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PALEOECOLOGY AND DEPOSITIONAL ENVIRONMENT  
OF FORT HAYS LIMESTONE MEMBER, NIOBRARA CHALK  
(UPPER CRETACEOUS), WEST-CENTRAL KANSAS

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### ABSTRACT

In west-central Kansas the Fort Hays Limestone Member (lower Coniacian) of the Niobrara Chalk ranges in thickness from about 45 to 80 feet; it consists predominantly of thick to massive beds of nearly pure chalky limestone separated by very thin to thin beds of chalky shale. Beds of chalk and shaly chalk are considerably less abundant.

Chalky limestones are texturally homogeneous and consist chiefly of cryptograined matrix, mostly coccoliths; subordinate constituents include foraminiferal tests, bivalve fragments, and authigenic iron compounds. Shaly chalks and chalky shales are thinly laminated to laminated and contain large quantities of clayey to silty terrigenous detritus.

Strata of the Fort Hays are remarkably persistent laterally, and in Trego County each exposure of the member may be correlated on a bed-by-bed basis; this provides an excellent stratigraphic framework for sampling, and attests to a stable, geographically widespread depositional regime.

Eleven macroinvertebrate species were observed in the Fort Hays and four in the lower part of the Smoky Hill. These include species of the bryozoan *Pyripora*, the annelid *Serpula*, and the bivalves *Inoceramus*, *Volviceramus*, *Pycnodonte*, and ?teredine tubes. In addition, the following miscellanea are noteworthy in both members: sponge and barnacle borings, small tubular structures attached to inoceramid valves, planktonic foraminiferans and coccoliths, scattered fish remains, and diverse burrow structures. Lateral and vertical trends in density and distribution of both macroinvertebrates and trace fossils are correlative throughout Trego County.

Three general assemblages are discernible among macroinvertebrates: 1) a gryphaeate *Pycnodonte* assemblage restricted essentially to the basal Fort Hays, dominated by *P. aucella*, 2) a bowl-shaped inoceramid assemblage ranging through most of the Fort Hays, dominated by *Pycnodonte congesta* and successive members of the *Inoceramus deformis* lineage, and 3) a rudist-like inoceramid assemblage appearing at the top of the Fort Hays and ranging well into the Smoky Hill, dominated by *Pycnodonte congesta* and *Volviceramus grandis*. The last two assemblages are closely related; within them are numerous examples of inter- and intraspecific relationships.

Various lines of physical and biological evidence indicate that 1) Fort Hays sediments in west-central Kansas were deposited far from shore, during maximum invasion of the Niobrara sea, 2) relatively little terrigenous detritus reached this part of the depositional basin, thus the sediments consisted essentially of pure carbonate mud, diluted periodically by brief influxes of clay and silt, 3) initial accumulation of Fort Hays sediments followed a long interval of nondeposition (latest Turonian through earliest Coniacian) in the Western Interior, 4) a regional slope and broad topographic irregularities were present on the pre-Niobrara surface, 5) Fort Hays deposition in west-central Kansas commenced in shoal areas subject to wave scour but the waters deepened progressively through Fort Hays and early Smoky Hill deposition, probably attaining depths comparable to those of the present midshelf region off the Atlantic coast, 6) the nearly pure carbonates of the Fort Hays accumulated slowly and the clayey sediments comparatively rapidly, 7) the substrate remained soft and mechanically unstable until late in diagenesis, 8) appreciable current activity accompanied Fort Hays deposition, although it began to wane toward the close of that epoch, 9) the basal part of the water column was probably extremely turbid, and may have promoted local small turbidity flows, 10) the waters and sediments were well aerated, 11) the waters were also warm and of normal salinity, and 12) major factors limiting the density and distribution of organisms were slurry substrates and murky waters.

The overall change from Fort Hays to Smoky Hill deposition apparently consisted chiefly of 1) deposition of greater quantities of terrigenous clay and silt, 2) correspondingly increased rates of deposition, 3) decreased current activity and water aeration, and 4) greatly decreased sediment aeration. The last factor was evidently an effective barrier against propagation of the endobenthos, and soft substrates continued to restrict epibenthos.

## INTRODUCTION

## GENERAL STATEMENT

The Niobrara Chalk was deposited during one of the most widespread of Late Cretaceous marine transgressions (Cobban & Reeside, 1952, p. 1025; Reeside, 1957, p. 525-528). The depositional basin, which inherited its configuration mostly from that of the preceding Greenhorn depositional basin (Fig. 1), occupied most of the Western Interior Region of Canada and the United States and was connected with both the Arctic Ocean and the Gulf of Mexico. This basin constituted a major thoroughfare for the migration and mixing of faunas, and the repeated association of certain assemblages with particular lithotypes reflects striking environmental cyclicity during transgressive-regressive phases of deposition (Kauffman, 1967, 1969). Strata within this basin thus play key roles in the reconstruction of Late Cretaceous history in the Western Interior, although to date the Niobrara and its equivalents have rarely been studied in detail.

An equally important incentive for studying the Niobrara is the fact that true chalk rocks have been neglected in America, relative to other major lithotypes, and thus remain poorly known ecologically and sedimentologically.

## PURPOSE AND SCOPE

The Niobrara Chalk in Kansas has been the object of stratigraphic and paleontologic studies for approximately a century, yet detailed biostratigraphic and paleoecologic investigations have not been made, and practically no attention has been devoted to trace fossils. The depositional environment has been reconstructed only in terms of its salient features.

The lower part of the formation, the Fort Hays Limestone Member, is especially suited for detailed investigation and was therefore selected for the present study. My primary goals were: 1) to analyze and correlate representative exposures of the Fort Hays, 2) to determine the identity, density, and distribution of macroinvertebrate fossils found in these rocks, 3) to identify and describe the trace fossils present and to determine their density and distribution, and 4) to use these data in making paleoecological interpretations and in reconstructing the environment of deposition. In addition, the lower few feet of the overlying Smoky Hill Chalk Member were studied in order to interpret the transitional change from Fort Hays to Smoky Hill deposition.

In order to glean greater detail from individual stratigraphic sections, the work was limited to a small area having exceptionally good exposures. Trego County (Fig. 2) especially meets these requirements, and is also

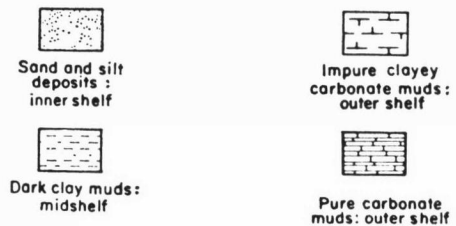
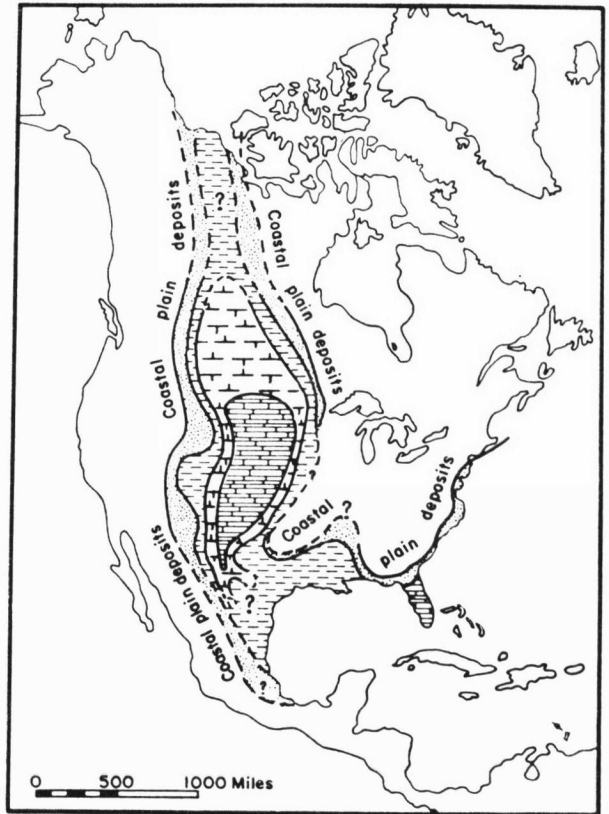


FIG. 1. General sediment distribution during peak transgression of the Cretaceous epeiric sea, Greenhorn cyclothem. Sediment distribution during the Niobrara transgression was extremely similar. (From Kauffman, 1969, fig. 1.)

important because here the Fort Hays is at approximately its maximum thickness along the Kansas outcrop belt. Field studies were conducted during the summer of 1967, and the exposures were revisited briefly in the spring of 1968.

This report consists chiefly of three parts: 1) a general section embracing important aspects of stratigraphy, petrology, and sedimentology, 2) a discussion of paleontology and biometry, and 3) environmental and paleoecological interpretations based upon these data. Regional and temporal perspective is achieved through

numerous references to previous work in the Western Interior Region. The trace fossils and their paleoecological and environmental implications, which agree closely with those presented herein, have been described in a separate report (Frey, 1970).

**DISCUSSION OF THE ROCKS AND LOCALITIES EXAMINED**

**GENERAL STATEMENT**

Niobrara or equivalent strata are well represented throughout the Western Interior Region (Cobban & Reeside, 1952; Reeside, 1957). A significant shift in facies distribution is apparent from Fort Hays deposition to Smoky Hill deposition (Fig. 3).

The Niobrara underlies approximately the northwestern one-fifth of Kansas (Merriam, 1963, fig. 19). It

attains a maximum thickness of more than 750 feet in Wallace County and thins markedly to the east and south. The eastern edge of the outcrop belt is extremely irregular due to stream dissection, and outliers farther to the east show that the unit was originally more widespread than at present.

The Fort Hays, as exposed in Kansas, ranges in thickness from about 45 to 80 feet and consists primarily of thick to very thick beds<sup>1</sup> of chalky limestone that are separated by very thin to thin beds of chalky shale. Chalk, shaly chalk, and bentonite are considerably less common in the member.

The Smoky Hill ranges in thickness from about 400 to more than 650 feet. This member consists mostly of shaly chalk and chalky shale but also contains notable beds of chalk; numerous bentonites are present.

<sup>1</sup> Terms pertaining to stratification are those recommended by Dunbar & Rodgers (1957, p. 97-98). Lithotypes are defined in Table 3.

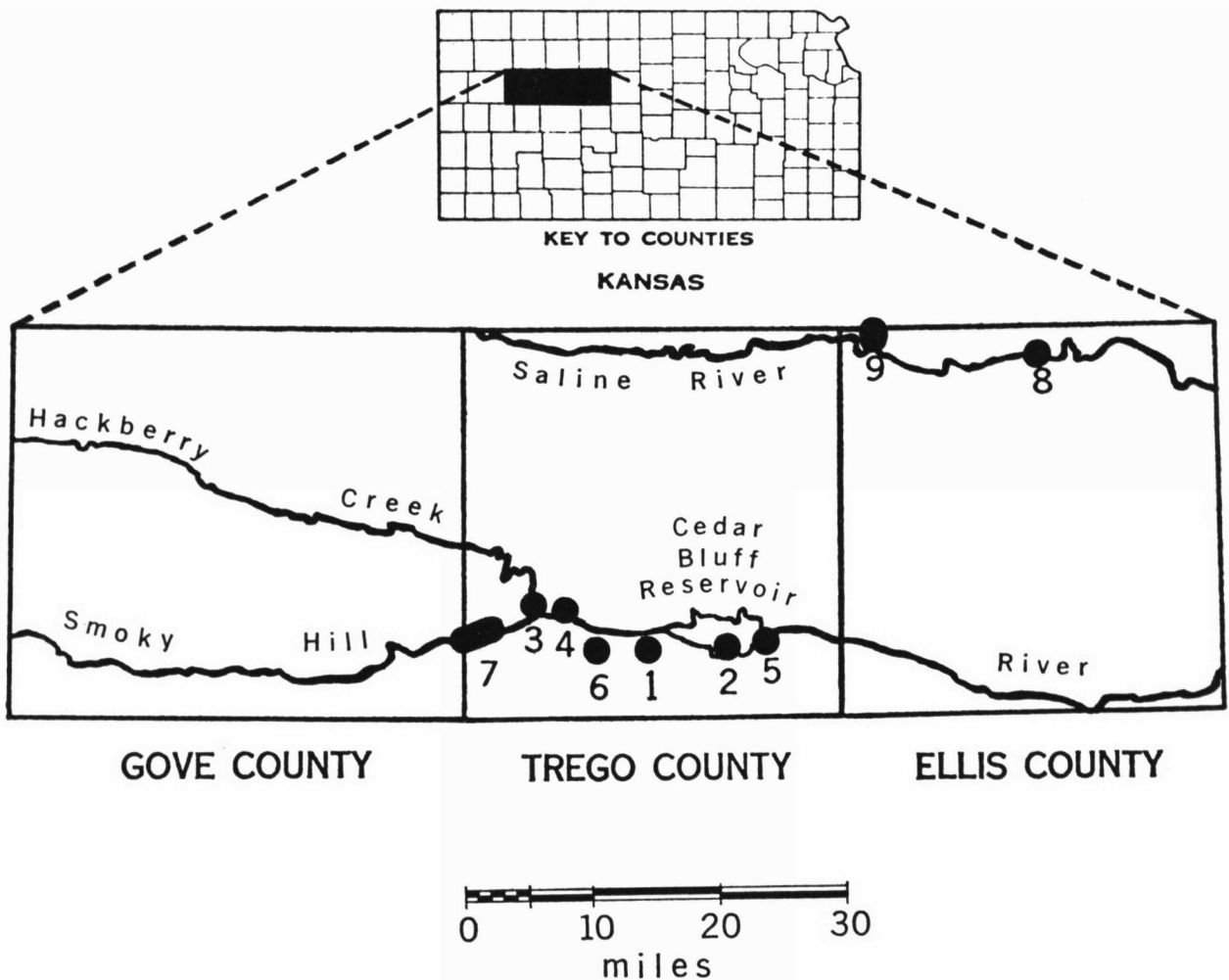


FIG. 2. Locations of Fort Hays exposures examined in west-central Kansas. Township and range locations are given in Appendix 1. (From Frey, 1970.)



The entire thickness of the Fort Hays, unlike that of the Smoky Hill, is exposed at numerous places in Kansas. The Smoky Hill contains larger quantities of terrigenous detritus, iron sulfide, and organic matter than the Fort Hays. Sedimentary structures, both inorganic and biogenic, are considerably more abundant in the Fort Hays. Both the Fort Hays and the Smoky Hill possess the attributes of a formation, as specified by the *Code of Stratigraphic Nomenclature*, and plans have been made to elevate them accordingly (Kauffman & Hattin, in preparation).

#### LOCAL SETTING

Exposures of the Fort Hays were examined closely at nine localities in Kansas (Fig. 2; Appendix 1). Abbreviated descriptions of three key sections are presented in Appendix 2).

Except for the outcrop at Locality 7, the Fort Hays is not exposed in Gove County (Hodson & Wahl, 1960, pl. 1). Scattered exposures of the Fort Hays are found in many parts of Ellis County (Bass, 1926, pl. 1), but the best (thickest) exposures are along the Saline River in the northern part of the county. With two exceptions, Fort Hays exposures in Trego County are restricted to the Smoky Hill River valley; the exceptions are small areas in the extreme northeastern and east-central parts of the county (Hodson, 1965, pl. 1).

Although Hodson (1965, table 1) indicated that the maximum thickness of the Fort Hays in Trego County is 55 feet, the section at my Locality 3 is 73 feet thick, and that at Locality 1 is 78 to 80 feet thick.

Individual strata of the Fort Hays and lower Smoky Hill are remarkably uniform and laterally persistent in Trego County (Pl. 1, fig. 1), and each exposure may be

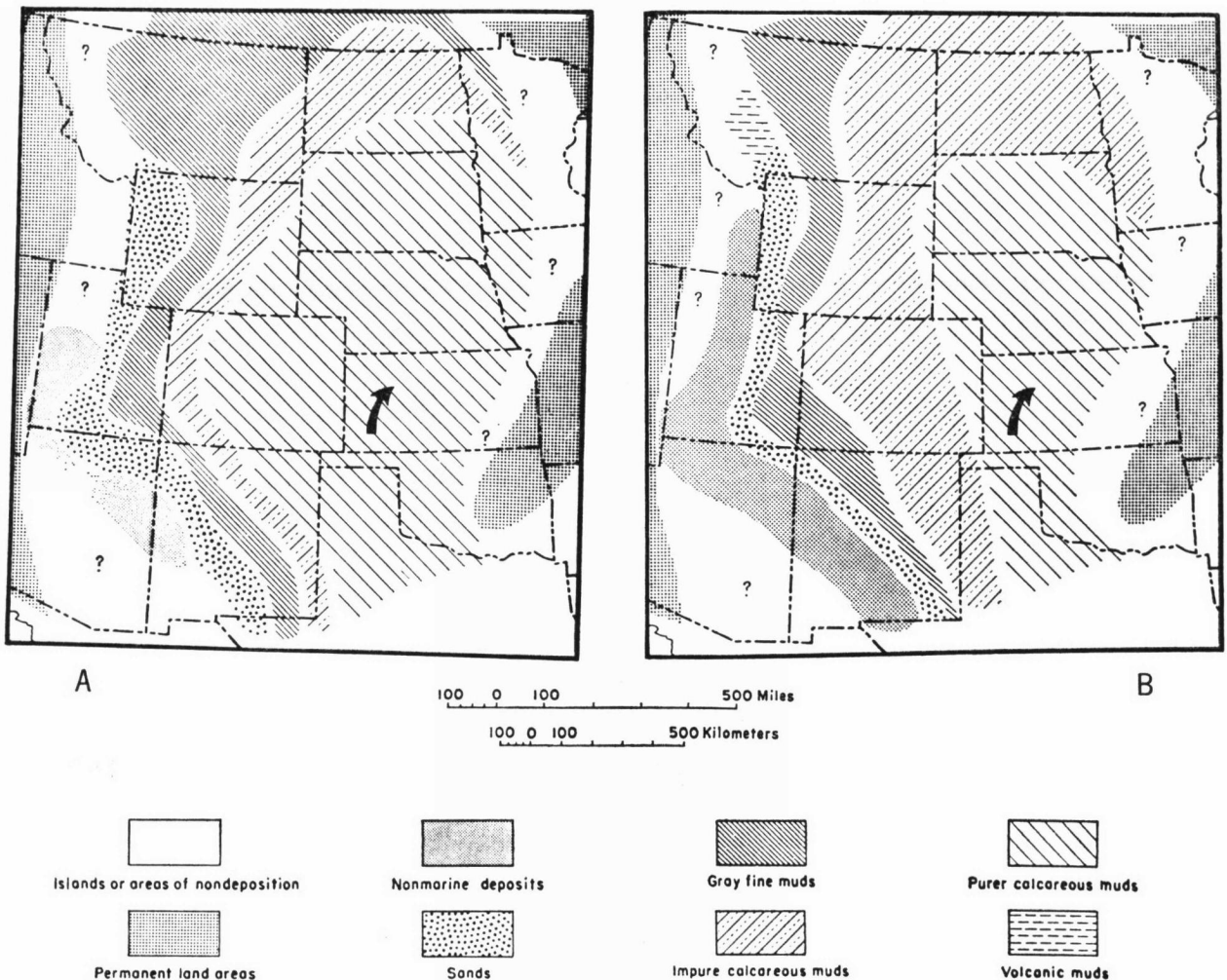


FIG. 3. Regional distribution of major facies during Niobrara deposition.—A. Fort Hays (early Coniacian) facies.—B. Smoky Hill (late Coniacian-early Santonian) facies. (Study area in Kansas indicated by arrows; see Fig. 2. From Reeside, 1957, fig. 14-15.)

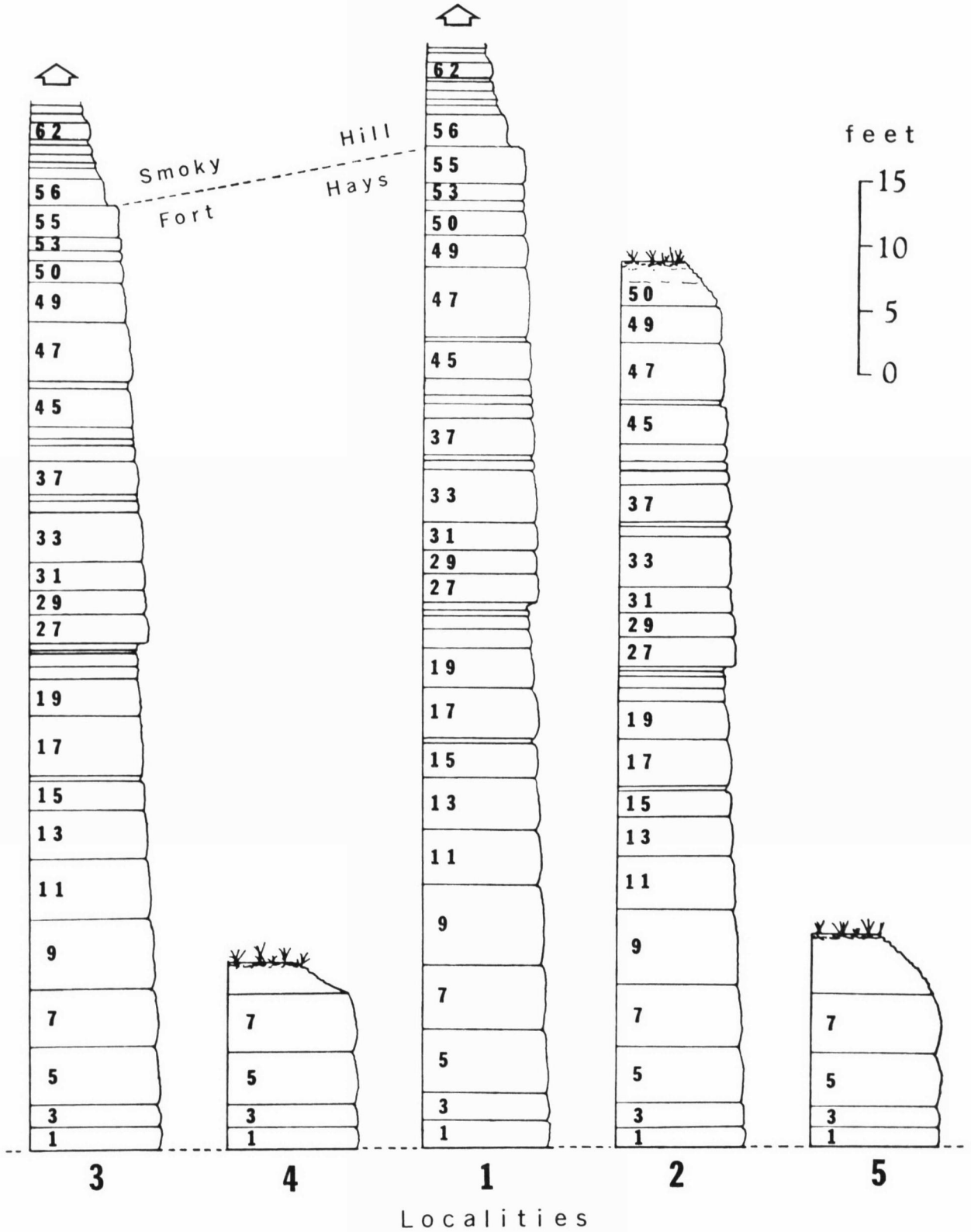


FIG. 4. Diagram of stratigraphic sections measured in Trego County, Kansas. Because exposures may be correlated on a bed-by-bed basis throughout the county, each bed was given a constant numerical designation. (Numbers for the thinner beds are not indicated in diagram.) Sections are described in Appendix 2. (From Frey, 1970.)

correlated on a bed-by-bed basis. Each bed was therefore given a standard numerical designation (Fig. 4; Appendix 2); these numbered bedding units are referenced frequently in subsequent parts of the paper.

The only unfortunate circumstance of Fort Hays exposures in west-central Kansas is that close stratigraphic control is limited to an east-west direction. Certain features of the exposures in northern Ellis County are different from those in southern Trego County, for example, and one has little opportunity to document the intermediate or transitional stages in a north-south direction.

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## STRATIGRAPHY AND PETROGRAPHY

### PHYSICAL STRATIGRAPHIC SETTING

The Niobrara Chalk, as presently defined, is the uppermost formation of the Colorado Group (Zeller, 1968, pl. 1). Units of this group comprise about 900 ( $\pm$ ) feet of calcareous and noncalcareous shale, silt, sand, chalk, and chalky limestone, as well as numerous bentonites, and they bear the striking imprint of two major marine cycles of sedimentation (Hattin, 1966; Kauffman, 1967, 1969). These are the Greenhorn and Niobrara cyclothems, each named for the deposits that reflect maximum transgression during that cycle. A model for these cycles is presented in Figure 5 and is discussed in other parts of this paper.

### UNITS IN CONTACT WITH THE NIOBRARA

The Niobrara in west-central Kansas rests disconformably upon the Carlile Shale and, where uneroded during Cenozoic times, is overlain conformably by the Pierre Shale (Table 1).

Either the Blue Hill or the Codell Member of the Carlile may underlie the Niobrara. The lithology of either member is easily distinguished from that of the Fort Hays (see Hattin, 1962, p. 60-72, 92-95). The Blue Hill is ordinarily overlain by the Codell, but the latter is not present everywhere. Locally in Trego County a thin shale lithologically very similar to that of the Blue Hill intervenes between sands of the Codell and chalky limestones of the Fort Hays (Frey, 1970, pl. 7, fig. 7).

At one place or another in Kansas the Ogallala Formation (Pliocene) rests with slight angular unconformity

upon each unit of the Colorado Group. It may therefore be present at any stratigraphic level of the Niobrara. In west-central Kansas the Ogallala has been stripped away by erosion along the major stream valleys, except for scattered lag deposits, such as siliceous pebbles and fragments of petrified wood. (See Merriam, 1963, p. 22-32, for additional information.)

Unconsolidated Pleistocene deposits of colluvial, fluvial, and eolian origin are also in contact with the Niobrara in west central Kansas. The fluvial deposits, loosely termed "slope wash," are encountered commonly at Fort Hays exposures. Numerous Pleistocene channels were entrenched into the chalky limestones of the Fort Hays (Pl. 1, fig. 2), and the channels later became congested with poorly sorted debris derived from various sources, including the Fort Hays (Pl. 2, fig. 1).

### PHYSIOGRAPHIC AND GEOMORPHIC EXPRESSION OF THE NIOBRARA

The Fort Hays, much more resistant to erosion than either the underlying Carlile or the overlying Smoky Hill, forms a prominent erosional escarpment in Kansas. This escarpment extends irregularly southward from Jewell County to the Arkansas River and marks the physiographic boundary between the High Plains on the west and the Dissected High Plains on the east (Schoewe, 1949, fig. 22). Local relief along the escarpment is as much as 300 feet. Where the escarpment is breached by streams, north-facing slopes are typically much more prominent and cliff-like than south-facing slopes (Pl. 1, fig. 1). However, the opposite is true of Fort Hays



exposures along the Smoky Hill River in southwestern Trego County (Frey, 1970, pl. 1, fig. 1).

The Smoky Hill is less commonly found in bold, vertical exposures, and in many places has been stripped away to leave small plateaus held up by the Fort Hays (Pl. 1, fig. 3). In Kansas, the Smoky Hill typically forms small areas of badlands topography; such landforms are spectacular locally, especially in Gove County (Merriam, 1963, pl. 4) and in Logan County.

Where the Carlile Shale is fully exposed to weathering, erosional removal of these soft shales and sands undermines the overlying Fort Hays, and large joint blocks of chalky limestone topple downslope (Pl. 1, fig. 1). These fallen blocks provide numerous bedding-plane views that, except at Locality 2, are otherwise rare among Fort Hays exposures in west-central Kansas.

During seasons of freeze-and-thaw these rocks may deteriorate rapidly through small-scale spalling (e.g., Frey, 1970, pl. 8, fig. 3). Small solutional features are

also common locally; these consist typically of cavernous or pothole-like surfaces (Pl. 2, fig. 2), some of which are sculpted grotesquely. The exfoliation and corrosion surfaces are helpful because they commonly reveal the features of physical and biogenic sedimentary structures in considerably more detail than do adjacent surfaces.

**STRUCTURE**

Except for prominent vertical jointing, the only conspicuous structures found in typical Niobrara outcrops are faults. Throws of more than 100 feet were reported by Russell (1929, p. 601), but displacement is ordinarily much less.

Small normal faults are widespread in the Fort Hays (Runnels & Dubins, 1949, p. 6) and are common in Trego County (Pl. 2, fig. 3). Slickensided surfaces and thin zones of mineralized fault gouge are seen commonly. Displacement along these faults is typically less than 10 feet, and most of the structures are sufficiently

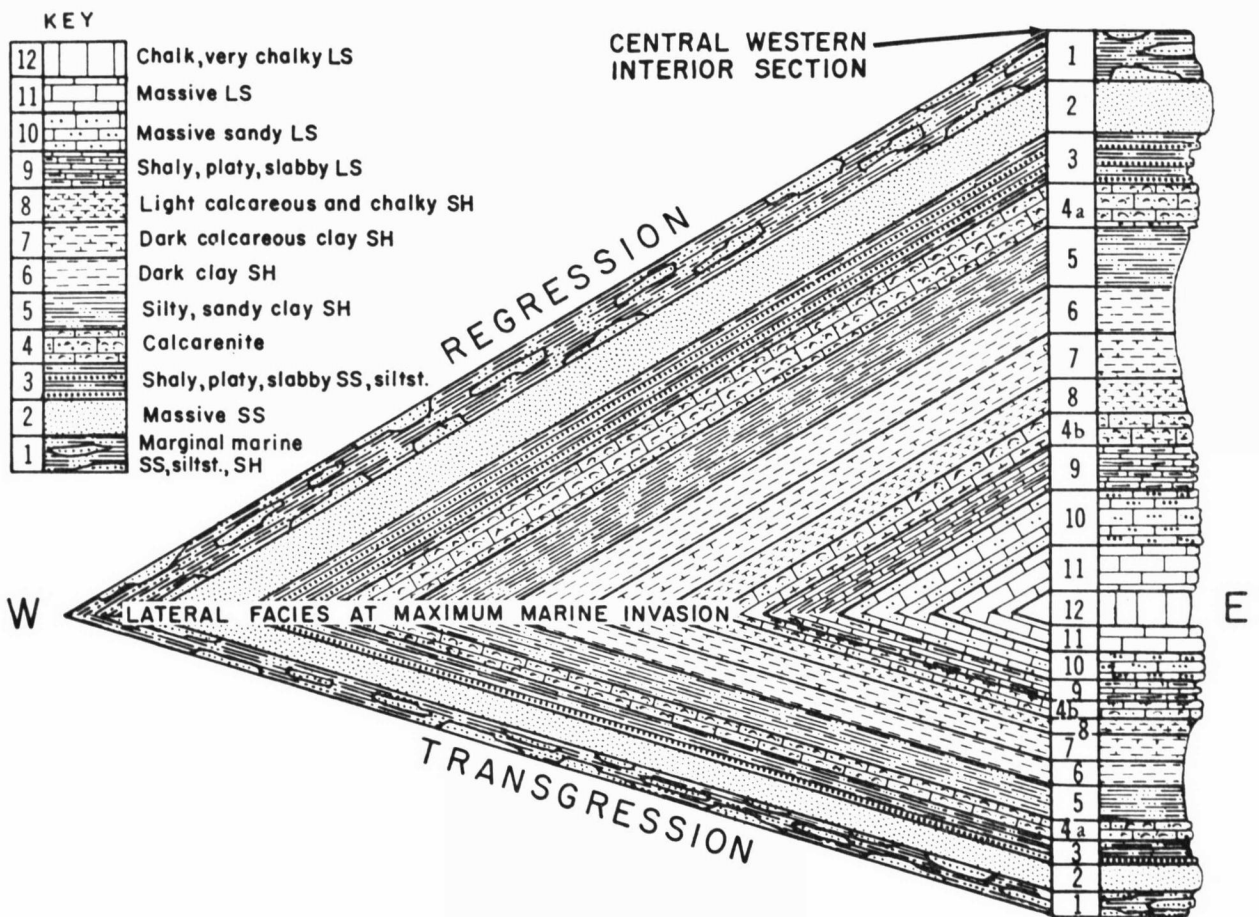


FIG. 5. Model for Cretaceous marine sedimentation in the Western Interior. Lithologies 1-4a represent an inner shelf clastic belt; lithologies 4b and 5-8 a middle shelf clay belt; and lithologies 9-12 a middle basin carbonate belt. Western margin of diagram represents east-central Utah; eastern margin represents eastern Colorado, west-central Kansas, and panhandle Oklahoma. (From Kauffman, 1969, fig. 4.)

TABLE 1.—*Stratigraphic Units in the Upper Part of the Upper Cretaceous Series, Western Kansas.*

(Adapted from Hattin, 1965a, table 1.)\*

STAGE	FORMATION	MEMBER	APPROXIMATE THICKNESS		DOMINANT LITHOLOGY
			(feet)	(meters)	
Campanian		Weskan Shale	170	52	Shale, dark gray, bentonitic; clay-ironstone and limestone concretions, phosphate nodules.
		Pierre Shale	Sharon Springs Shale	155	47
—?—		Smoky Hill Chalk	560-620	171-189	Shaly chalk and chalky shale, olive gray to grayish orange and yellowish gray, bentonitic; limonite nodules.
Santonian-Coniacian	Niobrara Chalk	Fort Hays Limestone	55-80	17-24	Chalky limestone, light olive gray to pale grayish orange and yellowish gray.
		Codell Sandstone	0-30	0-9	Sandstone and siltstone, quartzose, light olive gray; shaly, calcareous locally.
Turonian	Carlile Shale	Blue Hill Shale	170-185	52-56	Shale, dark gray, silty near top; calcareous and clay-ironstone concretions.
		Fairport Chalk	90-120	27-37	Shaly chalk, olive gray, laminated, bentonitic, having beds of chalky limestone and marly chalk.

\* See also Zeller (1968). (Upper Cretaceous Series=former Gulfian Series).

obvious that they present no problem in correlation of beds or in selection of places to measure bedding thicknesses.

### SUBSURFACE DISTRIBUTION OF THE NIOBRARA

Merriam (1957, p. 14, fig. 1) published three correlation charts that show the general subsurface thickness relations of the Niobrara in Kansas. Along his lines of cross section the thickness of the Fort Hays ranges from about 40 to 90 feet, averaging about 50 feet, and the thickness of the Smoky Hill ranges from about 400 to more than 650 feet, probably averaging about 550 feet.

Variation in subsurface thickness of the Fort Hays is nearly negligible along an east-west cross section extending from Cheyenne County to Phillips County (Merriam, 1957, pl. 1). Subsurface thickness and irregularity of the member increases both southward and southeastward, however, as shown by a northwest-southeast cross section extending from Cheyenne to Gove County (*ibid.*, pl. 2) and a north-south cross section from Cheyenne to Wichita County (*ibid.*, pl. 3); maximum thicknesses were noted in Gove, Wichita, and Greeley Counties. (See Fig. 6 for locations of counties.)

Data from exposures along the Fort Hays outcrop

belt (Runnels & Dubins, 1949, p. 5) generally confirm these trends (although some of the variations in thickness are due to differences in technique and precision among the several workers involved; particularly important in this respect is the placement of the gradational Fort Hays-Smoky Hill contact).

The reported variations in thickness are not obviously related to Mesozoic structures in central and western Kansas (Fig. 6) and may therefore reflect differential sedimentation or topographic irregularities on the sea floor at the time of deposition.

### UPPER AND LOWER CONTACTS OF THE FORT HAYS

At most places in Trego County the Fort Hays is underlain by the Codell Sandstone Member of the Carlile Shale (Pl. 2, fig. 4). The contact is ordinarily very distinct because of sharp contrasts in color and lithology. Although this contact represents a disconformity of considerable magnitude (Hattin, 1962, p. 88-92), it is practically planar and parallel with both Carlile and Niobrara bedding at numerous places along the Smoky Hill River (Pl. 1, fig. 1; Pl. 2, fig. 3).

Locally, however, conspicuous small-scale relief is found on the pre-Niobrara surface. At Locality 4 the

lowermost bed of chalky limestone in the Fort Hays thickens abruptly from its typical thickness of about 1.9 feet to more than 6.0 feet, within a lateral distance of less than 20 feet. At Locality 2 this bed thickens locally from 1.7 feet to about 3.1 feet, and at Locality 1 from about 2.2 feet to 4.6 feet.

At such contacts the thicker part of the basal bed of the Fort Hays clearly truncates bedding features within the Carlile Shale (Pl. 2, fig. 5); the contacts are extremely sharp, without compaction or distortion of bedding in the Carlile. Small channels were scoured into the Carlile sediments, and the thickening of the chalky limestone bed represents channel fill. This scour-fill is evidenced further by small laminated to cross-laminated zones present in the thicker parts of the chalky limestone beds.

Although such channels are not found commonly, the lithology of the basal bed of chalky limestone suggests that scour along the pre-Niobrara surface was actually widespread. This bed contains significant quantities of terrigenous detritus, especially quartz, feldspar, and mica, that were reworked from the Carlile. The detritus is most abundant near the base of the chalky limestone bed and decreases markedly toward the top. This bed also contains numerous shark teeth and phosphatic granules (Pl. 9, fig. 2) (but not phosphate nodules containing fossils, such as reported by Tourtelot & Cobban (1968) from the basal Niobrara in South Dakota). Elsewhere

in Kansas the basal part of the Fort Hays is so sandy locally that the Carlile-Niobrara contact at first appears to be gradational (Hattin, 1962, p. 90). Such relationships are apparently responsible for the statement by Fishel & Leonard (1955, p. 103) that the Niobrara conformably overlies the Carlile. Paleontologic evidence belies this possibility, however.

In spite of the apparent sharpness of the Codell-Fort Hays contact (Pl. 2, fig. 4), good exposures of the contact ordinarily disclose pronounced, small-scale irregularities caused by burrowing organisms (Pl. 3, fig. 1). These burrows are absent only at scoured contacts such as that shown in Plate 2, Figure 5. The burrows have permitted chalky sediments of the Fort Hays to be deposited locally as much as 0.6 foot below the highest Carlile sediment, and in places small chips and lenses of Carlile shale have been isolated within the chalky limestone. (The Codell Sandstone also contains pre-Niobrara burrows, hence one must distinguish these from the chalk-filled burrows that penetrate the Carlile-Niobrara contact.)

The contact between the Fort Hays and the overlying Smoky Hill is completely gradational (except for small-scale scour horizons), and the positioning of an exact boundary between them has varied among authors. The transition is marked by the change from beds consisting predominantly of chalky limestone to those consisting predominantly of shaly chalk or chalky shale; in places

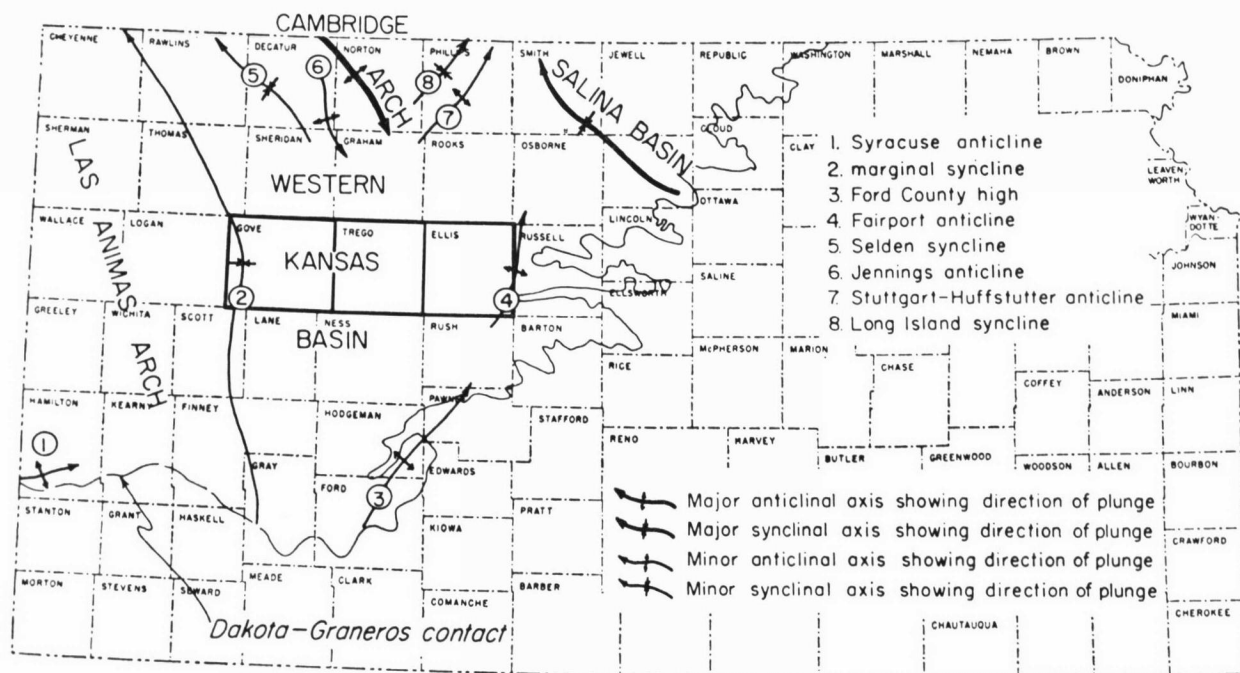


FIG. 6. Index map of major and minor Mesozoic structures in central and western Kansas; study area outlined in heavy black lines. (From Merriam, 1958, fig. 1.)

this transition zone encompasses a stratigraphic interval of several feet. In such places a pair of thin bentonite layers is traditionally taken to be the top of the Fort Hays (Pl. 3, fig. 2); the lithologic change that marks the top of the Fort Hays is several feet lower, but the bentonites are commonly substituted as a convenient and distinctive horizon at which to make a division (Runnels & Dubins, 1949, p. 6-7). These bentonites have not been reported from several Kansas counties, however, and are possibly missing in such places. Furthermore, the Fort Hays-Smoky Hill contact so placed is not in keeping with procedure established by the *Code of Stratigraphic Nomenclature*. Contacts drawn at bentonites are less mappable than those drawn at major breaks in lithology, and recourse to bentonites implies that time, rather than lithology, is a valid criterion for establishing stratigraphic boundaries.

In Trego County the lithologies within this transition zone are distinctive, and the Fort Hays-Smoky Hill contact may be defined with relative ease. Although Landes & Keroher (1939, p. 14) placed the boundary at the twin bentonites mentioned previously, the chalky limestones typical of the Fort Hays terminate abruptly upward and are overlain by thinner beds of chalk and shaly chalk. The uppermost bed of chalky limestone in a continuous sequence of such beds (Unit 55; see Appendix 2) is taken to be the top of the Fort Hays. At weathered exposures it is ordinarily much more resistant and prominently exposed than stratigraphically higher beds. Locally the overlying chalk bed (Unit 56) becomes case-hardened and therefore relatively resistant to weathering (Pl. 1, fig. 3), but such instances are comparatively uncommon.

Among exposures examined in Trego County, the bed of chalky limestone at the top of the Fort Hays is 6.5 to 7.0 feet below the base of the twin bentonites. This interval is included in the Fort Hays by many of the workers cited by Runnels & Dubins (1949, p. 5), hence masking some of the true variations in thickness of the member.

### CORRELATION OF BEDDING UNITS

A total of 55 bedding units were established for the Fort Hays and 11 for the lower part of the Smoky Hill (Appendix 2); each bed is taken to represent a single, more or less uninterrupted pulse in deposition. Except where removed by erosion during the Cenozoic, these units are persistent throughout Trego County; among them are numerous key marker beds or groups of beds, hence each exposure of the Fort Hays in that county may be correlated on a bed-by-bed basis (Fig. 4).

Lithologic correlations by means of key beds or bedding intervals have been generally successful in the lower part of the Smoky Hill (Bass, 1926, p. 19-23) but, contrary to the statement by Miller (1968, p. 3-5), no

previous attempts have been made to correlate individual lithologic units in the Fort Hays.

Most beds of chalky limestone in the Fort Hays may be defined uniquely in terms of thickness relations and the configuration of thin shale partings and scour or bioturbation zones, which are also persistent laterally (Fig. 7). Such features are ordinarily so distinctive that numerous fallen blocks of chalky limestone may be referred to their exact stratigraphic positions. (The configuration of these zones and the consistent concave-upward orientation of *Inoceramus deformis* valves also serve as excellent geopotals.)

Most bentonites in the Fort Hays are too thin and discontinuous to be used consistently in correlations.

Although exposures of the Fort Hays in Trego County may be correlated exactly, many of these bedding units cannot be traced into certain areas outside the county. At Localities 8 and 9, for example, the Fort Hays is considerably thinner and contains fewer total beds than at localities in Trego County; the bedding units, shale partings, and bioturbation zones are also configured differently. A striking exception is the group of beds comprised by Units 39 through 47, which may be traced from the eastern border of Gove County (Loc. 7) to the north-central part of Ellis County (Loc. 8), a straight-line distance of about 45 miles. Throughout this extent the individual beds are remarkably uniform in thickness (Table 2), lithology, macrofossil content, and, in Unit 47, shale partings and stylolitic zones.

TABLE 2.—*Thickness Data (in Feet) for Correlative Fort Hays Strata in Gove, Trego, and Ellis Counties, Kansas.*

BEDDING UNITS	LOCALITIES				
	7 ← (4 mi) → 3	← (7 mi) → 1	← (4 mi) → 2	← (29 mi) → 8	
47	4.60	4.60	5.05	4.3	4.20
46	0.60	0.45	0.40	0.45	0.35
45	2.55	2.90	3.00	2.90	1.90
44	0.15	0.15	0.10	0.10	0.10
43	1.25	1.10	1.15	1.35	1.10
42	0.05	0.05	0.10	0.10	0.05
41	0.30	0.40	0.35	0.35	0.30
40	0.05	0.10	0.10	0.10	0.10
39	1.00	1.10	1.10	1.10	1.05
TOTAL THICKNESS	10.6	10.9	11.4	10.8	9.2

(Localities are arranged from west to east—see Figure 2. Bedding units are described in Appendix 2. Thicknesses reported here were measured to the nearest 0.05 foot.)

Bedding units of the Smoky Hill studied in Trego County are as distinctive and persistent as those of the Fort Hays; these Smoky Hill strata were easily identified and correlated by noting their relations to the Fort Hays contact and to the twin bentonites in the lower part

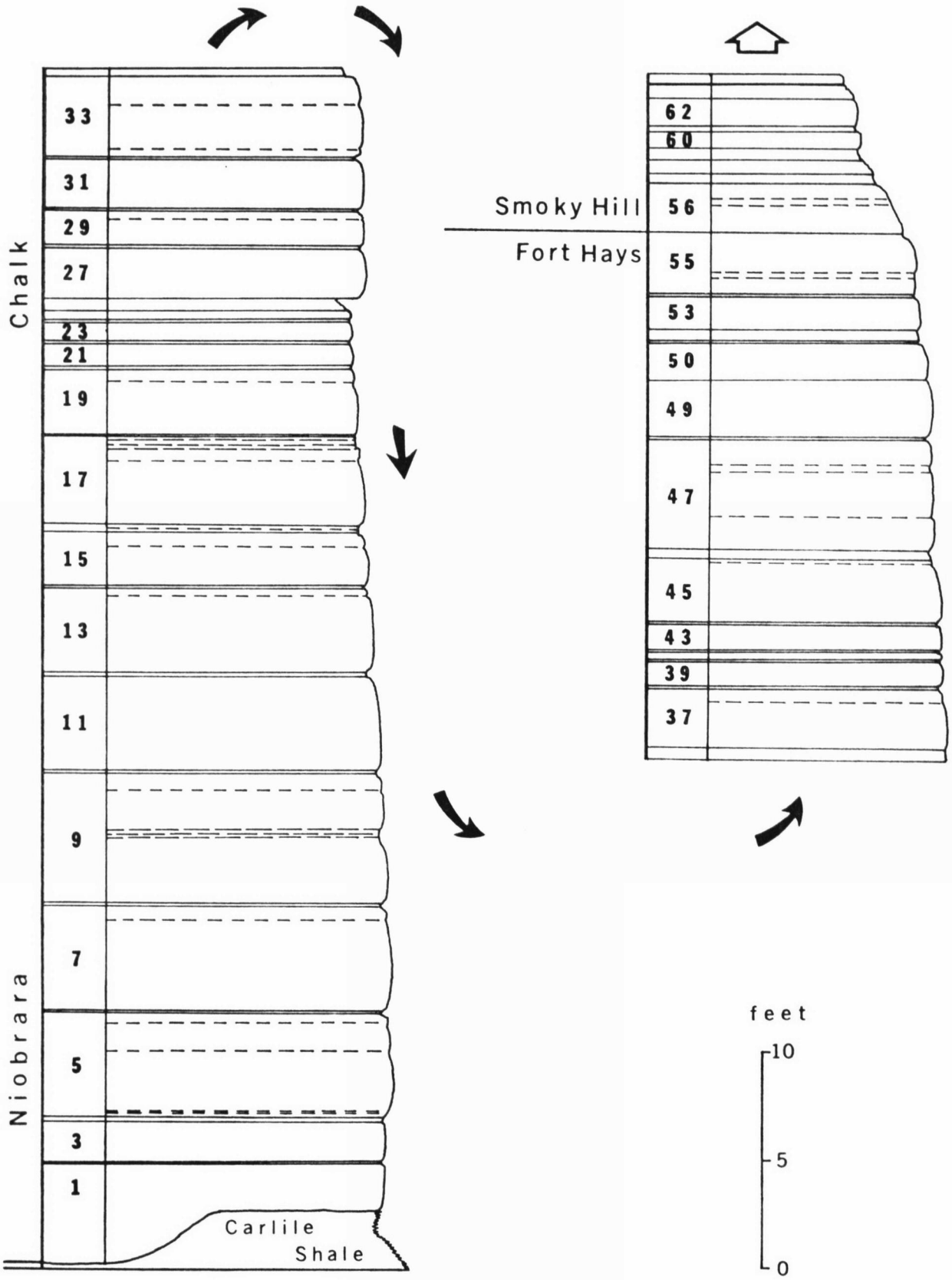


FIG. 7. Stratigraphic section at Locality 1, bedding units indicated at left. Diagram shows persistent shale partings, laminae, and bio-turbation zones that are the most useful in correlating Fort Hays beds from one outcrop to another in Trego County, Kansas. (Compare with Fig. 4.)



of the Smoky Hill (Pl. 3, fig. 2). No attempt was made to correlate strata above these bentonites, although bedding units in a 15-foot interval above the bentonites were noted to be virtually identical at Localities 1 and 3.

Bentonites in both the Fort Hays and lower Smoky Hill reflect a constant stratigraphic position relative to other bedding units, thus all bedding units observed in west-central Kansas represent discrete intervals of time.

Attempts to correlate strata throughout the Smoky Hill have been less successful than Bass' work (1926, p. 19-23) in the lower part of the member. No single exposure of the Smoky Hill in Kansas is stratigraphically complete, and only one composite section has been constructed to date (Russell, 1929); even in this attempt no actual bedding measurements or field locations are indicated. Recently there has been renewed interest in employing groups of bentonites to effect regional correlations, and the method shows considerable promise.

The lateral continuity of individual strata observed in Trego County attests to a remarkably uniform depositional regimen, and the units traced from Gove to Ellis County show that particular environmental conditions were at times very widespread. I suspect that certain beds are traceable for even greater distances, e.g., although Moss (1932, p. 20-21) stated that individual beds of the Fort Hays in Ness County are not persistent, I feel confident that Units 33 through 47 of my report are illustrated in his Plate 4 (cf. Frey, 1970, pl. 1, fig. 1), as may also be true of the exposure in Hamilton County illustrated by Bass (1926, p. 62, fig. 17). A regional study of Fort Hays bedding features is obviously needed.

Such persistent and easily identified units also provide an excellent three-dimensional, stratigraphic framework for precise sampling and for making lateral and vertical comparisons of quantitative data.

## PETROLOGY

### MAJOR LITHOTYPES

Strata of the Fort Hays consist almost exclusively of four intergradational lithologies: chalk, chalky limestone, shaly chalk, and chalky shale (Table 3,A). Very thin bentonites and irregular, discontinuous bentonitic lenses constitute a negligible fraction of the total volume of rock.

Chalks feel earthy where fresh but may be slightly more firm where weathered. Macrofossils, authigenic minerals, terrigenous detritus, and organic matter may be present in various amounts but are invariably subordinate to the coccolithophorid micrite. Microfossils are considerably less abundant in chalky shale than in chalk or chalky limestone, but the abundance of macrofossils and authigenic minerals among the three may be similar.

Except for fossils and skeletal fragments (Pl. 3, fig.

TABLE 3.—Major Lithotypes Comprising the Fort Hays Member in Trego County, Kansas.

A—DEFINITION OF LITHOTYPES			
CHALK: A very soft, friable, low-density, coccolithophorid micrite; in addition to nannoplankton remains, the crypto- to micro-grained particles of CaCO <sub>3</sub> include fragmentary and whole planktonic foraminiferal tests. Earthy consistency.			
CHALKY LIMESTONE: Differs from chalk chiefly in being somewhat harder and less friable; it is nevertheless substantially softer and less dense than typical Paleozoic micrites. Breaks with conchoidal fracture.			
CHALKY SHALE: Consists predominantly of clay minerals and fine-grained argillaceous detritus, admixed with subordinate quantities of chalk. Commonly thinly laminated; breaks with blocky fracture where fresh but has moderately good to good fissility where weathered.			
SHALY CHALK: Essentially intermediate between chalk and chalky shale, but chalky components are more abundant than terrigenous detritus. Usually thinly laminated to laminated and typically contains very thin shale partings.			
B—THICKNESS AND PROPORTION OF LITHOTYPES			
LITHOTYPE	THICKNESS OF INDIVIDUAL BEDS		PERCENT, BY VOLUME, OF TOTAL ROCK
	Range (ft)	Mean (ft)	
Chalky limestone	0.68-6.00	2.70	90.2
Chalk	0.25-1.00	0.51	3.7
Chalky shale	0.06-0.58	0.13	3.5
Shaly chalk	0.05-0.74	0.32	2.5

3), the chalks and chalky limestones are remarkably uniform in texture. Skeletal limestone (calcarenite) is represented by scattered small lenses of shell debris and disaggregated *Inoceramus* prisms (Pl. 2, fig. 2), but grain-supported rocks are generally extremely rare. Skeletal limestones formed by the disintegration of the prismatic layer of *Inoceramus* valves have been termed "inoceramite" (Hattin, 1962, p. 41); this informal term is apt and is used frequently in subsequent parts of my paper.

### THICKNESS AND ABUNDANCE OF LITHOTYPES

The bulk of the Fort Hays consists of thick to very thick beds of chalky limestone (Appendix 2). Beds made up of chalk, shaly chalk, and chalky shale are consistently much thinner, and they constitute a much smaller fraction of the total volume of rock (Table 3,B). Bentonites and other lithologies are insignificant by comparison, comprising only about 0.1 percent of the rock.

Strata of the Smoky Hill that lie below the twin bentonites consist largely of chalk (70.9% of total rock volume). Shaly chalk is much less common (27.1%),

and chalky shale is relatively insignificant (2.0%). Chalky limestone is not generally present.

### COLOR

Specific colors of rocks in the Fort Hays range through a broad spectrum; more than 30 colors or hues were recorded. Many of these colors are found in more than one kind of lithology, although a few are characteristic of particular lithologies (Table 4).

TABLE 4.—Colors Encountered Commonly among Rocks of the Fort Hays Exposed in Trego County, Kansas.\*

(X=less common, XX=more common, XXX=most common)

COLOR OR HUE*	CHALKY LIMESTONE		SHALY CHALK	CHALKY SHALE
	LIMESTONE	CHALK	CHALK	SHALE
Olive black	....	....	XX	XX
Dark gray	....	....	....	XX
Medium dark gray	....	....	XX	XX
Medium gray	....	....	X	X
Medium light gray	X	....	XX	X
Light gray	X	X	X	....
Very light gray	XX	XX	XX	....
Nearly white	X	....	....	....
Olive gray (5Y 4/1)	....	X	XX	XXX
Medium olive gray	....	XX	....	X
Light olive gray (5Y 5/2)	....	XX	XX	XXX
Dark yellowish gray	X	....	X	X
Yellowish gray (5Y 7/2)	XXX	XX	XXX	XX
Light yellowish gray	XX	XX	....	....
Pale orange	X	....	....	X
Very pale orange	XXX	XXX	XX	....
Pale yellowish orange	XXX	XX	X	X
Dark yellowish orange	XX	XX	....	X
Grayish orange	X	X	X	X
Dark grayish orange	X	XX	X	....
Dusky yellow	X	X	....	....

\* Color designations invariably refer to wetted samples and, insofar as possible, are based upon the *National Research Council Color Chart* (Goddard and others, 1948); color-code designations appear in parentheses after names for which two colors are shown in the chart. The uppermost three or four colors within each lithologic category are the colors of the fresher exposures of that kind of rock; the remaining colors are seen on moderately to highly weathered rocks, but these colors could not be arranged strictly according to successive stages of weathering.

Runnels & Dubins (1949, p. 7) stated that locally the lower 10 feet of the Fort Hays is blue-gray in color, apparently because of a high shale content. Actually, development of such colors depends more on degree of weathering; these colors may be seen on fresh rock at most stratigraphic levels.

The colors of chalk, shaly chalk, and chalky shale within the lower few feet of the Smoky Hill are generally very similar to those of equivalent lithologies in the Fort Hays. Higher in the section the colors are commonly deeper and more vivid. Many Smoky Hill exposures may be identified at a distance by their striking hues of orange, yellow, white, or bluish gray.

Finely disseminated iron compounds probably account for the yellow and orange hues among the chalks and chalky limestones. These compounds, and also the dark carbonaceous colors exhibited by very fresh rock, probably attest to the presence of considerable organic detritus in the depositional environment.

### MICRITE PETROLOGY

Constituent analysis of several rock samples from Trego County (Loc. 3) have been presented in an unpublished report by Al-Shaibani (1964). These samples are mostly from chalky limestones of the Fort Hays but a few are from chalks of the lower part of the Smoky Hill. I examined Al-Shaibani's individual thin sections and original petrographic reports, and have incorporated his data with only very minor modification and reinterpretation. The specimens were collected by Donald E. Hattin, who fortunately recorded their exact stratigraphic positions (Hattin, 1965a, p. 64-68) so that I was able to relate them to the bedding units used in this report (Fig. 8).

The chief constituents of samples from the Fort Hays and lower Smoky Hill at Locality 3 are indicated below.

#### Major Constituents of Samples from Fort Hays and Lower Smoky Hill, Locality 3

CONSTITUENT	PERCENT COMPOSITION	
	Range	Mean
Matrix (including nanofossils)	48 to 77	63
Microfossils (excluding nanofossils)	13 to 30	22
Bivalve fragments	2 to 29	11
Iron compounds	1 to 4	2

Practically all of the specimens are texturally homogeneous (e.g., Hattin, 1965a, fig. 6.8; his sample is from Unit 49, Loc. 3). The only exceptions are lenses of inoceramite (Pl. 5, fig. 1) and rare places where foraminiferal hash and fragments of *Inoceramus* prisms have been concentrated in the castings of sediment-ingesting organisms.

The matrix consists not only of cryptograined particles and coccoliths but also of finely comminuted foraminiferal remains. Microfossils consist predominantly of globular-chambered foraminiferans such as *Heterohelix* and *Hedbergella*; other foraminiferans are minor in comparison, and only rare traces of ostracodes were observed. The preponderance of foraminiferal tests are filled with sparry calcite, which is thus widespread in most samples; sparry calcite is not conspicuous interstitially, however. A few foraminiferal tests are filled with limonite or pyrite. Bivalve fragments are composed essentially of *Inoceramus* prisms, either singly or in small aggregates. Small fragments of the valves of *Pycnodonte*

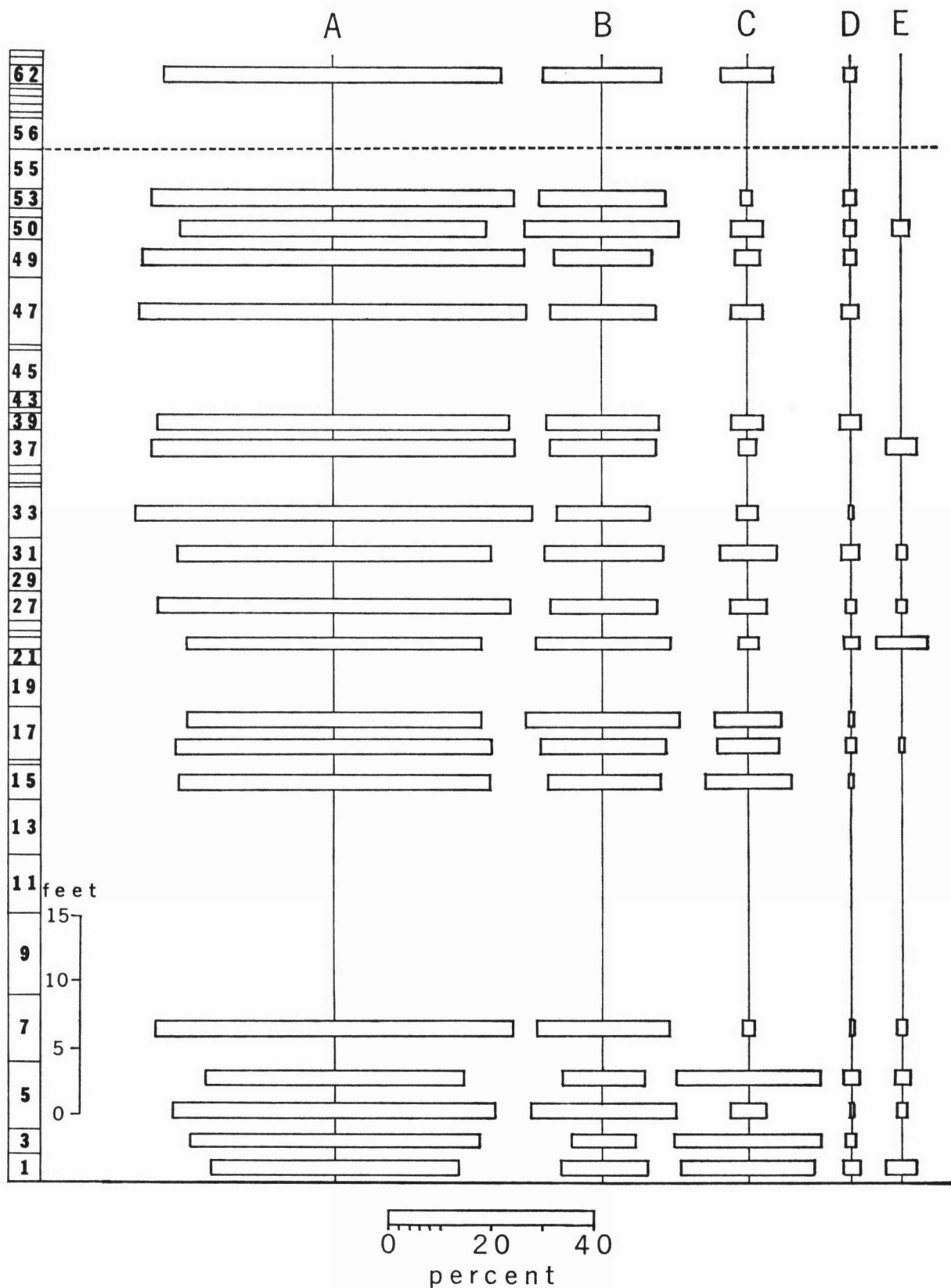


FIG. 8. Stratigraphic distribution of major constituents of chalky limestone and chalk at Locality 3, bedding units plotted at left. [A, micrograined and cryptograined matrix (including nannoplankton); B, microfossils; C, bivalve fragments; D, iron compounds; E, "other."] Percentages were established by point counts of petrographic thin sections (Al-Shaibani, 1964). Dashed line represents the Fort Hays-Smoky Hill contact.



rarely exceed 4 percent of a sample and are generally present in much smaller amounts. The iron compounds consist mostly of limonite or related oxides, but pyrite is also present. The iron compounds may be massive and isolated, or associated with fossils and burrows.

The remaining constituents, lumped under "other" (Fig. 8), consist mostly of sparry calcite that fills microfissures and tubular burrow structures. Also included are trace quantities of quartz, biotite, chalcedony, ?fish scales or bones, rare traces of colophonite and blebs of organic or carbonaceous matter, and indeterminate grains.

The Fort Hays at places in Colorado exhibits distinctly pelletal matrices, partly obscured by diagenesis (N. R. King, 1970, personal communication). Anomuran fecal pellets have been observed among English chalks, in beds that contain the burrow *Thalassinoides* (Kennedy, 1967, p. 134-140; Bromley, 1967, p. 172); these and other pellets must also have been present originally in the Fort Hays of Kansas, although they are not conspicuous now among the thin sections examined by me. Dearth of fecal pellets among these rocks cannot be attributed solely to physio-chemical obliteration, otherwise coccoliths (Pl. 15, fig. 1-2) would be more poorly preserved. Biogenic reworking (Pl. 5, fig. 4) and the incohesiveness of the pellets themselves (cf. Häntzschel and others, 1968, p. 3-4) were probably largely responsible for the nonpreservation of these small structures.

The thin-section analyses disclosed very little difference between the major constituents of chalky limestones of the Fort Hays and chalks of the lower part of the Smoky Hill. In addition to the sample from Unit 62 (Fig. 8), two other chalk beds from the Smoky Hill were sampled. The results are compared below.

Comparison of Major Constituents of Three Smoky Hill Chalk Beds

APPROXIMATE DISTANCE (FEET) OF SAMPLE ABOVE TOP OF FORT HAYS	COMPOSITION (percent)		
	5*	8	52
MATRIX	65	75	75
MICROFOSSILS	23	23	17
BIVALVES	10	1	6
IRON COMPOUNDS	2	1	2

\* Unit 62

The data shown in Figure 8 agree generally with the constituent analyses by Runnels & Dubins (1949, p. 10-14, table 3), who studied the Fort Hays regionally.

They suggested that, as revealed by an electron micrograph of one of their samples, the matrix of chalky limestones consists of rhombohedrons ranging in size

from 0.2 to 0.55 microns. Recent micrographs of samples from the Fort Hays of Trego County, taken by the scanning electron microscope, show that the matrix consists essentially of myriad coccoliths (Pl. 4, fig. 1-4). The micrographs were taken by J. M. Hancock and G. McTurk in the Department of Geology, University of Leicester, England; the Fort Hays samples are being used in a comparative study of American and European chalks.

Tentative results indicate similarity between the Fort Hays and certain soft white chalks of England (Hancock & Kennedy, 1967, pl. 1a, 3a); the rocks consist predominantly of coccolith debris, generally containing only subordinate quantities of clay. The micrographs reveal relatively greater quantities of clayey materials in the basal bed of the Fort Hays, but higher in the section little stratigraphic variation is discernible. The matrix of chalks from the lower part of the Smoky Hill (Pl. 4, fig. 4) is very similar to that of chalky limestones from the Fort Hays (e.g., Pl. 4, fig. 2), as is true of microscopic constituents (Fig. 8).

Runnels & Dubins (1949, p. 10) stated that calcite acts as cement in Fort Hays rocks, but they did not document or explain the relationship of cement to the grains. This relationship is not apparent among petrographic thin sections and electron micrographs from Trego County. The micrographs, like those of certain European chalks (Hancock & Kennedy, 1967, p. 249), reveal little evidence for chemical cement of any kind. The cryptograined matrix itself may act as a bonding agent; Kennedy (in preparation) suggested that electrostatic charges, such as van der Waal's forces (cf. Smalley, 1966, p. 672-674), may also be involved. Poorly cemented chalks such as these contrast strikingly with the dense, well-indurated chalks of Northern Ireland (Wolfe, 1968).

## INSOLUBLE RESIDUES

Runnels & Dubins (1949, p. 9-10, 14-26, tables 2, 4-6) also performed several geochemical and insoluble-residue analyses; they concluded that the calcium carbonate content of the Fort Hays, excluding the basal bed, ranges from 88.7 to 98.2 percent and averages 94.2 percent. The largest quantities of insoluble residue were almost invariably found in the lower part of the basal bed, where the residues amount to as much as 72.5 percent.

The insoluble fractions processed by Runnels & Dubins (1949) consisted of 1) the light minerals quartz, feldspar, and chalcedony or chert, and 2) the heavy minerals ilmenite, leucoxene, magnetite, tourmaline, zircon, muscovite, biotite, pyrite, and limonite (the last two being authigenic). Most of these minerals are extremely rare above the basal bed of the member. They noted that the amount of insoluble material decreases abruptly upward from the bottom to the top of the basal

bed, decreases gradually upward from there to the middle part of the Fort Hays, and then increases gradually from there to the top of the member.

Similar analyses have not been made systematically through the Smoky Hill, although data by Walter Hill (in Miller, 1968, appendix A) indicate a substantially lower concentration of CaO and a proportionately greater concentration of SiO<sub>2</sub> in this member.

None of the above workers specifically studied the chalky shales of the Fort Hays. Results of my analyses of this lithotype are indicated below (all samples are from Loc. 1).

*Insoluble Residues Found in Chalky Shale Units  
of Fort Hays*

UNIT	PERCENT INSOLUBLE RESIDUE
54	70.5
34	60.0
4	69.5

A sample of shaly chalk from the Smoky Hill (Unit 63, Loc. 1) contained an insoluble residue of 30.0 percent. The preponderance of all residues consisted of clay minerals, although scattered particles of coarse silt to fine-grained sand were noted; these consisted chiefly of quartz, biotite, and authigenic iron compounds.

#### AUTHIGENIC AND EPIGENETIC MINERALS

Diagenetic and post-diagenetic minerals in the Fort Hays and lower Smoky Hill consist essentially of pyrite, limonite, sparry calcite, and gypsum or selenite. Pyrite and limonite are by far the most abundant, occurring chiefly as nodules and as replacement minerals in fossil shells and burrow structures. Nodules range in size from less than 1 mm to more than 30 cm, and are present (although generally rare) in almost every bed of the Fort Hays. Nodules less than 15 cm across are typically spherical or irregularly ellipsoidal (Pl. 2, fig. 4), but larger ones are strongly flattened. The latter commonly contain cores of inoceramid valves or valve fragments that have been replaced by iron sulfide. The organic layers between *Inoceramus* prisms were very thick, and decay of this matter helped concentrate pyrite in numerous small masses (Pl. 3, fig. 4); occasionally these masses continued to grow until they coalesced and eventually replaced the entire valve. Similarly, numerous burrowing organisms apparently lined the interior of their burrows with heavy coats of mucus, the decay of which led ultimately to the formation of pyrite-filled burrows or pyrite-replaced burrow walls. (Cf. Taylor, 1964.) These structures are discussed at length in another paper (Frey, 1970, p. 24-26).

Nodules that are not associated with fossils or bur-

rows are generally distributed more or less randomly through the rocks, although locally, in both the Fort Hays and the Smoky Hill, the nodules are concentrated in thin stratigraphic zones (Pl. 3, fig. 5). The latter may represent substrate scour or nondeposition, some episodes of which may have been of regional diastemic proportion.

In certain beds of the Fort Hays very thin seams of limonitic (and possibly bentonitic) clayey materials are laterally persistent and generally parallel with bedding (Pl. 5, fig. 2). Locally such seams are slightly undulatory; the amplitude of a periodicity of such undulations may be surprisingly regular, resembling megaripples. Some of these seams truncate burrow structures, suggesting that concentration of the iron compounds is somehow related to substrate scour. Nondeposition is suggested further by the even heavier concentrations of pyrite and limonite found along the bottoms of certain channel structures (Pl. 2, fig. 5; Pl. 6, fig. 1). Phosphate nodules are associated commonly with such contacts among poorly consolidated Cretaceous and Cenozoic sediments of the Gulf and Atlantic Coastal Plain and at certain places within the Western Interior (e.g., Tourtelot & Cobban, 1968), although none were found during my study. The phosphate granules noted by me (Pl. 9, fig. 2) are evidently allochemical and of vertebrate origin.

Sparry calcite is considerably less abundant than pyrite and limonite, and except for small fractures in the rock and on slickensided surfaces, it is almost invariably associated with fossils or burrows. Foraminiferal tests are commonly filled with spar. Serpulid tubes and certain cylindrical burrows commonly contain cores of drusy calcite, which may or may not be admixed with chalky sediment. Other burrows are completely filled with coarsely crystalline spar (Frey, 1970, p. 24-25); the burrow walls consist of microcrystalline calcite, evidently representing recrystallization or replacement of original materials used in construction of the burrow.

White powdery gypsum and finely crystalline selenite are common locally in parts of the Fort Hays and Smoky Hill, although generally inconspicuous. They occur as very thin lenses and stringers within beds of shaly chalk, chalky shale, and bentonite, and as linings along certain slickensided surfaces. The lenses and stringers are conformable with bedding but are clearly secondary in origin, apparently forming by the processes outlined by Schleh (1967) and Hattin (1965b, p. 63-64).

Glauconite and flint, common in certain English chalks, are conspicuously absent from the Fort Hays.

#### SKELETAL ARAGONITE PRESERVATION

Aragonite is generally rare among Mesozoic carbonate rocks and is conspicuously absent from the Fort Hays. Feigl's solution (Feigl, 1943, p. 201-202) was ap-

plied to numerous rocks, fossils, and burrow structures, all yielding negative reactions. Neither was the mineral detected in petrographic and X-ray diffraction analyses.

The absence of aragonite in the Fort Hays is due largely to original composition of constituent particles; planktonic foraminiferal tests, coccoliths,<sup>1</sup> practically the entire valve of *Pycnodonte*, and the thick prismatic layer of inoceramid valves consisted originally of calcite (see Chave, 1954; Taylor and others, 1969). Curiously, inoceramid pearls in the Niobrara consist of prismatic calcite (Brown, 1940). Serpulid tubes and the zoaria of *Pyripora*—by analogy with other electrid bryozoans (Rucker & Carver, 1969, table 1)—probably also consisted mostly of calcite. However, the nacreous layer of inoceramid valves and possibly parts of serpulid tubes consisted originally of aragonite, which was thus relatively widespread in the depositional environment.

In general, Mesozoic skeletal aragonite has been either removed and replaced, or converted to calcite (e.g., Dodd, 1966). In the Fort Hays and lower Smoky Hill, only extremely rare traces of the nacreous layer are found in *Inoceramus* valves. Almost without exception the inoceramid nacreous layer has been completely dissolved away; the solution occurred so early in diagenesis that adjacent chalky sediment collapsed into the void, obliterating practically all traces of the structure of this layer. (Internal molds of such fossils thus record the morphology of the prismatic layer, not the actual interior of the bivalve shell.) This process was designated "solution-deposition type one" by Dodd (1966, p. 734-735). At places in the Fort Hays, solution may have occurred above the sediment-water interface.

The only exception to this widespread solution-collapse phenomenon that I noted was in a thin section from Unit 1, Locality 3, where a small inoceramid fragment retains traces of both skeletal layers; optical continuity between layers indicates recrystallization of the lamellar layer.

Thus, as noted by Tourtelot & Cobban (1968, p. L17-L18), nonpreservation of aragonite in the Fort Hays and lower Smoky Hill probably accounts largely for the present dearth of ammonites and other mostly aragonite fossils, rather than certain "abnormal" environmental conditions that actually barred the living organisms.

Paucity of skeletal aragonite has also been observed in European chalks (Kennedy, 1969, p. 462-464), including selective removal of inoceramid nacre. Hudson (1967, p. 473-476) noted that, as compared with calcium carbonate equilibria in modern oceans, the very early diagenetic solution of aragonite from *Inoceramus* valves suggests low temperatures and tremendous depth. However, Hudson (p. 476-479) concluded from paleoecological evidence that the solution of inoceramid nacre in

certain Cretaceous chalks of Europe must have occurred in substantially shallower water, perhaps at depths of as little as 200 meters. Paleoecological data from the Fort Hays imply warm and even shallower water than that postulated by Hudson.

As noted by Kennedy & Hall (1967), skeletal aragonite solution reflects the oxidation of proteinaceous skeletal constituents that would otherwise remain and enhance the stability of aragonite. The process "solution-deposition type one" thus implies that the waters (or the enclosing sediments) were well aerated at the time of aragonite solution.

## PRIMARY SEDIMENTARY STRUCTURES

Inorganic and biogenic sedimentary structures are abundant in the Fort Hays, and have important environmental implications. Discrete burrow structures (e.g., Pl. 5, fig. 3) and profusely mottled sediments (e.g., Pl. 5, fig. 4) are especially widespread and significant; these have been recounted in a separate report (Frey, 1970) and thus will not be discussed at length here. Representative burrow structures are illustrated in Figure 9.

Most inorganic sedimentary structures observed in the Fort Hays are restricted to beds of chalky limestone and are at least partly obscured by bioturbation. Scattered well-preserved structures and numerous poorly preserved structures suggest that substrate scour, primary lamination, cross lamination, and very thin cross bedding were widespread originally in this chalky sediment, especially in the lower one-half of the member.

Laminae and cross laminae, as seen in most exposures, are generally restricted to thin zones parallel with bedding (Pl. 6, fig. 4). In several places these zones are so thin that they are easily mistaken for simple shale partings (Frey, 1970, pl. 10, fig. 4), yet fresh exposures of this rock reveal primary structures. The thickest zones are found most commonly in the upper part of chalky limestone beds (Pl. 6, fig. 3). All of these zones truncate underlying burrow structures and are therefore related to substrate scour; furthermore, most such zones, including the very thin ones (Fig. 7), may be traced throughout Trego County, attesting to a large, uniform current regime.

Cross laminae that are not concentrated in particular zones are rarely observed. Such laminae are conspicuous locally on solution-etched surfaces, especially in the middle and lower parts of Unit 7. Elsewhere the laminae are generally inconspicuous, unless composed of finely fragmented fossil debris such as inoceramite (Pl. 2, fig. 2; Pl. 5, fig. 1).

Beds of shaly chalk and chalky shale are commonly laminated. Most such laminae, which pass through burrows or bend around fossils, nodules, and concretionary structures, were produced during compaction. Exceptions are rare places where small lenses of lami-

<sup>1</sup> All known coccoliths are composed of calcite, although aragonite may be produced under laboratory conditions (Wilbur & Watabe, 1963).

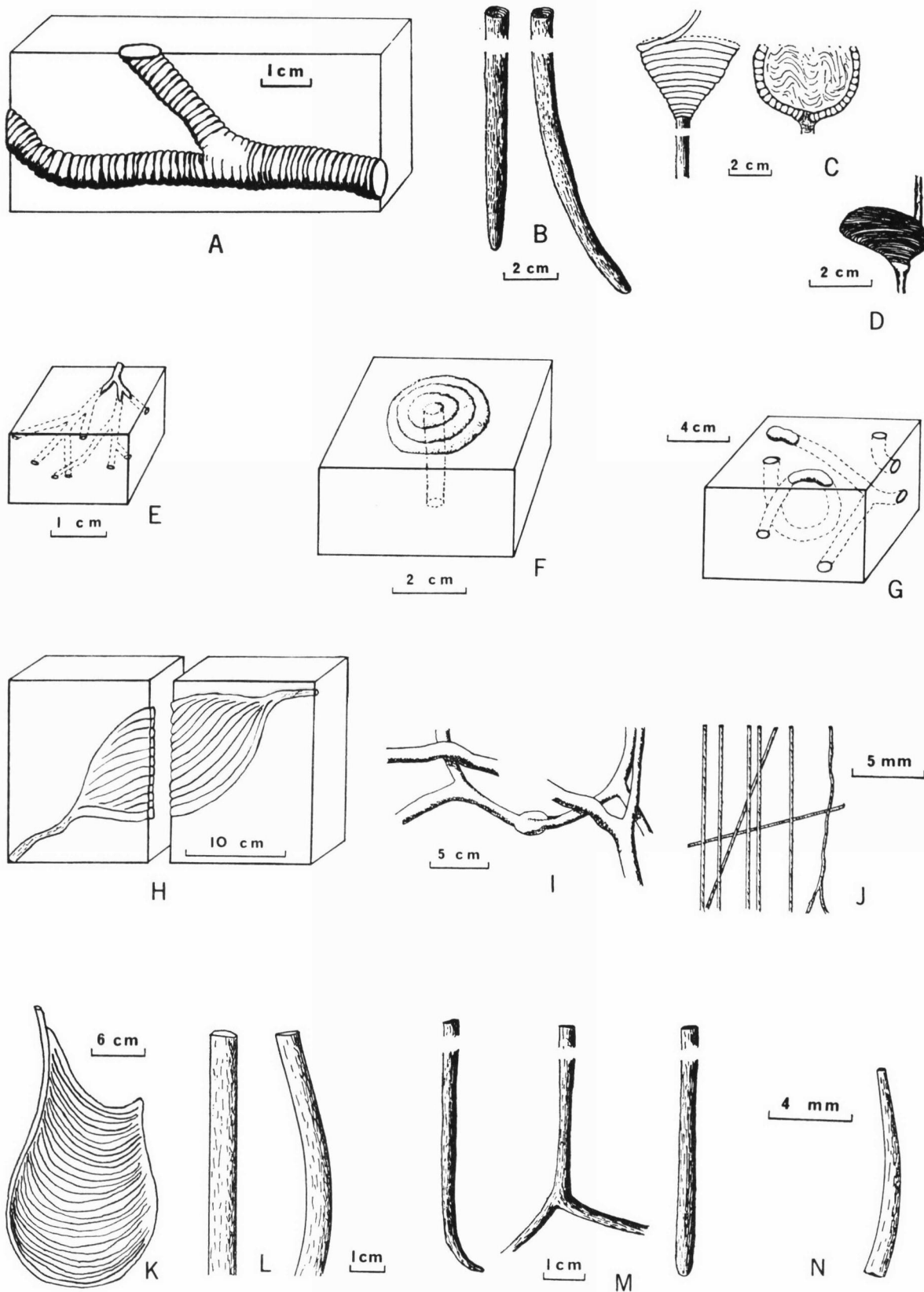


FIG. 9. (For explanation see facing page.)



nated shale dip down at low angles into underlying beds of chalk or chalky limestone.

In addition to the channel structures found along the Carlile-Niobrara contact (Pl. 2, fig. 5), two channels were found entirely within the Fort Hays. The larger of these (Frey, 1970, pl. 1, fig. 3) is restricted essentially to Unit 7, Locality 1. The axis of this channel seems to be aligned west-southwest/east-northeast. During its active existence the channel migrated gradually upward and to the north, as evidenced by overstepping of thin cross beds. These cross beds are strongly laminated to cross laminated, and they contain small quantities of argillaceous and arenaceous detritus. The overall structure is about 37 feet across and 3 feet deep, but at any given time the active channel was probably slightly smaller than this.

The unit containing this channel is characteristically cross laminated and has a thick scour zone at its top (Pl. 6, fig. 3); whether these structures are related genetically to currents that cut the channel remains unclear, however.

The other channel, which is considerably smaller and shows less indication of lateral or vertical migration (Pl. 6, fig. 1), lies in Unit 50, Locality 1. It is apparently aligned northeast-southwest and is about 9 feet wide and 0.8 foot deep. The channel fill is laminated and cross laminated, although these structures are partly obliterated by bioturbation. The base of the channel, like that in Plate 2, figure 5, is separated from the underlying rock by a thin layer of pyrite and limonite. The northwestern side of the channel (left side in Pl. 6, fig. 1) seems to have migrated laterally, but the extent of this movement could not be traced.

The only other conspicuous sedimentary structures in the Fort Hays are beds of chalky limestone that either thin abruptly (Pl. 6, fig. 2) or are completely truncated laterally. Overlying beds generally thicken in compensation. Cross laminae and very thin cross beds may be associated with these structures, but they are not obviously the result of channel-type scour. One such structure was found at Locality 1 (Unit 49) and another was noted at Locality 9. According to Donald E. Hattin (1967, personal communication), these structures are fairly common elsewhere in the Fort Hays.

Mud cracks have been reported from a shale bed in the Fort Hays (R. G. Moss, in Landes & Ockermann, 1930, p. 18), but these structures are evidently produced by outcrop weathering, not by submarine cracking or subaerial dessication of unconsolidated sediments. In

Trego County such cracks are common among beds of chalky shale (Pl. 7, fig. 1), especially in the lower one-third of the member. The shale polygons are seen only on relatively open exposures, and the cracks are typically fresh; none are filled with consolidated sediment.

The abundance of both inorganic and biogenic sedimentary structures declines abruptly in the lower few feet of the Smoky Hill. In Trego County burrow structures are either absent or extremely rare above Unit 62, and scour structures are very rare throughout. Most bedding features and laminations are entirely conformable and are well preserved.

## DIAGENETIC STRUCTURES

Although most evidence points to late-diagenetic lithification of Fort Hays sediments, scattered chalky concretionary structures indicate that early cementation occurred locally. Such structures, which may be several decimeters across, caused considerable distortion of bedding (Pl. 7, fig. 2). They are most common in beds of chalky limestone but may be found in beds of chalk and shaly chalk. The concretionary structures in shaly chalk typically retain vestigial laminae or shale partings. These features are especially large and abundant locally in northern Ellis County (e.g., Pl. 7, fig. 3) and at Locality 6.

Bedding deformation resulted also from differential compaction of sediments around fossils, especially the large inoceramids, although generally conspicuous only at lithologic interfaces (Pl. 7, fig. 4). Such deformation shows that compaction occurred before the sediments were well lithified, else the inoceramid valves would have been flattened or distorted during the process.

Small stylolites and "solution seams" are scattered through the Fort Hays but are abundant and persistent only in Unit 47 (Pl. 7, fig. 5). According to the classification by Park & Schot (1968, fig. 2.5a), most of the stylolites are of the interconnecting network type. Most systems are either horizontal or gently inclined to bedding. A thin layer of clayey material, generally present at the stylolitic contacts, resembles detrital residues and may also contain small quantities of finely divided iron sulfide or oxide.

According to Park & Schot (1968, p. 187-189), most stylolites originate during diagenesis and the process probably ceases when cementation approaches its final stages. Stylolitic seams bearing marginal microfaults are exceptional and indicate that pressure solution occurred

FIG. 9. Diagrammatic reconstructions of burrow structures from the Fort Hays (Frey, 1970). Several burrow types (*Thalassinoides* sp. cf. *T. paradoxicus*, *Zoophycos* sp. B, mechanically filled burrows, feeding burrows penetrating other trace fossils, and burrows and tubes associated with bivalve shells) are not depicted here; see Frey (1970) for descriptions of these.—A. *Arthropycus*-like burrows.—B. *Asterosoma* form "*Cylindrichnus concentricus*."—C. *Asterosoma* form "helicoid funnel" Type B.—D. *Asterosoma* form "helicoid funnel" Type A.—E. *Chondrites* sp.—F. *Laevicyclus* sp.—G. *Planolites* sp.—H. *Teichichnus* sp.—I. *Thalassinoides* sp.—J. *Trichichnus linearis*.—K. *Zoophycos* sp. A.—L. Cylindrical shafts.—M. Mineral-filled burrows (calcite, limonite, pyrite).—N. Scaphopod-shaped tubes.

after the sediments had become well cemented (Schot & Park, 1968, p. 112). Fort Hays stylolites lack microfaults and were apparently formed while the sediments remained relatively incompetent and poorly lithified.

## BIOSTRATIGRAPHY

### GENERAL STATEMENT

Fossil assemblages in the Niobrara of the Western Interior Region are generally much less diverse than those in equivalent strata of the Gulf Coastal Plain. Similarly, assemblages in the Niobrara of Kansas are generally less diverse than those of the Niobrara elsewhere in the Western Interior.

Ammonites, traditional guide fossils of the Mesozoic, are rare or absent in most of the Niobrara, hence other taxa must be used in biostratigraphy. *Inoceramus* faunal zones have been established for the Late Cretaceous in many parts of the Western Interior (Kauffman, 1966, table 1), and these have proven to be reliable for correlations. Most of these zones are depicted in Table 5.

This general scheme is the best zonation established to date for the Western Interior but is not entirely adequate in terms of the inoceramid succession in west-central Kansas (see Fig. 10). Unfortunately, I was not able, on the basis of my specimens, to devise a more suitable alternative.

### REGIONAL SETTING

Certain of the above-mentioned *Inoceramus* zones are missing from the Late Cretaceous of Kansas. The Turonian-Coniacian boundary, as placed in Table 5, coincides with the Carlile-Niobrara contact in west-central Kansas. The highest well-documented Turonian zone in the Carlile is that of *I. flaccidus*-*I. cf. I. dimidius* (Hattin, 1962, p. 79-86, 97-99), although the *I. howelli*-*I. cf. I. dimidius* zone is probably also present (D. E. Hattin, 1968, personal communication). The lowest Coniacian zone found here in the Niobrara is that of *I. erectus*. This species has not been reported from Kansas previously, but a probable specimen was found in the basal bed of the Fort Hays in Trego County, and several additional specimens were found subsequently in the lower part of the member in Hamilton County by D. E. Hattin (1968, personal communication). Fossils and sediments within this interval of missing zones either were never present in Kansas or were removed by ero-

TABLE 5.—*Inoceramid Faunal Zones for Part of the Late Cretaceous of the Western Interior of the United States.*

(From Kauffman, 1966, Table 1.)

STANDARD AGES		INOCERAMIDS DIAGNOSTIC OF ZONE
Santonian	Late	<i>I. balticus</i> (early form); <i>I. cf. I. patootensis</i>
	Middle & Early	* <i>I. platinus</i> ; <i>I. cordiformis</i> (late form) <i>I. undulatopticatus</i> ; <i>I. cordiformis</i> (early form)
	Late	<i>I. undulatopticatus</i> ; <i>I. cf. I. stantoni</i> <i>I. stantoni</i> (late form); * <i>V. grandis</i>
Coniacian	Middle	<i>I. stantoni</i> (early form); * <i>V. grandis</i> (?= <i>involutus</i> ) <i>I. inconstans</i> ; <i>I. wanderi</i> ; <i>I. naumanni</i> <i>I. n. sp. aff. I. browni</i> * <i>I. browni</i>
	Early	* <i>I. deformis</i> ; <i>I. problematicus</i> (late form) <i>I. erectus</i> (late form) * <i>I. erectus</i> (early form); <i>I. "problematicus"</i> (late form)
	Late	<i>I. problematicus</i> (= <i>aviculoides</i> ) (early form) <i>I. perplexus</i> n. subsp. <i>I. perplexus perplexus</i> <i>I. dimidius</i> (late form) <i>I. dimidius</i> (early form); <i>I. howelli</i> (late form)
Turonian	Middle	<i>I. howelli</i> (early form); <i>I. n. sp. aff. I. dimidius</i> <i>I. flaccidus</i> ; <i>I. n. sp. aff. I. dimidius</i> <i>I. latus</i> ; <i>I. cuvieri</i> (late form) <i>I. labiatus</i> aff. <i>I. hercynicus</i> ; <i>I. cuvieri</i> (early form)

\* Indicates taxa found in the Niobrara of Trego County, Kansas.

sion prior to Niobrara deposition; the interval represents a span of considerable time, possibly as much as 2 million years (Kauffman, 1969, p. 234), and constitutes the most extensive disconformity in the Cretaceous of the Western Interior. It is also represented in certain parts of Wyoming, Colorado, New Mexico, and Texas, and in places three or more stratigraphically distinct disconformable surfaces are present (Kauffman, 1967, p. 80; 1969, p. 234).

Biostratigraphic zones for the Western Interior show that this unconformity is diachronous, climbing stratigraphically upward from west to east and from south to north. The diachroneity is well defined by the successive omission of inoceramid zones in the basal Fort Hays. In southern and southeastern Colorado, Kauffman (1966; and 1968, personal communication) erected the following zones, in ascending order: 1) *Inoceramus*

FIG. 10. Stratigraphic ranges of macroinvertebrate fossils in the Fort Hays and basal Smoky Hill, Trego County, Kansas. [A, *Inoceramus* cf. *I. erectus*; B, *Pycnodonte aucella*; C, *Serpula* sp.; D, *Serpula* cf. *S. semicoalita*; E, ?teredine tubes; F, *Pyripora shawi*; G, *Pycnodonte congesta*; H, *Inoceramus deformis*; I, *Inoceramus browni*; J, *Inoceramus* aff. *I. platinus*; K, *Volviceras grandis*; L, *Inoceramus platinus*.] Bedding units indicated at left are based upon thicknesses at Locality 1. Dashed lines indicate beds in which taxa were not found or were not positively identified. Arrows show taxa that range above plotted strata.

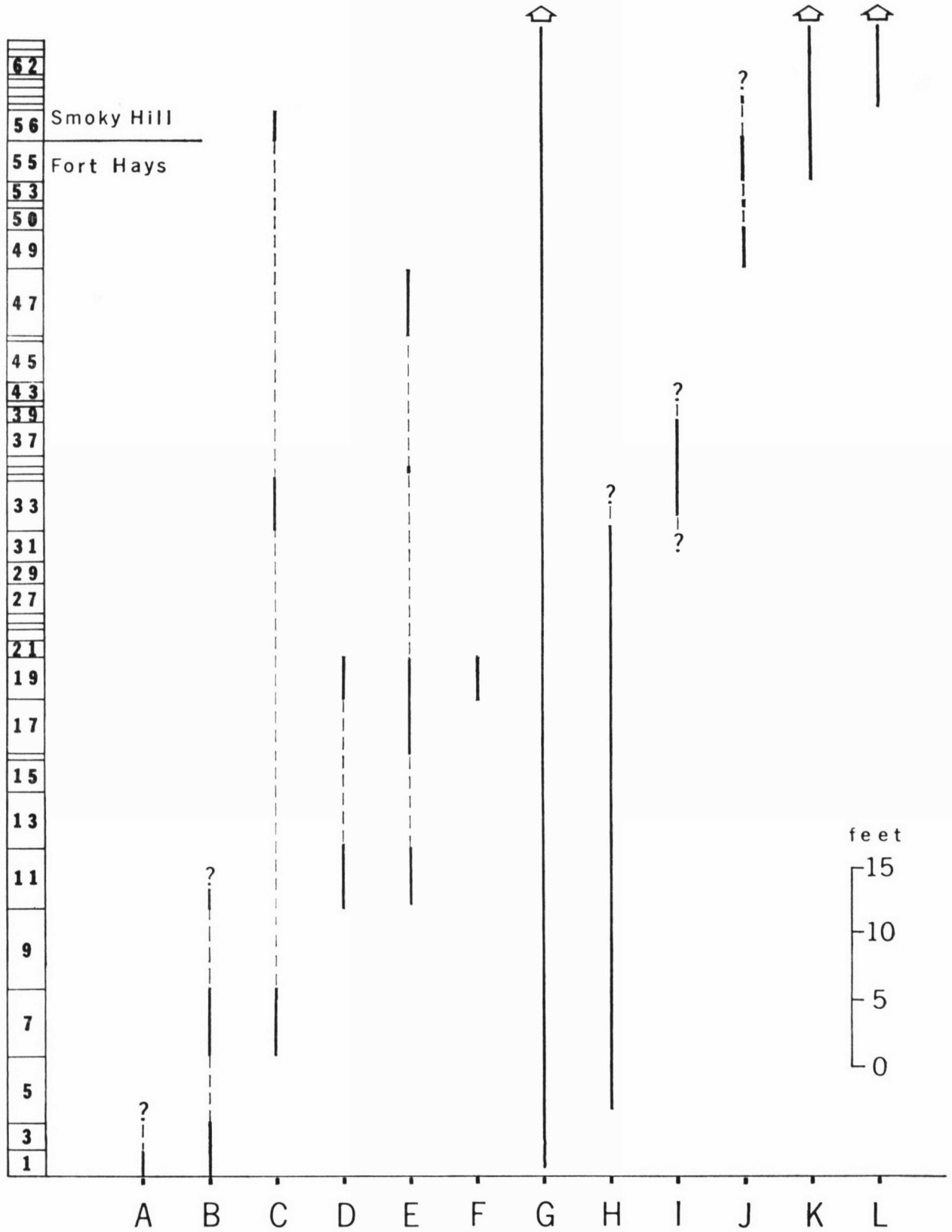


FIG. 10. (For explanation see facing page.)

*problematicus*, 2) *I. erectus*—a small, early form having irregular, sharply bent, concentric rugae, 3) *I. erectus*—a large, late form having more regular ornamentation, and 4) *I. deformis*. From southern Colorado northward along the Front Range, *I. problematicus* disappears north of Colorado Springs, Colorado, *I. erectus* (early form) at about the Colorado-Wyoming border, and *I. erectus* (late form) in central Wyoming; here the *I. deformis* zone directly overlies the zone of *Prionocyclus wyomingensis*. Similarly, the zone of *Inoceramus problematicus* disappears eastward from Colorado into Kansas. Part of the *I. erectus* (early form) zone is evidently present in the basal Fort Hays of western and west-central Kansas (Fig. 10); *I. erectus* (late form) has not been positively identified from these strata, probably because of poor preservation of inoceramids in the lowermost part of the member.

Finally, the positions of given time lines relative to these zones may be debated. The chronologies determined by Cobban & Reeside (1952, chart 10b) and Scott & Cobban (1964, table 2) agree fairly closely with those in Table 5, but the ages established by Jeletzky (1968, fig. 2) for the Western Interior of Canada are markedly different relative to the Turonian-Coniacian boundary. According to Jeletzky, who geared his work to European type areas, *Inoceramus deformis* represents late Turonian time (Jeletzky, 1968, p. 31-32) and *Volviceramus grandis* (*s.l.* = *Inoceramus involutus*, *s.l.*) represents much of the Coniacian (p. 33-34). Resolution of this controversy will depend in part on better descriptions and taxonomies of inoceramids in the European type areas, and better correlations of these with time-equivalent species in North America. However, a difference in philosophy is also involved; in Europe the taxa designated as indices of major time units have traditionally been selected more or less independently of the remainder of the faunas, whereas in the Western Interior of the United States relatively more emphasis has been placed upon major breaks in overall faunal composition. Even when European and American inoceramid zonations are ultimately refined, therefore, the established time lines will probably remain somewhat different.

## PALEONTOLOGY AND BIOMETRY

### GENERAL STATEMENT

Bivalves are particularly important in biostratigraphic and paleoecologic studies of the Cretaceous of the Western Interior, and they once could be collected in Kansas "literally by the wagon load" (Williston, 1893, p. 110). In spite of this heritage, most of the fossils remain taxonomically and morphologically poorly documented.

### BIOSTRATIGRAPHIC ZONATION OF THE FORT HAYS MEMBER

The Fort Hays in Trego County embraces the ranges of several species (Fig. 10), the individual or concurrent ranges of which might be used for zonation of the member. Few of these taxa are sufficiently abundant that such zonation would be practical, however. Presently, the only useful zones are those of: 1) *Pycnodonte aucella*, found in the lower part of the member, 2) *Inoceramus deformis-I. browni*, which range through most of the member, and 3) *Volviceramus grandis*, which ranges from the top of the member upward into the Smoky Hill Member. The exact range of *Inoceramus browni* and the upper extent of the range of *I. deformis* could not be established on the basis of my specimens. *Pycnodonte aucella* has a more embracing range than is indicated in Figure 10 (probably including the zones of *Inoceramus problematicus* through *I. deformis*; E. G. Kauffman, 1968, personal communication), but its full range is seldom realized at any given locality. Within its overall range this *Pycnodonte* is essentially a facies fossil, generally found in abundance only near the base of the Fort Hays, in spite of the diachroneity of that unit. This distribution thus diminishes somewhat the usefulness of *P. aucella* regionally.

The range of *Pycnodonte congesta* spans the Fort Hays and extends into the Smoky Hill, and the bryozoan *Pyripora shawi* has been found in the Santonian of Arkansas (Shaw, 1967).

Miller (1968, p. 5-9) tentatively zoned the Fort Hays and the Smoky Hill in Kansas, mostly on the basis of mollusks, but his zones are poorly defined and in some instances are ambiguous. His Zone A may be interpreted either as an *Inoceramus erectus-Pycnodonte aucella* zone or as an *Inoceramus deformis-Pycnodonte congesta* zone. As defined, his Zone C applies only to Units 55 and 56 in Trego County (Fig. 10); *I. platinus* appears in Unit 57, and *Volviceramus grandis* does not range below Unit 55. The ranges of *V. grandis* and *Inoceramus deformis* (*s. s.*) do not overlap, as suggested by his Zone B.

Trace fossils in the Fort Hays also exhibit more or less distinctive ranges (Frey, 1970, fig. 5), although these ranges mostly reflect paleoecological and preservational factors, not phylogeny.

Fortunately, E. G. Kauffman of the U.S. National Museum has undertaken an extensive study of Cretaceous mollusks, particularly the Inoceramidae. His studies have already yielded considerable information on functional morphology, biostratigraphy, paleozoogeography, and paleoecology (Kauffman, 1962, 1965a, 1965b, 1966, 1967, 1968, 1969, 1970; Kauffman and others,



1969), and the work is still in progress. Because most of the macroinvertebrate taxa found in the Niobrara of west-central Kansas are included in Kauffman's study, no attempt has been made here to substantially alter existing nomenclature or to describe and illustrate species in morphologic detail. Instead, the objectives of this part of the study were 1) to identify the macroinvertebrates present and to place in proper perspective their paleontologic, biostratigraphic, and paleoecologic significance, and 2) to document qualitatively and quantitatively the assemblages of organisms present and also the distribution, abundance, orientation, and size characteristics of component species. Results of the first objective are presented mostly in the following discussion of fossils, and the second in a subsequent discussion of assemblage and population characteristics. Partial synonymies are included for the macroinvertebrates, primarily to help dispel possible ambiguities concerning the identity and significance of a particular taxon. Macroinvertebrates and other fossils are discussed where appropriate, but, except for trace fossils, these constituted relatively minor aspects of the overall study. The trace fossils were described and reconstructed in detail because they had not been studied previously. Such fossils represent animal activity or behavior rather than preserved body parts, however, and they require certain modifications in taxonomic and even paleoecologic concepts; these fossils were thus described, figured, and interpreted in a separate report (Frey, 1970). Most of the characteristic trace fossils are presented diagrammatically in Figure 9.

Except for certain museum specimens, photographs stress the appearance of fossils in the rock matrix or as collected in the field. In the terminology and orientation of bivalves, I have followed the convention of Moore and others (1952, fig. 10-5); their terminology has been modified recently in the *Treatise on Invertebrate Paleontology*, Part N.

## DISCUSSION OF FOSSILS

### Phylum BRYOZOA Ehrenberg, 1831

#### Class GYMNOAEMATA Allman, 1856

#### Order CHEILOSTOMATA Busk, 1852

#### Family ELECTRIDAE Lagaaij, 1952

#### Genus PYRIPORA d'Orbigny, 1849

The encrusting zoarium of *Pyripora* is uniserial or pluriserial and consists of pyriform zooecia that bud distally, unilaterally, and (or) bilaterally. The zooecia are tapered proximally and may bear a slender tubular stolen (cauda). The aperture is elongate and oval. Ovicells, spines, avicularia, and calcified wall bases are lacking (Thomas & Larwood, 1960, p. 370).

Cretaceous species of *Pyripora* typically encrust

smooth, flat surfaces, and they are found commonly on *Inoceramus* valves (Thomas & Larwood, 1960, p. 370).

### PYRIPORA SHAWI Frey & Larwood, 1971

Plate 8, figures 1-2

*Pyripora* sp. Shaw, 1967, p. 1400, pl. 178, fig. 2.

*Pyripora shawi* Frey & Larwood, 1971, p. 971-974, pl. 115, fig. 1-3; pl. 116, fig. 1-4.

Zooecia of Fort Hays specimens range in length from 0.73 to 1.40 mm and in width from 0.24 to 0.44 mm; apertures range in length from 0.40 to 0.60 mm and in width from 0.15 to 0.29 mm; caudae range in length from 0.11 to 0.91 mm and in width from 0.04 to 0.13 mm. The apertural ratio is 2.0 to 3.2.

Insofar as I am aware, no species of *Pyripora* (or any other bryozoans) have been reported previously from the Niobrara of Kansas. Fort Hays specimens are somewhat larger than Shaw's (1967) specimens from Arkansas, but the two forms are judged to be conspecific (Frey & Larwood, 1971).

*Pyripora shawi* was noted only in Unit 19, Locality 3, where several incompletely preserved zoaria were found on a single inoceramid valve (Pl. 3, fig. 4).

REPOSITORY.—The holotype for *Pyripora shawi*, collected at Locality 3, has been deposited in the paleontological collections of the Indiana University Department of Geology, no. 10993-2.

## Phylum ANNELIDA Lamarck, 1809

### Class POLYCHAETIA Grube, 1850

#### Order SEDENTARIDA Lamarck, 1818

#### Family SERPULIDAE Burmeister, 1837

#### Genus SERPULA Linné, 1768

The tube of serpulid worms is typically long, slender, and narrowly conical; it may be slightly to strongly curved, coiled, or contorted. Concentric growth lines or other ornamentations are usually present. The apertural end may be capped by a horny operculum. Shell material consists of calcite, aragonite, or alternate phases of each (Chave, 1954, p. 279). The tubes are typically attached to consolidated detritus or to other organisms. Individuals may be solitary or gregarious.

#### SERPULA cf. S. SEMICOALITA Whiteaves, 1889

Plate 8, figure 3; Plate 9, figure 3

Rare epizoal serpulids from the Fort Hays strongly resemble *Serpula semicoalita* Whiteaves, as described and figured by Hattin (1952, p. 28-30, pl. 1, fig. 1-3; 1962, pl. 13D) and Miller (1968, p. 57-58, pl. 5, fig. 3).

Only fragmentary specimens were recovered; the greatest tube length observed is about 3 cm, but the tubes were evidently much longer originally; taper of the tubes is almost imperceptible within such short distances. Overall diameter of the tubes ranges from 0.9 to 4.0 mm,

but most specimens are between 2.5 and 3.0 mm in diameter. The circumference of the apertural end of the tube commonly bears a band-like thickening 1.0 to 1.5 mm wide and about 0.5 mm greater in diameter than adjacent parts of the tube (Pl. 9, fig. 3). Walls of the tube are 0.2 to 0.4 mm thick.

Serpulids such as this have not previously been reported specifically from the Fort Hays. *Serpula plana* Logan, synonymous with *S. semicoalita*, was questionably collected from the Niobrara of western Kansas but may be from the Carlile Shale. (See Miller, 1968, p. 58.)

D. E. Hattin collected an inoceramid fragment from the Fort Hays at Locality 3 that bears two epizoal serpulids somewhat resembling *Serpula* cf. *S. semicoalita*. These specimens, which I examined, are as much as 2 mm in diameter; the largest tube is about 3.7 cm in length, and the diameter of this tube near its apical end is approximately 0.8 mm. Neither the apical nor the apertural end is preserved. The two tubes are closely appressed, parallel, and gently curved. Finely imbricated growth increments and small annulations, spaced 1 to 1.5 mm apart, are present throughout the length of the tubes. Prominence of the annulations varies, and in rare places they grade into transverse ribs; the latter are about 0.5 mm wide and 0.3 to 0.5 mm high. A keel courses along the dorsal axis of the tubes.

The dorso-median keel or carina perhaps allies these specimens with *Serpula tenuicarinata* Meek & Hayden (Hattin, 1962, pl. 13C; Miller, 1968, pl. 5, fig. 1-2). As noted by Hattin (1952, p. 31), however, the keel may be a varietal or sexual character rather than a phylogenetic one. The forms of *S. semicoalita* and *S. tenuicarinata* are otherwise very similar.

In Trego County I found *Serpula* cf. *S. semicoalita* only in Units 11 and 19; it is typically rare even in these beds, although in certain specimens a profusion of tubes encrusts a single inoceramid valve (Pl. 8, fig. 3). Hattin's specimens were recovered from float but evidently came from the lower few beds of the Fort Hays.

REPOSITORY.—Paleontological collections of the Indiana University Department of Geology, no. 10991-1.

**SERPULA** sp.

Plate 9, figure 1

*Serpula* sp. is considerably smaller and less abundant than other serpulids encountered. Tubes are straight to very gently curved and are attached throughout their lengths to the interior of inoceramid or *Pycnodonte* valves, especially the former. The plane of attachment is not marked by a conspicuous lateroventral flange. Overall diameter of the tubes ranges from 0.6 to about 1.3 mm, and the tubes are as much as 1.5 cm in length. Tubes taper perceptibly to a sharp-pointed apical end. Few other details are discernible because of poor preservation of specimens.

*Serpula* sp. was found only in Units 7, 33, and 56 (base of Smoky Hill Chalk). Two widely spaced individuals were observed on a single inoceramid fragment (Pl. 9, fig. 1), but the remaining specimens occurred singly. Among the specimens seen only one was sufficiently well preserved for detailed study, and this specimen shattered and was lost during my attempt to collect it. The serpulid is possibly a new species, but additional specimens are needed in order to establish its taxonomic position.

**Phylum MOLLUSCA Linné, 1758**

**Class BIVALVIA Linné, 1758**

**Order PTERIOIDA Newell, 1965**

**Family INOCERAMIDAE Giebel, 1852**

**Genus INOCERAMUS Sowerby, 1814**

Inoceramids are extremely variable in general shape, size, and weight, but practically all species have a toothless pernid hinge containing numerous resilifers (a multivincular ligament) that are oriented perpendicular to the hinge line. All are inequivalved, to varying degrees; the left (lower) valve is largest. Valves may be thick and biconvex or thin and flat, but both forms have a relatively thick prismatic layer consisting of visible units of crystalline calcite (e.g., Pl. 8, fig. 3). The nacreous layer is also relatively prominent but is rarely preserved in chalks or chalky limestones (hence internal molds in such rocks record the internal morphology of the prismatic layer, not the morphology of the actual valve interior); in dark shales and where associated with concretions, the aragonitic nacreous layer is more apt to be well preserved. None of the inoceramids are known to have an anterior adductor scar or a pallial sinus, although the pallial line of certain species is pitted.

Several sources indicate that development of the byssus is a dominant generic or suprageneric trait among members of this group, yet the studies by Kauffman (mentioned previously) show that inoceramids may be split into three groups, two of which either lacked a byssus or atrophied it. The species studied in west-central Kansas are among the latter; indeed, no evidence in this part of the Niobrara suggests a substrate capable of supporting rigid byssal attachment.

The closest living relatives of *Inoceramus*, the Isognomonidae, are found typically in warm temperate to tropical waters, where they attach to mangrove roots or other hard objects in the littoral zone and the upper part of the sublittoral zone (Abbott, 1954, p. 358; Kauffman, 1967, p. 103). Because the habitats occupied by Late Cretaceous inoceramids were evidently much more diverse, most attempts at direct analogies with the Isognomonidae are futile. The stratigraphic distribution and functional morphology of nonbyssate inoceramids never-

theless have considerable paleoecological significance (Kauffman, 1965b, 1967, 1969).

**INOCERAMUS cf. I. ERECTUS Meek, 1877**  
[not illustrated]

A single, incomplete specimen of a small inoceramid resembling *Inoceramus erectus* Meek (1877, p. 145, pl. 13, fig. 1, 1a, pl. 14, fig. 3; Scott & Cobban, 1964, pl. 2, fig. 6) was found in the upper part of Unit 1, Locality 1, in Trego County. The valve is consistently much thinner and less coarsely rugated than that of *I. deformatis*. Rugae on this specimen are more or less irregularly spaced and are moderately sharply ridged. According to E. G. Kauffman, who examined the specimen, the rugae most closely resemble those of typically flattened *I. erectus* (small subspecies; early form) in the Fort Hays of Colorado.

*Inoceramus erectus* has not been reported previously from the Niobrara of Kansas, although several additional specimens have been found recently near the base of the Fort Hays in Hamilton County, Kansas (D. E. Hattin, 1968, personal communication).

REPOSITORY.—Paleontological collections of the Indiana University Department of Geology, no. 10991-2.

**INOCERAMUS DEFORMIS Meek, 1871**

Plate 3, figure 4; Plate 9, figure 4,7; Plate 13, figure 9

*Inoceramus deformatis* Meek, 1871, p. 296, and 1877, p. 146-147, pl. 14, fig. 4, 4a; Logan, 1898, p. 486-487, pl. 92, fig. 2, pl. 96, fig. 1-2; Hattin, 1965a, fig. 5.2; Miller, 1968, p. 23-24, pl. 4, fig. 1-3; Frey, 1970, pl. 8, fig. 13; not Scott & Cobban, 1964, pl. 1.

Scott & Cobban (1964, p. L9) regarded *Inoceramus browni* as a synonym of *I. deformatis*, but the two are here considered distinct species.

Specimens of *Inoceramus deformatis* in west-central Kansas are typically 11 to 16 cm long, 13 to 24 cm high, and 8 to 14 cm thick. A few specimens are considerably larger.

The largest inoceramid found in the zone of *Inoceramus deformatis* is at least 45 cm in maximum diameter; the specimen, which is strongly flattened, articulated, and incomplete (Pl. 9, fig. 6), is apparently atypical of *I. deformatis* with regard to both size and the configuration of rugae, and is possibly a different taxon.

In Trego County *Inoceramus deformatis* is restricted to approximately the lower two-thirds of the Fort Hays, although somewhat closely related forms, in addition to *I. browni*, were found in the upper part of the member. Inoceramids of this lineage are rare above Unit 35, however, and well-preserved specimens are extremely scarce. Taxonomy and biostratigraphy of the species resembling *I. deformatis* in this part of the section must await the collection of better material than I was able to find.

*Inoceramus deformatis* was not noted below Unit 5, but very small shell fragments of *Inoceramus* were found

abundantly in Units 1 and 3 (Fig. 8). The only moderately distinctive specimen found in these lower beds was the fragment of *I. cf. I. erectus*, mentioned previously. From this specimen I infer that the lower beds represent the zone of *I. erectus*, which is succeeded in Unit 5 by the zone of *I. deformatis*. As suggested by the fine, irregular rugae of poorly preserved inoceramids in the lower part of Unit 5, *I. erectus* (large subspecies; late form) may be present at this stratigraphic level (see Table 5).

Completely articulated specimens of *Inoceramus deformatis* preserved in growth position are extremely rare. Loosely articulated specimens having fully open valves are seen occasionally (Pl. 9, fig. 7), as are juxtaposed left and right valves. When observed in vertical exposures, the valves appear to be completely disassociated and scattered through the rocks more or less randomly; when observed on bedding surfaces, however, pairs of valves typically remain discernible. The reason for this difference is simply that both valves of a given pair are not nearly as likely to be situated in the single plane of a vertical exposure as along a bedding exposure. Individual valves are almost invariably oriented concave upward, which makes them useful as geopetals.

*Inoceramus deformatis* was apparently tolerant of a wide range in environmental conditions and thus populated diverse habitats through most time-equivalent parts of the Niobrara depositional basin (Reeside, 1957, p. 526).

**INOCERAMUS BROWNI Cragin, 1889**

Plate 10, figures 7-9

*Inoceramus browni* Cragin, 1889, p. 65-68; Logan, 1898, p. 489-490.

*Inoceramus deformatis* Scott & Cobban, 1964, pl. 1.

*Inoceramus browni* is very similar to *I. deformatis*, thus the two have been treated variously as synonyms (Scott & Cobban, 1964, p. L9), as ecovariants, or as distinct species (Logan, 1898, p. 489-490; Kauffman, 1966, table 1). The unfigured type specimen and original description have also been dismissed as a *nomen nudum* (Miller, 1968, p. 31).

The largest intact specimen of *Inoceramus browni* found in west-central Kansas is 22.0 cm high, 18.5 cm long, and 16.0 cm thick; fragmentary specimens indicate that considerably larger sizes may have been attained by a few individuals.

The change from fine rugae on the juvenile part of the valve to coarse rugae on the adult part may be marked by an equally abrupt change in slope (Pl. 10, fig. 7-8). Such deformation was seen on most specimens from west-central Kansas and is also apparent on the specimen figured by Scott & Cobban (1964, pl. 1). Similar deformation has been noted in another species of *Inoceramus* and has been interpreted as a response to paleoecological stimuli (Toots, 1961, p. 167-168, fig. 1-3,

5). Evidence for such adaptation is lacking among Fort Hays specimens of *I. browni*, thus the break in slope is either genetically controlled or is perhaps related to ontogenetic irregularities. According to E. G. Kauffman (1968, personal communication), this is a genetic character common only to certain lineages, and may mark the break between juvenile and adult stages in some species.

*Inoceramus browni* is apparently sparse to extremely rare in the area studied; it seems to be most common in strata about 50 to 60 feet above the base of the Fort Hays and is not thought to range substantially above or below these beds. It is thus potentially but not practically suited for supplementation of the *I. deformis* zone.

REPOSITORY.—One specimen in the paleontological collections of the Indiana University Department of Geology, no. 10993-3.

#### INOCERAMUS PLATINUS s. l.

Plate 14, figure 3

Specimens of large, thin-shelled inoceramids such as *Inoceramus platinus* Logan (1898, p. 491-492, not pl. 116, fig. 2; Scott & Cobban, 1964, pl. 9, pl. 11, fig. 1; Hattin, 1965a, fig. 5.3; Miller, 1968, pl. 3, fig. 1-3) are notoriously difficult to collect; intact specimens are exceptionally rare. Among the few well-preserved specimens known, one in the Fort Hays Kansas State College Museum (Pl. 14, fig. 3) is 90 cm high and 86 cm long. Miller (1968, p. 30) reported additional measurements, including one specimen at least 127 cm in height and 137 cm in length that was incomplete and too fractured to be collected. My own searches yielded nothing other than incomplete, highly fragmented specimens, the largest being about 50 cm across.

The fragility inherent in the coarse prismatic layer is enhanced by the extreme thinness of the valve; in spite of their large size, single valves of *Inoceramus platinus* rarely exceed a thickness of 2 mm, except near the hinge and valve margins.

The large size and general shape of *Inoceramus platinus* are not unique among inoceramids within this biostratigraphic zone, and the dearth of well-preserved specimens has partly rendered this species a "catch-all" taxon for many such inoceramids. Fragmentary specimens from west-central Kansas compare favorably with the specimen of *I. platinus* in the Fort Hays Kansas State College Museum, but none of these fragments exhibit clearly the large umbonal area: the most critical part of the valves in determining species of the lineage. The concept of *I. platinus* in this report is thus *sensu lato*.

Bivalves having the general size and shape of *Inoceramus platinus* range through most of the Smoky Hill in Kansas (Hattin, 1965a, p. 21) and are relatively abundant in numerous places. In Trego County incomplete specimens were found in beds as low as Unit 57, and fragmentary specimens of a smaller inoceramid generally very similar to *I. platinus* were found in the

upper part of the Fort Hays (Units 49, 52, and 55). Specimens of the latter, which have been noted elsewhere in the Western Interior at this biostratigraphic level, possibly represent the progenitor of *I. platinus*. Better specimens are needed in order to figure and describe this species, referred to here as *I. aff. I. platinus*.

As evidenced by the superposition of shell fragments that are mirror images of each other, well-articulated specimens of *Inoceramus platinus* and *I. aff. I. platinus* were initially relatively common. Their present fragmentary condition is due partly to weathering at the outcrop. Specimens found in west-central Kansas are invariably recumbent.

#### Genus VOLVICERAMUS Stoliczka, 1871

Inoceramids of this lineage are similar in many ways to those discussed above, except that here the valves are large and highly inequivalve; the left valve is coiled in a spiral and the right valve is only slightly to moderately convex. Valves bear concentric plications, and the beaks point anteriorly.

#### VOLVICERAMUS GRANDIS (Conrad, 1875)

Plate 10, figure 1; Plate 11; Plate 12, figures 3-4;

Plate 13, figure 1

*Haploscapa grandis* Conrad, 1875, p. 23-24, pl. 66; Logan, 1898, p. 492-493, pl. 94.

*Inoceramus involutus* Scott & Cobban, 1964, pl. 3, fig. 4; Miller, 1968, p. 32, pl. 2, fig. 1-2, 5-6, pl. 9, fig. 8.

*Inoceramus grandis* Hattin, 1965a, fig. 5.1; Miller, 1968, p. 25-27, pl. 1, fig. 1-12, pl. 2, fig. 3-4.

This species consists of a deep, broadly coiled lower valve and a considerably smaller, caplike upper valve. In most specimens the lower valve is crushed flat, however, which reveals little of the true valve structure (Pl. 11; Pl. 13, fig. 1). Consequently, most collections consist entirely of upper (right) valves.

Among juvenile specimens of *Volviceramus grandis* the rugae may extend to the valve margins (Pl. 10, fig. 1), thus resembling small specimens of *Inoceramus deformis* (Pl. 13, fig. 9).

In Trego County *Volviceramus grandis* was found only in the uppermost bed of the Fort Hays (Unit 55) and the lower part of the Smoky Hill, of which the species is most characteristic. The upper limit of its range has not been established in terms of feet above the base of the Smoky Hill.

Fishel & Leonard (1955, p. 105) reported *Volviceramus grandis* from the Fort Hays, although they must have confused this species with *Inoceramus deformis* (a common error among older geologic reports on areas in Kansas). Miller (1968, p. 26-27) also reported *V. grandis* from the upper part of the Fort Hays, but he did not define the Fort Hays-Smoky Hill contact; it is thus unclear whether these specimens actually came from the Fort Hays or from the interval between the



top of the Fort Hays and the twin bentonites that lie in the lower part of the Smoky Hill (Pl. 3, fig. 2).

Specimens from the Fort Hays and lower beds of the Smoky Hill are typically smaller and thinner shelled than those higher in the section, many of which exceed 30 cm in maximum diameter. Within the rocks studied, the largest specimen of *Volviceramus grandis* found (nearly complete right valve) is 19 cm in length and 15 cm in height.

Well-articulated specimens of *Volviceramus grandis* preserved in growth position are considerably more abundant than those of *Inoceramus deformis* or *I. browni*, although the lower valves of *V. grandis* are almost invariably crushed flat and may not be conspicuous. Upper (right) valves are typically oriented convex-upward in the rock.

The fossil pearls reported by Brown (1940, p. 367-369) from the Niobrara were probably associated with *Volviceramus grandis*. E. G. Kauffman (1968, personal communication) has found pearls of *V. grandis* that weigh as much as one pound.

### Family OSTREIDAE Rafinesque, 1815

#### Genus PYCNODONTE Fischer de Waldheim, 1835

Valves of extant *Pycnodonte* are vacuolated and have a froth-like structure. The valves are unequal, large, and heavy; the hinge is broad, and the lower valve is slightly recessed. Neither valve is sculptured, except for sharp crenulations along the margins. A row of small denticles is present along the edges of each valve, on both sides of the hinge. The adductor scar is elevated on a small shelflike projection. (See Galtsoff, 1964, p. 7, 12.)

Although *Pycnodonte* is found frequently on navigation buoys off Key West, Florida, and near the entrance to Miami Harbor (Merrill, in Galtsoff, 1964, p. 12), the genus is predominantly a deep-water form, most common in continental shelf areas more than 50 feet in depth (Kauffman, 1967, p. 101-102). Certain Niobrara species seem to be early representatives of this group, and some of them evidently had similar environmental preferences. This is especially true of *Ostrea*-like species such as *Pycnodonte congesta* (Conrad).

Another lineage in the Western Interior that is apparently related to extant *Pycnodonte* is represented by gryphaeate oysters such as *P. aucella* (Roemer). (See Plate 8, figure 4.) During the Cretaceous these types of *Pycnodonte* were able to inhabit a variety of habitats, ranging from shallow, nearshore, turbulent waters to deeper, quiet, offshore carbonate banks; they evidently preferred the latter (Kauffman, 1967, p. 124).

#### PYCNODONTE CONGESTA (Conrad, 1843)

Plate 3, figure 4; Plate 9, figures 5-7; Plate 10, figures 1-3; Plate 12, figures 1,4-5; Plate 14, figures 3,6

*Ostrea congesta* Conrad, 1843, in Nicolle's Rept. of Explor. in Northwest (not seen); Meek, 1876, p. 13-14, pl. 9, fig. 1a-f;

Logan, 1898, p. 444-445, pl. 99, fig. 10-11, 13; Hattin, 1965a, fig. 4.2; Miller, 1968, p. 33, pl. 2, fig. 7-8; not Hattin, 1962, pl. 13, A, F.

The growth form of *Pycnodonte congesta* is much like that of the extant oyster *Ostrea equestris*. Configuration of the lower (left) valve depends essentially upon the substrate to which the valve is attached, secondarily upon the degree of crowding of individuals upon that substrate, and possibly upon the rate of sedimentation.

Initial spatfalls of *Pycnodonte congesta* almost invariably settled onto *Inoceramus* valves, but members of subsequent spatfalls attached to the previous generation of oysters. The size and shape of various individuals are thus highly irregular. Among first-generation oysters the lower valves are typically 1.0 to 2.5 cm in diameter and 0.5 to 2.0 cm in height, although numerous exceptions to this range may be found. The largest specimen collected in west-central Kansas (Pl. 14, fig. 6) is 4.5 cm in diameter and about 3.5 cm in height. Successively younger generations are typically successively smaller and less regular in shape.

*Pycnodonte congesta* ranges throughout the rocks studied, although it is extremely rare below Unit 5 and in other strata containing few inoceramids. It extends into the Smoky Hill considerably higher than the beds examined in west-central Kansas. The form resembling *P. congesta* in the underlying Carlile Shale (e.g., Hattin, 1962, pl. 13, A, F) is now thought to be taxonomically distinct (D. E. Hattin, 1968, personal communication).

The valves of *Pycnodonte congesta* are more resistant to breakage and abrasion than those of *Inoceramus*, hence moderately well-preserved specimens of the former may be found in rocks containing only small fragments or prisms of the latter. In the lower few beds of the Fort Hays fragmentary specimens of *Pycnodonte congesta* are easily confused with fragmentary specimens of *P. aucella*.

#### PYCNODONTE AUCELLA (Roemer, 1849)

Plate 8, figure 4; Plate 10, figures 4-5; Plate 13, figures 2-6

*Gryphaea aucella* Roemer, 1849 (not seen) and 1852, p. 74-75, pl. 9, fig. 4a, b; Hill, 1901, pl. 45, fig. 4, 4a; Richards and others, 1962, p. 203, pl. 94, fig. 4.

The growth form of *Pycnodonte aucella* is typically gryphaeate. The larger (left) valve is broadly bowl-shaped and the smaller (right) valve is caplike and nearly flat. Walls of both valves are ordinarily less than 0.5 mm thick, except for the middorsal area of the left valve; here the wall may be as much as 2.5 mm thick.

Adult specimens of *Pycnodonte aucella* from the Fort Hays range in length from about 0.8 to somewhat more than 2.5 cm, in height from about 1.2 to slightly more than 3.0 cm, and in thickness from about 0.6 to more

than 1.2 cm. Much of this variation is related to the degree of alateness of valves (Pl. 13, fig. 3, 5-6).

This species, which has not been reported previously from the Niobrara of Kansas, was not encountered above the lower part of Unit 11 in Trego County; it is common only in Unit 1.

Although the Carlile-Niobrara contact is diachronous, *Pycnodonte aucella* is nearly everywhere found relatively near this contact in the Western Interior. Within its biostratigraphic range (probably the zones of *Inoceramus problematicus*—late forms—through *I. deformis*; see Table 5), the abundance of *P. aucella* is correlative largely with sediment type. This species apparently preferred impure carbonate muds, rendered somewhat coherent by terrigenous detritus reworked from the Carlile.

REPOSITORY.—Paleontological collections of the Indiana University Department of Geology, no. 10991-3.

### Order MYOIDA Stoliczka, 1870

Calcareous tubes having characteristics attributable to the suborders Myina Newell, 1965, and Pholadina Newell, 1965, are common locally in the Fort Hays. I previously assigned these tubes to the genus *Gastrochaena* Spengler, 1783 (Frey, 1970, p. 9), but now feel that they may instead be teredine siphonal tubes (suborder Pholadina, family Teredinidae Latreille, 1825), as discussed below.

#### ?TEREDINE SIPHONAL TUBES

Plate 8, figure 5; Plate 10, figure 6; Plate 13, figures 7,10

Tubes of this species are large and subcylindrical, and may be found singly or in thick clusters (Pl. 8, fig. 5). Valves were not observed. The tubes may be weakly to strongly sinuous but do not double back upon themselves. Tubes of gregarious individuals may be deformed slightly by contact with other tubes but are not attached to each other or to a substrate. All specimens collected are fragmentary; apical and apertural ends are not present. The greatest tube length observed is somewhat more than 10 cm; intact specimens would undoubtedly be much longer. Tube diameter varies considerably—somewhat within certain individuals but especially within populations; in Unit 11, Locality 1, the tubes range in diameter from about 0.4 to 1.4 cm, most being about 1.0 cm in diameter, whereas in Unit 17, Locality 3, the tubes range from about 0.3 to 0.8 cm, most being about 0.5 cm in diameter. Taper of the tube is generally insignificant, although among certain smaller specimens the diameter of the tube may vary as much as 3 mm within an axial distance of less than 3 cm. Well-preserved specimens exhibit subdued yet conspicuous transverse annulations (Pl. 13, fig. 7) spaced about 5 to 7 mm apart; exteriors of such tubes may appear polished and glossy.

The tube wall is 0.2 to 0.5 mm thick and consists of multiple concentric layers.

In general morphological characteristics, these ?teredine tubes compare well with certain species among the families Gastrochaenidae, Pholadidae, and Clavagellidae (Order Pholadomyoidea Newell, 1965). However, otherwise comparable species among these families construct tubes of aragonite (R. G. Bromley, 1970, personal communication). The tubes from the Fort Hays are calcitic; skeletal aragonite is not preserved in these rocks. Furthermore, tubes of the above species typically have a rough exterior because foreign matter is incorporated indiscriminately, whereas those from the Fort Hays have a very smooth exterior. Among known tube-building bivalves, the Teredinae are exceptional because they produce smooth-walled tubes of calcite (see Bromley, 1970, p. 64-66, and references cited). Primarily on this basis, I tentatively refer my specimens to a *Teredo*-like borer among the Teredinae.

Tubes secreted by pholadid clams similar to *Goniochasma* (Weller, 1907, pl. 74, fig. 1-2; Richards and others, 1958, pl. 39, fig. 17-19)—as well as traces of the original wood in which the clams bored—have been found in the Greenhorn Limestone of Kansas. Fossil wood bored by pholadid clams has also been reported from the Fort Hays (Miller, 1968, p. 39). No remnants of wood were observed in association with the ?teredine tubes, and perhaps none was ever present. In places the matrix among biostromal tube masses consists of inoceramite; fragmented valves of *Inoceramus* and *Pycnodonte* are seen commonly among the tubes. The spatial relationships of the tubes indicate that they remain in their original position (the fragmentation noted earlier being an artifact of outcrop weathering and the difficulty of freeing specimens from massive rock), which eliminates the possibility of a “lag concentrate” formed by the settling of tubes as the wood decayed and disappeared. Absence of wood is suggested further by abundant burrows of sediment-ingesting organisms that coursed among the tubes (Pl. 13, fig. 10); such burrows also rule out the possibility that the tubes represent borings in chalk hardgrounds. This ?teredine species may therefore have burrowed in unconsolidated carbonate mud; this burrowing adaptation is atypical of the family as a whole, although at least one extant species of similar habit has been reported (Oosting, in Kennedy, 1967, p. 129).

On the other hand, R. G. Bromley (1970, personal communication) noted that the preservation of wood in chalk rocks is exceptional, at best, and that in this case, the wood might have been destroyed by the ?teredine animals and subsequent scavengers. He offered the following interpretation of the tubes:

“The occurrence in clumps indicates that they [the animals] lived in a special substrate. This substrate *could*

have been a soft-bodied animal, but I prefer the idea of floating timber. In a very short time (a few months) a small piece of wood can be totally riddled by *Teredo*, their tubes coming to lie side by side with the thinnest remnant wood partitions between them. Such a piece would lose buoyancy and sink, killing the *Teredo*. The little remaining wood might be nutritious to bottom fauna, the scavengers themselves removing the wood and introducing the sediment now found between the slightly disturbed tubes."

Density of the Fort Hays  $\delta$ teredine tubes, even in the "biostromal masses," is far less than that of *Teredo*-riddled wood observed by me along the Georgia and North Carolina coasts, however.

Considerable additional work thus remains to be done on the taxonomy and paleoecology of these fossils.

Except for bedding units mentioned above, the  $\delta$ teredine tubes are rare in west-central Kansas. They were not found below Unit 11 or above Unit 47 in Trego County.

REPOSITORY.—Paleontological collections of the Indiana University Department of Geology, nos. 10991-4, 10991-5, 10993-4.

## MISCELLANEA

### BORING ORGANISMS

Excavations made by shell-boring organisms are abundant locally in the rocks studied. Such borings are in fact trace fossils and might well have been included in my report on burrow structures (Frey, 1970). However, the origin and paleoecological significance of these borings allies them more closely with shelled macro-invertebrates than with burrowing organisms. (The distinction between burrows and borings is important; the former are made in unconsolidated sediments whereas the latter are made in either rock or organic hard parts, including wood; Frey, 1971, fig. 1, table 1).

Borings among the rocks studied consist of two basic types, noted in both *Inoceramus* and *Pycnodonte* valves. One kind of boring is nearly perfectly circular in transverse section (Pl. 13, fig. 11-12) and consists of interconnected galleries (Pl. 9, fig. 5) that duplicate excavations in Recent shells made by clionid sponges. The other type of boring is a shallow, curved pit that is weakly to strongly elongate in transverse view (Pl. 13, fig. 13-14; Pl. 14, fig. 2); such structures are produced in Recent shells by acrothoracican barnacles. Although both types of borings may be found on the same valve (Pl. 14, fig. 4), the two types ordinarily seem to be mutually exclusive. All specimens collected have been corroded somewhat, thus diminishing their morphological distinctiveness and, consequently, the precision of measurements.

Diameters of representative surface openings of clionid borings are indicated below.

### Diameters (mm) of Surface Openings of Clionid Borings

SUBSTRATE	N	RANGE	MEDIAN	MEAN	MODE	STANDARD DEVIATION
<i>Inoceramus</i>	18	0.86	0.46	0.54	0.41	0.22
<i>Pycnodonte</i>	9	0.72	0.97	0.94	0.97	0.26

The length and width of surface openings of cirriped borings are as follows:

### Measurements (mm) of Surface Openings of Cirriped Borings

DIMENSION	N	RANGE	MEDIAN	MEAN	MODE	STANDARD DEVIATION
<i>In Inoceramus Valves</i>						
Length	10	0.62	1.56	1.49	1.58	0.21
Width	10	0.66	0.74	0.74	0.92	0.20
<i>In Pycnodonte Valves</i>						
Length	10	0.76	0.59	0.73	0.56	0.26
Width	10	0.31	0.31	0.31	0.31	0.089

Rare acrothoracican borings are considerably larger than the above measurements indicate. These borings have a bulbous enlargement at one end of the structure (Pl. 13, fig. 8) and possibly represent a different species of boring organism. The length and maximum width of these borings, observed only in inoceramid valves, are indicated below.

### Measurements (mm) of Surface Openings of Larger Acrothoracican Borings

DIMENSION	N	RANGE	MEDIAN	MEAN	MODE	STANDARD DEVIATION
Length	8	0.71	2.38	2.38	.....	0.24
Width	8	0.63	1.19	1.20	1.20	0.088

Borings of all types are seen on either the interior or exterior of bivalve shells but are most common on the latter. *Pycnodonte* is much less frequently bored than *Inoceramus*, and inoceramid valves are rarely bored where epizoal oysters are present.

Occasionally, the walls of acrothoracican borings are more resistant to corrosion and abrasion than the remainder of the bivalve shell (Pl. 12, fig. 2). The boring organism possibly secreted some sort of lining for the structure, or its body chemistry may have caused slight recrystallization of adjacent parts of the valve.

The nacreous layer of inoceramid valves is not preserved, hence it remains uncertain whether the borings on valve interiors 1) originally penetrated both layers of the valve, 2) were made after the lamellar layer had been dissolved away but before the valve was buried by sediment, or 3) were made prior to the demise of the bivalve, on a part of the shell interior initially devoid of

nacre. By present-day analogies, the third choice is most probably true.

The size data seemingly reflect significant differences between the size of borings in *Inoceramus* and *Pycnodonte* valves—noted among both the *Cliona*-like and the cirriped structures—although this contention was not tested statistically. Such differences might be attributed either to different species or to ethological variation among local populations, correlative with the particular substrate exploited. Morphological similarity among clionid borings supports the latter interpretation, although two species of clionids are sometimes found together in Tertiary and Recent environments (see Lawrence, 1969).

Taxonomy of Recent clionids is based primarily upon spicule type; although sponge spicules have been reported from the Niobrara of Kansas (McClung, 1898, p. 427), I failed to detect siliceous clionid spicules among my specimens, either through insoluble residue analyses of bored shells or X-ray diffraction of powdered rock and shell material.

According to Arnold Ross, who examined most of my specimens of acrothoracican borings, identification of the Niobrara structures, by process of elimination, can be narrowed down to about three or four "genera" within two families; poor preservation prevents further identification.

Trace fossil names that have been used for such sponge and barnacle borings are listed by Häntzschel (1962, p. W228-W232). The ichnogenera *Zapfella*, *Rogerella*, and other acrothoracican borings have been reported from English chalks (Kennedy, 1970, pl. 8,a,d), and the sponge boring *Entobia* is also common there (*ibid.*, pl. 8,b; Bromley, 1970). Neither type of boring figured here has been reported previously from the Niobrara of Kansas, although the cirriped borings have been illustrated inadvertently (see Logan, 1898, pl. 114-115).

The two basic types of borings range stratigraphically throughout the rocks studied but are distributed patchily. Borings are extremely rare below Unit 5 and in other beds containing few bivalves. Although the borings may be abundant in certain valve fragments, such fragments are only locally abundant. Boring organisms thus contributed relatively minor quantities of micrite to Fort Hays sediments.

Most of my specimens of cirriped borings have been deposited in the museum of the San Diego Society of Natural History, San Diego, California, catalog number SDSNH 4260. Representative clionid borings have been placed in the paleontological collections of the Indiana University Department of Geology, specimen number 10993-5.

#### PROBLEMATICA

Clusters of small tubular structures attached to the interior of inoceramid valves (Pl. 14, fig. 1) are abun-

dant locally in the rocks studied. These tubes, which are solidly infilled with finely crystalline calcite, are typically cylindrical and nearly straight; they are distorted only where crossed by other tubes or where flattened by compaction. A few are weakly sinuous. The tubes range in diameter from 0.15 to 0.43 mm, most being about 0.3 mm in diameter; dimensions may vary slightly within a given specimen. The structures are as much as 2 cm in length. True branching is rare, although the tubes frequently truncate or penetrate each other diagenetically. Branches are not necessarily the same diameter as the parent trunk.

The origin of these structures remains speculative. Their general configuration suggests that a tube-building vermiform epizoan occupied the interior of detrital inoceramid valves. On the other hand, the structures are attached to the interior of the prismatic layer, not the lamellar layer, and could therefore represent borings at the interface between these layers.

This problem is not easily resolved because oysters and serpulids are also found encrusting the interior of the prismatic layer, suggesting that solution and removal of the lamellar layer of Niobrara inoceramids occurred so early in diagenesis that the remainder of the valves still projected above the sediment-water interface and were settled by epizoans. On the other hand, the chemical environment necessary for solution of the aragonite in such manner would perhaps have been detrimental to inoceramids and epizoans living there. Furthermore, it has been suggested (D. E. Hattin, 1968, personal communication; see also Arkell, 1937, p. 448, and Kennedy, 1969, p. 463) that these "epizoans" may in fact have been attached originally to the interior of the lamellar layer and that the solution of this layer simply allowed the epizoans to settle onto the prismatic layer. Such process presumably would have operated beneath the sediment-water interface, otherwise the tubes would not have remained in situ. These tubes may also be related to certain mineral-filled burrows associated with inoceramid valves elsewhere (Frey, 1970, p. 26, pl. 8, fig. 14; pl. 9, fig. 1).

The problematical tubes are distributed patchily; they were not found below Unit 11, but they apparently range into the Smoky Hill well above the units studied. They are most abundant in Units 55 and 56, where densities of 8 to 10 tubes per centimeter (linear transect) are observed commonly.

Specimens of these tubular structures have been deposited in the paleontological collections of the Indiana University Department of Geology, catalog number 10993-6.

#### FORAMINIFERA AND OSTRACODA

Although a large number of foraminifers and several ostracodes have been reported from the Niobrara of Kansas (Morrow, 1934; Loetterle, 1937), few species are



abundant. The foraminiferal assemblages consist predominantly of planktonic forms. (Cf. Clark & Bird, 1966.)

Total foraminiferal abundance among certain strata in Trego County is indicated crudely in Figure 8. Several rock samples from the Fort Hays and lower Smoky Hill were disaggregated through ultrasonic vibration, and the sediment was washed over a 200-mesh sieve. Washed residues from chalks and chalky limestones were rich in foraminiferal remains, although the fossils consisted largely of specimens representing only two genera: *Heterohelix* and *Hedbergella*. Samples from the lower part of the Smoky Hill consisted almost exclusively of these two genera. Foraminifers of any kind were exceedingly rare among the residues of chalky shale and were little more abundant among shaly chalks. This distribution suggests that the deposition of clayey sediments was rather rapid and that it substantially diluted the accumulations of foraminiferal tests.

Species identified among Fort Hays samples included *Heterohelix globulosa* (Ehrenberg), *H. globifera* (Reuss) [= *H. moremani* (Cushman)], and *Hedbergella cretacea* (s.l.). Rare fragmentary ostracodes were observed but no attempt was made to identify them.

Kent (1967, p. 1446) observed morphological intergradations between *Heterohelix globulosa* and *H. globifera* (= *H. moremani*) and therefore treated them as members of an intergradational series. My observations, admittedly limited, did not establish such complete intergradations among specimens from west-central Kansas, nor did the work by Morrow (1934, p. 195). Length-width measurements on 10 specimens of each species from Trego County are indicated below:

*Length-width Measurements of Specimens of  
Heterohelix globulosa (Ehrenberg)*

	RANGE	MEDIAN	MEAN	STANDARD DEVIATION
Length (mm)	0.25-0.31	0.27	0.27	0.0021
Width (mm)	0.16-0.25	0.20	0.20	0.0082

*Length-width Measurements of Specimens of  
Heterohelix globifera (Reuss)*

	RANGE	MEDIAN	MEAN	STANDARD DEVIATION
Length (mm)	0.25-0.27	0.26	0.25	0.010
Width (mm)	0.11-0.15	0.14	0.13	0.019

Miller (1968, table 1) used a few such measurements in an attempt to show that certain Niobrara foraminifers are smaller than their Gulf Coast counterparts. He attributed this (p. 11-13) to unfavorable physio-chemical condition of the water during Niobrara deposition. My measurements on *Heterohelix globifera* reflect even

smaller dimensions than those quoted by Miller (reported as *Gümbelina globifera*) and therefore fit this pattern. (See also Kent, 1968, table 3.) Considerably more and better data, both morphological and taxonomical, are needed to confirm this idea, however. In addition to the above problems, Pessagno (1969, pl. 3) indicated that the ranges of *H. globifera* and *H. globulosa* do not overlap and that neither species ranges into the Coniacian!

#### VERTEBRATES

The Smoky Hill Chalk is noted particularly for its abundant, well-preserved vertebrate fossils (e.g., Williston, 1898). Localities in and around Logan and Gove Counties, Kansas, have yielded many excellent specimens that are exhibited in large natural history museums of several nations. Miller (1958, p. 14-20) listed 135 species of vertebrates that have been found in this member. The better known of these include primitive birds, mosasaurs, plesiosaurs, turtles, flying reptiles, at least one dinosaur, and many kinds of fish. Shark teeth, including those of shell crushers, are common locally. Larger vertebrates are relatively rare in the Fort Hays, although a plesiosaur was recovered from this member in Jewell County (Williston, 1897, p. 237).

The only vertebrate fossils encountered during the present study are scattered bone fragments, fish scales, and shark teeth, found in both the Fort Hays and lower Smoky Hill. Fish scales are by far the most abundant of these fossils. Scattered scales and scale fragments were noted in numerous beds of chalky limestone and chalk, and systematic searches would probably disclose their presence in practically every bedding unit studied. The scales are generally well preserved (Pl. 14, fig. 5); a few retain small delicate features such as growth rings.

Shark teeth (Pl. 9, fig. 2) are generally much less abundant, except for the basal bed of the Fort Hays, which contains numerous small teeth. Rare larger teeth were found in overlying units; none included the teeth of shell-crushing sharks.

Small, faceted to well-rounded phosphatic particles are abundant locally in the basal part of the Fort Hays (Pl. 9, fig. 2). These grains range in size from coarse sand to granules and are evidently of vertebrate origin. Many of them resemble the teeth of pycnodont fish (e.g., Hussakof, 1947, fig. 9). Phosphate nodules containing fossil fragments, such as those reported by Tourtelot & Cobban (1968) at the base of the Niobrara in South Dakota, were not observed in Kansas.

Fragments of bone, consisting mostly of fish vertebrae and ribs or fin rays, are scattered through the rocks examined. Articulated vertebrae were not observed. Rarely one finds small thumblike masses of chalk containing a hash of fish scales and bone fragments, apparently the coprolites of large predaceous animals.

The articulated, well-preserved vertebrate skeletons recovered from the Smoky Hill have been cited as evidence for lack of bottom scavengers (Miller, 1968, p. 18) and lack of strong currents in the depositional environment (Clark & Stearn, 1968, p. 246).

The dinosaur discovered in the Smoky Hill was apparently washed out to sea after death. Its presence in these rocks provides a novel means of equating marine and terrestrial biostratigraphic zones in the Western Interior; assuming that such skeletons could not be transported great distances intact, its presence here also suggests that the eastern strand of the Niobrara depositional basin may have been much closer to west-central Kansas than the western strand (Fig. 3).

#### PLANT FOSSILS

The most abundant plant remains in the Niobrara are those of calcareous nannoplankton, especially coccoliths.

Although English chalks were known earlier to consist chiefly of coccoliths and other microscopic skeletal remains (Sorby, 1861), geologists doubted until 1875 whether any true chalks were present in America. Even when the presence of chalk and chalky limestone in Kansas was established, such deposits were at first thought to be the result of direct geochemical precipitation and thus devoid of microfossils. Microorganisms as components of Kansas chalk were finally documented in 1882 (McClung, 1898, p. 415-416), although Kansas floras have as yet received meager study.

The scanning electron microscope strikingly demonstrates the abundance of coccoliths in rocks from Trego County (Pl. 4, fig. 1-4). Representative taxa are illustrated in Plate 15, figures 1-2.

According to Rezak & Burkholder (1958), coccoliths are the major constituents of the Niobrara throughout the Western Interior; these nannoplankton remains comprised as much as 80 percent of some of their samples. In general, *Zycolithus* is the dominant genus among these fossils (Trexler, 1967, p. 1360). According to W. W. Hay, who examined some of my material, samples from the Fort Hays and lower Smoky Hill in Trego County lie within the range of *Marthasterites tribrachiatus*.

The plant assemblages also include fragments of fossil wood, especially in the Smoky Hill. Most of the wood in this member has been altered to lignite. Wiliston (1897, p. 243) reported a tree from Logan County that was 30 feet long. Prescott (1951, p. 74) found a tree trunk in Lane County that was 6 feet long. Although Waite (1947, p. 175) reported a coal bed 3 inches thick from a well drilled in Scott County, the drill evidently penetrated a tree limb or a chunk of allochthonous coal rather than an autochthonous coal bed.

Small, fairly well-preserved wood fragments were found locally in Unit 61, Locality 3, in Trego County.

Fossil wood bored by pholadid clams has been reported from the Fort Hays (Miller, 1968, p. 39), but the only wood found in this member during my study consists of a few, very small, poorly preserved fragments from Unit 30, Locality 1.

The fossil wood from both members must have been washed out to sea from distant marginal marine environments. Coal-bearing deposits are present in equivalent rocks far to the southwest (Reeside, 1957, p. 526), although the wood may have come from otherwise non-preserved floras along the eastern strand.

## ASSEMBLAGE AND POPULATION CHARACTERISTICS

### DEPOSITIONAL SETTING

The Niobrara Cyclothem is the second of two major depositional cycles in the Late Cretaceous of the Western Interior (Hattin, 1966; Kauffman, 1967, 1969). In each cyclothem the composition and distribution of fossil assemblages are generally correlative with particular phases of deposition. Many of the fossil organisms were evidently adapted to environmental conditions represented by a single, narrowly defined rock type, and fossils reflecting such adaptations appear more or less regularly each time the proper lithotype is repeated in the cyclothem—from marginal marine siliceous sediments at the beginning and termination of a cycle, to offshore, nearly pure carbonates at maximum transgression (Fig. 5).

### FAUNAL ASSEMBLAGES

The macroinvertebrate faunas of the Fort Hays and lowermost Smoky Hill in west-central Kansas represent Assemblages N and Z of Kauffman (1967, p. 112-133). Assemblage N, a "*Gryphaea*" biostrome assemblage, consists essentially of species of *Pycnodonte* such as *P. newberryi* and *P. aucella*. In typical assemblages of the Western Interior these bivalves comprise thin biostromes, small lenticular clusters, or beds of profuse but isolated individuals. Associated with these fossils are various forms of *Inoceramus*, small *Exogyra*, small non-gryphaeate *Pycnodonte*, and sinous burrow structures. The assemblage is found characteristically in pure to sandy limestones and, according to Kauffman (1969, p. 238), reflects a firm to moderately firm substrate, normal salinity, weak to moderate current activity, and water depth greater than 50 feet but less than 500 feet.

In Trego County this *Pycnodonte* assemblage is poorly developed and is restricted essentially to Unit 1. Except for trace fossils, the assemblage is dominated by *P. aucella*. Specimens of *P. congesta* are scattered to

rare, and *Inoceramus* cf. *I. erectus* is very rare. Numerous trace fossils are found in this bed (Frey, 1970, fig. 5) but scaphopod-shaped tubes, *Arthropycus*-like burrows, *Thalassinoides* cf. *T. paradoxicus*, and *Laevicyclus* are probably more nearly related environmentally to the gryphaeate assemblage. (See Fig. 9.)

This assemblage grades into Assemblage Z (Kauffman, 1967, p. 133). It is dominated in the Western Interior by thick-shelled inoceramids having at least one highly convex valve; the assemblage is itself structurally gradational. The oldest such inoceramid is *Inoceramus erectus*, a small biconvex form, which is succeeded stratigraphically upward by larger biconvex forms such as *I. deformis* and *I. browni*. These are succeeded in turn by the rudist-like inoceramid *Volviceramus grandis*. Associated with these inoceramids are gryphaeate and non-gryphaeate *Pycnodonte* oysters, serpulid worms, boring and pedunculate barnacles, and rare ammonites and rudists. The assemblage is found in all limestones and chalky to calcareous shales of the Niobrara in the Western Interior, and the succession of species apparently reflects evolutionary adaptations for life in very soft carbonate muds. According to Kauffman (1969, p. 239), the last phase of this succession—that dominated by *Volviceramus grandis*—further reflects quiet to active waters, slow sedimentation, and water depths of 200 to 400 feet, possibly shallower. [Kauffman (1969, p. 239) redefined his Assemblage Z (1967, p. 133) to exclude all phases other than that of *V. grandis*; his previous definition seems to be more applicable to the situation in west-central Kansas, however, and is retained here for that reason.]

The structure of this overall assemblage is generally very similar to that found in Trego County (Fig. 10). The oldest phase, that dominated by *Inoceramus erectus*, is either largely missing or the organisms are extremely poorly preserved; it is perhaps represented in Units 3 through 5. The phase dominated by *I. deformis* and *I. browni* is well represented in the Fort Hays from Unit 5 through Unit 35. Bivalves are sufficiently scarce in Units 36 through 54 that, except for trace fossils, a definite "community" structure is not ordinarily perceptible. Associated with *I. deformis* and *I. browni* are abundant *Pycnodonte congesta* and trace fossils, and rare ?teredine tubes, serpulid worms, and barnacle and sponge borings. *P. aucella* is found sparingly in this assemblage below Unit 11, and the bryozoan *Pyripora shawi* is present in Unit 19. Above Unit 48 *Inoceramus* aff. *I. platinus* is common locally. Among trace fossils (Frey, 1970, Fig. 5), *Asterosoma* form "cylindrichnus," *Zoophycos* sp. B, *Asterosoma* form "helicoïd funnel" type A, and *Teichichnus* seem to be most characteristic of this part of the inoceramid assemblage. (See Fig. 9.)

The *Volviceramus grandis* phase first appears in Unit 55 and continues stratigraphically upward well beyond

the rocks studied. *Inoceramus platinus* is found as low as Unit 57 and is abundant locally in overlying beds. Higher in the section *I. platinus* is characteristic of another assemblage (the "very large, flat, thin-shelled inoceramid assemblage"; Kauffman, 1967, p. 132), but in the rocks studied it is clearly a component of the *V. grandis* assemblage. Among trace fossils, *Zoophycos* sp. A and possibly *Asterosoma* form "helicoïd funnel" type B (Frey, 1970, Fig. 5), are more intimately related to the *V. grandis* assemblage, although endobionts of any kind are exceedingly rare above Unit 62. Boring barnacles and sponges and epizoal serpulid worms are also represented, and *Pycnodonte congesta* is abundant. Pedunculate barnacles, ammonites, and rudists were not encountered during this study, although the rudist *Durania* was found in the Fort Hays of Trego County by D. F. Merriam (1967, personal communication) prior to my study; it has also been found in the lowermost part of the Smoky Hill in this part of Kansas (M. V. Walker, 1967, personal communication). The specimens noted by Merriam were found in a roadcut (Merriam, 1963, pl. 5A) near my Locality 1; the fossils evidently came from some level between my Units 33 and 47. The species is probably *D. maxima* (Logan, 1898, pl. 115, pl. 119, fig. 1; Miller, 1968, pl. 4, fig. 6-8).

#### POPULATION STRUCTURES

The abundance and distribution of foraminifers are indicated roughly in Figure 8.

As established by counting each individual within a vertical surface area of 8.8 m<sup>2</sup>, the density of the *Pycnodonte aucella* population in Unit 1, Locality 1, is 2.4 specimens per m<sup>2</sup>. (Most specimens are nearly or completely intact and were thus counted as individuals rather than as single valves.) Abundance is greatest in the middle part of this bed, however, so that a mean density value is somewhat misleading; in the middle one-third of the unit the density is about 4.5 specimens per square meter. A comparable population density was found in the same level at Locality 2, but individuals may be somewhat less abundant at Locality 3. In Unit 3 the abundance of *P. aucella* is markedly less, and in higher units only scattered individuals were found.

Population densities of *Pycnodonte congesta* cannot be established in like manner because this oyster is almost invariably restricted to inoceramid valves. Its density and distribution are thus correlative largely with those of the inoceramids. More than one generation of oysters commonly encrust a single inoceramid valve, and the oysters are ordinarily so crowded that individual growth forms are modified substantially.

The remainder of the epizoal organisms—two species of *Serpula* and the bryozoan *Pyripora*—are generally too rare to deserve mention here.



Density of the ?teredine calcareous tubes is a matter of extremes; the tubes are either extremely dense or, if present at all, are extremely sparse. They were noted only in the following units:

*Density of ?Teredine Calcareous Tubes in  
Units of Fort Hays*

UNIT	LOCALITY 1	LOCALITY 3
47	single specimen	.....
35	.....	single specimen
19	single specimen	single specimen
17	.....	profuse locally*
11	profuse locally*	.....

\* As explained below, in text.

In the middle part of Unit 11, Locality 1, I observed a ?teredine tube mass constituting a small biostromal lense 0.4 to 0.5 foot thick and about 13 feet long. Within parts of this lense and in stratigraphically equivalent zones adjacent to it the tubes are generally scattered, though common locally, but within most parts of the lense they are extremely numerous. Because of their crowding and contortions, individual tubes are difficult to count. (The line-transect method is impractical here because of the strong horizontal component of tube orientation.) Such tubes are commonly in loose contact with each other but are generally not intertwined in intricate fashion. The tubes of most individuals are about 1.0 cm in diameter.

A similar situation was noted at one place in the middle part of Unit 17, Locality 3, except that the periphery of the mass, a crude sphere about 1.5 feet in diameter, is less well defined and individual tubes are smaller in size. Density is greatest in the central part of the mass, where 55 individuals were counted within an area of 0.21 square feet (vertical surface); this is equivalent to a density of 2,820 specimens per square meter. Tube abundance declines markedly on all sides of this small area, however, and specimens are scattered to rare only a short distance away. Most individuals are about 0.5 cm in diameter. As in Unit 11, Locality 1, the horizontal component of tube orientation is dominant. Another similarity between the two is that a few feet away from either mass, specimens are absent or extremely rare.

A semi-quantitative, bed-by-bed study of inoceramid populations shows that members of the *Inoceramus deformis* lineage increase in abundance gradually upward from Unit 5 to bimodal peaks in Units 11 and 17 (Fig. 11); densities decline gradually in successively higher units. Measurable inoceramids<sup>1</sup> are absent below Unit 5

<sup>1</sup> Densities were determined by counting within a measured surface area each inoceramid valve judged to be at least two-thirds complete. The thickness of each bed was measured during the study of stratigraphic sections, thus obtaining the area of vertical exposures merely required measuring

and are rare or absent above Unit 35, although rare to scattered small fragments of *Inoceramus* are present in each of these intervals (Fig. 8).

In addition to the larger population peaks in the lower middle part of the Fort Hays, numerous smaller peaks are also evident. Most of these are correlative through the three stratigraphic sections and show that the bivalves were distributed similarly within discrete time intervals—as evidenced by the lateral continuity of beds and their consistent stratigraphic position with respect to bentonites. The only major discrepancies in the lateral correlations are the “abnormally” high densities in the lower part of Unit 31, Locality 1, and in the lower two-thirds of Unit 13, Locality 3.

Although most population changes are systematic and reflect correlative trends, the actual numerical values are not constant within given sample intervals (Fig. 11). The regional population distribution is therefore somewhat heterogeneous along particular time planes. In certain places the local population distributions are also heterogeneous. In Unit 11, Locality 1, the total area measured was arbitrarily broken into two parts during sampling so that local heterogeneity might be estimated. The results are tabulated below:

*Density of Inoceramid Populations of Fort Hays in  
Sampled Area, Unit 11*

	AREA EXAMINED (m <sup>2</sup> )	N	POPULATION DENSITY (valves/m <sup>2</sup> )
First part of area*	7.1	12	1.7
Second part of area*	3.6	12	3.3
Total area	10.7	24	2.2

\* Laterally equivalent parts of same bed.

The inoceramids are not ordinarily so patchily distributed, yet a certain amount of patchiness is probably to be expected; clustered, rather than evenly or randomly distributed, individuals are typical of Recent mollusk populations (Warme, 1969, p. 142-143).

In addition to vertical surfaces, several bedding surfaces were also examined at Locality 2. Data for these vertical and bedding-plane surfaces are compared in Figure 12. The trends in distribution are extremely

the lateral distance traversed and multiplying it by the thickness of the bed (this procedure becomes impractical in very thin beds, where tens of meters of lateral distance are necessary to constitute an area of 1 or 2 m<sup>2</sup>). In order to make the thickness of sampling intervals more nearly constant, the thicker units were subdivided into halves or thirds—depending upon the thickness of the bed—and the data in Figure 11 were recorded specifically for these intervals. Total data per bed are presented in Appendix 3.

Because most specimens were seen only in various cross-sectional views, it was not always possible to distinguish between upper and lower valves or even between *Inoceramus deformis* and *I. browni*. These two species are probably stratigraphically distinct, but strict terminal points for their ranges could not be established (Fig. 10). The data are therefore presented without reference to particular valves or to inoceramid species; for the sake of consistency, articulated specimens are counted as two valves.

Although generally disarticulated, the valves are thought to be essentially at their life sites; sedimentological evidence indicates that, except locally, currents capable of transporting these heavy shells were not present during Fort Hays deposition. Consequently, the density data in Figure 11 probably could have been divided by 2 to obtain a reasonably accurate indication of the actual number of individual bivalves present at a given time.

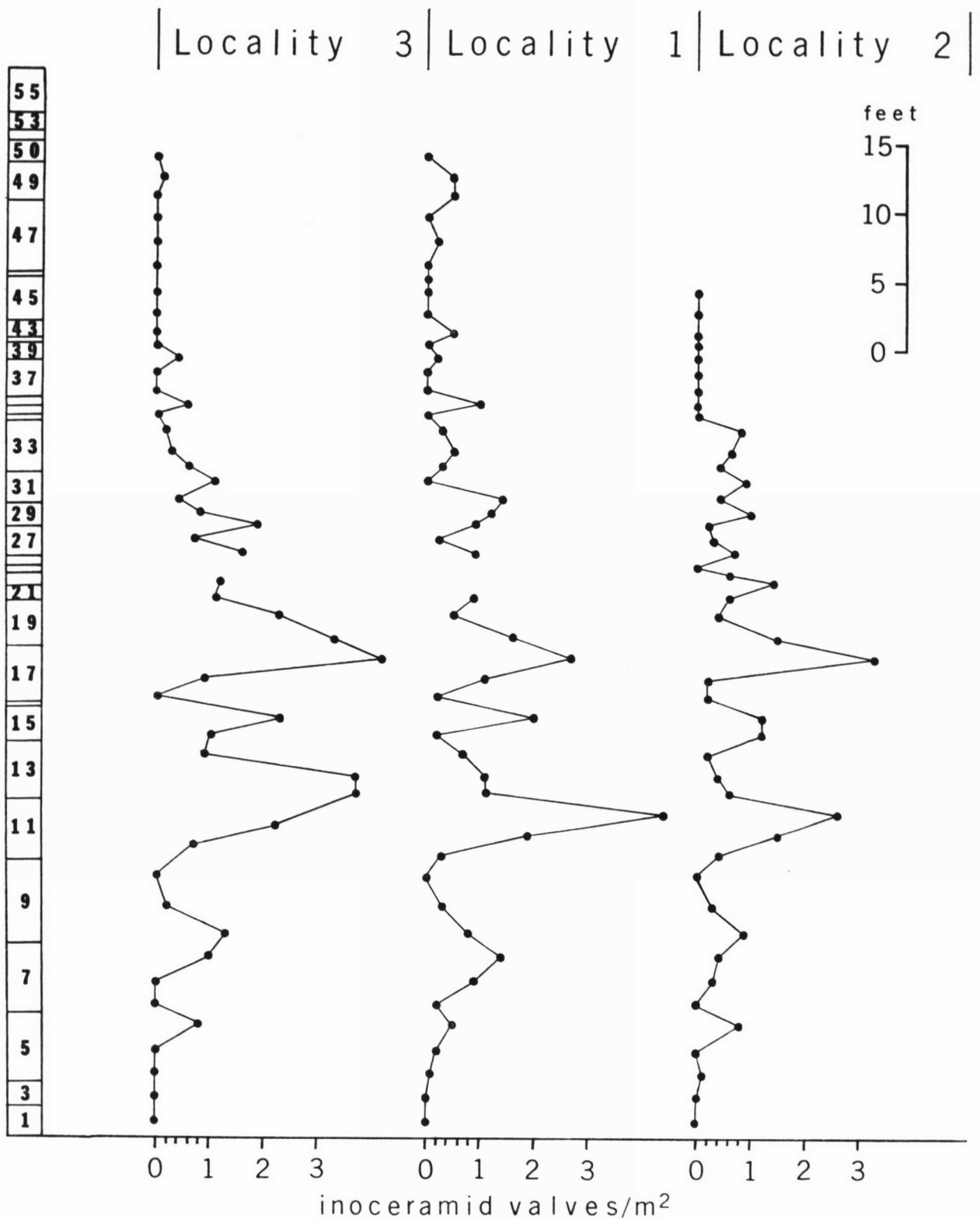


FIG. 11. Density and distribution of members of the *Inoceramus deformis* lineage. Data were gathered on vertical rock surfaces. Bedding units, based upon thicknesses at Locality 1, are plotted at left. Because *Pycnodonte congesta* is restricted essentially to the valves of *Inoceramus*, these data also reflect in a general way the density and distribution of that oyster. The abundance of larger *Inoceramus* valve fragments also follows these trends, although the abundance of microscopic particles of *Inoceramus* and *Pycnodonte* is conspicuously different (see Fig. 8).



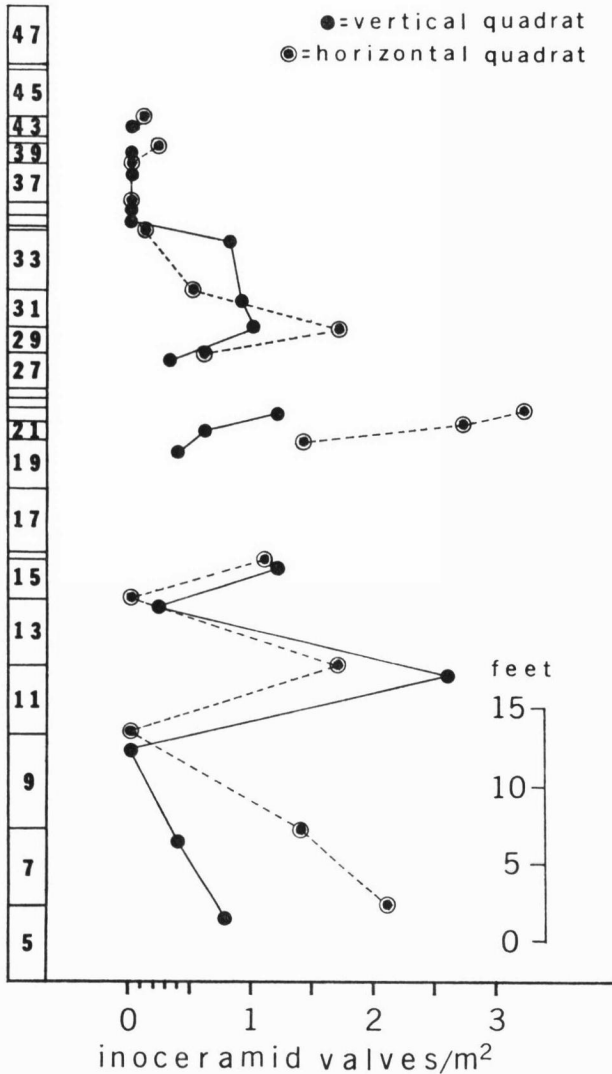


FIG. 12. Comparison of vertical and horizontal quadrat density data for members of the *Inoceramus deformis* lineage from Locality 2. Only those sampling intervals for which both kinds of data were available are plotted. Bedding units plotted at left.

similar. The only major differences are in the data for Units 5, 21, and 23. In Units 5 and 21 the differences are exaggerated by the mode of presentation of the vertical quadrat data; in both instances the valves are somewhat more crowded in the upper part of the units so that on these vertical exposures the mean density of specimens is less than their actual density in the upper few centimeters of rock. To a certain extent, the same is true of Unit 7. The situation in Unit 23 is apparently different in that the upper bedding surface actually contains a much greater population density than any other horizontal plane through the unit; a similar trend was noted at Locality 3, as indicated below:

Density of Inoceramid Populations in Unit 23 of Fort Hays

LOCALITY	VERTICAL EXPOSURE		BEDDING PLANE	
	AREA EXAMINED (m <sup>2</sup> )	POPULATION DENSITY (valves/m <sup>2</sup> )	AREA EXAMINED (m <sup>2</sup> )	POPULATION DENSITY (valves/m <sup>2</sup> )
3	1.7	1.2	2.2	5.5
2	4.3	1.2	5.0	3.2

The size of individuals also changes systematically through the sections, although it does not vary as strikingly as the population densities. Mean and median sizes among bedding populations (maximum diameter of specimens as exposed on rock surfaces) gradually increase stratigraphically upward (Fig. 13).

Except for markedly smaller specimens in Unit 5 and larger specimens in Unit 15, the increase in size, although slight, is practically linear. As with density data, abrupt trends in size distribution are generally correlative through the three sections.

Variations in size of specimens within individual populations<sup>1</sup> is roughly correlative with the distribution of mean sizes; the greater the mean size, the greater the standard deviation (Fig. 14). (A major exception is the data for Units 27 through 33, Locality 3 (Appendix 3), which are not correlative with any obvious parameter.) Differences between the mean and median sizes of individuals are greatest in Unit 19, Localities 1 and 2, and here the standard deviation is also very high.

One might expect to find a relationship between size of individuals and local population density; specimens might be smaller where crowded, for example, or large where sparse. Such relationships are not evident from the data, however. Figures 11 and 13 reflect the general independence of size and density data on a large scale, and the same is true among local populations. In spite of the heterogeneous distribution of valves in Unit 11, Locality 1, tabulated above, the size of individuals is homogeneous, as shown below.

Size of Inoceramid Individuals in Sampled Area, Unit 11

	MEDIAN SIZE (cm)	MEAN SIZE (cm)	STANDARD DEVIATION (cm)
First part of area	10.0	11.0	2.2
Second part of area	10.5	11.0	2.3
Total area	10.0	11.0	2.2

<sup>1</sup> Only those samples for which at least 5 measurements were available are used in the size analysis; at least 8 measurements were available in about 80 percent of these samples, and at least 10 measurements were available in over 60 percent of them. The values obtained are necessarily imprecise and are invariably less than the true height of the valves, yet as judged by field observations, the data nevertheless reflect significant trends. The standard

Unless correlative with rate of deposition or increasing water depth, size trends among members of this lineage are probably more nearly related to phylogenetic tendencies during the time of Fort Hays deposition than to paleoecological parameters. The abrupt

increase in size noted in Unit 15 is evidently an exception, but the parameter with which it is correlative remains unknown.

**ORIENTATION OF BIVALVE SHELLS**

Observations on the positions of 20 specimens of *Pycnodonte aucella* at Locality 1 revealed no consistent trends in orientation of valves of this species, although no attempt was made to measure specific angles of in-

deviation within each sample is used as a crude index of size variation; these data also reflect more or less consistent trends. (Additional measurements on valves within a given bed at a given locality could not be obtained because the density of valves among these rocks is too low relative to the total area of exposure of each bed; see Appendix 3.)

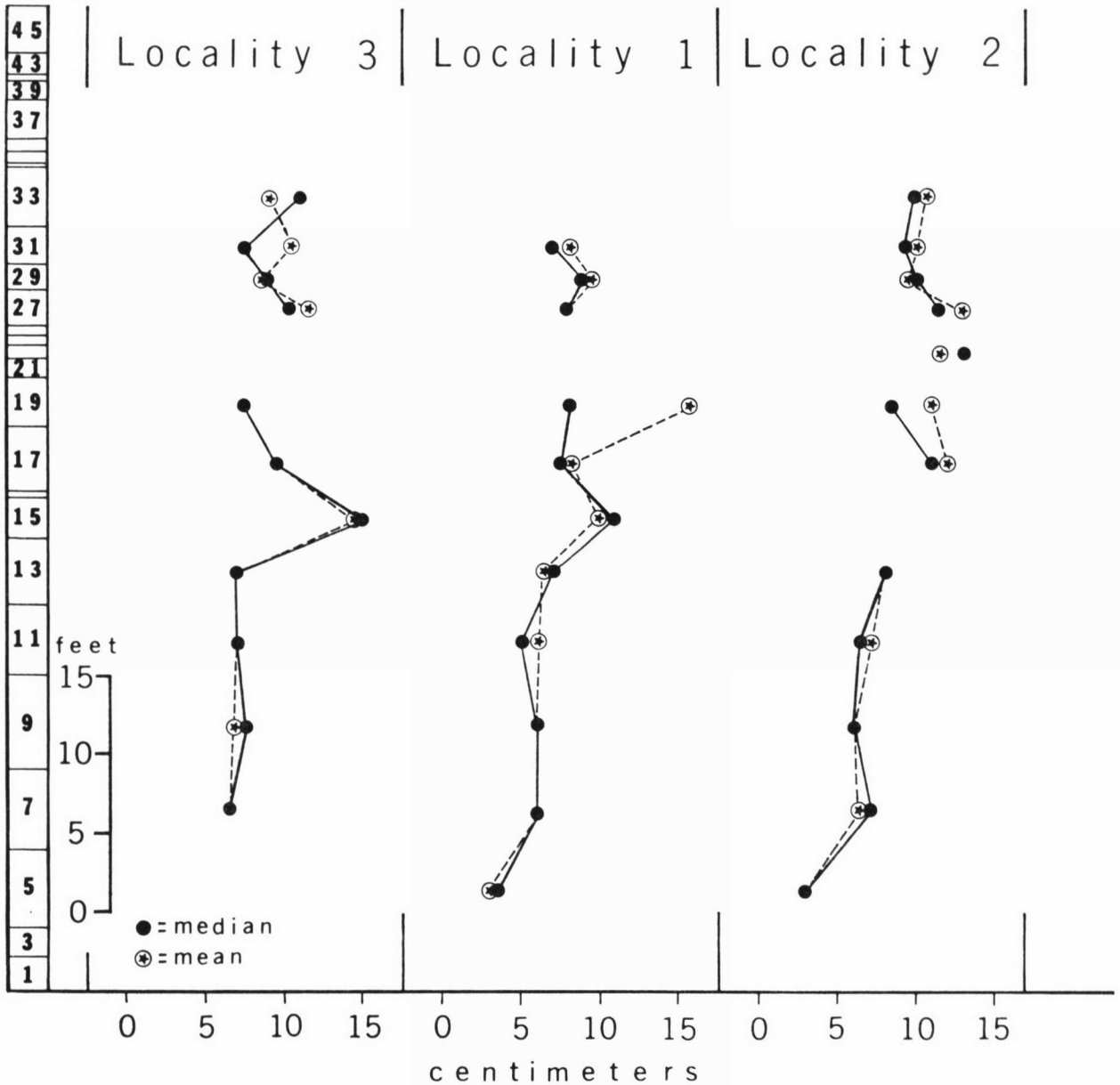


FIG. 13. Size trends among members of the *Inoceramus deformis* lineage, bedding units plotted at left. "Absence" of dashed line indicates coincidence with solid line.

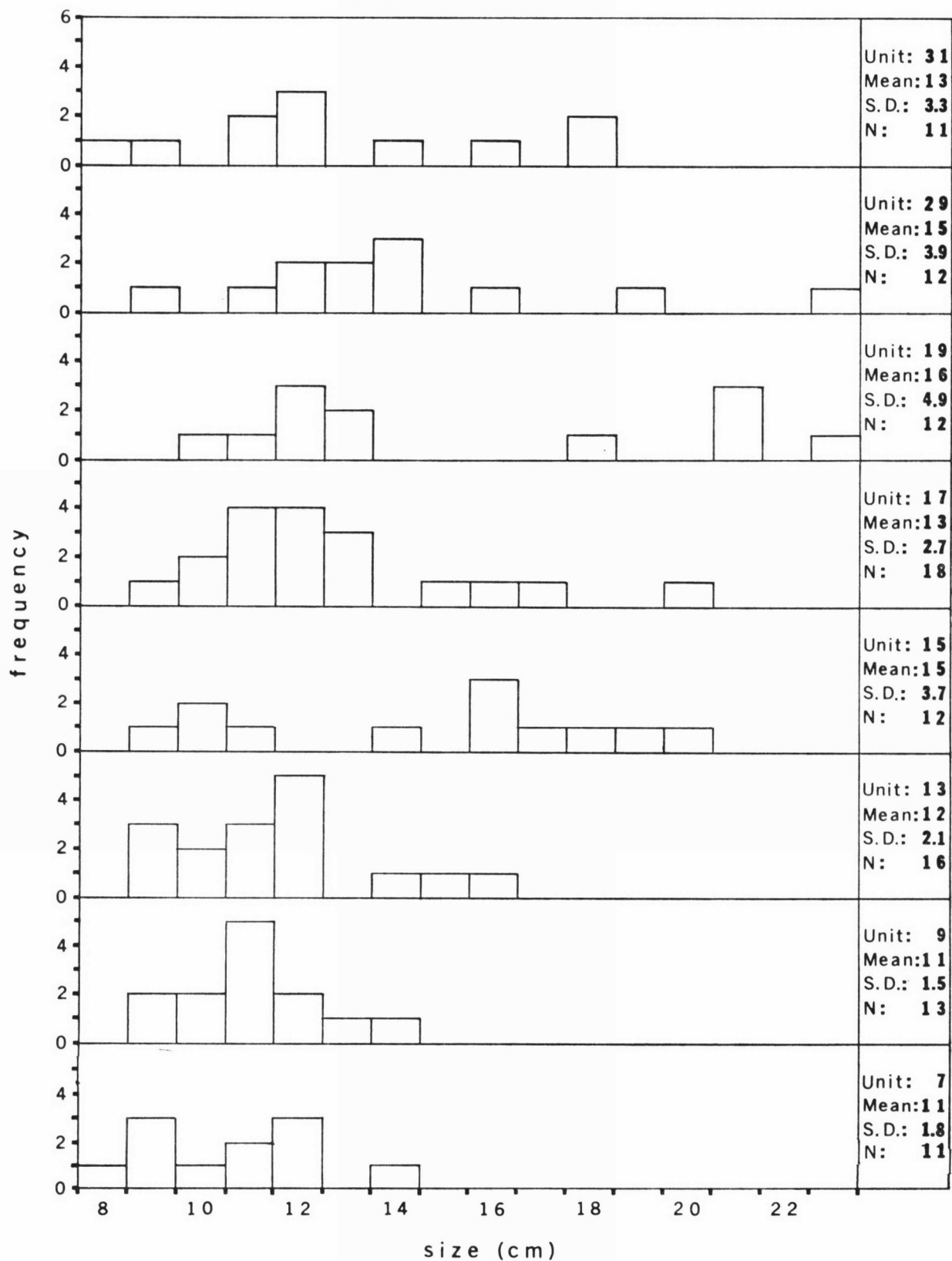







FIG. 14. Size-frequency distribution of valves within the *Inoceramus deformis* lineage, from Locality 1. The bedding unit, mean size, standard deviation, and number of measurements are indicated at right.

clination. The valves appeared to be oriented more or less randomly, suggesting that they had been disturbed by some post-mortem event. The same was true of disarticulated upper valves of *P. congesta* and fragments of *Inoceramus deformis* valves observed through the lower two-thirds of the Fort Hays.

In striking contrast, most intact valves of *Inoceramus deformis* reflected a consistent orientation. Of 414 valves measured in Trego County (Table 6), 79.3 percent were

TABLE 6.—Orientation of *Inoceramus deformis* Valves in the Fort Hays Member, Trego County, Kansas.

UNIT	LOCALITY	NUMBER OF VALVES COUNTED	ORIENTATION OF VALVES (PERCENT)				
							
33	3	7	71.6	.....	14.2	14.2	.....
33	1	4	100.0	.....	.....	.....	.....
33	2	9	77.8	11.1	11.1	.....	.....
31	3	8	87.6	.....	.....	.....	12.4
31	1	11	72.8	9.0	.....	.....	18.2
31	2	6	83.4	16.6	.....	.....	.....
29	3	10	70.0	10.0	20.0	.....	.....
29	1	12	75.0	.....	16.7	.....	8.3
29	2	7	71.6	.....	14.2	.....	14.2
27	3	2	100.0	.....	.....	.....	.....
27	1	6	100.0	.....	.....	.....	.....
27	2	7	85.7	14.3	.....	.....	.....
25-21	3	12	66.7	25.0	.....	.....	8.3
25-21	2	11	63.6	9.1	.....	.....	26.3
19	3	14	100.0	.....	.....	.....	.....
19	1	12	91.8	8.2	.....	.....	.....
19	2	11	72.7	18.2	.....	.....	9.1
17	3	19	78.9	5.3	.....	.....	15.8
17	1	18	77.8	5.6	5.6	.....	11.0
17	2	18	88.8	5.6	.....	.....	5.6
15	3	10	90.0	.....	.....	.....	10.0
15	1	12	83.4	8.3	.....	.....	8.3
15	2	3	100.0	.....	.....	.....	.....
13	3	11	100.0	.....	.....	.....	.....

13	1	16	81.3	12.4	.....	.....	6.3	
13	2	6	66.6	.....	16.7	.....	16.7	
11	3	15	66.6	6.7	.....	6.7	20.0	
11	1	24	75.0	25.0	.....	.....	.....	
11	2	24	95.8	4.2	.....	.....	.....	
9	3	13	69.2	7.7	15.4	.....	7.7	
9	1	13	69.2	.....	.....	15.4	15.4	
9	2	11	72.8	18.2	.....	9.0	.....	
8	1	4	25.0	25.0	25.0	25.0	.....	
7	3	8	87.5	12.5	.....	.....	.....	
7	1	11	54.5	36.5	9.0	.....	.....	
7	2	9	66.7	22.2	11.1	.....	.....	
5	3	2	100.0	.....	.....	.....	.....	
5	1	8	75.0	25.0	.....	.....	.....	
5	2	10	90.0	.....	10.0	.....	.....	
Total Valves Counted			414	328	39	15	6	26
Percent of Total			.....	79.3	9.4	3.6	1.4	6.3

oriented predominantly horizontally ( $\pm$  ca. 20 degrees) concave upward; an additional 9.4 percent were inclined concave upward at an angle of 45 degrees ( $\pm$  ca. 20 degrees). Only 3.6 percent were oriented predominantly vertically ( $\pm$  ca. 20 degrees) leaving 7.7 percent oriented concave downward at various angles. Similar trends are probably true for valves of *I. browni*, although valves of this species are too rare for significant measurements.

Reliable observations could not be made on the lower valves of *Volviceramus grandis* because all specimens examined were crushed and scattered. Upper valves typically remain more or less intact and are oriented dominantly concave downward, which is the presumed position of growth; this is in contrast with the orientation of equivalent valves of *Inoceramus deformis*.

Specimens of *Inoceramus platinus* examined in west-central Kansas are invariably recumbent; most are also in their presumed position of growth. In general, therefore, about half of the valves are oriented concave upward and the other half are concave downward, although all valves are in fact practically flat.

The significance of these valve orientations is discussed in a subsequent part of the paper.

## DEPOSITIONAL ENVIRONMENT AND PALEOECOLOGY

### GENERAL STATEMENT

Paleoecology is the study of environmental parameters that governed the abundance and distribution of ancient organisms; the emphasis is upon organisms and their responses to given conditions in the depositional environment. This kind of study is thus conceptually distinct from overall paleoenvironmental studies, which

endeavour to reconstruct a set of environmental conditions prevailing in a certain place at a certain time; the emphasis here is upon factors and processes that influence the environment. The two concepts cannot be pursued *in vacuo*, however. The reconstruction of depositional environments depends not only upon stratigraphic and sedimentologic evidence but also upon paleoecologic evidence supplied by associated fossils; con-

versely, paleoecological studies depend in part upon physiochemical evidence supplied by the rock and its inorganic components. The two approaches are therefore considered together in this section of the report.

## DEPOSITIONAL SETTING

### THE DEPOSITIONAL REGIME

The Niobrara depositional basin, which inherited its characteristics essentially from the preceding Greenhorn depositional basin (Fig. 1), is one of the largest marine basins known from the entire Mesozoic Era; it was the site of strikingly cyclic sedimentation during late Turonian to Maastrichtian time (Kauffman, 1967, 1969), represented by terrigenous detrital, marginal marine deposits at the beginning and termination of the cycle to pure, offshore carbonate muds (Fort Hays Member) at maximum transgression (Fig. 5). The distribution of macroinvertebrate assemblages in the Western Interior reflects similar cyclicality, many of the animals apparently being narrowly adapted to environmental conditions represented by particular lithotypes. As represented (albeit sparsely) in the stratigraphic record, the transgressive hemicycle of the Niobrara Cyclothem was evidently of shorter duration and produced lesser thicknesses of sediment than the regressive hemicycle (Kauffman, 1969, p. 234-235).

The advent of the Niobrara depositional cycle is not recorded in Kansas because of the disconformity between the Carlile Shale and the Niobrara Chalk (Table 1); practically the entire transgressive part of the cyclothem is missing. Local relief along this disconformable surface is slight, and no concrete evidence suggests subaerial erosion. Most evidence indicates that the sea floor in Kansas lay above wave base for a considerable time during the very latest part of the Greenhorn regressive hemicycle and most of the Niobrara transgressive hemicycle (Hattin, 1962, 1966, 1965a). During the latest part of the Niobrara transgression, the sea floor in west-central Kansas—a carbonate bank-type area—was returned slightly below wave base and began receiving Fort Hays sediments. The shore line was by this time very distant (Fig. 3A), and relatively little terrigenous detritus was transported to this part of the basin.

Fort Hays sediments in Kansas comprised part of a central-basin carbonate belt which, according to Kauffman (1969), was influenced periodically by active currents and which lay predominantly within the photic zone—at depths of 100 to 200 feet. This carbonate belt was at least 400 miles wide, and extended from northern United States to Mexico.

### STRUCTURAL HISTORY

When Cretaceous sedimentation began in western Kansas, the only significant structural feature present

was a slight regional slope that dipped southward (Merriam, 1957, p. 17-19). Except for the formation of a small syncline in western Gove and eastern Thomas Counties (Fig. 6), local structural movements during the Cretaceous were evidently nearly negligible. Slight movement occurred on the Cambridge Arch, a topographic high during most of Jurassic time that was eventually buried beneath sediments of the Morrison Formation. Differential movement continued on the arch through deposition of the Niobrara, possibly culminating at the end of the Cretaceous when the area was tilted north-westward toward the Denver Basin.

Large scale isostatic adjustments may have occurred regionally, however. Kauffman (1969, p. 244-245) suggested that a large structural platform, on which Niobrara and some pre-Niobrara sediments accumulated, was elevated in the central part of the depositional basin (Fig. 1); this postulated structure was separated from the western margin of the basin by a deeper trough. The "mid-basin platform" was the site of carbonate bank deposition; clay muds accumulated in the trough, while nearshore clastics accumulated along the western strand line.

Such movements are presumed to have occurred also during deposition of the preceding Greenhorn cyclothem (Kauffman, 1969). Structural configurations resulting from these two movements would have had to be very similar regionally, however; in western Kansas, for example, structural contours on the top of the Niobrara are generally similar to those at the base of the Graneros Shale (Merriam, 1957, p. 17-19). (See Hattin, 1965b.)

On a very local scale, subsidence of the sea floor may have influenced to some extent the thickness of Fort Hays deposits in Trego County. The total thickness of the Fort Hays is slightly greater at Locality 1 than at Localities 2 and 3, and the preponderance of individual beds are also somewhat thicker at Locality 1 than at the other localities (Appendix 2; Fig. 4). The upper few feet of the Fort Hays at Locality 2 have been removed by erosion, but the part that remains is thinner than its counterpart at Locality 1. Perhaps the sea floor in the vicinity of Locality 1 subsided slightly relative to adjacent areas to the east and west (Fig. 2) and gradually accumulated relatively larger quantities of sediment. However, certain differences in thickness of the member may also have resulted from predepositional basins and swells, as explained below.

### THE DEPOSITIONAL SURFACE

Although the sea floor during Late Cretaceous sedimentation in Kansas evidently lacked significant local structural features and substantial local relief, the pre-Niobrara surface was probably somewhat undulating regionally. Such topographic irregularity is suggested by geographic variations in thickness of the Fort Hays



(Runnels & Dubins, 1949, p. 5; Merriam, 1957, pl. 1-3), and especially by the fact that individual beds in the lower part of the member cannot be traced from Trego County into the northern part of Ellis County whereas Units 39 through 47 may be traced from Gove to Ellis County (Table 2; Fig. 2). Topographic features having a few feet of relief would have modified the regional distribution of Fort Hays sediments until these features became more or less buried; as their influence became less pronounced, similar thicknesses of sediment would have spread over larger areas—as reflected by the increased lateral continuity of individual beds.

These topographic irregularities were possibly linear features that trended more or less east-west. The subsurface correlation charts by Merriam (1957, fig. 1, pl. 1-3) reveal little variation in thickness of the Fort Hays in an east-west direction whereas thicknesses are irregular in a north-south or northwest-southeast direction. I noted similar thicknesses of the member in an east-west direction at Localities 8 and 9 in Ellis County (Fig. 2) and at Localities 1 through 3 in Trego County, yet the member is considerably thinner in northern Ellis County than in southern Trego County. Furthermore, the subsurface thickness of the Fort Hays in northern Trego County (about 50 feet; see Twenhofel, 1925, p. 1067) is comparable with that of exposures in northern Ellis County.

Although the thickness of the Fort Hays in Kansas varies considerably, the member tends to thicken southwestward (Runnels & Dubins, 1949, p. 5); this conforms to the regional pattern of Fort Hays thicknesses in adjacent states. Biostratigraphic data indicate that the lowest beds of the Fort Hays in southeastern Colorado are not represented in Kansas and north-central Colorado. Simultaneously with late Turonian and earliest Coniacian deposition in southeastern Colorado, marine erosion of the Codell Sandstone surface evidently occurred in Kansas and northern Colorado.

## SEDIMENTOLOGY

### PROVENANCE

Recent deposits of carbonate mud have been attributed mostly to 1) disaggregation of algal needles, 2) activity of boring organisms, 3) mechanical abrasion, and 4) accumulation of foraminiferal and pteropod oozes (e.g., Matthews, 1966).

Chalky sediments belong to an intermediate category. Boring organisms and mechanical abrasion or disaggregation produced minor quantities of fine-grained sediment in the Niobrara, but the chalks and chalky limestones consist mostly of coccoliths and the tests of planktonic foraminifers. Comparable Recent deposits remain unknown, although foraminiferal and pteropod oozes contain subordinate quantities of coccoliths.

The shaly chalks and chalky shales of the Niobrara, in contrast, contain large quantities of terrigenous silt and clay.

Most of the arenaceous and rudaceous constituents of Fort Hays and Smoky Hill sediments were contributed by bivalves. The valves of *Inoceramus* were fragile, especially after the solution and removal of aragonite, and broke down readily into scattered small fragments or into disaggregated prisms. The valves of *Pycnodonte* were more durable, producing relatively large skeletal fragments. Serpulid tubes, shark teeth, and phosphatic granules constitute the only other noteworthy fraction of coarse particles, other than terrigenous detritus reworked from the Carlile Shale. Scattered small grains of quartz and mica are found in the chalky shales.

A paradox in the distribution of bivalve debris is that the abundance of microscopic particles declines gradually from the base to the top of the member (Fig. 8) whereas megascopic particles, including both fragmentary and intact valves (Fig. 11), are rare in the basal and upper parts of the member.

The regular alternation of chalky limestone and chalky shale in the Fort Hays constitutes a "pararhythmic succession" (Termier & Termier, 1963, p. 355). Similar alternations have been observed in other chalks, and various mechanisms have been proposed to explain them (Kennedy, in preparation; Jefferies, 1962; and Hattin, 1971). Evidence from the Fort Hays suggests that carbonate deposition was continuous but that these sediments were diluted periodically by brief influxes of clayey to silty terrigenous detritus. These influxes resulted from abrupt increases in terrestrial erosion and sediment transport, perhaps caused by periodic, small scale lowering of sea level (cf. Hallam, 1964).

No attempt was made to determine the clay mineralogy of bentonites. Certain of these bentonites thicken very slightly toward the western part of the study area, suggesting a volcanic source much farther west. During earlier episodes of Colorado Group deposition this source may have been located in the vicinity of Idaho (Hattin, 1965b, p. 62).

### RATE OF SEDIMENTATION

Most of the chalky sediments of the Fort Hays and lower few feet of the Smoky Hill were evidently deposited slowly. Epizoal organisms, particularly *Pycnodonte congesta*, are among the most conspicuous indicators of the depositional rate. Two or more generations of *P. congesta* are attached to inoceramid valves in most of these rocks, indicating that the host valves projected above the sediment-water interface for considerable periods of time. The various generations of oysters apparently represent periodic, probably annual spatfalls.

Three (and possibly four) generations of oysters may be discerned on certain inoceramid valves (Pl. 12, fig. 1), suggesting that at least three to four years elapsed before the host inoceramid became buried by sediment. Furthermore, the large size of the inoceramids themselves implies that they lived through several seasons of growth.

The foregoing conclusions presuppose that the inoceramids did not keep abreast of sedimentation by simply moving themselves upward periodically in an aggrading substrate. These animals lacked well-developed pedalyssal musculature, however; this suggests that adult forms were largely incapable of bodily movement, unless by "valve flapping" such as is done by the extant scallop *Argopecten irradians*. Nevertheless, the flat recumbent giant *Inoceramus platinus* must have had some means of combating burial by sediment; its extreme size implies that it lived for several years, yet it was potentially capable of being buried by approximately 2 cm of sediment.

Foraminifers are relatively abundant in chalks and chalky limestones of the Fort Hays but are sparse to extremely rare in shaly chalks and chalky shales; these distributions suggest that the sediments comprising the thin shaly units were deposited considerably more rapidly than equivalent thicknesses of chalky sediments and that the total number of foraminiferal tests accumulated per unit volume of sediments was correspondingly diminished.

Differential rates of sedimentation are indicated also by the ichnofauna. Burrow structures are abundant to profuse in chalks and chalky limestones (Pl. 5, fig. 3-4) but are comparatively sparse in shaly chalks and chalky shales (Frey, 1970, pl. 9, fig. 9; pl. 10, figs. 2-3). The burrowing animals evidently had considerably less time available for reworking of sediments during deposition of clay than during deposition of chalk (Frey, 1970, p. 30-32).

Burrows are exceedingly rare above Unit 62, probably attributable to poorly oxygenated sediments (Frey, 1970, p. 32), and thus cannot be used as indicators of depositional rate in the Smoky Hill. Shaly strata, containing relatively fewer foraminifers per unit volume of sediments, become increasingly more numerous above the base of the Smoky Hill, corresponding to the overall decrease in abundance of beds of chalk and chalky limestone relative to the Fort Hays. This distribution suggests that the rate of deposition of Smoky Hill sediments in this stratigraphic interval was generally greater than during Fort Hays deposition. Other than this observation, little paleontological evidence within the rocks studied suggests conspicuous differences in the rate of sedimentation of the two members. Higher in the section indications are, at least in places, that the sediments of the Smoky Hill were deposited relatively rapidly (Hattin, 1965a, p. 22).

## HYDROGRAPHY

### TEMPERATURE

Two major biotic realms in the Western Interior Region have been correlated more or less with two broad, climatic provinces (e.g., Cobban & Reeside, 1952, p. 1025; Reeside, 1957, p. 505). A boreal fauna is distinguished primarily by the presence of certain ammonite genera and especially by abundant belemnites (Jeletzky, 1950; cf. Jefferies, 1962, p. 636-640). These cephalopods are decidedly rare in the Niobrara of Kansas (see Miller, 1968), and none were found during my study. (The overall paucity of cephalopods here is probably also due in part to poor preservation of aragonitic shells.) In contrast, macroinvertebrates observed in the Niobrara of west-central Kansas are generally well represented in the Cretaceous of the Gulf Coast and Mexico and are clearly components of a southern, tropical or subtropical fauna.

The size of the larger inoceramids also suggests warm waters, although their growth histories are not a reflection of temperature alone. Nicol (1964, p. 969-976) suggested that temperature is the single most important physical parameter controlling the size of marine bivalves, and he noted (p. 974) certain gross similarities in size between Late Cretaceous inoceramids and the extant *Tridacna* of the Pacific Ocean. Interestingly, the distribution of *Inoceramus platinus* is somewhat correlative with the warmest period of the Late Cretaceous, as determined by the oxygen-isotope method (Lowenstam & Epstein, 1954, fig. 15). This simple comparison does not account in like manner for the presence of relatively large inoceramids in the upper part of the Greenhorn Limestone, lower part of the Carlile Shale, or the Pierre Shale in Kansas; yet paleotemperatures based solely upon belemnitids may not be accurate. On the basis of *Inoceramus* and *Baculites*, Tourtelot & Rye (1969) were not able to substantiate a general decline in temperature during late Campanian and early Maastrichtian time in the Western Interior Region, as Lowenstam & Epstein (1954, fig. 15) had indicated. On the other hand, as explained subsequently, the size (and shape) of the larger inoceramids was probably influenced also by their mode of life and consistency of the substrate.

The nearly pure carbonates of the Fort Hays consist predominantly of plankton remains and were thus biochemically secreted; the abundance of such organisms during Fort Hays deposition is also an indication of warm waters, by Recent analogy (Sverdrup and others, 1942, p. 853). Chave (1967) pointed out some misconceptions that have arisen concerning the relationship between temperature and carbonate deposition, but his discussion pertained more to highly impure carbonates than to such deposits as the Fort Hays in Kansas.

These warm waters evidently extended northward

from the Gulf of Mexico (Fig. 1) and, according to foraminiferal evidence, probably reached as far north as central Wyoming (Kent, 1969, fig. 2); this position is considerably farther south than the apparent northern influence limit of warm waters on the Pacific coast of North America during the Coniacian and Santonian (*ibid.*, fig. 1). Locally, the influence of boreal waters extended even farther southward, into Colorado; this distribution is conspicuous only along the western part of the seaway, indicating control by the circulation pattern of surface water (*ibid.*, p. 326). The pattern was evidently related to the trough-and-bank regional structure discussed earlier; the cooler waters were probably channeled along the western trough and the warmer waters were spread out over the broad midbasin platform.

### SALINITY

Diverse and abundant trace fossils, such as those found during this study (Frey, 1970), bespeak marine waters for Fort Hays deposition in Kansas. The general marine character of this depositional environment is hardly in doubt, however, considering the well-documented regional stratigraphic relationships responsible for Figures 1 and 3.

The waters during Fort Hays and early Smoky Hill deposition must in fact have been of at least full marine salinity. Planktonic foraminiferans are generally indicative of open seas (Smith, 1955, p. 147), and cheilostome bryozoans are exclusively marine (Moore and others, 1952, p. 187). Acrothoracican barnacles thrive only at normal marine salinities (Arnold Ross, 1969, personal communication). According to Vokes (1948, p. 128), inoceramids probably inhabited waters of full marine salinity. The Niobrara *Pycnodonte* is related to species that today are typical of offshore areas (Kauffman, 1967, p. 102); furthermore, the growth form and general habits of *Pycnodonte congesta* are very similar to those of the extant oyster *Ostrea equestris* (Galtsoff & Merrill, 1962), which is found typically in waters of high salinity (Parker, 1955, p. 203). Clionid sponges occur in both fully marine and somewhat brackish waters (Lawrence, 1969). Serpulids are dominantly marine but some may be found in fresh water (Howell, 1962, p. W155). Although fresh-water coccolithophorids have been reported, most forms cannot tolerate salinities substantially below 25‰ (Black, 1965).

Actually, the waters may have been slightly hypersaline. According to A. B. Shaw (1964, p. 6-13), definite salinity gradients must have been present in certain epeiric seas; the wider the sea the higher the salinities developed across it. Such gradient, from normal marine salinity near the present Gulf Coast to higher than normal salinity in the Western Interior, possibly accounts

for part of the marked decrease in abundance of fossils from the first area to the second.

Prolonged exposure to high salinity can also result in decreased size of individuals (e.g., Moore, 1958, p. 45). Miller (1968, p. 11-13) suggested that certain foraminiferans from the Niobrara of Kansas may be smaller than equivalent species from the Cretaceous of Texas; he listed several general factors that may have led to the diminution of Niobrara individuals, including "abnormal" salinities. However, increased salinity cannot be invoked in like manner to account for the smaller size of Gulf Coast specimens of *Pyripora shawi* relative to those of the Fort Hays (see measurements given by Frey & Larwood, 1971, table 2). Indeed, Shaw's (1964) argument pertains more to semi-enclosed embayments than to an open seaway (Fig. 1). Fort Hays deposition in Kansas represents maximum transgression during the Coniacian and therefore the time of greatest water circulation through the Niobrara depositional basin. Furthermore, acrothoracican barnacles are not known to live today in truly hypersaline waters (Arnold Ross, 1969, personal communication) and most coccolithophorids cannot long tolerate salinities much above 38‰ (Black, 1965). Hypersalinity may thus have influenced the size and distribution of certain organisms during Fort Hays deposition, but as a definite barrier to dispersal it must have been far less important than such factors as substrate coherence.

### BATHYMETRY

Recent carbonate muds consisting of algal needles and the products of mechanical abrasion and boring organisms are found most commonly in the infralittoral zone; foraminiferal and pteropod oozes are ordinarily found in the bathyal and abyssal zones—above the depths at which carbonates are soluble (Fairbridge, 1955, p. 44-46).<sup>1</sup> The chalky sediments of the Fort Hays are similar to the globigerinid and pteropod oozes in that the Fort Hays deposits contain globigerinids and the Recent oozes contain coccoliths. Unlike deep-water oozes, however, most chalks seem to have been deposited in the circalittoral zone (Termier & Termier, 1963, p. 244-245) or shallower. Deep-water oozes may have accumulated locally in the Niobrara depositional basin during maximum transgression (Kauffman, 1967, p. 90-92); but stratigraphic and paleoecologic relationships indicate that the Fort Hays in west-central Kansas was deposited in shallow water—in spite of great distance from the strand line (Fig. 3).

As mentioned previously, the accumulation of Niobrara sediments in Kansas followed a long interval of nondeposition, probably reflecting renewed submergence of this area near the time of maximum transgression

<sup>1</sup> Terms pertaining to bathymetric zonation are those reiterated by Ager (1963, fig. 2.3).



(Fig. 5). Sediments apparently began to accumulate as soon as the sea floor lay predominantly below effective wave base. Initial sediments remained under the influence of wave base, however, as evidenced by channel structures (Pl. 2, fig. 5), widespread substrate scour, and reworking of terrigenous detritus from the Carlile Shale into the basal bed of the Fort Hays. From this point onward the water must have been somewhat deeper; the dearth of extensive shell concentrates and worn and highly fragmented *Inoceramus* valves higher in the section indicates that the substrate everywhere lay well below effective wave base. The absence of *Skolithos* and (or) *Glossifungites* "facies" among trace fossils also indicates decidedly sublittoral deposition (Frey, 1970, 1971).

In spite of the presence of substantial currents at great depths in Recent oceans (Heezen & Hollister, 1964), small, well-defined channels such as those in the Fort Hays (Pl. 6, fig. 1) closely resemble shallow tidal channels on Recent carbonate banks (although the latter are considerably more abundant); the Fort Hays channels were evidently cut in somewhat (but not greatly) deeper water. The very thin, laterally persistent scour zones found throughout the Fort Hays (Pl. 6, fig. 4) at first suggest periodic lowering of wave base and thus widespread substrate scour in very shallow water; however, lag concentrates of shells and broken-shell debris—especially of the very fragile inoceramids—would undoubtedly have been left under such conditions. Given the above postulated topographic irregularity on the sea floor in Kansas, one may speculate that the very thin scour zones represent small turbidity flows from broad highs into local basins (this would also help explain the differences in Fort Hays bedding features observed between northern Ellis and southern Trego County).

The stratigraphic succession of trace fossils in the rocks studied (Frey, 1970, fig. 5) suggests gradually increasing water depth throughout Fort Hays and early Smoky Hill deposition. This increase is suggested also by the macroinvertebrate succession, discussed below, and by the regular decline in abundance of channels and other current-influenced sedimentary structures from the base to the top of the stratigraphic sections.

Depth implications of Niobrara bivalves have been outlined by Kauffman (1967, p. 100-133; 1969, p. 237-242), and much of the following is based upon his observations. Specimens of gryphaeate *Pycnodonte* are found in sediments reflecting a variety of water depths, but they were most common in carbonate bank areas; the abundance of *Pycnodonte aucella* near the base of the Fort Hays suggests that it, like true *Gryphaea* (e.g., Imlay, 1957), strongly preferred shallow waters. Ostreid *Pycnodonte* of the Western Interior are also found in sediments reflecting a wide range in depth of water. Morphologically similar *Ostrea* are found today mostly

in the infralittoral zone, at depths of about 10 to 200 feet; *Pycnodonte congesta* of the Fort Hays and lower Smoky Hill apparently reflects a similar range in depth, although this species is associated with inoceramids elsewhere that must have lived in substantially deeper water. Both Fort Hays species of *Pycnodonte* are related phylogenetically to extant species of *Pycnodonte* that generally inhabit open shelf areas greater than 50 feet in depth. I suggest that *P. aucella* appeared abundantly in the Fort Hays depositional environment as soon as wave scour diminished and the substrate became sufficiently stable, and that *P. congesta* appeared abundantly after the waters had deepened somewhat—not necessarily to the 50 feet implied by analogy with Recent species—represented now by the upper part of Unit 5 (Fig. 11). The inception of *P. congesta* depended also upon the presence of a substrate suitable for attachment, however, and individuals of this species might have been more abundant earlier in deposition if host inoceramids had been more numerous at that time.

The inoceramid succession from *Inoceramus* cf. *I. erectus* through *I. deformis*, *I. browni*, and *Volviceramus grandis* to *Inoceramus platinus* is evidently correlative with increasing depth of water, although this correlation is not a simple cause-effect relationship with bathymetry alone. (Within the *I. deformis* lineage, for example, it is also a matter of organic evolution.) Certain inoceramids in the Western Interior were characteristic of very shallow water (e.g., Toots, 1961). Those of the Niobrara in west-central Kansas were probably less tolerant of excessively shallow water, as evidenced by the rarity of inoceramids in the lower few feet of the Fort Hays (Fig. 11). Paucity of individuals within this interval may also mean that *Inoceramus* cf. *I. erectus* was less successful in exploiting unstable substrates or turbid waters than its successors, but there is no evidence—from function morphology or other aspects of *I. erectus*—to indicate that these were the only major factors governing its distribution; the inception of abundant inoceramids at the top of Unit 5 suggests that bathymetry was at least partly responsible. On the other hand, variations in population densities within the *I. deformis* lineage (Fig. 11) are probably not correlative with bathymetry; a plausible exception is the possibility that the overall higher densities in the lower-middle part of the Fort Hays represent optimum depth for individuals and that the low densities above and below reflect stresses associated with the animals' tolerance limits for depth: the waters being first too shallow and then too deep. This idea remains speculative, however, and does not account for the marked changes in population density observed locally within a single bed or commonly from one bed directly to another.

Regardless of the specific details among the above relationships, the waters must have continued to deepen

perceptively, although probably not rapidly, during the inoceramid succession. This is indicated also by the gradual change in trace fossil assemblages mentioned earlier (Frey, 1970, fig. 5)—reflecting a progressive change from the inner or middle part of the *Cruziana* “facies” to the outer part of that “facies,” possibly to the inner part of the *Zoophycos* “facies” (see Seilacher, 1967; Frey, 1970, p. 34, and 1971, table 4)—and also by the inoceramid assemblages (Kauffman, 1967, 1969). The assemblage dominated by *Volviceras* *grandis*, according to Kauffman (1969, p. 239), reflects “mid-shelf” areas 200 to 400 feet in depth, possibly shallower. This assemblage appears in the uppermost part of the Fort Hays in west-central Kansas, suggesting a maximum depth for Fort Hays deposition there. The trend toward increasing water depth apparently continued well into Smoky Hill deposition, although the Niobrara depositional cycle had elsewhere begun its overall regressive phase by then. *Inoceramus platinus* is associated with *V. grandis* in the lower Smoky Hill and is a component of that assemblage; but higher in the section it becomes the dominant species of a different assemblage, which reflects “mid-” and “outer-shelf” areas 200 to 500 feet in depth. Unfortunately, trace fossils are rare to absent in this part of the section and thus cannot substantiate the bathymetric implications of the bivalves.

No attempt was made during my study to detect microfaunal successions that might be comparable to those of trace fossils and bivalves. However, the microfossils apparently do substantiate the general depth implications of other fossils.

The relative abundance of planktonic foraminifers suggests depths comparable to those indicated by the inoceramid mollusks. In the Gulf of Mexico today planktonic species are generally absent from waters less than 70 feet deep (Lowman, 1949, fig. 13), and they may be absent from waters less than 160 feet deep (Phleger, 1951, p. 67). In other places, however, they may be abundant in considerably shallower water (Phleger, 1960, p. 242). Similarly, living coccolithophorids, like other photosynthetic algae, are restricted essentially to the upper 100 m of ocean water; in tropical seas their greatest concentrations are found at depths of about 50 m (Black, 1965).

Foraminiferal evidence (Kent, 1968, p. 2107-2110) suggests that, within the trough lying westward of the central-basin carbonate belt, water depth was at least as great as that across the outer part of the present continental shelf, and may have been as great as that across the upper part of the continental slope. Unfortunately, foraminiferal depth indicators based upon planktonic/benthonic ratios, such as those used by Kent and others, cannot be used with confidence in studies of incoherent deposits such as the carbonate muds of the Fort Hays in west-central Kansas; here the benthonic foraminiferans

were evidently eliminated by their inability to exploit slurry substrates, as discussed below, independently of water depth. The ratio was thus skewed markedly in favor of the planktonic forms.

Furthermore, the abundance of planktonic foraminifers in sediments is related primarily to proximity of their source area and secondarily to depth of water (Smith, 1965, p. 147); planktonic forms are known to accumulate in abundance upon certain beaches, for example. In addition, their abundance in the rocks studied is also due partly to slow deposition of sediments relative to the accumulation of foraminiferal tests; the water itself may not have been especially rich in living individuals at any given time during deposition.

In my study I have, therefore, placed primary emphasis upon depth implications of trace fossils, which cannot have been reworked or transported from the life site of the respective endobenthic organisms, and upon the large epibenthic inoceramids, which evidently also remain in the general vicinity of their original life sites; both kinds of organisms were thus more closely related to the immediate depositional environment than the plankton.

The shallow waters reconstructed above, combined with the absence of flint nodules in the Fort Hays, casts interesting light on certain older concepts that linked the mode of preservation of chalky sediments with deeper water deposition (e.g., Termier & Termier, 1963, p. 244-245).

## CURRENTS

Reworking of sediment from the Carlile into the basal bed of the Fort Hays is an obvious result of current and (or) wave activity. The presence of currents during Fort Hays deposition is also reflected by several kinds of sedimentary structures. Among these, channel structures are the most conspicuous; the channels, which are shallow and relatively broad, are most abundant along the Carlile-Niobrara contact (Pl. 2, fig. 5) but were found as high as Unit 50 (Pl. 6, fig. 1). The channel fill is ordinarily cross laminated to cross bedded, although these structures are typically very poorly preserved. Substrate scour along the Carlile surface and the channels themselves represent the highest energy level recorded by Fort Hays sediments; these currents alone were evidently capable of reworking substantial quantities of sediment and of highly fragmenting bivalve shells.

The other kinds of current-influenced sedimentary structures are less obvious but are nevertheless important. Examples are the thin to very thin, laminated to cross laminated scour zones that truncate subjacent burrow structures (Frey, 1970, pl. 10, fig. 4), and the comparatively thicker intervals of cross laminated chalky sediment (Pl. 6, fig. 3). Cross lamination is very distinct



where the sediments consist largely of inoceramite (Pl. 5, fig. 1), but elsewhere most small scale structures such as these were either modified or nearly obliterated subsequently by burrowing organisms. In most places the thick beds of chalky limestone now appear massive and structureless, suggesting either that the sediments were never laminated in such places or that all traces of laminae were destroyed by burrowers or other processes; the sedimentological importance of burrowers was probably most important (e.g., Pl. 5, fig. 4), yet the sheer instability of the watery substrate may also have been a factor. Scattered well-preserved structures and numerous poorly preserved structures nevertheless indicate that currents capable of producing minor substrate scour, cross lamination, and very thin cross bedding were commonplace during Fort Hays deposition.

These currents were generally very weak, as evidenced by the paucity of fragmented mollusk valves associated with scour zones. They were also intermittent and of short duration individually, as indicated by the dearth of lag deposits and—possibly—by the thicker intervals of structureless sediment separating scour and lamination zones. (The only lag deposits noted during my study of these structures consisted of thin, small, discontinuous lenses of shell debris found very rarely along certain planes in chalky limestones.)

The exact competence of the above currents is not clear. Velocities required for erosional removal of fine silt and clay-size particles are generally greater than for medium-grained sand because 1) finer particles have little relief and therefore do not project far into the overlying flow of turbulent water and 2) particles within the finest size grades generally exhibit a mutually cohesive force that tends to resist erosion by running water (e.g., Dunbar & Rodgers, 1957, p. 7). The second factor probably applies less to the angular carbonate particles of the Fort Hays (Pl. 4) than to layered clay minerals, but the first factor must have been important. I therefore suggest that these currents were somewhat stronger than is implied by the magnitude of the structures produced by them, although they were clearly much weaker than the currents that cut channels elsewhere in the Fort Hays.

The abundance of current-influenced sedimentary structures (and also of biogenic sedimentary structures) declines gradually in the upper part of the Fort Hays and abruptly in the lower part of the Smoky Hill, reflecting an overall decrease in current activity during this part of Niobrara deposition. This distribution is evidently related in part to increasing depth of water, but it may also be related to the accumulation of sediments and their modification of the depositional surface, as discussed below.

Unless considered simply as detrital particles, the fossils of the Fort Hays impart very little direct information on the strength or persistence of currents in the

depositional environment. Small fragments of *Inoceramus* and *Pycnodonte* valves are widely scattered in numerous beds of chalky limestone. Although much of this scattering may be attributed to the activity of burrowing organisms, part of it must have been caused by currents. The cross-laminated lenses of inoceramite and rare places where shell debris is concentrated within thin discontinuous zones have been mentioned previously. The effects of currents are also evidenced by large open burrows that acted as sediment traps for shell debris (Frey, 1970, pl. 8, fig. 2-3).

Indirectly, however, the fossils themselves suggest that currents of some significance—or at least appreciably turbulent water movements—must have constituted an important environmental parameter throughout Fort Hays deposition. All of the macroinvertebrates were evidently suspension feeders; as noted by Purdy (1964) and others, a certain minimal amount of current activity or turbulence is ordinarily required to hold organic matter in suspension and thus make it available to organisms depending upon it as a food source. Among trace fossils, burrows made by presumed suspension feeding animals are dominant but burrows made by deposit feeding animals are also numerically very important (Frey, 1970, table 3). This distribution indicates that large quantities of organic matter were in fact deposited upon the substrate, and it argues in favor of the intermittent current activity mentioned above; evidently because of frequent, small scale fluctuations in current strength or degree of turbulence, large populations of both suspension and deposit feeding animals were able to coexist.

The discontinuity of very thin bentonites in the Fort Hays probably reflects sediment reworking by the same kinds of currents that caused scour and cross lamination elsewhere.

## TURBIDITY

As discussed under animal-sediment relationships (p. 52), the substrate during Fort Hays deposition evidently contained large quantities of interstitial water and was very soft and unstable. Sedimentary structures indicate that, commensurate with the strength and persistence of currents, the surficial layers of carbonate mud were shifted about frequently. These conditions must have resulted ultimately in the suspension of substantial quantities of fine silt- or clay-size particles.

The height in the water column to which this turbidity extended would have been related more or less directly to current competence, which, as suggested above, may have been somewhat greater than is indicated by the magnitude of most sedimentary structures. Except in the vicinity of channels and the large scour structures (Pl. 6, fig. 3), where turbulence must have been considerable, most of the suspended material was

probably concentrated in a zone extending only a few centimeters or decimeters above the sediment-water interface; otherwise, photosynthetic coccolithophorids would have been substantially less abundant in the depositional environment. The turbidity and current regimes were thus probably similar to those reported by Rhoads & Young (1970) from parts of Buzzards Bay, Massachusetts.

Turbid water, as postulated above, would have exhibited within itself a definite density stratification, the actual density values within and between given layers varying with the degree of water agitation; increased densities would have occurred during periods of decreased turbulence, when the suspended load began to settle downward. I suggest that under such conditions the denser lower layers occasionally behaved as density flows, wherever topographic irregularities provided sufficient gradient in slope.

In previous sections I concluded that the pre-Niobrara depositional surface in west-central Kansas undulated somewhat regionally and that these topographic features modified the distribution of sediments and the configuration of bedding features during Fort Hays deposition. I believe that the numerous very thin scour zones in the member (Pl. 6, fig. 4) represent small-scale turbidity flows and that less intense density flows (which left little or no evidence of their passing) were probably commonplace during much of Fort Hays deposition; the water masses moved from broad topographic highs into outlying basins, e.g., from the northern parts of Ellis and Trego Counties (Fig. 2) to the southern part of Trego, and possibly Ellis, County. Such flows evidently became less common and important during later episodes of deposition, as the topographic irregularities eventually became more or less smoothed out by continued differential accumulation of sediments. The occurrence of other kinds of currents also decreased during this time, correlative in part with increasing depth of water during the Niobrara transgression, so that less detritus was put into suspension; this further diminished the potential importance of turbidity flows.

As noted by Parker (1956, p. 321), Rhoads & Young (1970), and others, the chief ecological effect of turbidity upon benthos is a tendency to clog or otherwise incapacitate the food-filtering mechanism. Many suspension-feeding animals thus may be unable to exploit certain areas of the sea floor, even though suspended food matter is abundant. This situation was evidently true for many benthonic organisms of the Fort Hays depositional environment, accounting partly for the low species diversity observed in west-central Kansas relative to time-equivalent faunas elsewhere in the Western Interior and along the Gulf Coast; no other single factor so nearly explains the marked scarcity of epizoans (other than *Pycnodonte congesta*) in the Fort Hays. *P. congesta* and other larger species (the primary benthos—*P. auce-*

*la* and the inoceramids) were evidently less effected by murky waters than the smaller species, which probably tended to be precluded by their smaller scaled filtering mechanisms. Boring organisms, serpulids, and bryozoans were more successful than other potential inhabitants, but they probably lived under conditions that approached their tolerance limits for suspended sediment.

Turbidity resulting from substrate reworking alone cannot account for the low species diversity among Niobrara epizoans, however. The apparent diminution of current activity or water agitation during later parts of Fort Hays deposition and most of Smoky Hill deposition must have decreased the concentration of suspended matter, yet there was not a corresponding increase in diversity of suspension feeding animals. The problem has no simple answer, but the decline in importance of current-suspended sediment at this time was probably offset to some extent by the increased primary deposition of terrigenous detritus. Poor oxygenation evidently also became an important limiting factor during this episode of deposition, as suggested below. *Pycnodonte congesta*, from all evidence, was simply broadly adapted and could therefore tolerate many different kinds of stress conditions that barred other epizoans.

## WATER AND SEDIMENT AERATION

Currents and water movements capable of cutting channels, scouring the substrate, transporting shell fragments, and putting sediments and food matter into suspension must have kept the water well circulated, thus enhancing the oxygenation of water and sediments during Fort Hays deposition. Additional evidence is derived from the substrate itself.

The upper part of the substrate was evidently well aerated. A study by Kennedy & Hall (1967) indicates that the presence of skeletal organic matter retards the alteration of skeletal aragonite and that the presence of a reducing agent inhibits oxidation and removal of the organic matter. This study thus suggests that the widespread solution of aragonite in the Fort Hays occurred above the reducing zone in the sediments, whether well within the substrate or at or near the sediment-water interface.

Trace fossils provide some of the best evidence for sediment aeration. As noted by Seilacher (1964, p. 303), the absence of trace fossils suggests euxinic conditions whereas their presence argues against such conditions. Burrowing organisms were numerous and diverse during Fort Hays deposition, and the abundance of sediment-ingesting organisms, especially, indicates that the sediments through which the animals coursed were well oxygenated (Frey, 1970). Biogenic structures produced by them penetrated deeply into the substrate.

The abundance and diversity of biogenic and inorganic sedimentary structures decline somewhat in the

upper part of the Fort Hays and markedly in the lower few feet of the Smoky Hill, evidently correlative largely with increasing depth and quietness of water. Dearth of biogenic and current-influenced sedimentary structures through most of the Smoky Hill suggests that sediments of this member were poorly oxygenated. Macro-invertebrate faunas during this time consisted almost exclusively of epibenthos. Hattin (1965a, p. 21) suggested that the extremely broad, thin valves of *Inoceramus platinus* may have provided a mechanism for increasing the animal's respiratory tissues, in response to poorly oxygenated waters of the Smoky Hill.

### ANIMAL-SEDIMENT RELATIONSHIPS

In addition to various depositional relationships discussed above, the most important animal-sediment relationships reflected by Fort Hays and lower Smoky Hill sediments are those involving substrate adaptations.

Ichnological evidence (Frey, 1970) indicates that the substrate during deposition of the Fort Hays member was generally very incoherent, contained large quantities of interstitial water, and was apparently far too soft to have supported the byssal attachment of large bivalves. This condition is suggested also by the lack of primary benthonic specimens of *Pycnodonte congesta*, by the dearth of benthonic foraminiferans, by the morphology of the inoceramids, and possibly by the absence (? = nonpreservation) of certain delicate sedimentary structures. (This last category especially includes surficial trace fossils, and possibly primary laminae lost through incohesiveness of the carbonate mud.)

Within the rocks studied, all specimens of *Pycnodonte congesta* are secondary, or epizoal, upon inoceramids or other pycnodontes. None were able to establish themselves directly upon detrital substrates, as they had done elsewhere in the Western Interior (Kauffman, 1967, p. 122) or as did their Turonian counterparts in the underlying Carlile Shale (Hattin, 1962, p. 115, pl. 13A, F). Firm substrates, whether lenses and stringers of shell hash, coherent sediments, or chalk hardgrounds (Voigt, 1959), simply were not available to Fort Hays epibenthos.

*Pycnodonte aucella* is the only small species among bivalves studied that comprised part of the free-living benthos. Individuals of *P. aucella* evidently lay unattached to the substrate during much of their lives. Beaks of the lower valves of most specimens are slightly flattened (Pl. 13, fig. 4); the spat evidently attached to some firm object in the substrate, such as a small shell fragment, but later outgrew their need for firm attachment. Individuals were probably embedded in the substrate but kept the commissure slightly elevated above the sediment-water interface in order to prevent fouling. Only rarely does *P. aucella* bear epizoal specimens of *P. congesta*.

*Pycnodonte aucella* is common only in the lower few feet of the Fort Hays, especially where terrigenous detritus from the Carlile Shale has been reworked into the Niobrara; this detritus apparently rendered the basal Fort Hays sediments somewhat coherent and therefore more suitable for habitation by these animals. In spite of the diachroneity of the Carlile-Niobrara contact, the abundance of *P. aucella* throughout its biostratigraphic range in the Western Interior is related closely to such mixtures of sediment.

Inoceramids are so rare in these basal beds (Fig. 11) that the relationship of *Inoceramus* cf. *I. erectus* to sediments remains speculative. As discussed by Kauffman (1967, p. 103-106), however, the larger inoceramids of the Niobrara were well adapted for life in soft substrates. These species are either bowl shape to rudist-like, or are large and flat.

The bowl-shaped species *Inoceramus deformis* and *I. browni* are nearly equivalve; they apparently lay free. The exterior of upper valves is ordinarily encrusted throughout with thick epizoal growths whereas the lower valves bear such growths only in the vicinity of the commissure; thus, the bulk of the lower valve must have been embedded in the substrate. Elevation of the commissure above the sediment-water interface prevented fouling by sediments.

E. G. Kauffman (1969, personal communication) speculated that the large, irregular undulations and changes in slope among valves of these taxa may have been controlled in part by variations in rate of sedimentation. When deposition was slow the shell grew normally, but when it increased the valve margins turned inward during further growth, moving the feeding margin upward off the sediment-water interface. The animals could thus compensate somewhat for their immobility.

The overall adaptation of *Volvicceramus grandis* was very similar to that of the bowl-shaped inoceramids. This species was markedly inequivalve, however; the lower valve is coiled and highly inflated, and it is much larger and extended much farther into the substrate than the corresponding valves of bowl-shaped species. Epizoal growths indicate that the uppermost few centimeters of the lower valve of *V. grandis* remained above the sediment-water interface (Pl. 12, fig. 4).

A different kind of substrate adaptation is reflected by the very flat, recumbent, thin-shelled giant *Inoceramus platinus*; the large surface area and light weight of its valves must have buoyed up the animal in extremely soft, watery sediments. Because of its flatness and recumbent position, *I. platinus* must have had special adaptations for the prevention of fouling; the size and abundance of this species indicate that, whatever the specific functions of this mechanism, the adaptations were very successful ones.



Although Niobrara inoceramids were evidently well adapted for life in very soft substrates, the temporal succession from *Inoceramus* cf. *I. erectus* through *I. deformatis*, *I. browni*, and *Volviceramus grandis* to *Inoceramus platinus* is not necessarily a reflection of increasingly unstable substrates. There is little evidence, for example, that the substrates inhabited by *I. platinus* were less coherent than those inhabited by *I. deformatis* and *I. browni*, and in the early stages of Smoky Hill deposition *I. platinus* and *V. grandis* lived in close proximity. Indeed, this succession apparently reflects ecologically equivalent adaptations by different lineages to attain equilibrium with a given set of environmental conditions.

Except for the basal bed of the Fort Hays, discussed above, and possibly the larger lenses of inoceramite, no unequivocal evidence for differences in substrate coherence was discovered by me. However, if the ?teredine tube-building bivalves—like the Recent shipworm *Teredo polythalamia* (Oosting, in Kennedy, 1967, p. 129)—were in fact adapted for burrowing in somewhat coherent muds, then Fort Hays substrates must have varied in consistency locally. As suggested by the different parts of the section where tubes were found, larvae of this animal may have settled in many places but survived only in scattered “microhabitats” that were firmer and thus more nearly suitable for exploitation. Favorable conditions at most such places were ephemeral, however. The single tubes observed locally reflect only one generation of growth, and even where biostromal masses were established the animals failed to propagate themselves beyond the first stage of colonization. The latter situation indicates that substrate conditions were not the only environmental parameters governing the abundance and distribution of the species; one would expect that a dense colony of tubes would in themselves establish sufficient substrate stability that subsequent generations would have had no problem in maintaining the biostrome. Perhaps the turbid waters mentioned earlier were partly responsible.

Similarly, Hattin (1965a, p. 21) suggested that the immense valves of *Inoceramus platinus* may reflect an extraordinary development of respiratory tissue in response to poorly oxygenated water. The dearth of endobionts in the Smoky Hill is compatible with this view, although relatively large inoceramids are found elsewhere in deposits that were evidently better oxygenated than those of the Smoky Hill in Kansas; in addition to the upper part of the Fort Hays, discussed previously, these include the upper part of the Greenhorn Limestone, lower part of the Carlile Shale, and the Pierre Shale.

Nevertheless, the soft unstable substrate recounted above evidently constituted one of the single most important paleoecological controls operative during Fort

Hays and early Smoky Hill deposition. The abundance and diversity of trace fossils show that the overall depositional environment was considerably more favorable to life than is indicated by the low diversity and abundance of preserved epibenthos (Frey, 1970, p. 30) and that, in terms of such factors as currents and food supplies, this environment was not markedly different from certain nearshore, shallow-water, terrigenous-detrital environments in the Upper Cretaceous of Utah (Frey & Howard, 1970). Except possibly for the ?teredine animals, each free-living epibenthonic macroinvertebrate in this part of the Niobrara reflects more or less conspicuous morphological adaptations for combating soft substrates; organisms lacking such adaptations, including benthonic foraminiferans, are either rare or conspicuously absent. This apparent inability to exploit unstable substrates probably accounts in large part for the reduction in diversity and abundance of macroinvertebrates from the Gulf Coastal Plain to the Western Interior Region during Coniacian time. Burrowing animals, represented by trace fossils, evidently fared better because of their preadaptations for exploiting loose sediments.

Rhoads & Young (1970) and Rhoads (1970) have documented substrate and turbidity conditions in Buzzards Bay, Massachusetts, that are extremely similar to those postulated for the Fort Hays; because of considerable turbidity the juvenile and mature suspension feeders are subject to clogged filtering mechanisms, and because of substrate instability the larvae either do not or cannot settle in abundance, or once settled, are subject to resuspension or burial.

In Buzzards Bay, high water content and instability of the substrate is thought to be the result primarily of intense sediment reworking by abundant deposit feeders. Bioturbation of Fort Hays sediments may also have enhanced substrate water content and softness, but the slowly accumulating carbonate muds were probably slurry even without reworking by organisms. I discerned no obvious relationship between abundance or activity of endobionts and the diversity or abundance of epibionts in different parts of the Fort Hays (Frey, 1970), for example, and the abrupt disappearance of trace fossils in the lower part of the Smoky Hill is not marked by a corresponding change in the populations of suspension-feeding epibenthos.

An animal-sediment relationship of a different kind is the potential influence of volcanic ash falls. The numerous bentonites found in the Niobrara indicate that volcanic activity occurred frequently during this part of Cretaceous time. As noted by Reeside (1957, p. 525-526), these ash falls apparently had little effect upon the organisms present, however. In west-central Kansas the bentonites studied are generally too thin or discontinuous to have exerted significant influence—unless upon the plankton; among macroinvertebrates and trace fos-

sils there is no obvious evidence either for increased mortalities during the ash falls or for reductions in population density immediately after such ash falls.

## RELATIONSHIPS BETWEEN ORGANISMS

### INTERSPECIFIC RELATIONSHIPS

The most obvious interrelationship among organisms of the Fort Hays is that involving competition among epizoans for places of attachment. *Pycnodonte congesta* was singularly successful in this respect. These oysters did not establish themselves upon detrital substrates, but they lived in profusion upon inoceramid valves throughout the study area. All other epizoans are extremely rare by comparison.

The bryozoan *Pyripora shawi* was found on the exterior of an inoceramid valve that for some reason bore few oysters; its absence or extreme rarity through practically all of the Fort Hays may be due partly to its inability to compete with *Pycnodonte congesta*. *Pyripora shawi* was much more abundant in the Late Cretaceous of Arkansas (Shaw, 1967, table 1), where its chief competitors for attachment space were other bryozoans. There *Pyripora shawi* attached more commonly to the valves of *Gryphaea* and *Exogyra* than to *Inoceramus* (N. G. Shaw, 1968, personal communication). However, the scarcity of *Pyripora shawi*, like that of other suspension feeders in the Fort Hays, is evidently related to additional environmental parameters also; chief among these was probably water turbidity.

*Serpula* cf. *S. semicoalita* was only moderately more successful. At two places, both in Unit 19, specimens are thickly encrusted upon inoceramid valves (Pl. 8, fig. 3); oysters are lacking on one of these valves and are scarce on the other. Elsewhere only isolated specimens of this serpulid were found, all in association with *Pycnodonte congesta*. A single serpulid tube was found on the upper valve of an oyster; this oyster and those associated with it seem to have been stunted, suggesting that the oysters may have been incapacitated prior to the serpulid's attachment. In another specimen isolated serpulids lie between and at the base of thickly encrusting oysters. The valves of these oysters bulge out and overlap the serpulids. Spat of the two species evidently settled upon the inoceramid valve penecontemporaneously; their growth was unobstructed until their shells touched, but then the oysters overgrew and smothered the serpulids.

*Serpula* sp. was found only on interior surfaces of inoceramid valves (Pl. 9, fig. 1). This occurrence suggests that the serpulid larvae preferentially settled upon the valves of dead inoceramids, although the possibility remains that the larvae simply occupied whatever space was left to them by the oysters. Many additional speci-

mens are needed in order to evaluate confidently this serpulid's mode of life.

The boring organisms were apparently also less successful than *Pycnodonte congesta* in their quests for space on inoceramid valves. Borings are notably sparse where the oysters are abundant, and vice versa. A few borings were found on interior valve surfaces of *Inoceramus*, but they are generally common only on exterior surfaces. The borings are also common on broken parts of shells, suggesting that in many instances the organisms may have bored the fragmented shells of dead bivalves. The borers were evidently somewhat species-selective because only rarely did they bore *P. congesta* and *P. aucella*.

The foregoing competitive relationships should not be viewed only in terms of struggles among individuals of different species. The Niobrara depositional environment seems to have been generally unfavorable for exploitation by diverse assemblages of epizoa and boring organisms, hence the density and distribution of many of these organisms probably would have been restricted regardless of the success of *Pycnodonte congesta*. Much of the apparent competitive prowess of *P. congesta* is, therefore, attributable to its wider tolerance for conditions peculiar to this epeiric sea.

The boring organisms were apparently not excessively detrimental to their host inoceramids. Very few bivalve shells were deteriorated substantially as a result of borings, most of which were sparse and shallow, and neither the inoceramids nor *Pycnodonte* attempted to repair the damage by thickening or patching their valves.

Encrustations by *Pycnodonte congesta* probably caused the inoceramids more difficulty. This, as with the boring organisms, was evidently an antagonistic relationship in which one species benefitted at the expense of the other (Ager, 1963, p. 246-259). The more encrusted, the heavier the inoceramid shells became; the irregular surfaces produced by the oysters may also have acted as sediment traps, adding further weight to the shells. Such abnormal increases in weight of the upper valve would have made this valve more difficult to lift during feeding and respiration, and may have caused the inoceramid to sink farther downward into the soft substrate. This situation possibly led eventually to the death of some individuals, although death did not occur frequently until late in the respective life cycles, as evidenced by the large size attained by most Fort Hays inoceramids. Fully encrusted old, and even gerontic, shells are fairly common among Niobrara inoceramids elsewhere in the Western Interior.

*Pycnodonte congesta*, on the other hand, profited tremendously from the substrate afforded by the inoceramids; its distribution and abundance in the Fort Hays and lower Smoky Hill is in fact related directly to the abundance and distribution of inoceramids. This rela-



tionship changed drastically upon demise of the host, however. Upper valves of *Inoceramus deformis* are usually oriented concave upward (Table 6), which means that the oysters are preserved face downward. Inversion of the inoceramid valve must have caused the oysters to be smothered in sediment.

Unlike most articulated specimens of other inoceramids studied, both valves of *Inoceramus platinus* may be encrusted with oysters. *I. platinus* evidently lived in a recumbent position, and epizoans on either valve are oriented normal to the valve surface. Thus, specimens bearing epizoal growths on both valves must have been overturned, apparently while the animals remained alive. Considering the size of *I. platinus*, the mechanism for such overturning is problematical (although the valves were probably relatively light). Overturning evidently occurred also to scattered specimens of *I. deformis*. In certain individuals both upper and lower valves of this inoceramid bear heavy epizoal growths (Pl. 9, fig. 7), and rarely the upper valve bears fewer oysters than the lower valve. The latter suggests that the inoceramids were overturned at an early stage of development and that they remained alive in spite of their inversion. Again the mechanism for overturning is problematical, although it is probably related to the activity of another species. One possibility is that the dense oyster encrustations on upper valves of *I. deformis* made the animal "top-heavy"; as their delicate balance in the soft mud became impaired, the strongly biconvex valves simply toppled over and became more or less inverted. Hattin (1965a, p. 21) suggested that the overturning of *I. platinus* was affected by predaceous fish, by occasional storm activity, or possibly by the animal itself; he stressed the first alternative and noted the abundance of shell-crushing shark teeth in the Niobrara. Results of the present study shed little light on this problem, although it is perhaps noteworthy that no remains of shell-crushing sharks were found in beds containing overturned specimens of either *I. platinus* or *I. deformis*. Scattered specimens of *I. deformis* have been broken down into small clustered fragments suggestive of predation by large vertebrate animals (Pl. 15, fig. 3); although direct evidence for such predation is lacking, possible candidates include bottom-feeding fish, e.g., *Ptychodus*, or marine reptiles such as the shell-crushing mosasaur *Globidens* (cf. Kauffman & Kesling, 1960, p. 224). Perhaps these predators overturned certain inoceramids while groveling for others in murky waters.

#### INTRASPECIFIC RELATIONSHIPS

With few exceptions, there is little evidence either for or against significant relationships among individuals of the species studied. One of these exceptions is the lack of correlation between size and density of members

of the *Inoceramus deformis* lineage (Fig. 11, 13), which apparently shows that these individuals competed for neither food nor dwelling space. In terms of such parameters, larger populations could have been sustained.

The most striking interrelationship among individuals is again that of *Pycnodonte congesta*. Individuals of this species competed not only with others of the same spatfall but also with members of subsequent spatfalls; a single inoceramid valve may bear as many as three or four generations of oysters (Pl. 12, fig. 1).

Members of the first generation of oysters are in most instances of the same size and rather evenly distributed on the host valve (Pl. 12, fig. 5). If left to reach old age, the individuals continued to grow more or less evenly, their valves becoming taller and more closely crowded to form polygons. Peripheral individuals curved gently toward the center of the inoceramid valve in compensation for its sloping surfaces. Where sparse the individual oyster valves tended to be broad and squat, in contrast with the taller, narrower valves of crowded specimens. Within this matrix of valves, some individuals were apparently overrun by their neighbors; many were eventually either engulfed or left with small, grotesquely distorted valves. In places the individuals were unevenly distributed and showed considerable variation in size and shape, probably correlative with their attempts to expand into unrestricted space; in these instances numerous individuals were overwhelmed by their neighbors. Some spatfalls were evidently heavier than others because the number of first-generation oysters per unit area varies markedly (albeit irregularly) through the rocks studied.

The mass of first-generation oysters presented to the subsequent generation a much larger, more irregular surface area for attachment, hence individuals of the second generation are almost invariably much more irregular in size and distribution. The latter commonly attached to upper valves of the preceding generation, although they frequently attached to unobstructed surfaces on lower valves as well. Successively younger generations became successively more irregular.

Individuals from successively younger generations also tended to be smaller and to show more valve deformation and other evidence of competition. Only rarely did they constitute a solid encrustation sufficient to smother the previous generations, although they frequently interfered with the free articulation of upper valves among individuals of these generations. The latter were also resigned to gathering food and oxygen from water that already may have been sieved by overlying oysters.

With the rare exception of *Serpula* cf. *S. semicoalita* (Pl. 8, fig. 3), none of the remaining epizoans exhibit such relationships, nor were the boring organisms sufficiently crowded to compete vigorously for space or food.

## POSTMORTEM ORIENTATION OF BIVALVE SHELLS

As stated previously, intact valves of *Pycnodonte aucella* tend to be articulated but randomly oriented, whereas those of the *Inoceramus deformis* lineage tend to be disarticulated and oriented concave upward (Table 6). Valves of *Volvicceramus grandis* may or may not be articulated, but upper valves are oriented dominantly concave downward; those of *Inoceramus platinus* tend to be articulated and are recumbent.

Emery (1968) attributed the orientation of bivalve shells chiefly to 1) wave or current strength in the depositional environment, 2) the death history of the animal (i.e., the influence of the life position upon the eventual death position, plus the activity of predators and scavengers), and 3) the intensity of sediment reworking by burrowing organisms. I agree that these are the three most important mechanisms effecting valve orientation, yet I disagree that bioturbation should always tend to produce a concave-upward position for valves (cf. Emery, p. 1268; Clifton, 1971).

Toots (1965a, b) reasoned that bioturbation is one of the few processes that can yield a random orientation of shells. The disturbance caused by a single burrowing animal is not generally great, but repeated burrowing in the same sediment can substantially alter the structure and fabric of the substrate. An extreme example is the burrowing activity of the lugworm *Arenicola marina*, which contributes to the formation of shell beds in the Dutch Wadden Sea (van Straaten, 1952; and 1969, personal communication). Here individual valves in shell beds on the floor of channels and gullies show a preferred orientation, convex upward, and are imbricated like tabular river pebbles; those observed in beaches along the shore and in the exposed, abraded side of mussel beds are also convex upward, with their long axes at right angles to the trend of the beach; valves in subsurface shell beds formed by *A. marina*, however, do not exhibit a preferred orientation.

Bivalve shells in the Bay of Helgoland are typically oriented concave downward because of strong currents; where the sediments have been reoccupied by abundant burrowing organisms, however, the depositional orientation of valves is totally deranged and the new orientations are random (Hertwick, in Reineck & others, 1967, p. 231-232; and 1969, personal communication). Biogenic reworking also results in random orientation of valves observed by James D. Howard and me in Recent sediments off the Georgia coast.

Intense bioturbation (e.g., Pl. 5, fig. 4) is thought to be the cause for random orientation of specimens of *Pycnodonte aucella* in the Fort Hays, although gryphaeate valves such as these would probably behave differ-

ently from the more equisized valves of other species and are thus probably not typical indicators of currents or other factors. On the other hand, the disarticulated, flat to very gently curved, upper valves of *P. aucella* and *P. congesta* (Pl. 10, fig. 2-3, 4-5) are also oriented more or less randomly in the Fort Hays, and these valves should have behaved more typically in the face of currents or bioturbation than the irregularly shaped lower valves of *P. aucella*.

Measurements on the orientation of *Inoceramus deformis* valves in the Fort Hays (Table 6) appear to agree with the observations by Emery (1968) and thus to contradict the above argument. This concave-upward orientation of *I. deformis* valves is evidently due mostly to the death history of individuals, however. As mentioned previously, these animals lived in a horizontal position; the lower valve lay embedded in the substrate, concave upward, and the upper valve, oriented concave downward, projected into the overlying water. Upon death of the organism, the ligament evidently pulled the valves apart without dislodging the lower valve; the upper valve thus rotated 180 degrees so that it too lay concave upward in the substrate. Some valves were preserved in this position (Pl. 9, fig. 7), while others were separated gradually by currents, bioturbation, or predators and scavengers. Currents in the Fort Hays depositional environment were generally too weak to overturn the empty *I. deformis* valves, as discussed above, and more importantly for the present point, the valves were evidently too large and heavy to be reoriented appreciably by burrowing organisms. This conclusion is supported by the fact that disarticulated upper valves of *Pycnodonte aucella* and *P. congesta* and broken valves of *Inoceramus deformis* are oriented randomly in beds containing consistently oriented whole valves of *I. deformis*.

In general, valves of *Inoceramus platinus* and *Volvicceramus grandis* are oriented as consistently in the lower beds of the Smoky Hill as are those of *I. deformis* in the Fort Hays. The broad, recumbent valves of *I. platinus* are an obvious example of the influence of life orientation and shell size upon the final position preserved in the rock record; they represent an equally obvious size limit to the effectiveness of burrowing animals in reorienting shells. The study of *I. deformis* evidently shows, however, that the practical size limit for reorientation of shells by bioturbation is actually much less.

This study, and those by van Straaten (1952) and Hertwick (1967), contrasted with those of Emery (1968) and Clifton (1971), also show that each shell assemblage must be evaluated individually, in terms of the specific evidence at hand.

## DIAGENESIS

The processes and products of diagenesis *per se* are beyond the scope of my investigation, yet two aspects of diagenesis deserve mention. One is taphonomy, as relates to the diagenetic loss of skeletal aragonite, and the other concerns the stage in diagenesis at which the coccolithophorid micrites of the Fort Hays became lithified. Both of these have a bearing on paleontological, ecological, and environmental interpretations.

### CONSOLIDATION OF SEDIMENTS

Except for local concretionary structures (Pl. 7, fig. 2-3), lithification of Fort Hays sediments evidently occurred late in diagenesis. The same is true generally for Recent offshore carbonate deposits (numerous authors), although important exceptions have been noted locally (e.g., Milliman, 1966; see also Wolfe, 1968).

Three lines of evidence argue strongly in favor of slow lithification of Fort Hays sediments: 1) trace fossil configurations, 2) solution-collapse features associated with the removal of skeletal aragonite, and 3) deformational structures resulting from compaction of sediments.

The most important trace fossil configurations include: 1) profusions of irregularly interpenetrating burrows (Pl. 5, fig. 4) that represent burrowing activity by three or four different generations of endobenthic animals (Frey, 1970), 2) abundant deep, vertical burrows of sediment-ingesting animals (*ibid.*, pl. 2, fig. 7), and 3) burrows commonly skirting whole and fragmentary bivalve shells (*ibid.*, pl. 8, fig. 13; pl. 9, fig. 3) that lay well within the substrate. The slowly accumulating sediments thus remained loose for long periods of time and were thoroughly reworked to considerable depth by different populations of mobile organisms.

"Solution-deposition type one" (Dodd, 1966, p. 734-735) was a ubiquitous, very early diagenetic phenomenon during the alteration of Fort Hays sediments. Removal of inoceramid nacre occurred well before cementation began; the unconsolidated carbonate mud evidently settled into the void as it was being produced, obliterating virtually all traces of the nacreous layer.

In the Lower Chalk of England this solutional process apparently operated primarily before the inoceramid shells were buried by sediments (Kennedy, 1969, p. 464-465; in preparation). Preburial solution of aragonite may have occurred locally in the Fort Hays, but the dearth of epizoans on shell interiors shows that the process was predominantly postburial. *Pycnodonte congesta* was present in profusion upon exteriors of inoceramid valves (Pl. 3, fig. 4; Pl. 9, fig. 6; Pl. 10, fig. 1; Pl. 12, fig. 1, 4-5; Pl. 14, fig. 3; Pl. 9, fig. 7), and like its counterpart in the Carlile Shale (Hattin, 1962, p. 115), was able to establish itself upon nonliving substrates elsewhere in the Western Interior (Kauffman, 1967, p. 122).

If inoceramid valve interiors, denuded of aragonite, had been exposed at the sediment-water interface, these surfaces would have been settled quickly by oyster spat. Although deposition was slow in the early Niobrara sea, I suggest that empty inoceramid valves were filled in quickly by shifting bottom sediments (Frey, 1970, p. 26) and that the solution of aragonite occurred subsequently.

Deformational structures produced during compaction that reflect late-diagenetic lithification consist chiefly of 1) differential compaction of sediments around shells (Pl. 7, fig. 4) and 2) scattered thin zones of interconnected stylolites that lack marginal microfaults (Pl. 7, fig. 5). With few exceptions, fossils involved in differential compaction remain undeformed, or "in-the-round," which indicates that the sediments were still soft and yielding at that time; distortion thus occurred only to the primary stratification features.

As evidenced by cross-cutting relationships, genesis of the stylolites postdated all of the events discussed above, yet stylolites such as these are evidently formed prior to the final stages of cementation (Schot & Park, 1968, p. 112); the sediments apparently remained relatively incompetent during this process.

The foregoing conclusions contrast sharply with those drawn by Hattin (1971) regarding early diagenetic consolidation of lithologically similar sediments in the Greenhorn Limestone. As mentioned previously, the overall depositional regimes for Niobrara and Greenhorn deposition were extremely similar in many respects (see also Kauffman, 1967, 1969). Conspicuous differences do exist, however, and the diagenetic histories of the two were evidently very dissimilar.

### TAPHONOMY

Because of the complete, early diagenetic removal of skeletal aragonite from Fort Hays and lower Smoky Hill sediments, internal molds of *Inoceramus* record the morphology of the prismatic layer, not the actual valve interior. This process may account also for the absence of external molds of largely aragonitic fossils, such as ammonites; the latter are observed commonly in similar lithologies within the Greenhorn Limestone, where the sediments evidently became lithified sufficiently early in diagenesis that the external morphology of aragonitic fossils was preserved even after solution of the shells. Diagenetic loss of both shells and external molds of aragonitic fossils from the Niobrara thus may account partly for the low species diversity here, relative to that of equivalent deposits elsewhere in the Western Interior and the Gulf Coastal Plain, and loss of nacre and other aragonitic components complicates detailed studies on the morphology of partly aragonitic tests and valves.



**SUMMARY OF OBSERVATIONS****PHYSICAL STRATIGRAPHY**

As exposed in west-central Kansas, the Fort Hays Limestone Member of the Niobrara Chalk (Upper Cretaceous) ranges in thickness from about 45 to nearly 80 feet; it consists essentially of thick to very thick beds of yellowish-gray, pale orange, or yellowish-orange chalky limestone, separated by very thin to thin beds of light olive gray or yellowish-gray chalky shale.

The Fort Hays is underlain disconformably by the Carlile Shale (either the Blue Hill Shale Member or the Codell Sandstone Member) and is overlain conformably by the Smoky Hill Chalk Member of the Niobrara. The Carlile-Fort Hays contact is very distinct lithologically. The gradational Fort Hays-Smoky Hill contact is best drawn at the top of the highest bed of chalky limestone in a continuous sequence of chalky limestone beds, beginning at the Carlile-Niobrara contact.

Bedding units in the Fort Hays and lower few feet of the Smoky Hill are laterally persistent and remarkably uniform; by means of key marker beds or groups of beds, individual exposures in Trego County may be correlated on a bed-by-bed basis. Certain beds in the upper part of the Fort Hays may be traced from the eastern border of Gove County to the north-central part of Ellis County, a linear distance of about 45 miles. Such persistent and easily identified strata provide an excellent three-dimensional framework for precise sampling and for comparing lateral and vertical distributions of fossils.

**PETROLOGY**

The Fort Hays in west-central Kansas is comprised mainly of four intergradational lithologies: chalky limestone (90.2% of total volume of rock), chalk (3.7%), chalky shale (3.5%), and shaly chalk (2.5%). Bentonites, skeletal calcarenites, and other lithotypes constitute only about 0.1% of the rock. Chalky limestone is very rare in the lower part of the Smoky Hill, which contains proportionately greater quantities of chalk and shaly chalk than the Fort Hays.

Chalky limestones and chalks consist largely of: a micro- to crypto-grained matrix—mostly coccolith debris—(48 to 77%), foraminiferal tests (13 to 30%), bivalve fragments (2 to 29%), and authigenic iron compounds (less than 1 to about 4%). Most rock samples are texturally homogeneous. Relatively little stratigraphic variation is discernible among constituents. Shaly chalks and chalky shales are thinly laminated to laminated and contain large quantities of fine- to very fine-grained terrigenous detritus; they generally have good fissility on weathered surfaces. The basal bed of the Fort Hays contains considerable terrigenous detritus reworked from the Carlile Shale.

Authigenic minerals consist chiefly of pyrite, limonite, sparry calcite, and gypsum or selenite. The first three are associated primarily with fossils and burrow structures, and the last two with faults or fractures (they are also seen as weathering phenomena along bedding horizons). Allochemical phosphatic granules are common locally at the base of the member. Skeletal aragonite is conspicuously absent.

**SEDIMENTARY STRUCTURES**

Inorganic and biogenic sedimentary structures are abundant and diverse in the Fort Hays. Biogenic sedimentary structures, discussed at length in a separate report, include both distinct burrow structures and profuse burrow mottles. Tracks, trails, and related surficial traces were not observed.

Current-influenced inorganic structures include small to medium-sized channels, thin scour zones, and lenses or zones of laminated to cross-laminated sediments. Most of these structures are restricted to beds of chalky limestone and are partly or largely obscured by intense bioturbation. Bottoms of channels are commonly lined with a very thin layer of limonite. The thin scour zones persist laterally for tens of miles.

Abundance and diversity of both inorganic and biogenic sedimentary structures declines gradually in the upper part of the Fort Hays and abruptly in the lower few feet of the Smoky Hill; in overlying beds, burrows and current-influenced sedimentary structures are rare to absent in west-central Kansas.

**DIAGENETIC AND POSTDIAGENETIC STRUCTURES**

Aside from phenomena associated with solution of skeletal aragonite and formation of various authigenic minerals, the differential compaction of sediment around fossils, nodules, and concretions constitutes the most common and widespread diagenetic structure among Fort Hays strata in west-central Kansas. Chalky concretionary structures, up to several decimeters across and commonly retaining vestigial bedding features, are much less abundant but are more conspicuous. Small stylolites of the interconnecting network type, lacking marginal micro-faults, are scattered through the Fort Hays but are abundant and persistent only in one horizon, about 10 feet below the top of the member.

Mud cracks are common among beds of chalky shale in the lower part of the Fort Hays; these are post-diagenetic products of outcrop weathering, not primary structures produced by subaqueous cracking or subaerial dessication.

## BIOSTRATIGRAPHY

The presence of *Inoceramus* cf. *I. erectus*, *I. deformis*, *I. browni*, and *Volviceramus grandis* in the Fort Hays of west-central Kansas indicates early through middle Coniacian ages for these deposits; the presence of *V. grandis* and *Inoceramus platinus* in the lower part of the Smoky Hill suggests late Coniacian time. Higher in the section, *I. platinus* and other species are indicative of the Santonian.

Several additional species are present in the Fort Hays, but most of these taxa are too rare and (or) too poorly preserved to be used conveniently and consistently in biostratigraphy.

Many of the inoceramid zones found in Colorado and elsewhere are missing in west-central Kansas because of the disconformity at the Carlile-Niobrara contact. Most of late Turonian and earliest Coniacian time is not represented here, which thus constitutes the most extensive interval of nondeposition in the Cretaceous of the Western Interior.

## SYSTEMATIC PALEONTOLOGY

Eleven macroinvertebrate species were identified in the Fort Hays: the cheilostome bryozoan *Pyripora shawi*; the sedentary annelids *Serpula* cf. *S. semicoalita* and *Serpula* sp.; the pteriod bivalves *Inoceramus* cf. *I. erectus*, *I. deformis*, *I. browni*, *Inoceramus* sp. aff. *I. platinus*, and *Volviceramus grandis*; the ostreid bivalves *Pycnodonte congesta* and *P. aucella*; and calcareous tubes of a myoid bivalve resembling *Teredo*. In addition to these, the following miscellanea were observed: small excavations made in bivalve shells by acrothoracican barnacles and clionid sponges, problematical tubular structures attached to the interior of inoceramid valves, rare benthonic and abundant planktonic foraminifers (mostly *Heterohelix globulosa*, *H. globifera*, and *Hedbergella cretacea*), rare fragmentary ostracodes, scattered vertebrate remains (including bone fragments, fish scales, and shark teeth), profuse coccolithophorid algae (mostly unidentified, but including *Marthasterites tribranchiatus*, *Watznaveria barnesae*, *Cretarhabdus conicus*, and *Prediscosphaera cretacea*), and fragments of fossil wood. Trace fossils are also diverse; at least 20 taxonomic and ethologic variants

distributed among approximately 13 genera or morphologic forms have been figured and described in a separate report.

Only four macroinvertebrates were found in the lower few feet of the Smoky Hill: *Serpula* sp., *Inoceramus platinus*, *Volviceramus grandis*, and *Pycnodonte congesta*. Most of the above-listed miscellaneous fossils were also observed here, and they and the macroinvertebrates apparently range well above the interval of strata examined. Trace fossils, in contrast, are rare or absent above approximately the lower 6 feet of the member; only about 6 taxonomic or ethologic variants found in the Fort Hays range into the basal Smoky Hill.

## FAUNAL ASSEMBLAGES

Two major macroinvertebrate assemblages are discernible in the Fort Hays and lower Smoky Hill: a gryphaeate *Pycnodonte* assemblage and a bowl-shaped inoceramid assemblage. The first is poorly developed in west-central Kansas, and the second consists of two distinct subassemblages.

The gryphaeate *Pycnodonte* assemblage, dominated by *P. aucella*, is restricted essentially to the basal bed of the Fort Hays but grades vertically into the bowl-shaped inoceramid assemblage.

The oldest subassemblage among bowl-shaped inoceramids ranges through most of the Fort Hays and is dominated by the biconvex species *Inoceramus deformis* and *I. browni*. Macroinvertebrates of any kind are sufficiently sparse at most levels in the upper one-fourth of the Fort Hays that a definite assemblage structure is not ordinarily perceptible, however.

A younger subassemblage of bowl-shaped inoceramids appears in the uppermost part of the Fort Hays and ranges well into the Smoky Hill, dominated by *Volviceramus grandis*, a rudist-like bivalve.

Trace fossils also exhibit gradational assemblage structures, as discussed in a separate report. No attempt was made to determine specific foraminifer and coccolithophorid assemblages.

Trends in density, distribution, and orientation of *Pycnodonte* and inoceramid valves are generally closely correlative throughout Trego County, Kansas.

## CONCLUSIONS

1) Regional stratigraphic and paleontologic relationships indicate that Fort Hays sediments in Kansas were deposited far off shore, at the height of a major marine transgression. The sediments comprised part of a broad carbonate belt that extended from Mexico to northern United States; accumulation of these sediments terminated a lengthy interval of nondeposition in the Western Interior.

2) Variations in thickness of the Fort Hays, both

along its outcrop belt and in the subsurface of Kansas, suggest that regional topographic irregularities were present on the pre-Niobrara sea floor. These features evidently influenced for a while the areal distribution of Fort Hays sediments but were eventually buried by those sediments.

3) Fort Hays sediments of west-central Kansas accumulated initially in shoal areas, as indicated by widespread substrate scour along the Carlile-Niobrara con-



tact and penecontemporaneous reworking of Carlile sediments into the basal Fort Hays. All subsequent deposition occurred below effective wave base, evidenced by the dearth of highly fragmented shells concentrated in lag deposits and by the absence among trace fossils of a *Skolithos* or *Glossifungites* "facies." The stratigraphic succession of trace fossils, mollusks, and current-influenced sedimentary structures suggests that the waters deepened gradually but perceptibly through successive intervals of time; this trend apparently persisted well into Smoky Hill deposition, although the sea had by then begun its overall retreat from the Western Interior. Fort Hays and lower Smoky Hill fossils suggest that maximum water depth attained during this succession was comparable to that of Recent midshelf areas off the Atlantic Coast.

4) Throughout Fort Hays deposition the sediments consisted essentially of homogeneous carbonate mud, derived predominantly from microorganisms. These nearly pure carbonate sediments were diluted periodically by brief influxes of terrigenous clay and silt, represented now by thin to very thin beds of chalky shale intervening between thick to massive beds of chalky limestone. Such clayey deposition became abruptly more widespread with the inception of the Smoky Hill regime.

5) The purer sediments of the Fort Hays accumulated slowly, as indicated by a) successive generations of epizoans occupying single inoceramid valves, b) abundant to profuse accumulations of coccoliths and foraminiferans, and c) dense, interpenetrating burrow structures. Epizoans, coccoliths, foraminiferans, and burrows are considerably less abundant in beds of shaly chalk and chalky shale, suggesting that these sediments were deposited more rapidly. The predominance of these lithologies over chalky limestone in the Smoky Hill suggests further that the sediments of this member were deposited more rapidly (per unit volume) than those of the Fort Hays.

6) The slowly accumulating carbonate muds of the Fort Hays evidently remained very soft and yielding for long periods of time; this is suggested by a) the inability of oysters to exploit fine-grained detrital substrates, b) the dearth of benthonic ostracodes and foraminiferans, c) functional morphology of inoceramid valves—the species present having broad bowl-, disk-, or rudist-shaped valves that added buoyancy, d) abundant burrow structures, reflecting intense, continuous reworking of the substrate, e) nonpreservation of tracks, trails, and surficial grazing traces, f) the massive, structureless aspect of numerous beds of chalky limestone, and g) the compactional deformation of inorganic and biogenic sedimentary structures.

7) Initial accumulation of Fort Hays sediments was accompanied by substantial currents, evidenced by reworking of Carlile sediments into the basal bed of the

Fort Hays and by small channels cut into the Carlile that are filled with Fort Hays sediments. This general current regime persisted through most of Fort Hays deposition, documented by scattered cross laminae, local very thin to thin cross beds, widespread scour zones, and rare channel structures, all of which truncate underlying burrows. Current activity is indicated further by abandoned burrows filled mechanically with shell debris and by the predominance among fossil organisms of suspension feeders over deposit feeders. Most such currents were rather weak; fossil shells have been neither highly fragmented nor concentrated in lag deposits. The distribution of preserved sedimentary structures suggests that the strength and persistence of currents declined gradually during deposition of the upper part of the Fort Hays and abruptly during deposition of the lower part of the Smoky Hill.

8) The slurry substrate and active current regime present during Fort Hays deposition probably produced considerable turbidity in the basal part of the water column, and, where sufficient gradient in slope existed, may have led to small-scale turbidity flows. The latter would account for many of the thin, laterally persistent scour and laminated zones lacking extensive shell concentrates.

9) The current regime reconstructed above suggests further that the waters during Fort Hays deposition were well circulated, thus enhancing the oxygenation of water and surficial sediments. Very early diagenetic solution of skeletal aragonite also indicates good aeration, as does the profusion of burrows made by sediment ingesting animals. Dearth of biogenic sedimentary structures and current-influenced inorganic sedimentary structures in the lower part of the Smoky Hill suggests that these sediments were poorly oxygenated.

10) The sea occupying west-central Kansas during Fort Hays and early Smoky Hill deposition was warm, probably subtropical, evidenced by a) the large quantities of biochemically secreted carbonate, b) the marked affinity of local fossil assemblages with contemporaneous southern rather than boreal faunas, and c) the large size attained by inoceramids.

11) These waters were of approximately normal marine salinity, reflected by a) the numerous stenohaline organisms present, and b) the diversity and abundance of biogenic sedimentary structures.

12) The lateral persistence of individual beds and bedding features within the Fort Hays and lower Smoky Hill of west-central Kansas attests to a remarkably broad, stable depositional regime during discrete intervals of time. Trends in the abundance and distribution of mollusks and trace fossils are thus correlative over large geographic areas, the organisms everywhere responding similarly to given sets of paleoecological conditions.

13) The chief paleoecological factors limiting the

diversity and distribution of fossil organisms during Fort Hays and earliest Smoky Hill deposition are thought to be the slurry substrates and turbid waters outlined above. Fossil organisms not adapted to these conditions were conspicuously absent, probably because their larvae could not survive, or the maturing individuals tended either to sink down into the substrate or to be stifled by sediment-laden water. Thus, the only common megafossils are burrow structures (made by endobenthos preadapted to loose sediment), inoceramid clams (having broad, buoyant valves), and oysters (having, by modern analogy, filter-feeding devices adapted for straining murky waters); microfossils are, for the same reasons, predominantly planktonic forms that lived above the more turbid parts of the water column. Later in Smoky Hill deposition, poorly circulated waters and very poorly oxygenated sediments probably became major limiting factors.

14) Epizoal attachment of the oyster *Pycnodonte congesta* upon valves of *Inoceramus* apparently constitutes the most significant interspecific relationship among Fort Hays and lower Smoky Hill assemblages in west-central Kansas. Populations of this oyster wax and wane more or less regularly through the section, correlative with the density and distribution of firm substrates provided by inoceramids. Individuals within a cluster of oysters also exhibit numerous effects of intraspecific competition. Other epizoans (and boring barnacles and

sponges) were evidently less tolerant of the depositional environment as a whole but may also have been unable to compete vigorously with *P. congesta* for dwelling space. Overturned and (or) fragmented "in situ" valves of *Inoceramus* may represent the activity of a large pre-deceous animal, although this relationship is poorly understood.

15) The more or less random orientation of small bivalve shells or shell fragments in the Fort Hays is thought to be the result of intense bioturbation, whereas the consistent orientation of larger valves is taken as an example of the influence of life orientation and shell size and weight upon the final, preserved orientation; these valves were apparently too large and heavy to be re-oriented by mobile endobenthos.

16) Except for scattered concretionary structures, Fort Hays sediments remained loose and yielding until late in diagenesis, reflected by a) ubiquitous solution and removal of skeletal aragonite prior to consolidation of the mud, b) profuse interpenetrating burrow structures—especially deep, vertical feeding burrows—representing repeated reworking of the slowly accumulating sediment to considerable depth by successive generations of endobenthos, c) burrows commonly skirting bivalve shells deep within the substrate, d) differential compaction of sediments around undistorted valves, and e) local zones of interconnected stylolites lacking marginal microfaults.

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## APPENDIX 1.—LIST OF LOCALITIES EXAMINED

### MEASURED SECTIONS

- Numerous discontinuous, stratigraphically incomplete exposures of Fort Hays Member along small intermittent stream, E½ E½ sec. 8, W line sec. 9, and mutual corner secs. 9, 8, 16, and 17, T 15 S, R 23 W, Trego Co., Kansas. Offsets yield complete composite section of Fort Hays Member.
- Vertical, nearly complete exposures of Fort Hays Member on south shore of Cedar Bluff Reservoir, S½ NE¼ sec. 6, T 15 S, R 22 W, Trego Co., Kansas. Upper few feet of Fort Hays Member removed by erosion.
- Continuous, stratigraphically incomplete exposures of Fort Hays Member along north side of Smoky Hill River and west side of Hackberry Creek, SW¼ sec. 24 and NW¼ sec. 25, T 14 S, R 25 W, Trego Co., Kansas. Offsets yield complete section of Fort Hays Member.
- Roadcut directly north of Smoky Hill River, NW¼ NW¼ sec. 29, T 14 S, R 24 W, Trego Co., Kansas. Lower few feet of Fort Hays Member cap small butte.
- Roadcut at south end of dam, Cedar Bluff Reservoir, SE¼ NW¼ sec. 1, T 15 S, R 22 W, Trego Co., Kansas. Lower few feet of Fort Hays Member cap bluff overlooking reservoir.



**SUPPLEMENTARY LOCALITIES**

- 6. Continuous, stratigraphically incomplete exposures of Fort Hays Member along east side of Sand Creek, E½ sec. 13 and NE¼ sec. 24, T 15 S, R 24 W, Trego Co., Kansas. Thick but incomplete section of Fort Hays Member.
- 7. Bluffs along Smoky Hill River, NW¼ NW¼ sec. 32, T 14 S, R 25 W, and SW¼ sec. 6, T 15 S, R 25 W, Trego Co., Kansas

(and eastern border of Gove Co., Kansas). Upper part of Fort Hays Member.

- 8. Roadcut along U.S. Highway 183, beginning approximately one mile north of Saline River, secs. 10 and 3, T 11 S, R 18 W, Ellis Co., Kansas. Complete section of Fort Hays Member.
- 9. Bluffs along intermittent stream(s), NW¼ sec. 3, E½ sec. 4, and NE¼ sec. 9, T 11 S, R 20 W, Ellis Co., Kansas (and southern border of Rooks Co., Kansas). Offsets yield complete section of Fort Hays Member.

**APPENDIX 2.—DESCRIPTIONS OF THREE MEASURED SECTIONS**

**CONVENTIONS IN MEASUREMENT AND DESCRIPTION**

Bedding units less than 1.0 foot thick were measured to the nearest 0.01 foot; thicker units were measured to the nearest 0.05 foot.

Because individual beds of the Fort Hays and lower Smoky Hill may be correlated throughout Trego County, each bed was given a standard numerical designation, regardless of which strata appear at the base of a given exposure. A graphic column of the section at Locality 1 is presented in Figure 7; equivalent beds at other localities are generally very similar (Fig. 4). Unless stated otherwise in the following descriptions, each bedding unit is gradational with beds above and below.

Rock colors and the density and distribution of macroinvertebrate fossils are discussed at appropriate places in the text, and biogenic sedimentary structures were discussed by Frey (1970), thus these data are not repeated here. The emphasis is upon basic lithotypes.

shaly. Scattered small inoceramite lenses ..... 2.20  
*Thickness of exposed part of Smoky Hill Chalk Member: 24.5*

**FORT HAYS LIMESTONE MEMBER, NIOBRARA CHALK**

- 55 Chalky limestone. Local 0.4-ft-thick bioturbated zone, 0.8 ft above base. Scattered small inoceramite lenses in upper part. Unit thickens locally to 3.1 ft. Upper 0.05 ft locally contains small lenses of shaly chalk extending downward from 56 ..... 2.95
- 54 Chalky shale. Fissile on weathered surfaces. Unit undulatory locally ..... 0.08
- 53 Chalk and chalky limestone. Laminated and more chalky in lower part ..... 1.35
- 52 Chalk and shaly chalk. Laminated ..... 0.70
- 51 Bentonitic shale. Bentonite most abundant in middle part, chalky shale in upper and lower parts ..... 0.06
- 50 Chalky limestone. Laminated and cross laminated, especially in upper 0.3 to 0.4 ft; local channels and scour structures in upper part. Very thin shale parting 0.9 to 0.95 ft below top. Scattered small inoceramite lenses. Unit thickens to 2.35 ft where 49 is thinnest; the shale parting here is 1.2 ft below top ..... 1.60
- 49 Chalky limestone. Local very thin shale parting 0.55 ft below top. Separated from bed above by thin shale-parting zone, along which finely divided iron sulfide is concentrated in local, very thin layers. Unit thins locally to 0.3 to 0.4 ft thick. Chalky and laminated where thin ..... 2.85
- 48 Chalky shale. Scattered thin chalk and bentonite lenses, especially in upper part. Fissile on weathered surfaces. Unit undulatory ..... 0.07
- 47 Chalky limestone. Slightly stylonitic at top; 0.2 to 0.4-ft-thick stylonitic zone 1.1 to 1.6 ft below top. Local very thin shale parting 2.1 to 2.15 ft below top; 0.01 to 0.02-ft-thick shaly zone 1.6 ft above base ..... 5.05
- 46 Chalk (lower two-thirds) to chalky shale (upper one-third). Fissile on weathered surfaces, in upper part ..... 0.42
- 45 Chalky limestone. Very thin shale-parting zone 0.23 to 0.25 ft below top ..... 3.00
- 44 Chalky shale. Bentonitic shale 0.01 to 0.02 ft thick, at top. Fissile on weathered surfaces. Unit slightly undulatory; gradational with 45, fairly sharp contact with 43 ..... 0.11
- 43 Chalky limestone ..... 1.15
- 42 Shaly chalk. Scattered small lenses of chalk; scattered small limonitic, ?bentonitic lenses ..... 0.09
- 41 Chalk to shaly chalk. Obscure shale partings on weathered surfaces ..... 0.34

UNIT	LITHOTYPES	THICKNESS (FT)
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**LOCALITY 1**

**SMOKY HILL CHALK MEMBER, NIOBRARA CHALK**

* Interval between 66 and top of exposure consists of chalk and shaly chalk, very similar to equivalent beds at Locality 3 .....		17.2
66 Bentonite .....		0.02
65 Shaly chalk .....		0.41
64 Bentonite .....		0.05
63 Shaly chalk. Laminated. Very thin shale parting 0.15 ft below top .....		0.59
62 Chalk. Shaly near top and base. Shell fragments and limonite nodules concentrated locally in thin zone 0.5 to 0.6 ft above base .....		1.35
61 Shaly chalk. Slightly laminated .....		0.24
60 Chalk .....		0.67
59 Shaly chalk. Well laminated .....		0.55
58 Chalk. Shaly at top and base .....		0.64
57 Chalky shale (lower 0.15 ft) and shaly chalk (upper 0.37 ft). Moderately fissile in lower part; laminae and shale partings in upper part .....		0.52
56 Chalk. Slightly laminated. Bioturbated zone 0.3 ft thick, 0.6 to 0.65 ft below top. Upper 0.15 ft		

\* Numerous undesignated beds.

40	Chalky shale. Fissile on weathered surfaces .....	0.09	8	Chalky shale. Increasingly shaly toward base. Fissile in lower part. Scattered small lenses of inoceramite. Unit slightly undulatory .....	0.10
39	Chalky limestone .....	1.10			
38	Chalky shale. Fissile on weathered surfaces .....	0.11	7	Chalky limestone. Shale-parting zone 0.02 to 0.03 ft thick, 0.95 ft below top. Indistinctly laminated to slightly cross laminated, especially in lower part; local channel and scour structures. Scattered small lenses and stringers of inoceramite, most common in lower part .....	4.90
37	Chalky limestone. Thin shale-parting zone 0.55 to 0.57 ft below top .....	2.75	6	Shaly chalk to chalky shale. Moderately fissile on weathered surfaces. Slightly cross laminated in upper part. Unit undulatory locally .....	0.05
36	Shaly chalk (middle part) to chalky shale (at top and base). Well laminated .....	0.52	5	Chalky limestone. Very thin, undulatory, shale partings 0.21 and 0.35 ft above base, each slightly cross laminated; locally a third very thin shale parting is present in this part of unit. Upper 0.3 to 0.4 ft and lower 0.5 to 0.6 ft shaly. Very thin shale parting 1.1 to 1.2 ft below top. Scattered small lenses of inoceramite, most common in lower part .....	4.85
35	Chalky limestone .....	0.72	4	Chalky shale. Fissile on weathered surfaces. Scattered very small limonitic, bentonitic lenses. Undulatory lower contact .....	0.19
34	Chalky shale. Fissile on weathered surfaces. Gradational with 35; sharp contact with 33 .....	0.28	3	Chalky limestone. Upper 0.1 ft locally contains small, thin, shaly lenses extending downward from 4. Scattered phosphatic granules .....	1.80
33	Chalky limestone. Thin shale-parting zones 0.4 to 0.45 ft, 1.2 to 1.25 ft, and 2.4 ft above base. Local small, chalky, concretionary structures at base .....	3.75	2	Chalky shale. Fissile on weathered surfaces. Scattered very thin chalk lenses. Unit slightly undulatory .....	0.06
32	Chalky shale. Well laminated. Gradational with 33; fairly sharp contact with 31 .....	0.12	1	Chalky limestone. Shaly at top. Small limonite and pyrite nodules concentrated locally in zone 0.6 to 0.7 ft below top. Phosphatic granules common locally. Lower 0.2 to 0.3 ft very irregular locally, containing many small shaly lenses partly reworked from underlying beds. Subhorizontal chalk-filled burrows from basal Fort Hays extend downward as much as 0.2 ft into the Codell. Unit thickens locally to more than twice its normal thickness. Where thickest, the upper 0.85 to 0.9 ft is slightly shaly. Cross laminated zone 0.2 to 0.3 ft thick, 1.8 ft below top. Lower part slightly laminated and cross laminated. Scattered phosphatic granules and small lenses of inoceramite. Very sandy in lower 0.2 ft. Extremely sharp lower contact, containing thin layers of finely divided limonite; contact not penetrated by burrows; truncates bedding surfaces in Carlile Shale .....	2.15-4.55
31	Chalky limestone. Upper part slightly shaly; possibly cross laminated near top and base. Local small lenses of imbricated shell fragments. Base contains very thin shale lenses from 30 .....	2.20		<i>Total thickness of Fort Hays Limestone Member: 77.8-80.2</i> <i>Thickness of exposed part of Niobrara Chalk: 102.2-104.6</i>	
30	Chalky shale. Unit undulatory .....	0.12			
29	Chalky limestone. Shaly in upper 0.3 ft. Slightly stylolitic near top .....	1.60			
28	Chalky shale. Scattered small limonitic lenses. Obscurely stylolitic at top. Unit undulatory .....	0.11			
27	Chalky limestone. Shaly and slightly stylolitic in upper 0.15 to 0.2 ft. Thin, undulatory, shale-parting zone 0.7 ft below top .....	2.25			
26	Chalky shale and shaly chalk. Bentonitic in upper 0.08 ft and in thin zone 0.25 ft below top. Local limonitic lenses in middle part. Gradational with 25; sharp contact with 27 .....	0.61			
25	Chalk .....	0.45			
24	Shaly chalk. Slightly laminated .....	0.18			
23	Chalky limestone .....	0.88			
22	Shaly chalk. Moderately fissile on weathered surfaces ....	0.05			
21	Chalky limestone. Slightly laminated, especially in lower 0.45 ft .....	1.05			
20	Shaly chalk. Moderately fissile on weathered surfaces ....	0.09			
19	Chalky limestone. Thin shale-parting zone 0.54 ft below top .....	3.00			
18	Chalky shale. Moderately fissile on weathered surfaces ..	0.11			
17	Chalky limestone (lower 3.05 ft) to chalk and shaly chalk (upper 1.1 ft). Shaly zone 0.4 to 0.45 ft thick, 0.25 to 0.3 ft below top; thin shale-parting zones 1.1 and 1.4 ft below top, the lower one undulatory and containing much limonite. Moderately fissile in shaly zones .....	4.15			
16	Chalk and chalky shale (thin zones in middle part and near top and base). Moderately fissile in shaly zones ....	0.30			
15	Chalky limestone. Thin shale-parting zone 0.6 ft below top .....	2.50			
14	Chalky shale. Moderately fissile on weathered surfaces. Scattered small lenses of chalk .....	0.08			
13	Chalky limestone. Thin shale-parting zone 0.4 ft below top .....	4.00			
12	Chalky shale. Fissile. Unit slightly undulatory locally ..	0.12			
11	Chalky limestone. Thin shaly zone 0.7 ft below top. Local lenses of imbricated shell fragments, especially in 0.3-ft-thick zone, 1.0 ft below top. Rare small lenses of inoceramite .....	4.35			
10	Chalky shale. Fissile on weathered surfaces .....	0.17			
9	Chalky limestone. Shale-parting zone 0.3 to 0.35 ft thick, 3.05 to 3.1 ft above base; very thin shale partings 2.4 to 2.5 ft above base and 1.05 to 1.1 ft below top; thin shale parting 0.7 to 0.8 ft below top. Very thin shale partings present locally in other parts of unit .....	6.00			

#### CODELL SANDSTONE MEMBER, CARLILE SHALE

- \* Sandy shale to shaly, fine-grained sandstone. Numerous shale lenses in upper part. Abundant burrow structures, those in uppermost part infilled with chalky sediment from the Fort Hays .....

#### BLUE HILL SHALE MEMBER, CARLILE SHALE

- \* Shale and sandy shale, essentially like that described by Hattin (1965a, p. 68-69) .....

\* Numerous undesignated beds.

## LOCALITY 2

At the time this section was measured, the upper several feet of strata were fractured badly and were leaning precariously outward from a large fissure in the cliff. This interval was therefore measured indirectly, by means of a calibrated cord lowered over the side of the cliff.

FORT HAYS LIMESTONE MEMBER,  
NIOBRARA CHALK

50-53 In descending order: chalk, shaly chalk, ?bentonitic shale, and chalky limestone. Unit contacts indistinct .....	3.5
47-49 Lithologies generally very similar to those of equivalent units at Localities 1 and 3: 49—chalky limestone, 2.9 ft; 48—?bentonitic chalky shale, 0.1 foot; 47—chalky limestone, 4.3 ft .....	7.3
46 Shaly chalk. Laminated locally .....	0.43
45 Chalky limestone. Very thin shale parting 0.4 ft below top .....	2.90
44 Chalky shale. Slightly bentonitic. Fissile on weathered surfaces .....	0.12
43 Chalky limestone. More chalky in lower part .....	1.35
42 Chalky shale (lower part) to shaly chalk (upper part). Local thin, waxy, bentonitic, limonitic lenses, especially in lower part; thin chalky lenses in upper part. Moderately fissile to fissile .....	0.09
41 Chalk (middle part) to shaly chalk (near top and base). Scattered thin shale partings .....	0.34
40 Chalky shale. Poorly to moderately fissile on weathered surfaces .....	0.09
39 Chalky limestone .....	1.10
38 Chalky shale. Fissile. Unit slightly undulatory .....	0.12
37 Chalky limestone. Shale-parting zone 0.02 ft thick, 0.55 ft below top .....	2.80
36 Chalky shale (lower 0.04 to 0.05 ft) and chalk (middle 0.30 ft) to shaly chalk (upper 0.16 ft). Fissile in lower 0.05 ft. Scattered large, chalky, concretionary structures .....	0.50
35 Chalky limestone .....	0.64
34 Chalky shale. Fissile on weathered surfaces .....	0.21
33 Chalky limestone. Thin shale-parting zone 1.1 ft above base; local thin shale-parting zones throughout upper 1.35 ft. Shaly zones 0.1 to 0.12 ft thick, 0.4 ft above base, and 0.12 to 0.15 ft thick, 1.35 ft below top. Slightly stylolitic locally in upper part .....	3.65
32 Chalky shale. Moderately fissile to fissile on weathered surfaces. Local thin limonitic lenses .....	0.11
31 Chalky limestone. Shaly zone 0.2 ft thick, 0.4 ft below top .....	1.95
30 Chalky shale. Poorly to moderately fissile on weathered surfaces .....	0.12
29 Chalky limestone. More chalky in upper 0.2 ft .....	1.60
28 Chalky shale. Biotitic. Fissile. Unit slightly undulatory .....	0.09
27 Chalky limestone. Softer, more chalky near top .....	2.35
26 Chalky shale (near base) to chalk and shaly chalk (upper part) to limonitic, bentonitic shale (upper 0.04 to 0.05 ft). Slightly undulatory upper contact .....	0.32
25 Chalk and shaly chalk. Laminated to cross laminated, especially in upper part .....	0.51
24 Chalky shale. Slightly laminated .....	0.12
23 Chalky limestone. Slightly cross laminated in thin zone near top .....	0.74
22 Shaly chalk. Moderately fissile on weathered surfaces .....	0.07

21 Chalky limestone. Thin shale parting 0.67 ft below top, below which is a thin shaly zone .....	0.89
20 Shaly chalk. Slightly argillaceous; bentonitic in upper part. Gradational with 21; distinct contact with 19 .....	0.07
19 Chalky limestone. Thin shale parting 0.44 ft below top .....	2.80
18 Chalky shale. Argillaceous; very thin bentonite in upper part .....	0.11
17 Chalky limestone (lower 2.88 ft) to chalk and shaly chalk (upper 1.04 ft). Very-thin bedded in upper 1.04 ft; thin shale-parting zone 1.04 ft below top; 0.39-ft-thick shaly zone, 0.23 ft below top .....	3.90
16 Chalky shale (lower part) to shaly chalk (upper part) .....	0.25
15 Chalky limestone. Shale-parting zone 0.03 ft thick, 0.34 ft below top. Freshly chipped surfaces speckled locally with grayish flecks .....	2.05
14 Chalky shale .....	0.08
13 Chalky limestone. Shale partings in upper 0.2 ft .....	3.90
12 Chalky shale. Bentonitic. Fissile on weathered surfaces .....	0.09
11 Chalky limestone. Upper 0.6 ft slightly laminated. Scattered small lenses of inoceramite, in middle part .....	4.15
10 Chalky shale (upper part) to shaly chalk (lower part). Moderately fissile on weathered surfaces, especially in upper part. Fairly sharp contact with 9 .....	0.26
9 Chalky limestone. Shale-parting zones 0.2 to 0.25 ft thick, 2.35 ft below top, and 0.01 ft thick, 0.8 ft below top, each slightly cross laminated. Local small patches of inoceramite .....	5.25
8 Chalky shale. Argillaceous. Scattered small lenses of inoceramite. Unit thickens locally to 0.15 ft .....	0.10
7 Chalky limestone. Slightly cross laminated in zones near top and base; shale-parting zone 0.01 to 0.03 ft thick, 0.49 ft below top. Scattered small inoceramite lenses and concretions .....	4.70
6 Shaly chalk .....	0.05
5 Chalky limestone. Very thin shale-parting zones 0.13 ft and 0.18 ft above base; upper 0.4 ft slightly shaly. Scattered inoceramite concretions, in upper 1.5 ft; thin stringers and lenses of inoceramite in lower part .....	4.55
4 Chalky shale. Fissile. Gradational with 5; fairly sharp, slightly undulatory, contact with 3 .....	0.16
3 Chalky limestone. Rare phosphatic granules .....	1.50
2 Chalky shale. Slightly argillaceous. Unit thins locally to practically zero .....	0.03
1 Chalky limestone. Arenaceous, especially near base. Scattered phosphatic granules. Base locally very irregular and contains small lenses of shale and siltstone from underlying beds. Unit thickens locally to nearly twice its normal thickness; where thickest, lower part is softer, more shaly, and possibly cross laminated .....	1.70-3.10

*Thickness of exposed part of  
Fort Hays Limestone Member: 69.7-71.1*

CODELL SANDSTONE MEMBER,  
CARLILE SHALE

- \* Sandstone. Fine grained, quartzose, containing numerous very thin shale stringers. Abundant hollow burrow structures, especially in upper part; large horizontal to subhorizontal burrows in upper 0.1 to 0.2 ft infilled with Fort Hays sediment. Upper

\* Numerous undesignated beds.

0.2 ft partly reworked into Fort Hays, locally. Shale lenses up to 0.2 ft thick intervene locally between typical sandstone of Codell and chalky limestone of Fort Hays; shales contain scattered small chalk lenses and numerous chalk-filled burrows. Interval thickens locally to 2.5 ft ..... 0.90

### BLUE HILL SHALE MEMBER, CARLILE SHALE

\* Shale. Concretionary, arenaceous, containing numerous thin beds and stringers of siltstone and fine-grained sandstone, especially in upper 5 ft. Base inundated by reservoir; top gradational with Codell ..... 28.1

*Thickness of exposed part of Carlile Shale:* 29.0

*Total thickness of measured section:* 98.7

### LOCALITY 3

### SMOKY HILL CHALK MEMBER, NIOBRARA CHALK

\* Interval between Unit 66 and top of exposure consists of chalk and shaly chalk. (See measurements and descriptions by Hattin, 1965a, p. 64-65) ..... 47.7

66 Bentonite .....	0.02
65 Shaly chalk .....	0.42
64 Bentonite. Argillaceous .....	0.05
63 Shaly chalk. Very thin bentonitic layer 0.15 ft below top .....	0.64
62 Chalk. Shaly at top and base .....	1.35
61 Shaly chalk .....	0.32
60 Chalk. Shaly near top and base; chalky limestone locally in middle part .....	0.72
59 Shaly chalk. Moderately fissile .....	0.67
58 Chalk to shaly chalk (near top and base) .....	0.72
57 Chalky shale (lower part) to shaly chalk (upper part). Fissile on weathered surfaces, especially in lower part .....	0.40
56 Chalky. Shaly zone 0.4 ft thick, 0.45 ft below top .....	1.95

*Thickness of exposed part of Smoky Hill Chalk Member:* 55.0

### FORT HAYS LIMESTONE MEMBER, NIOBRARA CHALK

55 Chalky limestone. Chalky zone 0.3 to 0.4 ft thick, 0.7 ft above base. Unit thickens locally to 3.1 ft. Contact with bed above marked by 0.15 to 0.2-ft-thick chalky zone .....	2.60
54 Chalky shale. Bentonitic; biotitic. Rare small chalk lenses in lower part .....	0.10
53 Chalk .....	1.00
52 Shaly chalk .....	0.74
51 Bentonite. Shaly; chalky .....	0.05
50 Chalky limestone. Shaly at top and base. Local small limonitic, ?bentonitic lenses and stringers near top and base .....	1.45
49 Chalky limestone. Contact with overlying bed marked by 0.2-ft-thick shaly zone .....	2.95
48 Chalky shale. Biotitic. Scattered thin lenses of chalk and bentonite. Slightly stylolitic at top .....	0.07
47 Chalky limestone. Thin shale-parting zones 0.45 ft below top and 2.05 ft above base; stylolitic zone 0.15 to 0.2 ft thick, 3.11 ft above base .....	4.60
46 Shaly chalk to chalky shale. Scattered thin	

\* Numerous undesignated beds.

limonitic, bentonitic lenses, most common near base .....	0.43
45 Chalky limestone. Thin to very thin shale-parting zones 0.35 to 1.2 ft below top .....	2.90
44 Chalky shale. Slightly biotitic. Fissile on weathered surfaces. Scattered thin limonitic, bentonitic lenses, most common in upper part .....	0.15
43 Chalky limestone to chalk (near base) .....	1.10
42 Chalky shale. Scattered small limonitic, ?bentonitic, argillaceous lenses .....	0.05
41 Chalk (lower part) to shaly chalk (upper 0.14 to 0.15 ft) .....	0.40
40 Chalky shale. Argillaceous. Fissile on weathered surfaces. Scattered small lenses of chalk .....	0.08
39 Chalky limestone .....	1.10
38 Chalky shale. Argillaceous. Moderately fissile to fissile on weathered surfaces. Small thin lenses of limonitic chalk .....	0.10
37 Chalky limestone. Thin shale-parting zone 0.5 to 0.55 ft below top. Slightly stylolitic locally. Scattered large chalky concretionary structures .....	2.65
36 Chalk and shaly chalk (lower part) to chalky shale (upper 0.1 ft). Upper part argillaceous. Scattered large chalky concretionary structures .....	0.32
35 Chalky limestone. Slightly shaly near top and base. Locally, unit indistinguishable from 36 .....	0.68
34 Chalky shale. Biotitic. Fissile on weathered surfaces. Scattered thin limonitic, bentonitic lenses and stringers .....	0.18
33 Chalky limestone. Shale-parting zones 0.02 to 0.03 ft thick, 1.6 ft below top and 0.95 and 0.35 ft above base; very thin shale parting 0.65 ft below top ....	3.85
32 Chalky shale. Bentonitic. Fissile on weathered surfaces. Unit undulatory .....	0.08
31 Chalky limestone. Very thin shale-parting zones 0.4 to 0.6 ft below top and 0.25 ft above base .....	2.05
30 Chalky shale. Fissile on weathered surfaces. Unit slightly undulatory locally .....	0.09
29 Chalky limestone. Thin shale-parting zone 0.12 to 0.15 ft below top .....	1.75
28 Chalky shale. Biotitic. Fissile on weathered surfaces. Scattered small limonitic, bentonitic lenses. Unit undulatory locally .....	0.09
27 Chalky limestone. Softer in upper 0.8 ft. Scattered small lenses of inoceramite .....	2.25
26 Chalky shale. Fissile on weathered surfaces. Bentonitic in upper 0.05 ft .....	0.58
25 Chalk and shaly chalk. Moderately fissile in shaly parts .....	0.32
24 Chalky shale. Fissile on weathered surfaces .....	0.14
23 Chalky limestone. Softer in lower 0.1 to 0.2 ft .....	0.70
22 Chalky shale. Poorly to moderately fissile on weathered surfaces .....	0.07
21 Chalky limestone. Slightly shaly near top and base .....	0.95
20 Chalky shale. Moderately fissile on weathered surfaces .....	0.11
19 Chalky limestone. Thin shale-parting zone 0.4 to 0.45 ft below top .....	2.75
18 Chalky shale. Moderately fissile on weathered surfaces .....	0.10
17 Chalky limestone (lower 3.48 ft) to chalk and shaly chalk (upper 0.95 ft). Thin limonitic shale-parting zone 1.55 ft below top; thin shaly lenses and limonitic, ?bentonitic stringers common in middle part .....	4.45
16 Chalk and chalky shale. Unit consists of two thin chalk beds separated by chalky shale; shaly at top and base. Rare thin limonitic, ?bentonitic stringers in upper part .....	0.32



15	Chalky limestone. Thin shale-parting zones 0.55 to 0.6 ft below top and 0.5 to 0.55 ft above base. Scattered small lenses of inoceramite .....	2.35	4	Chalky shale. Moderately fissile on weathered surfaces. Slightly silty .....	0.11
14	Chalky shale. Fissile on weathered surfaces .....	0.09	3	Chalky limestone. Limonite nodules concentrated locally in 0.2 to 0.25-ft-thick zone 0.4 to 0.45 ft below top .....	1.60
13	Chalky limestone. Thin shale-parting zone 0.3 to 0.35 ft below top .....	3.75	2	Chalky shale. Moderately fissile on weathered surfaces. Rare phosphatic granules .....	0.07
12	Chalky shale. Unit undulatory locally. Gradational with 11, fairly sharp contact with 13 .....	0.09	1	Chalky limestone. Slightly arenaceous to argillaceous near base. Scattered phosphatic granules. Base irregularly burrowed. Small shale lenses partly reworked from underlying bed, locally .....	1.85
11	Chalky limestone. Scattered lenses of inoceramite .....	4.35	<i>Thickness of Fort Hays Limestone Member: 73.0</i>		
10	Chalky shale .....	0.23	<i>Thickness of exposed part of Niobrara Chalk: 128.0</i>		
9	Chalky limestone. Shale-parting zone 0.25 ft thick, 2.2 to 2.3 ft below top; thin shale partings present locally in other parts of unit. Scattered lenses of inoceramite in lower part .....	5.30	<b>BLUE HILL SHALE MEMBER,</b>		
8	Chalky shale. Moderately fissile on weathered surfaces. Scattered, extremely thin lenses of inoceramite ....	0.06	<b>CARLILE SHALE</b>		
7	Chalky limestone. Slightly shaly in upper 0.4 to 0.6 ft. Lower one-third slightly laminated to cross laminated. Scattered small lenses of inoceramite, most common in upper part .....	4.35	* Shale. Silty; numerous thin quartzose siltstone beds. Upper 0.05 ft locally contains dominantly horizontal subcylindrical burrows filled with chalky sediment from Fort Hays .....		
6	Chalky shale. Unit slightly undulatory .....	0.06	0.95		
5	Chalky limestone. Two very thin shale-parting zones 0.2 to 0.25 ft above base; cross laminated zone 0.05 to 0.12 ft thick, 1.15 to 1.2 ft below top. Local large chalky, concretionary structures near base .....	4.35	<i>Total thickness of measured section: 129.0</i>		

\* Undesignated beds.

APPENDIX 3.—QUANTITATIVE DATA ON THE INOCERAMUS DEFORMIS LINEAGE

LOCALITY 1

UNIT	AREA EXAMINED (m <sup>2</sup> )	N	MEAN DENSITY (valves/m <sup>2</sup> )	SIZE RANGE (cm)	MEDIAN SIZE (cm)	MEAN SIZE (cm)	STANDARD DEVIATION (cm)
1	8.8	0	0.0	.....	....	....	....
3	7.3	0	0.0	.....	....	....	....
5	27.8	8	0.3	4.0-9.5	8.5	8.0	1.9
7	13.0	11	0.8	8.5-14.0	11.0	11.0	1.8
9	35.8	13	0.4	9.5-14.5	11.0	11.0	1.5
11	10.7	24	2.2	8.0-16.0	10.0	11.0	2.2
13	17.2	16	0.9	9.0-16.0	12.0	11.5	2.1
15	10.7	12	1.1	9.5-20.5	16.0	15.0	3.7
17	13.5	18	1.3	9.0-20.0	12.5	13.0	2.7
19	11.6	12	1.0	10.0-23.0	13.0	15.5	4.9
21	1.2	1	0.9	.....	(15.0)	(15.0)	....
27	11.4	6	0.5	7.5-17.5	13.0	13.0	3.4
29	11.6	12	1.0	9.5-23.5	14.0	14.5	3.9
31	16.2	11	0.7	8.5-18.5	12.0	13.0	3.3
33	11.5	4	0.3	10.5-15.0	12.5	12.5	....
35	4.3	0	0.0	.....	....	....	....
36	3.1	3	1.0	10.0-11.0	10.5	10.5	....
37	18.0	0	0.0	.....	....	....	....
39	4.8	1	0.2	.....	(9.5)	(9.5)	....
41	2.8	0	0.0	.....	....	....	....
43	5.5	3	0.5	12.0-18.0	15.0	15.0	....
45	11.0	0	0.0	.....	....	....	....
46	1.1	0	0.0	.....	....	....	....
47	12.1	1	0.1	.....	(6.5)	(6.5)	....
49	6.5	3	0.5	13.0-14.5	14.0	14.0	....
50	9.7	0	0.0	.....	....	....	....

LOCALITY 2

A—VERTICAL QUADRAT DATA

UNIT	AREA EXAMINED (m <sup>2</sup> )	N	MEAN DENSITY (valves/m <sup>2</sup> )	SIZE RANGE (cm)	MEDIAN SIZE (cm)	MEAN SIZE (cm)	STANDARD DEVIATION (cm)
1	7.0	0	0.0	.....	....	....	....
3	6.0	0	0.0	.....	....	....	....
5	34.5	10	0.3	7.0-10.5	8.0	8.0	1.1
7	35.5	9	0.3	7.0-15.0	12.0	11.5	2.2
9	25.7	11	0.4	7.5-14.5	11.0	11.0	2.2
11	16.1	24	1.5	8.5-16.0	11.5	12.0	2.2
13	15.2	6	0.4	11.5-14.5	13.0	13.0	1.2
15	3.3	4	1.2	12.0-21.0	13.0	15.0	....
17	14.4	18	1.3	14.0-23.0	16.0	17.0	3.0
19	10.8	10	1.0	10.5-30.5	13.5	16.0	6.0
21	5.3	3	0.6	9.5-14.5	11.0	11.5	....
23	4.3	5	1.2	12.0-18.5	18.0	16.5	2.8
25	3.1	2	0.6	13.5-15.0	14.5	14.5	....
26	1.2	0	0.0	.....	....	....	....
27	14.8	7	0.5	15.0-24.0	16.5	18.0	3.1
29	12.2	7	0.6	11.0-19.0	15.0	14.5	3.4
31	9.3	6	0.6	11.5-18.0	14.5	15.0	2.4
33	15.6	9	0.6	10.5-23.0	15.0	16.0	4.4
35	2.5	0	0.0	.....	....	....	....
36	1.1	0	0.0	.....	....	....	....
37	11.4	0	0.0	.....	....	....	....
39	3.4	0	0.0	.....	....	....	....
41	0.7	0	0.0	.....	....	....	....
43	2.9	0	0.0	.....	....	....	....
45	2.3	0	0.0	.....	....	....	....

## B—BEDDING PLANE DATA

UNIT	AREA EXAMINED (m <sup>2</sup> )	N	MEAN DENSITY (valves/m <sup>2</sup> )	SIZE RANGE (cm)	MEDIAN SIZE (cm)	MEAN SIZE (cm)	STANDARD DEVIATION (cm)
5	2.8	6	2.1	7.5-14.0	12.0	11.5	2.4
7	2.9	4	1.4	7.5-14.5	13.5	12.5	....
9	3.0	0	0.0	.....	....	....	....
11	0.6	1	1.7	.....	(11.0)	(11.0)	....
13	0.9	0	0.0	.....	....	....	....
15	2.7	3	1.1	17.0-21.5	21.5	20.0	....
19	2.2	3	1.4	11.5-19.5	19.0	16.5	....
21	3.0	8	2.7	9.0-23.0	14.0	15.5	5.4
23	5.0	16	3.2	8.5-37.5	15.5	16.5	7.1
27	6.4	4	0.6	12.5-19.0	13.5	14.5	....
29	6.9	12	1.7	11.0-22.0	19.0	17.0	4.6
31	8.1	4	0.5	10.5-21.5	11.0	13.5	....
33	14.7	2	0.1	11.0-14.5	13.0	13.0	....
35	1.7	0	0.0	.....	....	....	....
36	0.6	0	0.0	.....	....	....	....
37	5.0	0	0.0	.....	....	....	....
39	5.0	1	0.2	.....	(9.0)	(9.0)	....
43	11.5	1	0.1	.....	(12.0)	(12.0)	....

## LOCALITY 3

UNIT	AREA EXAMINED (m <sup>2</sup> )	N	MEAN DENSITY (valves/m <sup>2</sup> )	SIZE RANGE (cm)	MEDIAN SIZE (cm)	MEAN SIZE (cm)	STANDARD DEVIATION (cm)
1	1.0	0	0.0	.....	....	....	....
3	3.3	0	0.0	.....	....	....	....
5	7.1	2	0.3	8.5-9.0	9.0	9.0	....
7	23.2	8	0.3	8.5-14.0	11.5	11.5	1.7
9	25.9	13	0.5	8.5-15.0	12.5	12.0	1.8
11	8.9	13	1.5	8.5-19.0	12.0	12.0	2.9
13	6.6	18	2.7	8.0-19.0	12.0	12.0	2.9
15	6.2	10	1.6	11.0-25.0	20.5	19.5	3.9
17	10.0	17	1.7	10.0-18.5	14.5	14.5	2.5
19	6.0	17	2.8	9.0-15.5	12.5	12.5	2.0
21	1.9	2	1.1	12.5-13.5	13.0	13.0	....
23	1.7	2	1.2	11.0-15.0	13.0	13.0	....
27	8.6	10	2.2	9.0-30.5	15.5	16.5	6.6
29	7.1	10	1.4	9.0-17.0	14.0	13.5	2.4
31	10.6	8	0.8	9.0-32.0	12.5	15.5	8.0
33	18.8	7	0.4	11.0-17.0	16.0	14.0	2.7
35	3.5	0	0.0	.....	....	....	....
36	1.7	1	0.6	.....	(7.5)	(7.5)	....
37	13.9	0	0.0	.....	....	....	....
39	4.6	2	0.4	10.5-14.0	12.5	12.5	....
41	1.3	0	0.0	.....	....	....	....
43	2.2	0	0.0	.....	....	....	....
45	2.4	0	0.0	.....	....	....	....
47	7.4	0	0.0	.....	....	....	....
49	10.7	1	0.1	.....	(12.5)	(12.5)	....
50	3.5	0	0.0	.....	....	....	....

## EXPLANATION OF PLATES

## PLATE 1

Stratigraphic aspects of the Fort Hays Member.

## FIGURE

1. Fort Hays exposure at Loc. 2, illustrating the lateral continuity of individual beds within the member and their geometric conformity with bedding in the underlying Carlile Shale. Typically prominent north-facing slope along Fort Hays escarpment; about 70 feet of the Fort Hays is present here.
2. Pleistocene channel cut into the Fort Hays at Loc. 7. Channel-fill consists of "slope wash." Thin bed of chalk (at arrow) is Unit 46.
3. Erosional plateau at Loc. 3, held up mainly by the Fort Hays but here capped by the lowermost bed of the Smoky Hill (Unit 56). Contact indicated by arrow. Overlying beds of the Smoky Hill are seen in distance.

## PLATE 2

Stratigraphic, structural, and weathering features of the Fort Hays Member.

## FIGURE

1. Pleistocene fluvial deposits in sharp contact with the Fort Hays, at Loc. 1. Most of this debris was derived from the Fort Hays. (Hammerhead, bottom center, is 15 cm long.)
2. Cavernous weathering in Fort Hays, Unit 11, Loc. 3. Cross-laminated lense of inoceramite (disaggregated prisms from the valves of *Inoceramus*) at arrow. (Hammer for scale, lower right.)
3. Small normal fault in Carlile Shale and Fort Hays Member, Loc. 6. Displacement is about 9 feet. Note geometric conformity between Carlile and Fort Hays bedding.
4. Carlile-Fort Hays contact at Loc. 4, illustrating the striking lithologic contrast. Irregularly spherical limonite nodule in Unit 3. Hammer for scale, lower center.
5. Carlile-Fort Hays contact at Loc. 1, illustrating local channel development. Basal bed of the Fort Hays (Unit 1) thickens to right, truncating beds within the Carlile. Dark line at contact (arrow) is a persistent seam of partly oxidized iron sulfide. (Knapsack for scale, lower left.)

## PLATE 3

## Stratigraphic and petrographic aspects of the Fort Hays and Smoky Hill Members.

## FIGURE

1. Carlile-Fort Hays contact at Loc. 1, illustrating irregular burrows and bioturbate textures. (Knife handles are 6.6 cm. long.)
2. Twin bentonites (Units 66 and 64, at arrows) at base of "Group A" beds of Bass (1926, p. 19-23), lower part of Smoky Hill, Loc. 1. Bentonites are separated by 0.4-foot-thick bed of shaly chalk (Unit 65).
3. Fragmented valves of *Inoceramus deformis*. Bedding plane in upper part of Unit 11, Loc. 1. All of these fragments were apparently derived from a single animal. Except for such debris, Fort Hays rocks are very uniform in texture.
4. Fragmentary *Inoceramus deformis* valve partly replaced by small masses of pyrite and limonite, especially along hinge (between arrows), in Unit 19, Loc. 3.
5. Thin zone of pyrite and limonite nodules, conformable with bedding, in middle part of Unit 62 (Smoky Hill), Loc. 1. (Quarter-dollar coin for scale.)

## PLATE 4

Scanning electron photomicrographs of chalk and chalky limestone from the Fort Hays and Smoky Hill Members. All specimens from Locality 1. Note predominance of coccolith debris and apparent absence of chemical cement (cf. Pl. 15, fig. 1-2). (Photos by J. M. Hancock and G. McTurk.)

## FIGURE

1. Chalk, Unit 25, ca.  $\times 1,200$ .
2. Chalky limestone, Unit 35, ca.  $\times 2,400$ .
3. Chalky limestone, Unit 55, ca.  $\times 2,500$ .
4. Chalk, Unit 62 (Smoky Hill), ca.  $\times 2,400$ .

## PLATE 5

## Inorganic and biogenic sedimentary structures in the Fort Hays Member.

## FIGURE

1. Cross-laminated inoceramite lenses, inclined at low angles to bedding. Lower part of Unit 5, Loc. 2. Scale (lower left) as in Fig. 3.
2. Very thin limonitic (and ?bentonitic) shaly zone, conformable with bedding, in middle part of Unit 17, Loc. 3.
3. Distinct burrow structures, mostly *Chondrites* (top) and *Planolites* (middle). Vertical exposure, middle part of Unit 9, Loc. 1.
4. Bioturbate textures in chalky limestone, reflecting sediment reworking by at least three generations of burrowing animals. Oblique surface; top of exposure inclined gently away from viewer. Lower part of Unit 7, Loc. 6.

## PLATE 6

## Current-influenced sedimentary structures in the Fort Hays Member.

## FIGURE

1. Small channel structure in upper part of Unit 50, Loc. 1. (Hammer for scale, near center.) Bottom of this channel, like that in Plate 2, figure 5, is lined with a thin layer of partly oxidized iron sulfide.
2. Abrupt lateral thinning of chalky limestone bed (base of hammer, center) in Unit 49, Loc. 1. Overlying beds thicken in compensation.
3. Cross-laminated to very thinly cross-bedded scour zone (extending ca. 0.9 foot below base of hammer), in upper part of Unit 7, Loc. 1.

4. Thinly laminated to slightly cross-laminated zone, ca. 0.1 foot thick, conformable with bedding, in upper part of Unit 5, Loc. 3.

## PLATE 7

## Diagenetic and post-diagenetic structures in the Fort Hays Member.

## FIGURE

1. "Pseudo-mudcracks" (a weathering phenomenon) in chalky shale. Bedding surface, Unit 2, Loc. 4. (Penny for scale.)
2. Concretionary structure causing deformation of beds above and below, in Unit 36, Loc. 3. Concretion retains vestigial shale laminae. (Penny for scale.)
3. Irregularly coalescent concretionary structures and bedding deformation, Loc. 8. (Hammer head at center of Unit 43.) Similar deformation was noted at Loc. 6.
4. Differential compaction of sediments around undistorted *Inoceramus* valve, in Unit 33, Loc. 3. Distortion of the very thin shale seam (arrow) is especially conspicuous.
5. Styolitic zone, conformable with bedding, in upper part of Unit 47, Loc. 1. (Quarter-dollar coin for scale.)

## PLATE 8

## Fossils from the Fort Hays Member.

## FIGURE

- 1-2. *Pyripora shawi* encrusting exterior of *Inoceramus deformis* valve, from lower part of Unit 19, Loc. 3,  $\times 31$ . (Photomicrographs by E. L. Håkansson.)
3. Mass of *Serpula* cf. *S. semicoalita* encrusting exterior of *Inoceramus deformis* valve (cross-sectional view), from middle part of Unit 19, Loc. 1. Several serpulid tubes are partly replaced and (or) filled by pyrite. Note coarseness of inoceramid prismatic layer. (Line=1 mm.)
4. Photomicrograph of longitudinal thin section through left valve of *Pycnodonte aucella*, illustrating vacuolated wall structure (cf. Müller, 1970, fig. 2), from middle part of Unit 1, Loc. 1. (Photomicrograph by R. E. Carver.) (Line=1 mm.)
5. Tubes of a ?teredine bivalve, stained locally by dendrites, from lower part of Unit 11, Loc. 1. (Line=1 cm.)

## PLATE 9

## Fossils from the Fort Hays Member.

## FIGURE

1. Two specimens (arrows) of *Serpula* sp. attached to interior of *Inoceramus deformis* valve. Bedding plane, middle part of Unit 33, Loc. 2.
2. Typical shark teeth and phosphatic granules (bottom right) from the Fort Hays, in molding clay, from various localities, Trego County. *Squalicorax* (at arrow) is perhaps the most common tooth throughout the member. Smaller teeth and the granules are common near base of member. (Line=1 cm.)
3. Apertural end (dorsal view) of *Serpula* cf. *S. semicoalita*, illustrating terminal, band-like thickening of tube (arrow). Lower part of Unit 19, Loc. 1. (Line=5 mm.)
4. Incompletely exposed internal mold of *Inoceramus deformis*. Sole of Unit 9, Loc. 2.
5. Clionid borings within valve walls of *Pycnodonte congesta* (transverse section). Arrows indicate areas of heaviest infestation. Float; middle part of Fort Hays, Loc. 3. (Line=1 cm.)
6. Crushed, incomplete, but fully articulated valves of *Inoceramus* aff. *I. deformis*, preserved in presumed position of growth. Bedding plane, top of Unit 23, Loc. 2. Upper valve encrusted by *Pycnodonte congesta*.
7. Exterior of fully open, loosely articulated valves of *Inoceramus deformis*, encrusted throughout by *Pycnodonte congesta*. Sole of Unit 11, Loc. 1. Hinge at arrow.

## PLATE 10

Fossils from the Fort Hays Member.

## FIGURE

1. Juvenile right valves of *Volviceramus grandis*, encrusted by *Pycnodonte congesta*. Bedding plane, top of Unit 55, Loc. 1.
- 2-3. Interior of right valves of *Pycnodonte congesta*. Float; lower part of Fort Hays, Loc. 1. (Line=1 cm.)
- 4-5. Interior of right valves of *Pycnodonte aucella*, from middle part of Unit 1, Loc. 1. (Line=5 mm.)
6. Incomplete ?teredine tube, from middle part of Unit 17, Loc. 3. (Line=1 cm.)
- 7-9. Front, side, and umbonal views, respectively, of internal mold of *Inoceramus browni*. Collected by Thomas O'Toole from upper middle part of Fort Hays, Loc. 3. (Line=10 cm.)

## PLATE 11

Interior of articulated valves of *Volviceramus grandis* from Smoky Hill Member, Gove County, Kansas. Coiled left valve (top of photo) is incomplete. (Photo courtesy of E. G. Kauffman; Am. Museum Nat. History, spec. no. 9374/1.) (Line=5 cm.)

## PLATE 12

Fossils from the Fort Hays and Smoky Hill Members.

## FIGURE

1. Fragmented *Inoceramus* valve encrusted by at least three generations of *Pycnodonte congesta*. Float; lower part of Fort Hays, Loc. 1. (Line=1 cm.)
2. Acrothoracican borings in *Inoceramus* fragment, illustrating resistance of bore walls to corrosion and abrasion. Upper part of Unit 56 (Smoky Hill), Loc. 3. (Line=1 cm.)
3. Interior of right valve of *Volviceramus grandis* from Smoky Hill, Kansas. (Fort Hays Kansas State Coll. Museum specimen.) (Line=10 cm.)
4. Crushed, incomplete, but articulated specimen of *Volviceramus grandis*, encrusted by *Pycnodonte congesta*. Hinge aligned with arrow; left valve below and to right of hinge. Bedding plane; top of Unit 55, Loc. 1. (Line=10 cm.)
5. Articulated valves of *Pycnodonte congesta*, encrusting an *Inoceramus* fragment. Float; middle part of Fort Hays, Loc. 3. (Line=1 cm.)

## PLATE 13

Fossils from the Fort Hays and Smoky Hill Members.

## FIGURE

1. Small, laterally crushed left valve of *Volviceramus grandis*, illustrating coiling, from Smoky Hill, Kansas. (Photo courtesy of E. G. Kauffman; Am. Museum Nat. History specimen.) (Line=1 cm.)
- 2-3. View of right and left valves, respectively, of articulated specimen of *Pycnodonte aucella*, from middle part of Unit 1, Loc. 1. (Line=1 cm.)
4. Oblique umbonal view of left valve of *Pycnodonte aucella*, illustrating abrupt truncation (arrow) at original place of attachment with shell fragment, from middle part of Unit 1, Loc. 1. (Scale as in fig. 2-3.)

- 5-6. Left valves of *Pycnodonte aucella*, illustrating variation in degrees of alateness (cf. fig. 2-3), from middle part of Unit 1, Loc. 2. (Line=1 cm.)
7. Intertwined ?teredine tubes. Tube at arrow exhibits subdued transverse annulations. Vertical exposure, lower part of Unit 11, Loc. 1. (Ten-cent coin for scale.)
8. Large acrothoracican borings in interior of *Inoceramus* valve fragment. Float; upper part of Fort Hays or lower part of Smoky Hill, Loc. 3. (Line=1 cm.)
9. Interior of nearly complete valve of *Inoceramus deformis*. Bedding plane; top of Unit 15, Loc. 2. (Penny for scale.)
10. Intermingling of burrow structures (whitish gray) and ?teredine tubes (outlined in ink). Vertical exposure; lower part of Unit 11, Loc. 1. Ten-cent coin for scale.
- 11-12. Clionid borings in exterior of *Inoceramus* valve fragments (11 from Unit 9, Loc. 3; 12 from Unit 11, Loc. 1.) (Line=1 cm.)
- 13-14. Acrothoracican borings in *Inoceramus* shell fragments (fig. 13, in exterior; fig. 14, in interior), from upper part of Unit 11, Loc. 1. (Line=1 cm.)

## PLATE 14

Fossils from the Fort Hays and Smoky Hill Members.

## FIGURE

1. Problematical tubes on interior of *Inoceramus* valve fragment, from upper part of Unit 55, Loc. 3. (Line=1 cm.)
2. Acrothoracican borings in exterior of *Inoceramus* shell fragment, from upper part of Unit 11, Loc. 1. (Line=1 cm.)
3. Remarkably well-preserved, fully articulated specimen of *Inoceramus platinus* from Smoky Hill, about 25 mi. southwest of Oakley, Kansas, and 7-8 mi. northwest of Elkader, Kansas (Fort Hays Kansas State Coll. Museum, specimen 2086). (Line=25 cm; certain specimens are known to exceed a length of 150 cm. (Kauffman, 1967, p. 132.))
4. *Pycnodonte* valve fragment containing both clionid and acrothoracican borings, from lower part of Unit 9, Loc. 3. (Line=1 cm.)
5. Well-preserved fish scale, from middle part of Unit 5, Loc. 3. (Line=5 mm.)
6. Large, isolated specimen of *Pycnodonte congesta* attached to exterior of *Inoceramus* shell fragment (arrow), oriented in presumed position of growth, from lower part of Unit 9, Loc. 3. (Line=1 cm.)

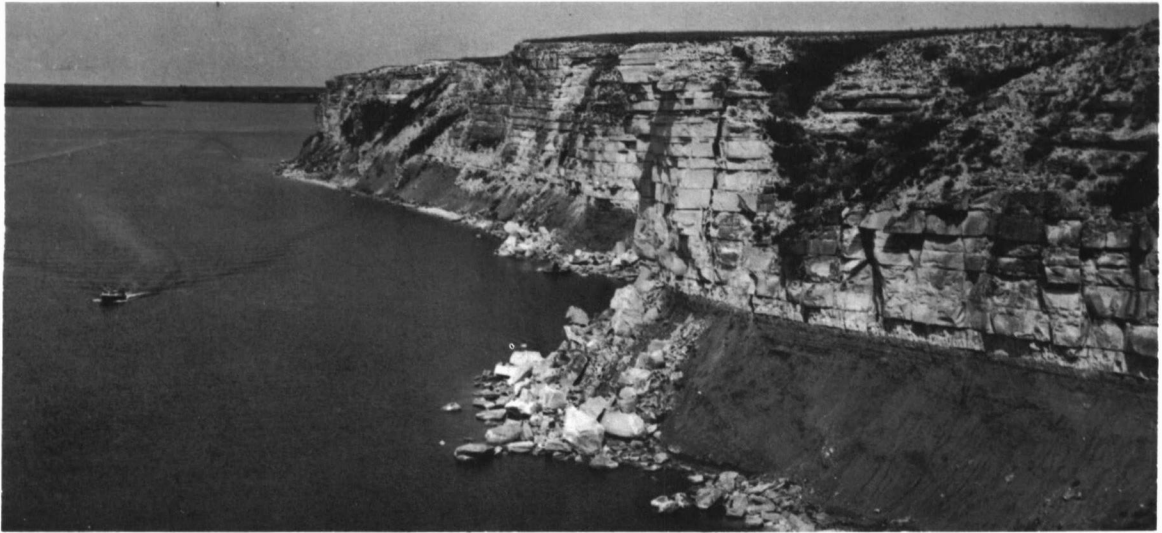
## PLATE 15

Fossils from the Fort Hays and Smoky Hill Members. (Fig. 1-2 are scanning electron micrographs by J. M. Hancock and G. McTurk; coccoliths identified by W. W. Hay.)

## FIGURE

1. *Watznaueria barnesae* (A), *Cretarhabdus conicus* (B), and other coccoliths, from Unit 25, Loc. 1,  $\times 6,000$ .
2. *Prediscosphaera cretacea* (arrow) and other coccoliths, from Unit 62 (Smoky Hill), Loc. 1,  $\times 6,000$ .
3. Fragmented valves of *Inoceramus deformis*, suggesting predation by a shell-crushing animal. Valve breakage is sharp and angular, and pieces excavated from the rock can be fitted back together. Bedding plane; upper part of Unit 11, Loc. 1.





1



2



3



1



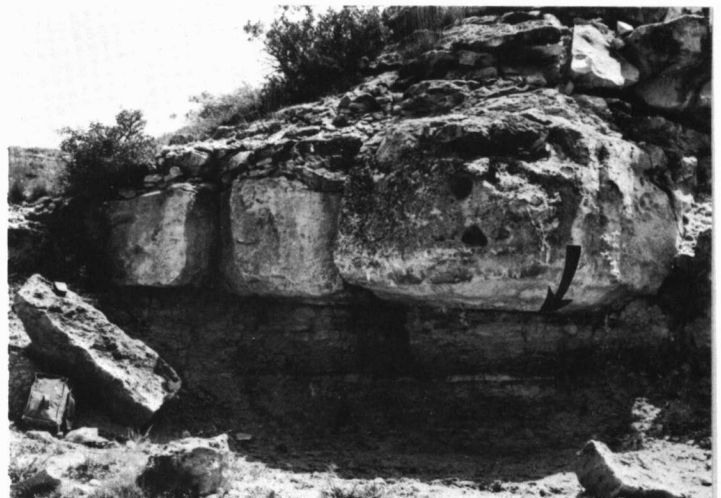
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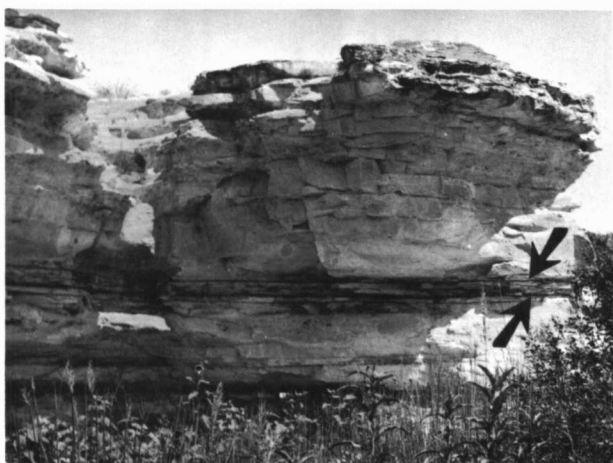
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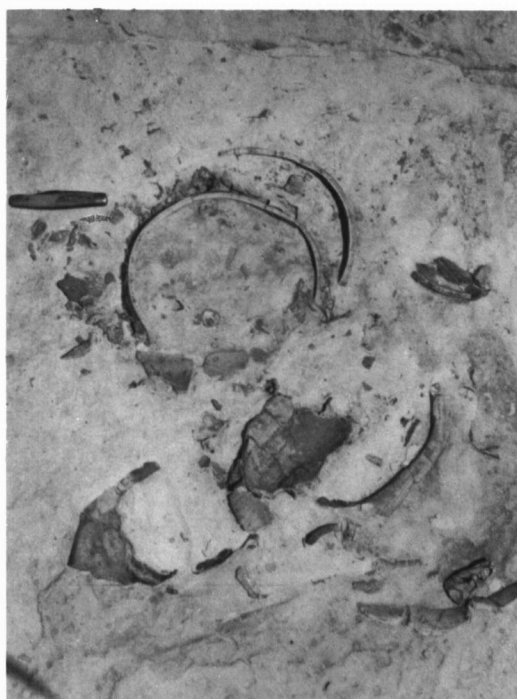
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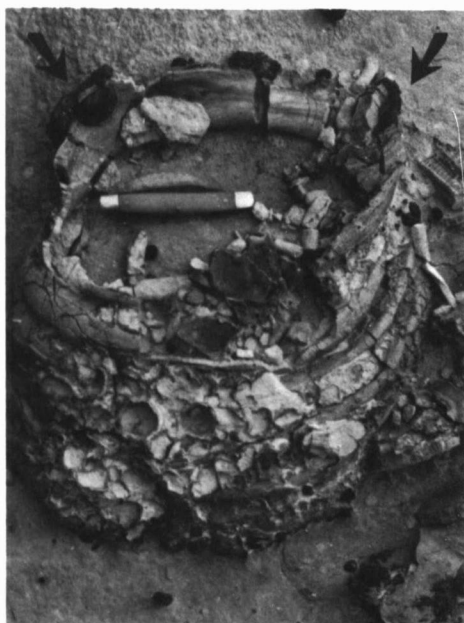
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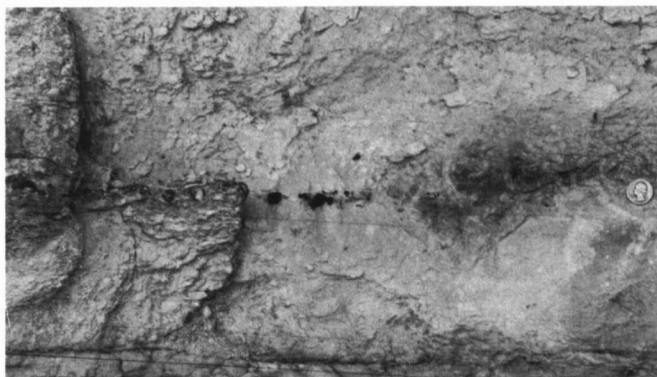
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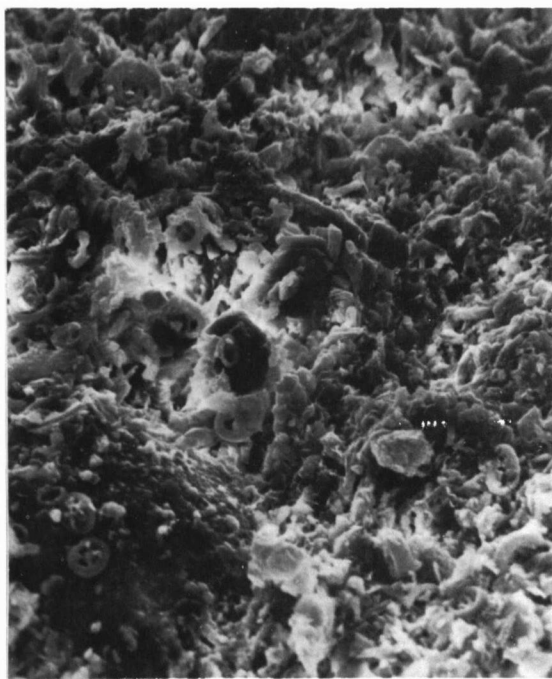
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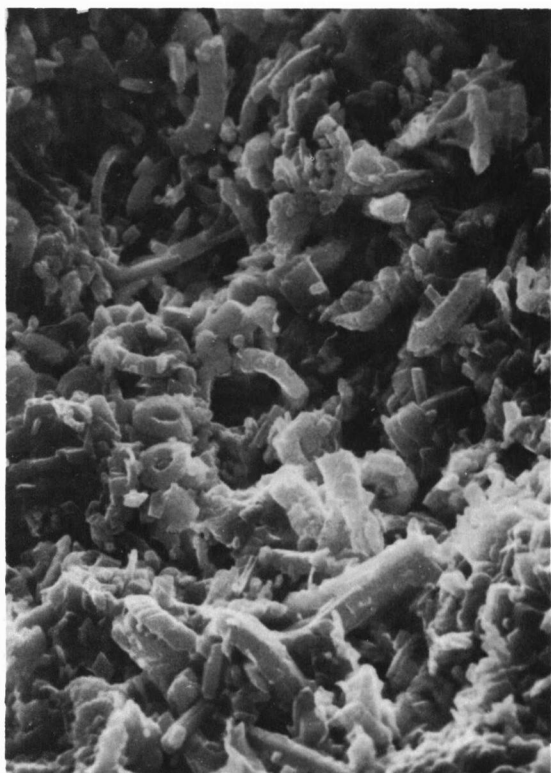
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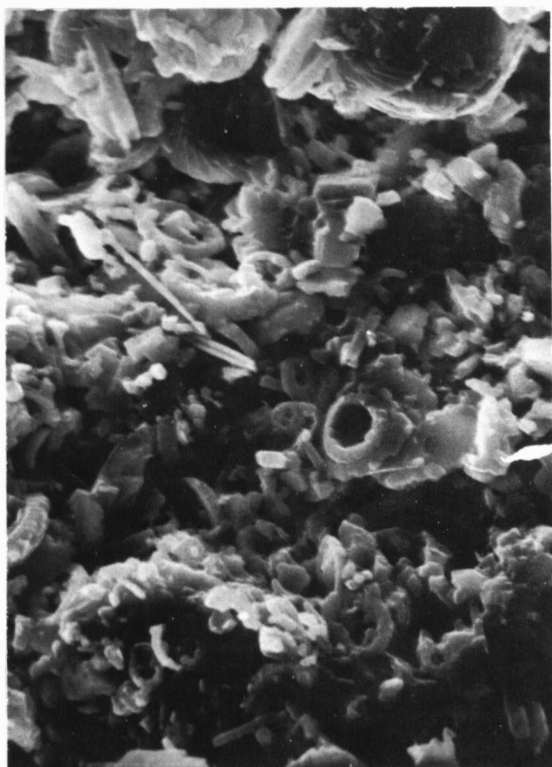
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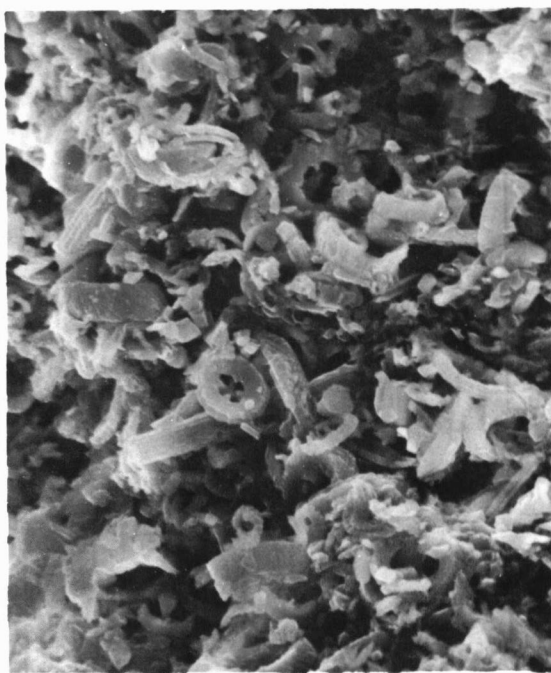
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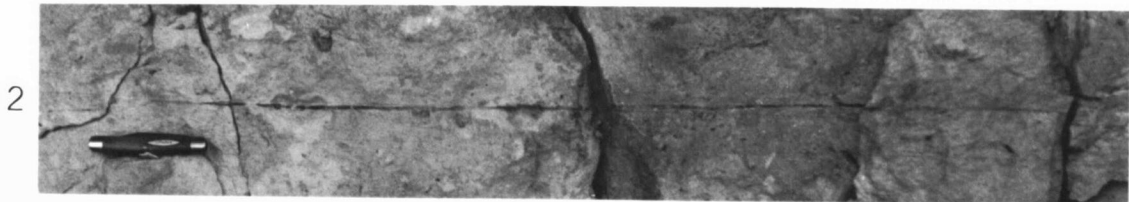


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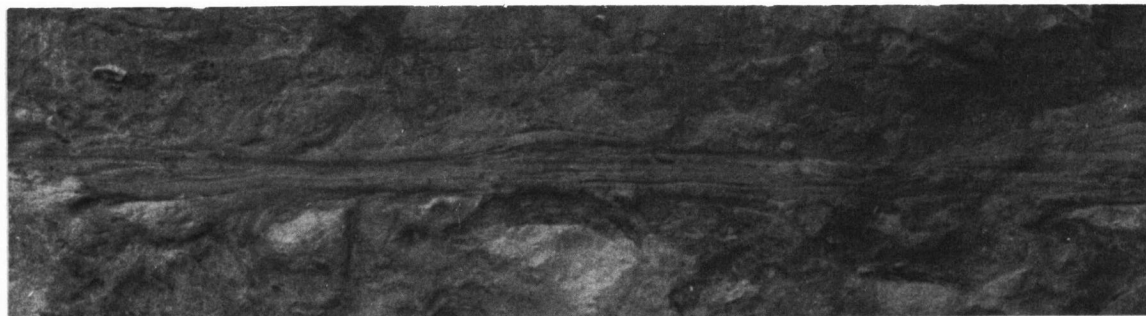
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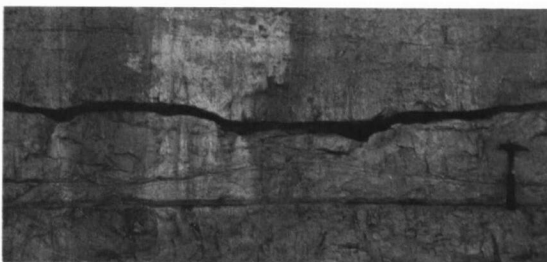
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3



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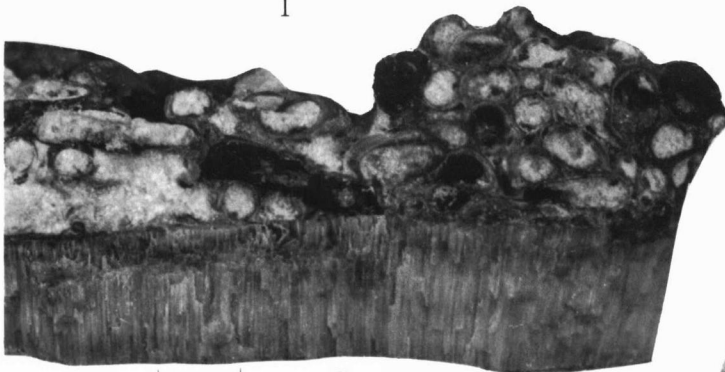
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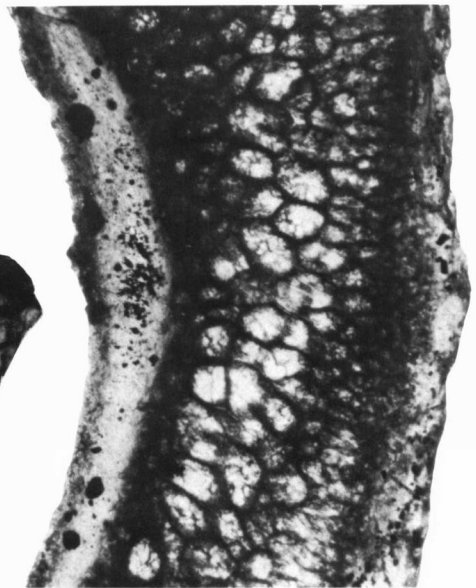
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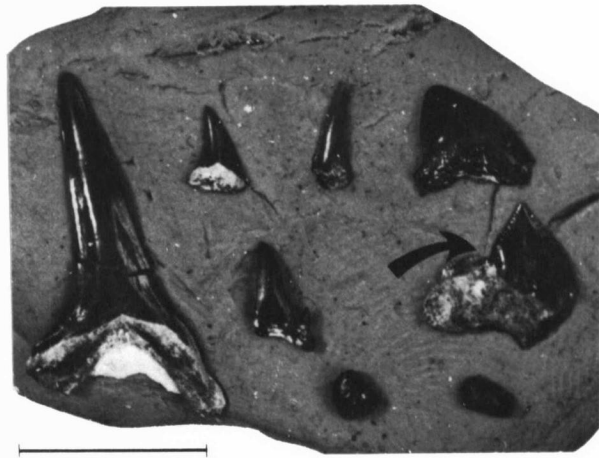


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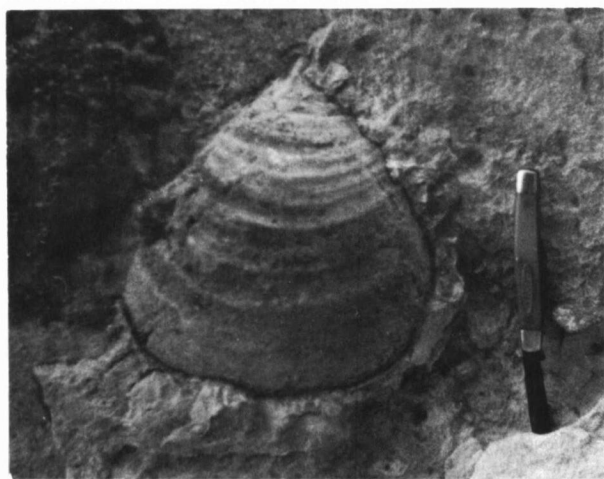




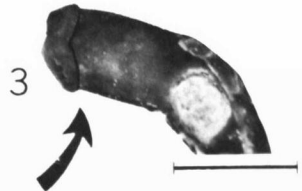
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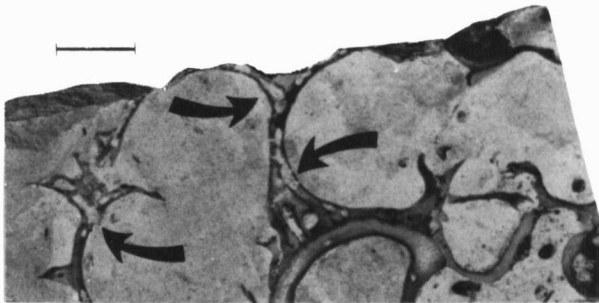
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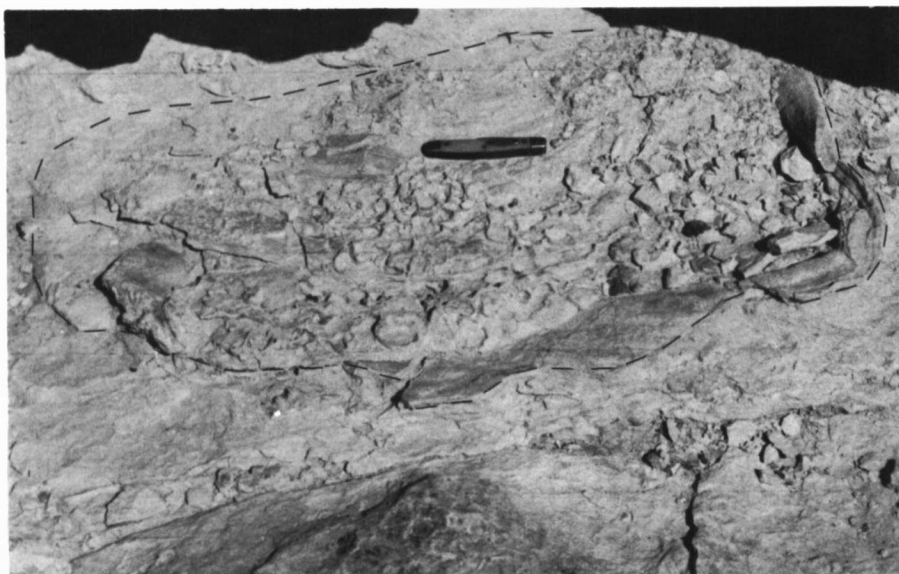
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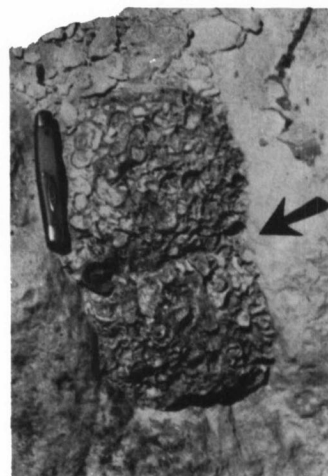
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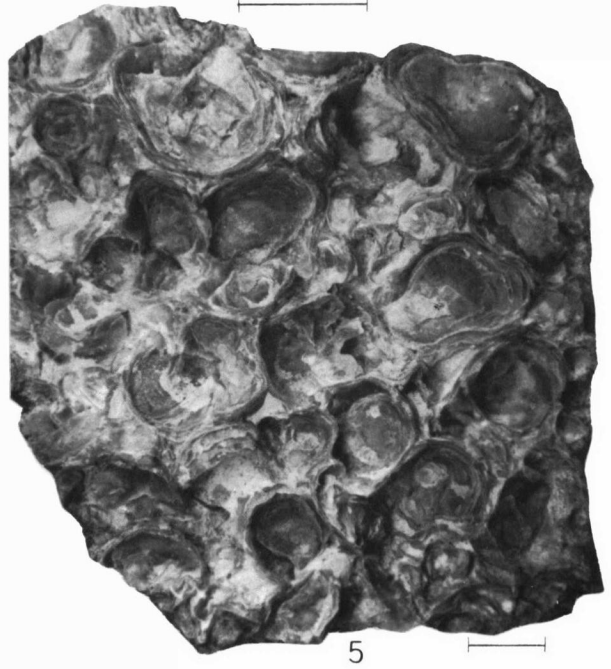
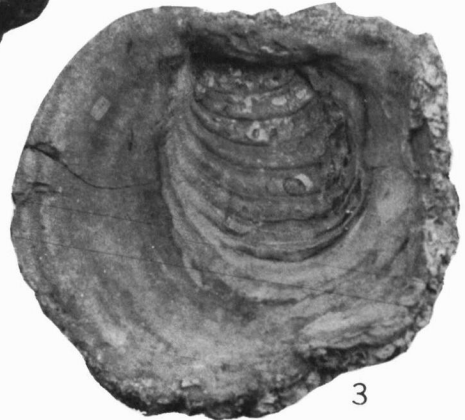
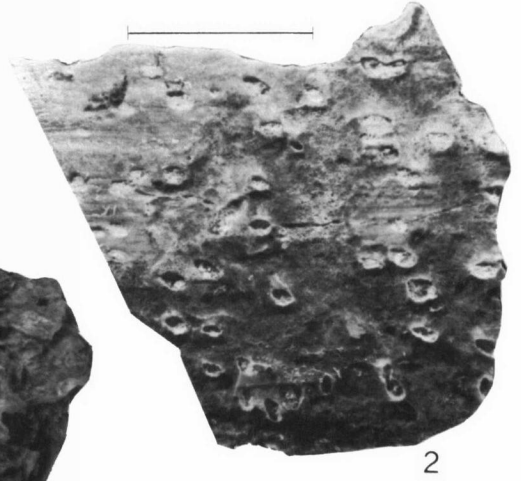
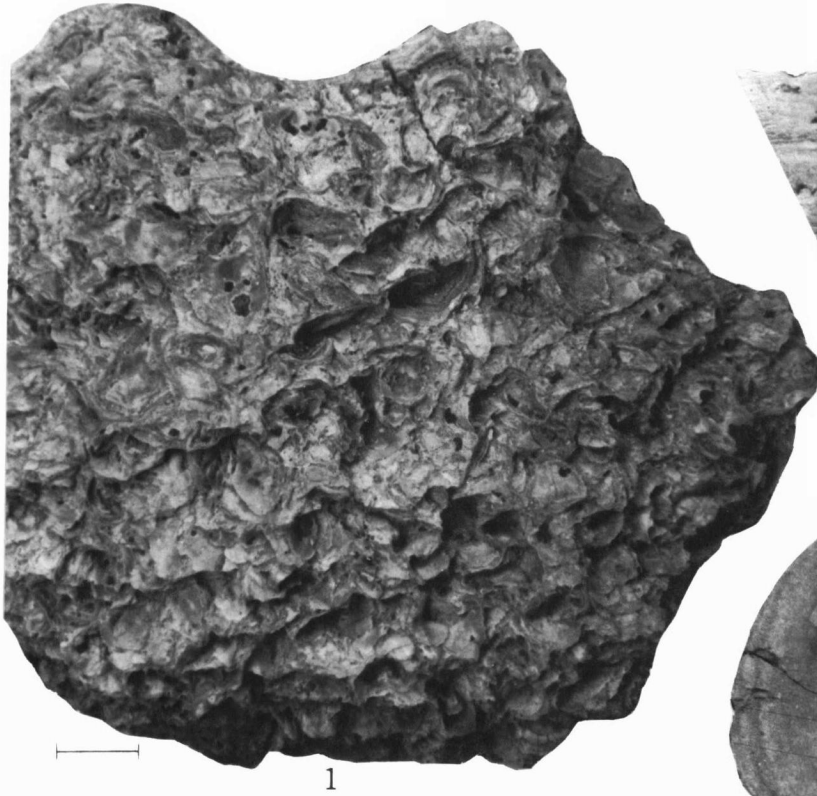


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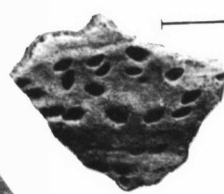
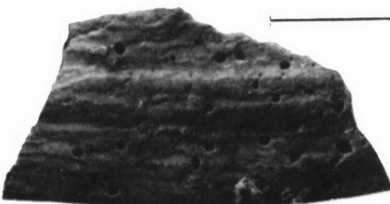
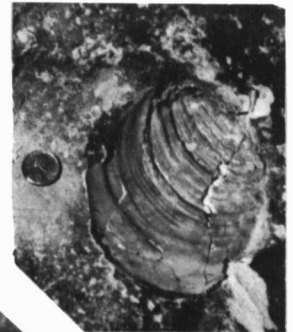
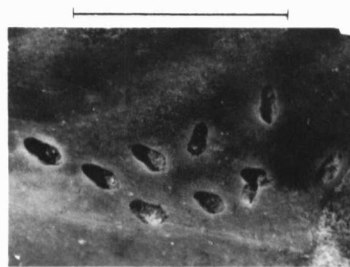
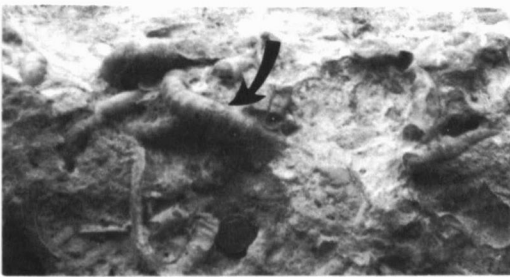
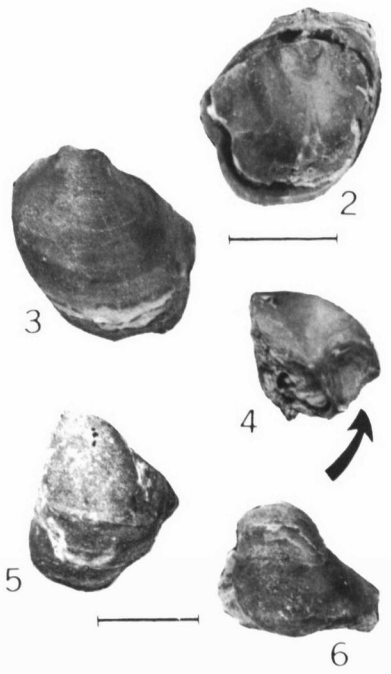


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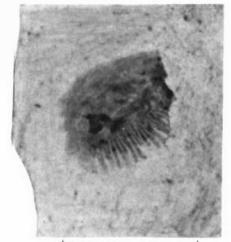
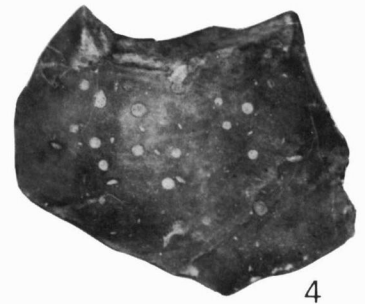


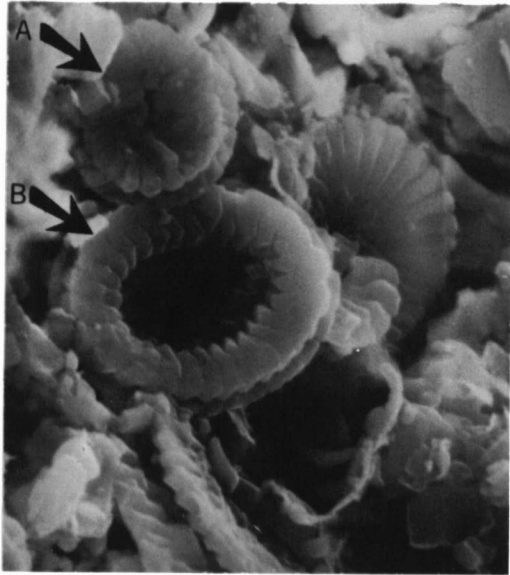
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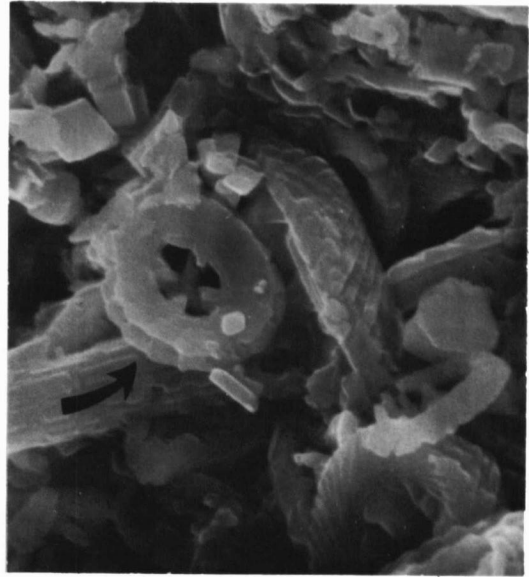
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