sizes.

Iron Post Coal specimens from Welch Locality 2 and the Vinita Locality are nearly identical in botanic content. Lycopods, particularly *Lepidocarpon, Lepidodendron, Lepidophylloides,* and *Stigmaria* are abundant and *Sphenophyllum, Calamites, Psaronius,* and *Medullosa* organs are common in coal balls from both localities. The Iron Post Coal nodules may be characterized by an almost complete lack of *Cordaites,* rarity of coenopterid ferns, and abundance of the organ genus *Lepidocarpon,* both as isolated sporophylls and as cone fragments. Coal balls from the Mineral Coal, both at Welch Locality 1 and the West Mineral Locality, may be readily distinguished from the Iron Post Coal specimens by their abundance of *Cordaioxylon* and *Cardiocarpus,* which are completely lacking in coal balls from the Vinita Locality and Welch Locality 2.

Floral assemblages of the Mineral and Fleming Coal nodules may be further distinguished from the Iron Post Coal specimens by their abundance of coenopterids, which are rare in the Iron Post Coal specimens. Lycopods, arthrophytes, marattiaceous ferns, and pteridosperms are common in the coal balls from the West Mineral Locality and Welch Locality 1.

The faunas of coal balls from the Mineral Coal localities are characterized by abundance of gastropods and scanty content of brachiopods. Gastropod genera are, for the most part, endemic to individual localities within the Mineral Coal. *Glabrocingulum* is abundant at Welch Locality 1 but apparently absent from the residues studied from the West Mineral Locality. The gastropod fauna at the West Mineral Locality is characterized by *Bulimorpha, Pseudozygopleura, Eucochlis,* and *Girtyspira.*

The Iron Post Coal marine coal balls are characterized by abundant brachiopod faunas. *Marginifera, Mesolobus,* and *Wellerella* are abundant at both the Vinita Locality and Welch Locality 2. Gastropods are virtually absent from the Vinita Locality specimens; however, *Donaldina* and *Shansiella* are common at Welch Locality 2. Marine coal balls from the Calhoun Coal at the Berryville Locality contain abundant crinoid columnals, bryozoans, *Donaldina,* and *Apterrinella.* The faunal assemblage of coal balls in the Bevier Coal at the Garland Locality contains abundant fusulines, bryozoans, and *Marginifera.*

## TEXTURAL TYPES OF COAL BALLS

Eight textural categories of coal balls are described in this study. It must be emphasized that all gradations exist among textures, and their categorizations are made in order to clarify interpretations as to the variable conditions of coal ball formation. Table 4 lists the number of specimens examined in each textural type.

*Type 1* (Fig. 4,*A*). Coal balls of Type 1 consist of masses of relatively uncrushed and unfragmented plant organs that are well preserved and relatively undecayed. In some of these specimens the preservation of the plant tissues is so perfect that it is possible to observe all details of the cell walls (primary and secondary pitting) as well as certain cytological details such as nuclei and ergastic compounds. Type 1 specimens consisting primarily of aggregations of leaves, stems, and fructifications show well-developed planar alignment or bedding of plant constituents. The long axes of twigs and other organs are often linearly

TABLE 4.—*Sample Sizes of Textural Types of Coal Balls from Localities in Oklahoma, Kansas, Missouri, Iowa, Illinois, and Indiana.* [Explanation of textural types.—1, relatively uncrushed, unfragmented, and undecayed plants; 2, moderately decayed or degraded plants; 3, brownish, homogeneous masses of thoroughly degraded plant debris; 4, highly fragmented, pulverized, and thoroughly mixed plant remains; C, two zones of textures of Types 1 and 3 and 3 and 4; 5, marine bioclastic mud mixed homogeneously with plant debris; 6, marine bioclastic mud mixed with plant debris in layered or bedded orientation; 7, central core of marine bioclastic mud sharply delineated from peripheral zone of plant remains; 8, pyrite masses.]

| LOCALITY | TYPE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | C | 5 | 6 | 7 | 8 | TOTAL |
| Welch 1 | 0 | 3 | 1 | 4 | 0 | 12 | 12 | 0 | 57 | 99 |
| Welch 2 | 3 | 10 | 0 | 20 | 1 | 11 | 2 | 0 | 0 | 47 |
| Welch 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vinita | 0 | 11 | 23 | 10 | 0 | 5 | 1 | 2 | 0 | 52 |
| W. Mineral* | 10 | 14 | 0 | 0 | 0 | 13 | 2 | 0 | 3 | 42 |
| Garland | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 7 | 9 |
| Berryville** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 0 | 13 |
| Cayuga** | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 3*** |
| Rich Hill** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Oskaloosa** | 2 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 4 |
| What Cheer** | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Totals | 16 | 39 | 24 | 34 | 2 | 45 | 18 | 16 | 67 | 271 |

* Marine coal balls are abundant in this sample due to selective collecting for this type.
** Borrowed, nonrandom sample.
*** This number reflects a coal ball aggregate.

aligned within the bedding. Bedding within the coal balls parallels the laminae of the surrounding coal. Other specimens of Type 1 consist nearly entirely of permineralized roots or rootlets, usually *Psaronius* or *Stigmaria,* or are composed entirely of a single permineralized plant fragment such as a lycopod stem or *Cardiocarpus* nucellus.

Type 1 coal balls are present at the West Mineral Locality and the Oskaloosa Locality, but are not nearly as abundant as nodules containing moderately decayed plants. Except for a few rootlet-bearing specimens, coal balls of Type 1 are absent from the sample of Iron Post Coal materials from Craig County, Oklahoma.

*Type 2* (Fig. 4,*B*). Much of the plant debris in Type 2 coal balls shows considerable evidence of decay or degradation. Most Type 2 specimens display a layered arrangement of plant organs with linear orientation of twigs as in the Type 1 texture; however, the effects of compaction, crushing, and fragmentation of plant debris are more severe in the Type 2 nodules. Plant fossils in the Type 2 texture are usually identifiable to species level although the cell structures are usually considerably altered. Early stages of decay are frequently evident as a dissolution of the middle lamella and primary walls, particularly in woody tissues. Degraded *Cordaioxylon,* lycopod periderm, and other woody tissues are occasionally broken up into geometrical fragments due to recrystallization by coarse-grained calcite. Plant tissues in some specimens are displaced or obliterated by varying amounts of pyrite. Type 2 specimens, especially those consisting of moderately degraded periderm, are common at the localities in Kansas and Oklahoma.

*Type 3* (Fig. 4,*C*). Type 3 texture consists of brownish, homogeneous masses of organic matter; probably peat that had decayed to near-lignite stages before mineralization. No cellular details are evident in any coal balls of this type, except in bits of dispersed fusain. Such specimens are common in the Iron Post Coal near Vinita, Oklahoma.

*Type 4* (Fig. 4,*D*). Nodules of Type 4 consist of crushed and highly fragmented plant organs in a matrix of pulverized and thoroughly macerated plant debris. Most of the fragmented plant remains are identifiable to generic or species level, since the permineralization by calcite did not obliterate cellular details. Type 4 texture is common in coal balls from the Iron Post Coal in northeastern Oklahoma, but is rare or absent elsewhere.

*Type 5* (Fig. 4,*E*). In Type 5 specimens marine carbonate mud containing abundant pyritic and calcareous shells is mixed homogeneously with fragmented, pulverized, resistant plant debris. The bioclastic debris is either swirled into roughly concentric bands or is distributed randomly within the carbonate mud matrix. This texture is the same as that described for homogeneous-mixed coal balls by Mamay & Yochelson (1962). Specimens of this type are abundant in the Iron Post Coal of northeastern Oklahoma, but represent

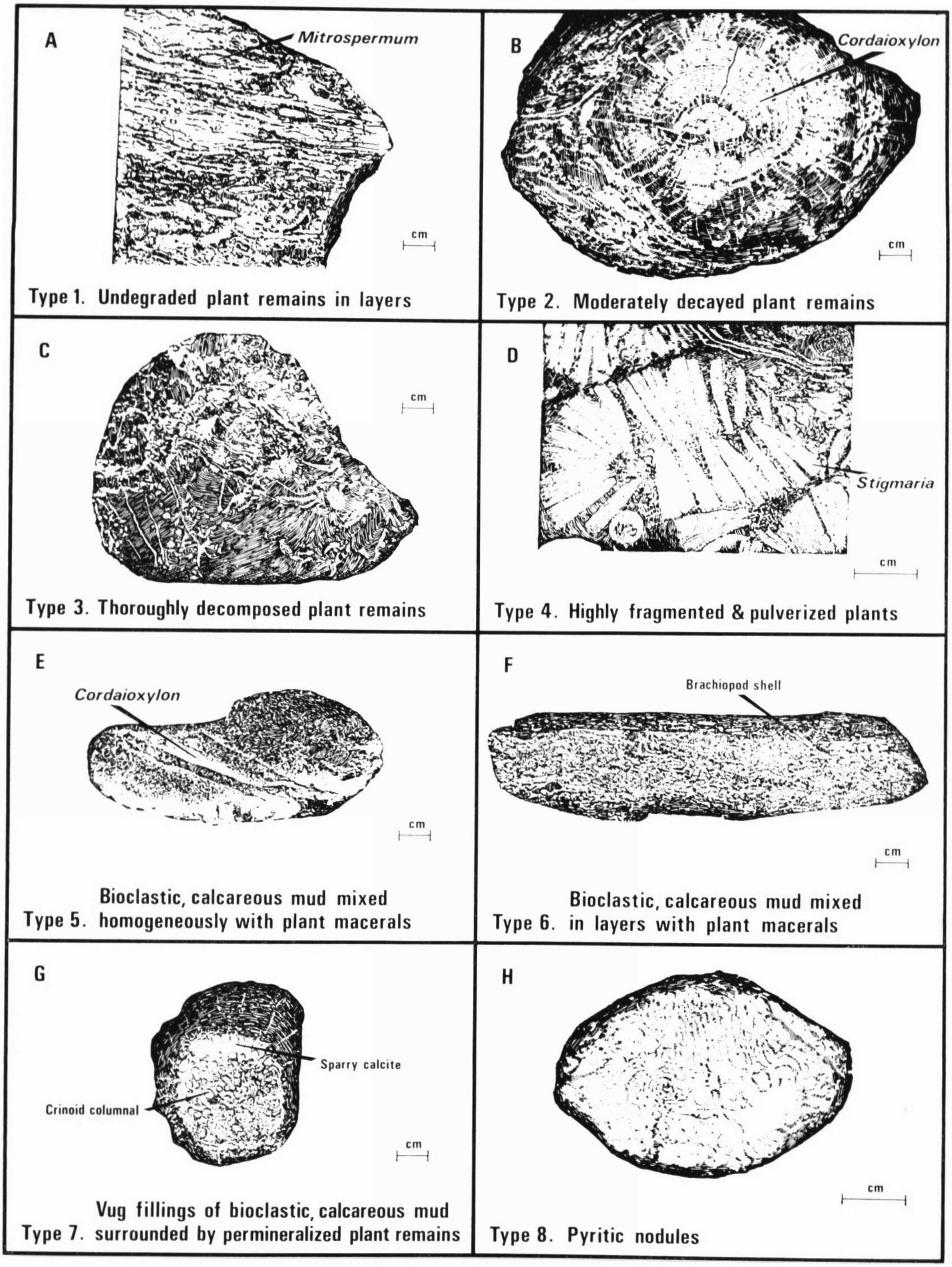


FIG. 4. Textural types of coal balls: A-H, sketch representations, traced from specimens.

only a small minority of the sample at localities in southeastern Kansas.

*Type 6* (Fig. 4,*F*). The fossil constituents of Type 6 coal balls are bedded in layers which roughly parallel the surrounding coal laminae. Shells are mixed with pulverized and amorphous plant debris within the layers. The shells are often unfragmented and unabraded and may be composed of their original material or they may be replaced by pyrite. Type 6 specimens are usually lenticular or sheetlike in external shape, the long dimensions paralleling the coal laminae. They are common at Welch Locality 1 (Mineral Coal) and present in small amounts at Welch Locality 2 (Iron Post Coal), West Mineral Locality (Mineral and Fleming Coals), and Garland Locality (Bevier Coal).

*Type 7* (Fig. 4,*G*). Type 7 specimens, described as heterogeneous-mixed coal balls by Mamay & Yochelson (1962), contain central cores of marine bioclastic mud sharply delineated from peripheral zones of permineralized plant remains. The marine cores are commonly cylindrical, although they may be irregular in shape, and commonly display "graded bedding" of bioclastic debris. In many specimens, sparry calcite occupies part of the core adjacent to the finest grained fraction of the calcareous mud. Such features of the marine cores strongly suggest that they are vug fillings. Type 7 nodules are common in the Calhoun Coal near Berryville, Illinois, and are rare in the Iron Post Coal near Vinita, Oklahoma, and the Rich Hill Coal near Rich Hill, Missouri.

*Type 8* (Fig. 4,*H*). A complete gradation exists between heavily pyritized coal balls containing recognizable fossils and pyrite masses lacking internal structure, yet surrounded by coal. These pyrite masses, which display a wide variety of external morphology—irregular casts of periderm, sheetlike bands displacing laminae in coal, and spheroidal to lenticular shapes—are of Type 8 texture. Pyrite masses occur within coal seams at all localities cited in this paper.

## DISCUSSION

Coal balls examined from southeastern Kansas and northeastern Oklahoma may have formed in swamp environments much more closely associated with marine proximity and sea level fluctuations than previously recognized. Textural variability in coal balls of Middle Pennsylvanian age may have been produced by conditions analogous to those existing in the southwest Florida mangroves today.

Scholl (1969) concluded that the succession of freshwater to brackish water to marine sediments in core sections obtained from the Florida mangroves is very similar to the stratigraphic succession of sedimentary rocks in some Pennsylvanian cyclothems. Since the paralic sediments in the southwest Florida mangroves are derived entirely from coastal sources, Scholl (1969) suggested that the stratigraphy in some Pennsylvanian cyclothems represents a partial duplication of sedimentary environments where there was a gradual rise in relative sea level across a coastal platform supporting peat-forming plants.

Wanless, Baroffio, & Trescott (1969) discussed the depositional environment of the Mulberry Coal, a seam slightly younger than the Iron Post Coal and cropping out along a northeast-southwest trending belt in eastern Kansas and western Missouri, and concluded that this seam was deposited in a coastal marsh environment. The similar pattern of outcrop of the coal ball-bearing Mineral and Iron Post Coals suggests that they, too, were deposited in coastal marsh environments. The coal seams may have been restricted to linear belts by the slope of the land away from the Ozark Uplift to the southeast. A shallow platform sea west and north of the marsh may have repeatedly advanced eastward, depositing marine sediments cyclically on numerous beds of coal. It is noteworthy that the Mineral and Iron Post Coals are directly overlain by marine sediments.

Scholl (1969) discussed the hydrology of the coastal mangrove waters in southwest Florida and stated that seasonal environmental changes produce marked fluctuations in the salinity of the water from values of only a few parts per thousand in the summer when amounts of freshwater runoff is high, to more than 40 parts per thousand in the winter and early spring drought months. Similar salinity fluctuations in the Desmoinesian peat bogs of southeastern Kansas and northeastern Oklahoma may have imposed strong enough vari-

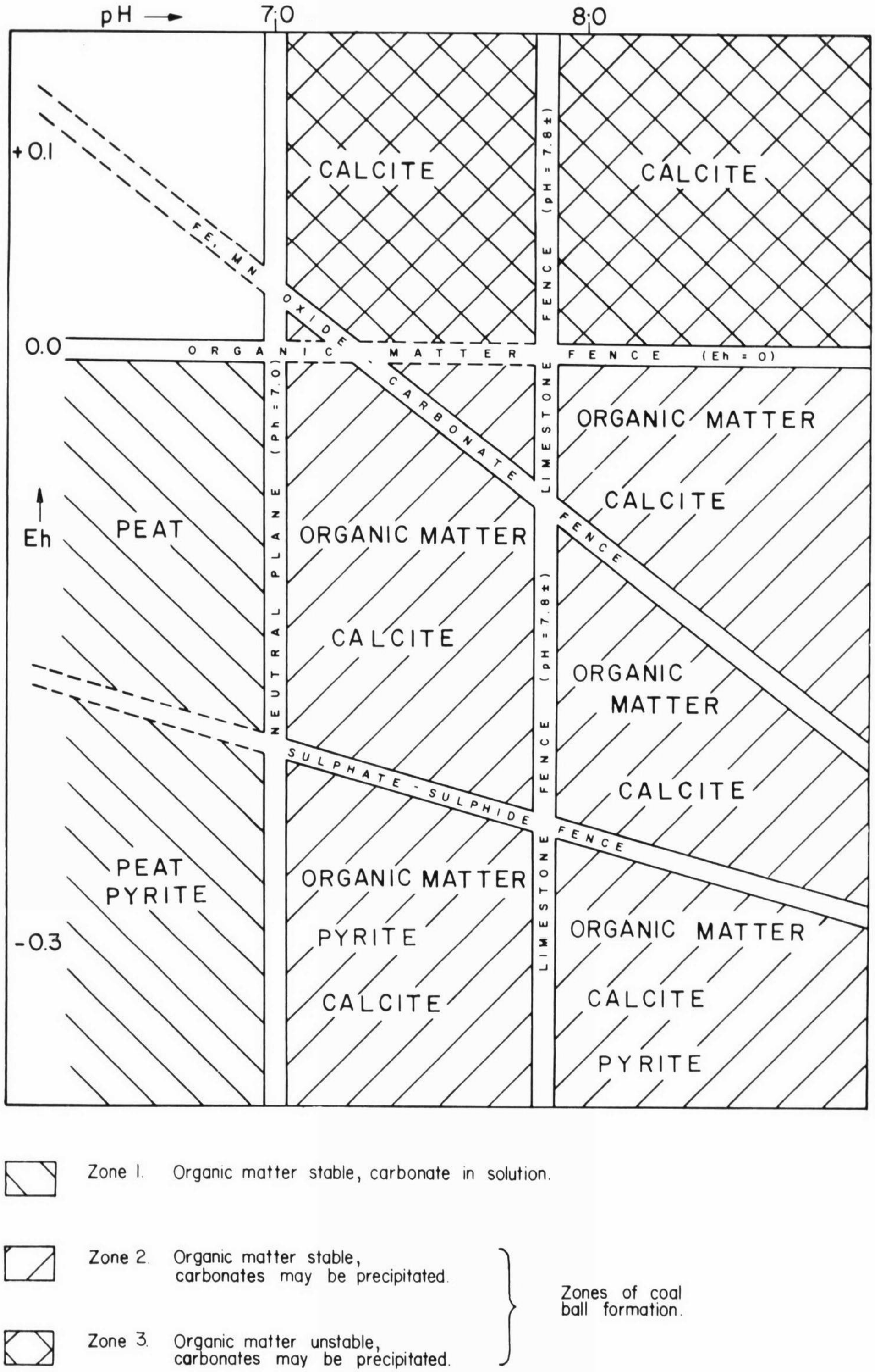


FIG. 5. Suggested relationship of Eh-pH conditions to coal ball formation in a coastal marsh subjected to marine transgression (adapted from Krumbein & Garrels, 1952).

ations in the Eh and pH of the swamp water to allow precipitation of calcite in some areas and solution of calcite in other parts of the swamp. A suggested pattern of Eh and pH changes accompanied by an increase in salinity of bog water and its controls on carbonate precipitation in the formation of coal balls is illustrated in Figure 5. Carbonate precipitation may not have been initiated until the acidity of the bog water was completely neutralized (Zones 2 and 3 of Fig. 5). Organic matter may have remained relatively undecayed as long as the swamp water was reducing (Zones 1 and 2 of Fig. 5). Rapid oxidation and aerobic decay of the plant remains may have occurred in oxidizing parts of the swamp water (Zone 3 of Fig. 5).

Coal balls containing plant remains that are aligned in planes paralleling the coal laminae may have formed in parts of the swamp far enough inland from the sea that the tidal currents were not powerful enough to pulverize the peat, yet enough current activity may have been present to align twigs in the peat along the direction of waterflow. Permineralization in specimens containing well-preserved plant tissues that are relatively uncrushed may have occurred either rapidly after deposition of the peat, or in reducing parts of the bog where decay was so slow that plant tissues may have remained relatively unaltered for long periods of time without the aid of a petrifying mineral. Coal balls containing highly degraded plants may have been permineralized in reducing parts of the bog after very long exposure to anaerobic decay, or may have formed after the bog water turned oxidizing and aerobic decay of peat took place. The crystallization of calcite in some specimens may have occurred around centers of bacterial decay enriched in carbonate. In other nodules, the precipitation may be related to selective absorption of mineral-laden water by thick-walled tissues, with crystallization occurring during an evaporative phase.

The fragmentation, maceration, and thorough mixing of plant remains in coal balls from the Iron Post Coal in northeastern Oklahoma suggests that these coal balls formed in a highly turbid environment. The occurrence of marine bioclastic mud mixed homogeneously with macerated plants in some specimens from the Iron Post Coal suggests that the turbidity may have been caused by wave agitation in eddy zones during a transgressive phase of a marine sea onto a coastal platform containing peat-producing plants. Pyritized marine invertebrates bedded between laminae of coal at the Vinita Locality may be evidence that these animals were able to live in the coastal marsh during the growth of plants and production of peat, at least for short periods of time before the marsh was buried by overlying sediments.

Bioclastic mud introduced to the coastal marshes may have been partially dissolved by acidic bog water. Numerous homogeneous-mixed (Type 5) coal balls from the West Mineral Locality display evidence of a partial solution of the marine mud. As significant quantities of the marine material dissolved, the bog water may have locally become alkaline, at which point soluble carbonates that penetrated the peat may have permineralized the plant tissues and formed nonmarine coal balls. Undissolved carbonate mud may have mixed with the peat and lithified to form the marine coal balls.

Heterogeneous-mixed coal balls (Type 7), which consist of central cores of marine mud sharply delineated from peripheral zones of permineralized peat, may have formed as bioclastic mud from overlying marine sediments oozed down through fractures and other open spaces in the peat. Seepage of carbonate-saturated water around the mud may have caused permineralization of the peat mass as the carbonate mud lithified in vugs. Since heterogeneous-mixed coal balls are the only type of marine coal ball found at the Berryville Locality, the transgressive phase of the sea responsible for introducing the marine sediments may have covered the vegetation so quickly at this locality that the only mixing of marine material with peat was by downfiltering the carbonate mud through open spaces in the buried peat debris.

## CONCLUSIONS

(1) At least eight textural types of coal balls of Middle Pennsylvanian age may be defined, with all gradations existing among them, which show the high variability in their environments of deposition and diagenesis.

(2) Specimens consisting entirely of relatively

unfragmented plant organs, usually arranged in layers roughly paralleling the surrounding coal laminae, may have formed in moderately low energy environments where there was mild current activity strong enough to align the long axes of plant debris along the direction of current flow. Three textural types of low-energy coal balls are recognized based on level of degradation of the plant debris: Type 1, undegraded plants; Type 2, moderately degraded plants; and Type 3, thoroughly decomposed plant debris.

(3) Coal balls containing or associated with marine bioclastic, calcareous mud may have formed in highly agitated environments where strong current or wave activity pulverized much of the plant debris. Specimens consisting entirely of thoroughly fragmented and macerated plants constitute Type 4; nodules containing plant macerals mixed homogeneously with calcareous, fossiliferous mud make up Type 5; and those containing marine and nonmarine components arranged in layers (formed by mixing, then settling of detritus from suspension) belong to Type 6.

(4) Hollows within spongy, buried peat masses occasionally may have been filled with calcareous mud ooze from overlying transgressive sediments. Coal balls thus formed consist of central cores of marine carbonate vug fillings surrounded by permineralized plants and comprise Type 7.

(5) A final type of coal ball, Type 8, consists nearly entirely of disseminated, fine-grained pyrite and may have formed as either secondary replacement of other coal ball types or as primary crystallization under acidic and reducing conditions within the bog.

(6) Coastal marshes formed during the transgressive phase of a typical Pennsylvanian cyclothem provide a suitable environment for coal ball formation. These marshes may have been analogous, although on a much larger scale, to the southwest Florida mangroves today, where repeated tidal and seasonal influxes of marine water occur within the mangroves (Scholl, 1969). The seawater influxes provide both the energy source and the proper geochemical conditions necessary to explain coal ball textures and diagenesis.

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