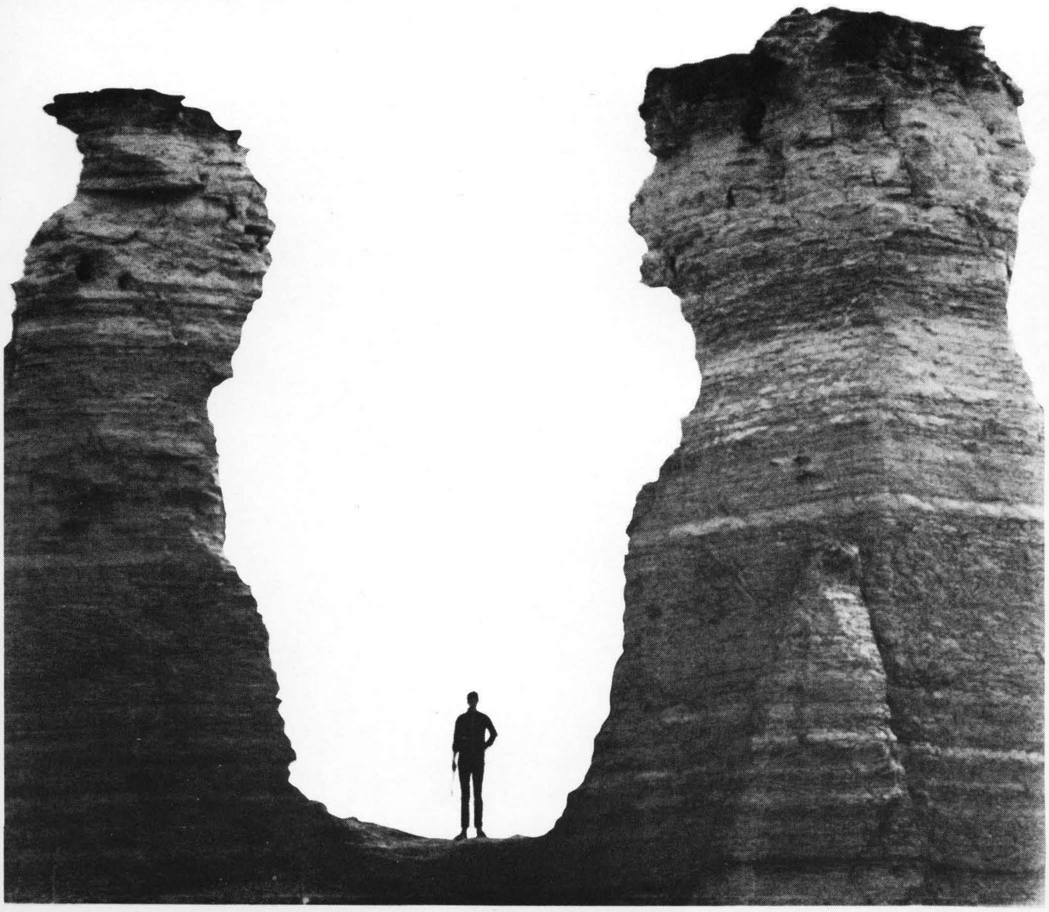
STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT OF SMOKY HILL CHALK MEMBER,

NIOBRARA CHALK (UPPER CRETACEOUS) OF THE TYPE AREA, WESTERN KANSAS



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Stratigraphy and Depositional Environment of Smoky Hill Chalk Member, Niobrara Chalk (Upper Cretaceous) of the Type Area, Western Kansas

By

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EXECUTIVE SUMMARY

For more than a century the Smoky Hill Chalk Member has attracted the attention of scientists studying the fossils of vertebrate and invertebrate animals. The Smoky Hill Member has become famous for the important skeletal remains of fish, sharks, marine reptiles, turtles, birds, and dinosaurs that have been found in the chalk in its badlands. The member is also the natural repository of well-preserved oysters, giant clams, and other shellfish. Specimens from the chalk adorn the halls of museums throughout the world.

Despite its popularity as one of the finest American collecting grounds, the chalk has never been described adequately and a detailed standard section has never been published. This bulletin remedies that lack. An exhaustive summary of the previous literature on the Smoky Hill is presented. The author has studied many exposures of the Smoky Hill Member in Kansas, describing the various kinds of rocks found as well as the fossils. Using these fossils, the member is divided into age zones. Deposits in various locations are correlated with each other.

The Smoky Hill Chalk Member, a portion of the Niobrara Chalk, was deposited in the Western Interior Sea about 80 million years ago in north central Kansas. While the Smoky Hill was being deposited the seawater was relatively deep, slightly less salty than normal, and had a temperature characteristic of mild-temperate to subtropical climates. The sea floor was almost perfectly flat, and the materials being deposited on it were soft and watery. The deposition of this material took place at a rate of approximately 0.036 mm per year. Bottom currents were weak and bottom waters were poor in oxygen. The scene at the bottom of the ocean was dark, monotonous, and hostile to many groups of marine organisms.

Today the Smoky Hill Chalk Member can be seen in bluffs and badlands of the Smoky Hill River drainage basin of Trego, Gove, and Logan counties, Kansas. It is made up mostly of various kinds of chalk, but also contains bentonite, jarosite, pyrite, and chert.

The Smoky Hill Member contains significant reserves of natural gas that formed as a result of the decay of the many organisms that lived in it. These reserves are being exploited currently in northwesternmost Kansas and adjacent parts of the bordering states. Exploration for this valuable energy resource should be enhanced by knowledge of the Smoky Hill Member, the composition and origin of its rocks, the changes that those rocks have undergone with time, and the relationship between deposits in different locations.

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ABSTRACT

Strata of the Smoky Hill Chalk Member (Coniacian-Campanian) are exposed extensively in the type area, where 12 key sections are the basis for a composite section that is 181.8 m (596.3 ft) thick. The member consists mainly of olive gray, well-laminated to nonlaminated, flaky-weathering, fecal-pellet-speckled, impure chalk consisting mostly of foraminiferal pelmicrite with wackestone or, less commonly, packstone texture, and characterized by well-stratified grain fabric. Ubiquitous constituents include micritic matrix, coccolith-rich fecal pellets, planktonic foraminiferal tests, wisps and angular silt-sized grains of black organic matter, skeletal remains of fish, and minute framboids of pyrite or its oxidized equivalent. Sparse grains of angular silt-sized quartz are the only detrital grains detected commonly in thin sections. Scattered through the member are very thin to thick beds of lighter-colored, bioturbated chalk and granular (probably microbioturbated) chalk, which form conspicuous bands on little-weathered exposures. Bioturbated and granular chalks contain the same basic components as stratified chalks, but fecal pellets are less obvious, black organic matter is less abundant, and pyrite framboids are less common in the matrix.

The Smoky Hill composite section contains more than 100 seams of bentonite, which range in thickness to as much as 11.3 cm (0.37 ft). Gypsum, jarosite, and limonite, usually in some combination, are common along weathered seams. Principal clay minerals in the bentonites are kaolinite (dominant) and smectite, and the most common accessory minerals are quartz, gypsum, and calcite.

Diagenetic phenomena of Smoky Hill laminated to nonlaminated chalks include compactional deformation of fecal pellets, foraminifers, sediment-filled burrows, macroinvertebrate remains, and grain fabric around large allochems; incipient microstylolites; dissolution of aragonitic skeletal remains; sparry calcite cement in foraminiferal chambers; interstitial micritic calcite cement; and secondary calcite overgrowths on skeletal remains, especially in matrix portions of the rock. Bioturbated and granular chalks are less well compacted than the well-stratified chalks, and have greater amounts of secondary calcite as interstitial cement and overgrowths on coccoliths. In such chalks, lithification was initiated earlier than in the well-stratified chalks. Bioturbation of these and other Kansas chalk deposits produced textures similar to those ascribed by others to deep-burial diagenesis and solution transfer. Most extensively altered by diagenesis are lenses of *Uintacrinus* limestone, in which skeletal elements have been altered to microsparite and the rock has been microstylolitized.

Several stratigraphic intervals, none more than about 1.5 m (4.9 ft) in thickness, are exceptionally rich in macroinvertebrate skeletal remains, which litter eroded slopes with shelly debris. Lenses of hard, brittle limestone, consisting mainly of *Uintacrinus* skeletal remains, occur sparingly in the zone of *Clioscaphites choteauensis*. Sparse biomicrudite lenses, consisting mainly of inoceramid bivalve debris, occur locally in the lower half of the member.

Bioturbated chalk beds, granular chalk beds, bentonite seams, shelly zones, and organic-rich chalk beds are useful stratigraphic markers. Twenty-three marker units are described in detail, and are indispensable tools for precise determination of stratigraphic position. The Smoky Hill Member contains vast numbers of macroinvertebrate body fossils, but at most horizons diversity is very low. Ammonites, which are the basis for the standard Western Interior zonation of Smoky Hill and equivalent strata elsewhere, are sparse in all but a few intervals, and many of the standard zonal indices have not been recorded in Kansas. The lower half of the composite section contains four easily recognizable zones, namely those of *Inoceramus (Volviceramus) grandis, I. (Cladoceramus) undulatoplicatus, Clioscaphites vermiformis,* and *C. choteauensis.* The upper half of the member contains the single, broadly defined zone of *Inoceramus (Endocostea) balticus.* On the basis of macroinvertebrate fossils and physical correlation (i.e., marker beds) the composite section has been determined to extend from the Upper Coniacian into the Lower Campanian.

Coccolith-rich Smoky Hill muds were deposited on the eastern shelf of the Western Interior Sea. Chalky strata of Kansas grade westward into progressively less calcareous beds, which in the western portion of the ancient seaway are dominated by terrigenous detritus. Stratigraphically upward variations in detrital components reflect varying rates of terrigenous detrital influx from the west. However, the principal component of most Smoky Hill strata is low-magnesium calcite, which consists largely of coccoliths, coccolith debris, coccolith-rich fecal pellets, tests of planktonic foraminifers, interstitial cement, calcite overgrowths on coccoliths, forams and other skeletal remains, and remains of inoceramid and ostreid bivalves.

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On the basis of biotic and physical considerations, depth of Smoky Hill deposition is estimated to have ranged from a minimum of 150 or 200 m (492-656 ft) to a maximum that probably exceeded 300 m (984 ft). What is now Kansas lay in a warm- or mild-temperate climatic zone. During deposition, Smoky Hill muds were mainly soft, perhaps even soupy oozes. Evidence of bottom currents is minimal, and bottom waters were at most times poorly circulated. Although interstitial conditions were largely anoxic, near absence of infaunal suspension feeders was apparently owing mainly to substrate fluidity. Wide lateral persistence of marker beds, coupled with absence of organically constructed banks, scour channels, or wedge-shaped stratigraphic units, is evidence for almost perfectly flat depositional topography. Based on data deriving from remains of pelagic organisms (e.g., low diversity of coccoliths and planktonic foraminifers and paucity of crinoids and ammonoids) the salinity is judged to have been somewhat lower than normal.

Inoceramids, rudists, and conchs of dead cephalopods were the principal substrates for other benthic organisms, such as ostreid bivalves, acrothoracican cirripeds, lepadomorph cirripeds, and clionid sponges. Inoceramids were nearly ubiquitous inhabitants of the sea floor, and manifest a variety of growth forms that reflect adaptation to soft substrates. The numerically predominant ostreid bivalves, represented by as many as four generations on a single host, commonly encrusted all available substrate area, and apparently grew even on the undersides of host inoceramids and rudists. Deposit-feeding organisms, lacking or very sparse in well-stratified chalks, produced bioturbated intervals whenever suitable substrates (i.e., purer chalk beds) were developed. Short intervals of increased circulation fostered proliferation of the macroinvertebrate epibenthos, and produced the present shelly zones in which biotic diversity is greater than normal. Nonfragmented epibenthic macroinvertebrates are preserved in life position, bivalve articulation ratios are high, and assemblages have remarkably uniform composition. These features suggest that Smoky Hill assemblages are true fossil communities. Except for infaunal deposit-feeding worms(?), Smoky Hill benthic macroinvertebrates were exclusively suspension feeders. Exceedingly soft substrates, possibly combined with marginally oxygenated bottom waters, seem the best explanation for absence of infaunal deposit feeders other than worms(?). Slow depositional rates (0.036 mm per year) help to account for the gigantic size of many Smoky Hill inoceramids and heavy encrustation of substrates by epizoans.

The Smoky Hill Member contains significant reserves of biogenic gas, which are being exploited currently in northwesternmost Kansas and adjacent parts of the bordering states. Knowledge of Smoky Hill stratigraphy, petrology, diagenesis, and correlation should enhance exploration for this valuable energy resource.

INTRODUCTION

Statement of the Problem

For more than a century the Smoky Hill Chalk Member has attracted the attention of vertebrate and invertebrate paleontologists. Badlands in the chalk outcrop have yielded important skeletal remains of teleosts, sharks, mosasaurs, plesiosaurs, turtles, pterosaurs, birds, and dinosaurs, which have earned for the Smoky Hill Member a place of enduring fame in the annals of Cretaceous marine paleontology. Aside from spectacular articulated vertebrate fossils, the member is also the natural repository of well-preserved rudists, crinoids, oysters, cirripeds, cephalopods, and giant clams. Specimens from the chalk adorn the halls of museums throughout the world.

Despite popularity as one of the premier American collecting grounds, the chalk has never been described adequately and a detailed standard section has never been published. Indeed, most descriptions of Smoky Hill fossils lack useful stratigraphic information. This deficiency stems from the fact that the member is exposed discontinuously, individual sections span only a small fraction of the full thickness, at first inspection the member appears to be monotonous stratigraphically, and few workers have attempted to determine the exact stratigraphic position of collected specimens.

In this report, I have documented a composite stratigraphic section, which will serve as a reference section for the type area. The lithology, petrology, and biostratigraphy are treated in detail, and the paleoecology and depositional history are interpreted on the basis of extensive field and laboratory documentation. Most importantly, the report includes a detailed graphic section (Pl. 1) of the Smoky Hill, based on exposures in Trego, Gove, and Logan counties, Kansas (Fig. 1), and includes descriptions of useful marker beds. These descriptions should make possible the accurate determination of the stratigraphic positions from which fossils and lithologic samples may be collected. Such treatment is especially timely in light of recent interest in chalk deposits as reservoirs for oil and natural gas.

Previous Investigations

Kansas geological literature is filled with references to the Niobrara Chalk in general and to the Smoky Hill Member and its fauna in particular. Many of the papers contain trivial mention of the Smoky Hill or add little to understanding of the stratigraphy or paleontology of the unit. Only papers judged to contain significant additions to knowledge of the member are reviewed. No attempt is made to include summaries of the numerous articles that are concerned with vertebrate paleontology, although the principal contributors are named.

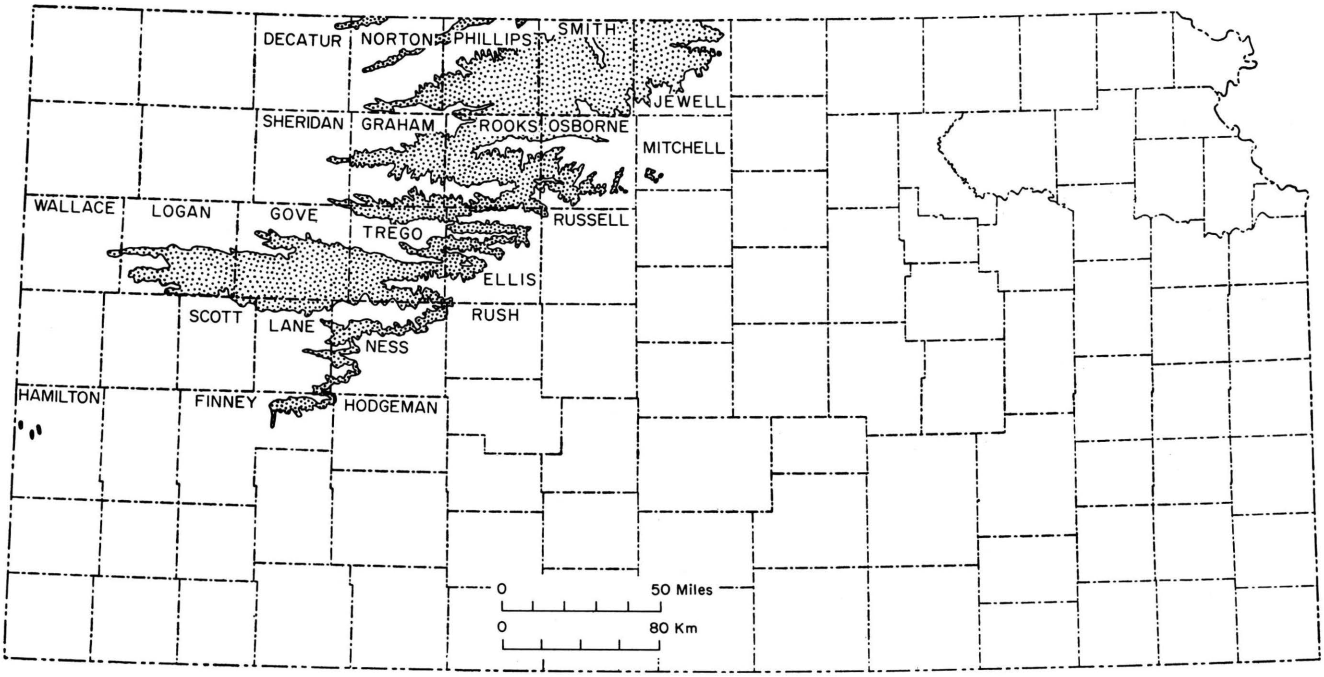


FIGURE 1. Map of Kansas showing outcrop (stippled) of Niobrara Chalk.

The earliest good description of the Smoky Hill Member is that of Engelmann (1858, p. 497, 498), whose investigations of Cretaceous strata along the Republican River included study of chalk beds shortly north of the Kansas-Nebraska border. He recorded the familiar upward gradation from dark- to light-colored chalk and opined that the white spots characterizing this chalk are "the exuviae of microscopic animals." Seventy-two years elapsed before these spots were mentioned by another worker. In the same year, Hayden (1858) published the first colored geological map of Kansas that included the Smoky Hill outcrop, but the Cretaceous was divided into only two map units, namely No. 1 (Dakota) and Nos. 2-3 (Benton plus Niobrara).

Despite clear recognition of the Kansas Niobrara before 1860, the first annual report on the geology of Kansas (Mudge, 1866, p. 10) states of the Cretaceous only that "chalk is said to have been found in it." All doubt about the existence in Kansas of Niobrara strata is dispelled in the report of LeConte (1868), in which the section of Smoky Hill strata exposed at Castle Rock (Gove County) and the upward gradation from gray beds to yellow beds that occurs along much of the Smoky Hill River Valley are described. LeConte's report also mentions occurrence of *Ostrea congesta* Conrad in the chalk. The distinction between a lower, dark-colored, usually thinner-bedded rock and an upper, yellow, more thickly bedded chalk was made also by Cope (1872, p. 325), who included a rhetorical essay on life in the sea during Niobrara deposition. His paper includes the earliest detailed account of Niobrara vertebrate fossils, and brief mention is made of bivalves, including a description of *Haploscapha grandis* Conrad (= *Inoceramus (Volviceramus) grandis* of this report) by Conrad. A short, more generalized account of the Niobrara, concentrating on the variety and preservation of vertebrate remains but also mentioning the abundance of oysters and inoceramids, was furnished by Mudge (1875). The first microscopical study of chalk from the Kansas Niobrara was by Patrick (1875, p. 14), who noted the absence of microscopic organic remains and therefore pronounced the chalk a product of chemical precipitation. In the following year, Grinnell (1876) described the remarkable crinoid *Uintacrinus socialis,* which was first discovered in the Uinta Mountains but which, he noted, occurs also in Kansas strata now referred to the Smoky Hill Member. Shortly thereafter a supplementary description of Kansas specimens was published by Meek (1876).

Division of the Niobrara into members was first attempted by Mudge (1876). He gave the name "Niobrara proper" to beds now referred to the Smoky Hill Chalk Member. These strata are described in some detail, a thickness of 200 feet (61 m) is reported for Rooks County, and a discussion of fossils is included. He mentions occurrence of *Ostrea congesta,* a large undescribed bivalve (= *Inoceramus (Platyceramus) platinus*), and the presence of large rudists. This paper includes extensive comments on vertebrate fossils of the Smoky Hill Member. Expanded (but nearly identical) versions of this paper were published in subsequent years (Mudge, 1877,

1878) and include additional notes on Niobrara fossils. The latter (Mudge, 1878) includes the earliest illustration of the famous Monument Rocks of Gove County and the first crude graphic section that includes the Cretaceous section in Kansas.

Among the many early generalized accounts of the Niobrara, those of Hay (1885, 1889) are of especial interest because the 1885 paper includes the earliest description of replacement of weathered chalk by chert and the 1889 paper includes the first illustrations of Smoky Hill chalk that were made from photographs, including one of Castle Rock in Gove County. Also included in the latter paper is first mention of the fact that a large *Inoceramus* (=*I. (Platyceramus) platinus*) "is invariably covered by colonies of the small oyster, *Ostrea congesta.*"

In a second article on microscopy of the Kansas chalk, Patrick (1883) credits a student, W. S. Bunn, with discovery of protozoan remains. He describes and illustrates several of these microscopic forms, which are, in fact, coccoliths. Several years later Williston (1890a, p. 249) reported that the chalk is composed almost wholly of coccoliths and rods, like those of the English Chalk, but that the sea was not deep because the Niobrara contains thick-shelled, and hence shallow-water, fossils such as *Inoceramus* and *Rudistes.* This article was followed shortly by another in which Williston (1890b) notes apologetically that W. S. Bunn was the first to discover coccoliths in the Kansas chalk. Dawson (1890, p. 276) hastened to point out that the Niobrara of Manitoba and Nebraska also contains abundant coccoliths, which are associated with foraminifers and rhabdoliths, and that he (Dawson, 1874) had described and illustrated these many years earlier.

Williston (1893) summarized briefly the history of investigations in the Kansas chalk country, and estimated the thickness of the Niobrara to be at least 430 feet (130 m), a figure which is far greater than had been supposed earlier. In this paper he correctly gives the dip of the chalk beds as north or northeast. Williston (p. 110) recorded for the first time the general stratigraphic distribution of invertebrate and vertebrate fossils and from his observations concluded that the sea became more shallow and the shorelines closer to western Kansas as deposition proceeded. He correctly ascribed the occurrence of *Uintacrinus socialis* to a stratigraphic position near the middle of the chalk sequence. A new and different classification of the Kansas Cretaceous was presented by Cragin (1896), who introduced several new names for units that were defined on lithologic criteria. The Niobrara was divided into Osborne Limestone, a name never adopted because the name "Fort Hays" had priority, and Smoky Hill Chalk. Although the name "Smoky Hill Chalk" is still in use in the sense of Cragin, Williston (1896) deplored Cragin's terminology, favoring instead the term "Pteranodon beds."

The first definitive descriptions of rock-stratigraphic units throughout the Kansas Cretaceous are by Logan (1897a). He reported (p. 220) a thickness of more than 300 feet (91 m) for "the Pteranodon beds, or Smoky Hill Chalk" and was first to note that the light-colored chalks are merely the weathered equivalent of the darker-colored, freshly exposed chalk. Logan also recorded the laminated appearance of some chalk beds and the abundance of chert that occurs in the upper part of the Smoky Hill at Norton, Kansas. In the same volume, Williston (1897) described the Niobrara, and especially the Smoky Hill Chalk, in considerable detail, covering such topics as subdivisions, thickness, structure, lithology, weathering of blue chalk to form the yellow chalk, erosional features and rates of erosion, invertebrate fauna, and vertebrate fossils. In this paper, first notice is given of numerous folds and faults that affected the formation. He mentions the great abundance of *Ostrea congesta,* the limitation of *Haploscapha grandis* to lower beds of the Smoky Hill, and the great size ("forty four by forty six or eight inches") of the thin-shelled inoceramid known today as *Inoceramus (Platyceramus) platinus* (Logan). Williston states erroneously that rudists occur only in the lower part of the Smoky Hill Member and correctly that ammonoids are represented almost exclusively by impressions. This paper includes first mention of Smoky Hill belemnites, which are said to be very sparse; a brief description of dibranchiates; and notice of a new cirriped species, *Pollicipes haworthi* (=*Stramentum haworthi* (Williston) of the present paper). This important contribution, the most significant concerning the Smoky Hill Member to that date, also includes a summary of Niobrara vertebrates and their distribution.

In an introductory chapter of Kansas University Geological Survey Volume IV, Adams (1898) presented an historical account of studies concerning Upper Cretaceous strata of the State. This work is highlighted by a tabular summary of stratigraphic nomenclature that is modified and updated in Table 1 of the present report.

The last decade of the nineteenth century brought forth a flurry of scientific articles concerned with description of Kansas Upper Cretaceous fossils. During the years 1894 through 1901, numerous papers were concerned with additional discoveries and description of the crinoid *Uintacrinus socialis* Grinnell. Among the most important of these is that of Bather (1896), who summarized the history of discoveries and study, presented a very detailed description based on Logan County slabs in the British Museum Collection, and mentioned briefly the pelagic, free-swimming nature of these creatures. The definitive study, however, is that of Springer (1901), whose monograph includes discussion of collecting localities, stratigraphic horizons, mode of preservation, life habits, and systematic description. Additional features of the species were described by Martin (1908).

Up to 1897, only a few valid species of Smoky Hill macroinvertebrates had been described on the basis of Kansas material. These include *Uintacrinus socialis* (Grinnell), *Stramentum haworthi* (Williston), and *Inoceramus (Volviceramus) grandis* (Conrad). This list was expanded by Logan (1897b), who described species of the cirriped genera *Stramentum* and *Squama* and later (1898) monographed the known macroinvertebrates of the member in the classic, but outdated, Volume IV of the Kansas University Geological Survey. In this work, six new Smoky Hill species are described, of which only *Inoceramus (Platyceramus) platinus* (Logan), *Durania maxima* (Logan), and *Tusoteuthis longa* Logan appear valid. In this same volume are descriptions by McClung (1898) of chalk foraminifera and coccoliths, and first mention of the calcite that fills chambers of most Smoky Hill foraminifers. McClung notes (p. 426) that, aside from color, the Smoky Hill chalks "differ but little from the true English chalk." Only one new species of foraminifer is described. Further additions to the Smoky Hill invertebrate fauna appear in articles by Logan (1899a,b) in which a total of seven new species of *Ostrea* and the new genus *Pseudoperna,* with four new species, are described. Although the genus *Pseudoperna* is regarded as valid by Stenzel (1971), only two of these 11 new species, *O. rugosa* and *O. exogyroides,* have been accorded validity by later workers. In his final paper concerned with Cretaceous strata of Kansas, Logan (1899c) correlated the Pteranodon beds (= Smoky Hill Member) with the upper 125 feet (38 m) of the Apishapa beds of the Colorado Niobrara. In this work, he drew attention to the mollusk-bored wood, amber, charcoal, and pyrite nodules of the Smoky Hill beds.

A review of nineteenth century Smoky Hill vertebrate studies is beyond the scope of this report. Literature on the subject is very large and no summary is attempted here. A list of principal workers is sufficient, and particular works can be identified in the standard geological bibliographies. Among the more important contributors to knowledge of the vast Smoky Hill vertebrate fossil resources are E. D. Cope, Joseph Leidy, O. C. Marsh, S. W. Williston, and Alban Stewart.

During the first two decades of the twentieth century, the Smoky Hill Member of Kansas received scant attention, aside from papers concerning vertebrate paleontology. Renewed study of the Niobrara coincided largely with petroleum exploration efforts in the Great Plains, and during the next two decades (twenties and thirties) much effort was focused on the area of Smoky Hill outcrop. Description of Smoky Hill surface structure, especially in the type area, is included in a paper by Lupton and others (1922), who mentioned numerous anticlines and faults that characterize the chalk beds. Methods for mapping these structures were challenged by Twenhofel (1925), who believed the true structure differs considerably from that mapped, and who postulated differential compaction of underlying Dakota, Graneros, and Carlile shales as the principal cause of anomalous dips and faults in the chalk. Russell (1929) disagreed with the differential compaction hypothesis, favoring instead the development of these features by structural forces originating in the crust, with faults supposedly resulting from tensional adjustments associated with major north-south folds. The origin of faults in the Niobrara is treated at length by Rubey and Bass (1925), who also discussed the origin of folds in Late Cretaceous strata of the region.

The year 1925 marked the beginning of a period during which geologic maps and detailed reports of several counties that embrace parts of the Smoky Hill outcrop were published. Details of stratigraphy and paleontology are included in Kansas Geological Survey bulletins on Russell County (Rubey and Bass, 1925), Ellis County (Bass, 1926), Hamilton County (Bass, 1926), Mitchell and Osborne counties (Landes and Ockerman, 1930), Wallace County (Elias, 1931), and Ness and Hodgeman counties (Moss, 1932). None of these bulletins includes a description of a complete section of the Smoky Hill Member, but details of the unit prepared by Bass (1926), Elias (1931), and Moss (1932) are most noteworthy.

Bass (1926) demonstrated the utility of bentonitic clay layers and chalk layers of differing hardness as a tool for detailed physical correlation within the lower part of the unit. Lithologic character of the Smoky Hill bentonite seams was described by Pinkley and Roth (1928), who noted the nearly uniform spacing of seams and suggested their usefulness in structural mapping and precise correlation of strata. A complete measured section of the Smoky Hill, based on surface sections, was published by Russell (1929), and groups of distinctive bentonites, each designated by a letter, were defined as key intervals for detailed correlation. However, Russell's section lacks lithologic detail, includes several intervals for which no data are given, and is on a scale that greatly limits its utility. Furthermore, many of the useful markers, other than bentonites, are not mentioned. Russell (1929, p. 603) emphasized the errors in stratigraphic measurement that can result from improper understanding of local structural relationships in the formation.

General features of Cretaceous stratigraphy and surface structure on a county-by-county basis are incorporated in a summary of western Kansas oil and gas resources by Ver Wiebe (1938) and Niobrara stratigraphy and surface structure are discussed in somewhat greater detail in a later oil and gas resources report concerned specifically with Logan, Gove, and Trego counties (Landes and Keroher, 1939).

In 1937, a program of cooperative groundwater investigations in Kansas was initiated by the Kansas Geological Survey and the U. S. Geological Survey. A long and continuing series of Kansas Geological Survey bulletins, most of which treat the geology and groundwater resources of individual counties, has resulted from this effort. Several of these bulletins are concerned with counties lying at least partly within the Smoky Hill outcrop and three, by Johnson (1958), Hodson and Wahl (1960), and Hodson (1965), cover Logan, Gove, and Trego counties, respectively. These bulletins contain brief descriptions of the Smoky Hill Member and are accompanied by useful maps.

For several years, beginning in 1947, the U. S. Geological Survey issued a series of circulars concerned with evaluation of construction materials of Kansas counties. Several of these circulars contain information on counties lying at least partly in the Smoky Hill outcrop, including generalized stratigraphic descriptions of the member, representative measured sections, and use of the rock for such purposes as road metal, riprap, calcareous binder, and structural stone. The Smoky Hill type area is treated specifically in circulars by Byrne and others (1947, 1949).

More recent studies of Smoky Hill invertebrate paleontology began with the work of Withers (1926), who described a new species of cirriped, *Calantica (Titanolepas) martini,* from Gove County. Morrow (1934, 1935) recorded foraminifers and cephalopods of the member and described one new foraminiferal species. Comprehensive treatment of the Colorado Group invertebrates, including those from the Smoky Hill, are included in an unpublished Ph.D. thesis by Morrow (1941). A more thorough investigation of Niobrara foraminifers was conducted by Loetterle (1937), who recorded 14 species, four of them new, in the Smoky Hill. More recently, Frerichs and Dring (1981) described stratigraphic occurrence of approximately 36 species of planktonic foraminifers from eight exposures of the Smoky Hill Member in Trego, Gove, and Logan counties. Although their sections are purported to comprise a composite section, two of the sections are almost identical and significant thicknesses of the member are not represented. Furthermore, their Orion, Gove, and Chalk Butte sections do not crop out at localities designated on the map that accompanies their paper. Fossil pearls from the Smoky Hill Member have been described in detail by Brown (1940) and are attributed to the genus *Inoceramus.* Fischer and Fay (1953) describe a new species of ammonite operculum, *Spinaptychus sternbergi,* more recently interpreted as a jaw apparatus, several specimens of which were collected from the member by the late George F. Sternberg. Smoky Hill coleoid cephalopods, including belemnoids and teuthids, have attracted considerable attention in recent years, and several papers (Jeletzky, 1955, 1961; Miller, 1957a,b; Miller and Walker, 1968; Green, 1974, 1977) have resulted from studies of these cephalopods. Locality data for the crinoid *Uintacrinus socialis* have been well documented in a paper by Miller and others (1957). This work is of especial importance because crinoid-rich slabs, such as seen in museums, are now exceedingly hard to locate in the field. Extensive stratigraphic and paleontologic work on the Niobrara by Miller (1958) resulted in a doctoral dissertation, parts of which were published in a work (Miller, 1968) that includes description of the Smoky Hill macroinvertebrate fossils known to date. This important paper contains the description of a new species of *Pecten.* Additional data on the Niobrara invertebrates, including new records of Smoky Hill fossils, were published subsequently by Miller (1969). Diachroneity of chalky limestone and chalk in the lower part of the Niobrara was demonstrated by the author (Hattin, 1975a) in a paper that documents occurrence of *I. (Volviceramus) grandis,* a typical lower Smoky Hill species, in Smoky Hill strata of Kansas but near the base of the Fort Hays Limestone Member in northeastern Nebraska. Most recently, I (1977a) have discussed and illustrated Smoky Hill stramentid cirripeds, re-evaluated the family Stramentidae, and suggested that the Smoky Hill genus *Squama* is not valid.

Macroinvertebrate paleontology and stratigraphy of the Niobrara has been described comprehensively by Scott and Cobban (1964) in a work concerned with the excellent section exposed along the Arkansas River at Pueblo, Colorado. Although not treating Kansas strata or fossils specifically, this work is a major contribution to knowledge of the Smoky Hill and deserves special mention here.

Correlation of Kansas Cretaceous formations with other units of the Western Interior Region is presented in the classic paper by Cobban and Reeside (1952). Subsurface correlation of Cretaceous units in Kansas is depicted in several cross sections prepared by Merriam (1957).

Maps showing thickness and general character of Cretaceous deposits in the U. S. Western Interior were prepared by Reeside (1944) and include a thickness map for the Niobrara and equivalent strata. Reeside (1957) also prepared a series of lithofacies maps for each of several Cretaceous time intervals, including that of the Smoky Hill, to accompany a text in which broad outlines of depositional environment and paleoecology are discussed. In an important work that summarizes the geologic history of Kansas, Merriam (1963) has included a brief description of the Smoky Hill, has incorporated several photographs of erosional features in the chalk, and has also presented a structure contour map based on the top of the Niobrara and an isopachous map of the entire formation. Specific features of Smoky Hill paleoecology and depositional environment are included in a series of field trip guidebooks prepared in connection with meetings of the Geological Society of America, North American Paleontological Convention II, and AAPG-SEPM (Hattin, 1965, 1977b; Hattin and Siemers, 1978).

Until recently, few papers were devoted to petrologic investigations of the Smoky Hill chalk. A few photomicrographs were included by Miller (1968) in his major published work on the Niobrara invertebrate fauna. Scanning electron micrographs of samples from the Smoky Hill Member of Kansas are included in general studies of chalk diagenesis by Neugebauer (1973, 1974, 1975a,b). Petrologic character and origin of coccolith-rich Smoky Hill fecal pellets are analyzed in a recent work by the author (Hattin, 1975b), who included photomicrographs and scanning electron micrographs of pellets and enclosing chalk matrix. In an excellent synthesis of chalk diagenesis, Scholle (1977) included discussion of the Niobrara Chalk, especially the Fort Hays Member, and concluded that slight cementation is owing principally to relatively shallow burial depths. Petrologic and physical properties of the gas-producing Beecher Island zone of the Smoky Hill Member have been described and illustrated by Lockridge and Scholle (1978) in a paper concerned with Niobrara gas in northeastern Colorado and northwestern Kansas. Neugebauer (1978a) has presented a thorough analysis of diagenesis in the thin lenses of *Uintacrinus* limestone, including micritization by dissolution, compaction, and cementation. In a subsequent paper, Neugebauer (1978b) addresses the problem of inoceramid bivalve preservation in chalk deposits, including the Niobrara, although he does not specify whether or not any of the studied specimens are from the Smoky Hill Member. Additionally, Neugebauer and Ruhrmann (1978) have studied the syntaxial overgrowth of diagenetic calcite on echinoderms and included an illustration of such calcite in the stereom of a Smoky Hill *Uintacrinus* specimen. I (Hattin, 1981) have undertaken a comprehensive analysis of Smoky Hill chalk petrology and origin, which is based on samples from throughout the member and differentiates several varieties of carbonate rock within the section.

Except for diagenetic studies of Smoky Hill chalk cited above, geochemical studies of the unit are few indeed. Amino acid composition of fish, bivalve, and cephalopod remains has been reported by Matter and Miller (1972), who also noted organic content of gray, presumably little weathered, chalk as great as 5.6 percent. Honjo and Tabuchi (1970) report the minor element composition of a large series (73) of Smoky Hill chalk samples, but unfortunately their work does not contain any discussion or conclusions of analytical results, and a promised sequel apparently has yet to be published. Most importantly, Arthur and others (1981) have presented (poster session) a detailed environmental analysis of the Colorado and Kansas Niobrara that is based largely on isotopic analysis of the chalk.

The current gas play in Smoky Hill strata of northeastern Colorado, southwestern Nebraska, and northwestern Kansas has been mentioned in several recent issues of scientific and trade journals. Characteristics and biogenic origin of the Niobrara gas have been discussed by Rice and Claypool (1981, p. 14). Finally, Hann (1981) has presented a stratigraphic analysis of the Niobrara Formation in the Denver Basin, with especial emphasis on petroleum potential. Her work contains numerous references to the Kansas section and includes a useful regional correlation chart.

Location and Description of the Area

Geography. In Kansas the principal Niobrara outcrop trends almost exactly northeastward from its southern terminus in north-central Finney County to the Nebraska border in northeastern Jewell County. This outcrop is 306 km (190 mi) in length along its eastern edge and reaches maximum width, measured normal to the northeasterly trend, of approximately 97 km (60 mi) on a line extending from south-central Osborne County to west-central Phillips County (Fig. 1). In places the Niobrara outcrop is less than 0.4 km (¼ mi) in width. From the main part of the outcrop, major westward extensions of the formation occur along drainage systems of the Smoky Hill River, Saline River, and the north and south forks of the Solomon River. In Smoky Hill River country, the outcrop extends almost without interruption for a distance of 196 km (122 mi) adjacent to a line at 30° 52′ north latitude, from a point shortly southwest of Hays Kansas, to a point situated in east central Wallace County (Fig. 1). Southwest of the main outcrop, in Hamilton County, the Niobrara crops out as small inliers along south-flowing intermittent streams tributary to the Arkansas River. The formation also crops out along Sappa Creek, in Decatur and Norton counties, and along Prairie Dog Creek in Norton and Phillips counties, as southwestward extensions of the Nebraska Niobrara outcrop (Fig. 1). Altogether, the Niobrara crops out in parts of 23 Kansas counties (Fig. 1).

Natural exposures of the Niobrara Chalk are too abundant to enumerate fully. The best known and most-visited exposures are along the valley of the Smoky Hill River and its tributaries, but excellent exposures occur also along the Saline River, both forks of the Solomon River, and along White Rock Creek in Jewell County. Construction of roads, especially those running north-south, has in many places produced excellent artificial exposures, especially of the Fort Hays Limestone Member.

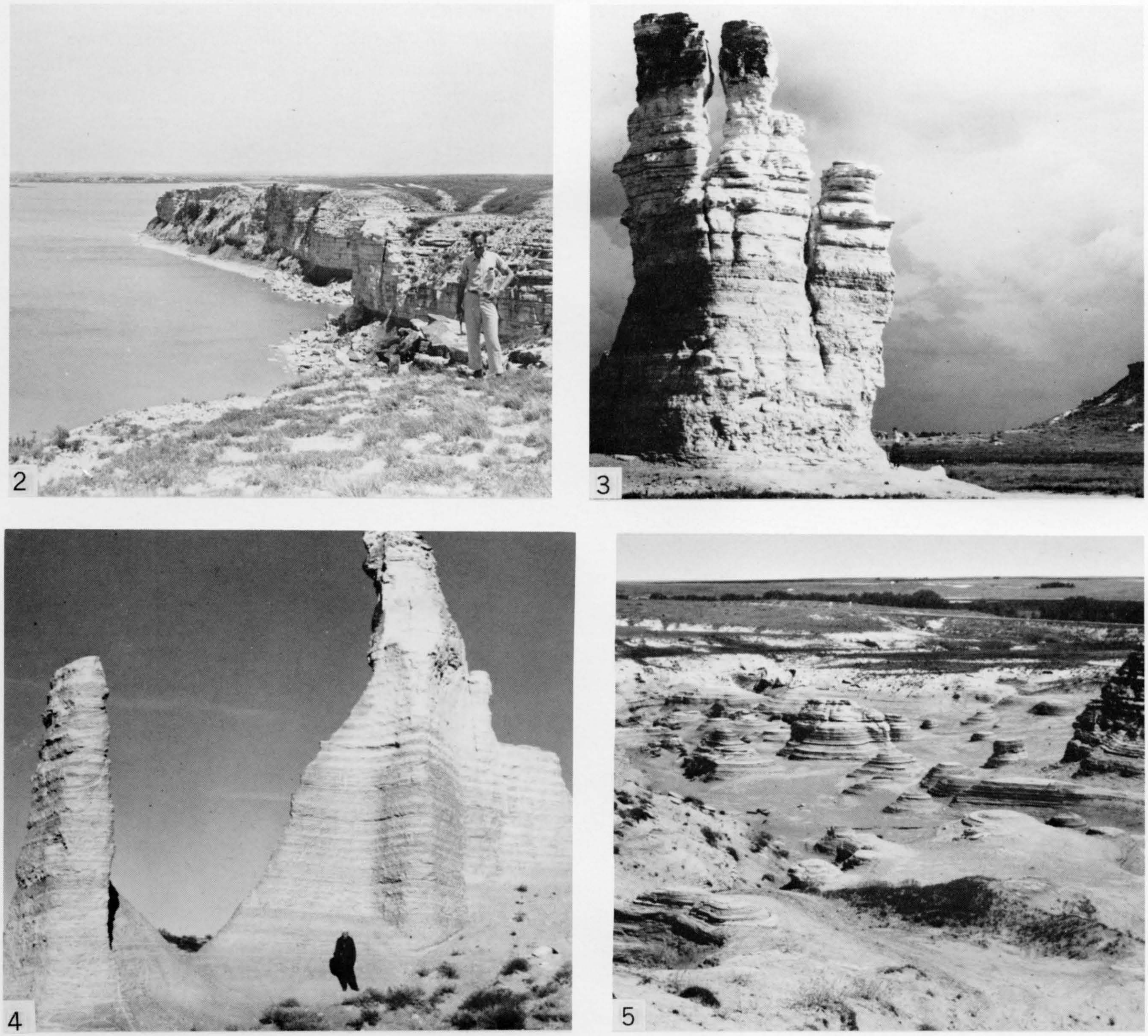
Along the Smoky Hill River and its tributaries topography includes broad, gently sloping outer valley walls (flanking pediments), steep bluffs and cliffs held up by the Niobrara Chalk, and nearly flat to extensively dissected uplands. Hilly terrain developed adjacent to water courses is devoted almost exclusively to cattle ranching. Level bottom land, upland surfaces, and gently sloped flanking pediments are mostly farmed. Wheat is the principal grain crop; sorghum is second in importance. Minor grain crops include corn, oats, barley, and rye. Hay and alfalfa are grown extensively. Except for cottonwood and willow, which are distributed patchily along most water courses, and a variety of juniper (''cedar'' of local parlance) that ocurs here and there along chalky cliffs overlooking Smoky Hill River and its tributaries, the region is largely treeless, and sweeping vistas are afforded from edges of the upland surface.

Erosion of the Niobrara has produced rock pinnacles, monuments, badlands and cliffs, which create fascinating scenery through much of the Smoky Hill drainage area (Figs. 2-5). Notable landmarks are Cedar Bluff, Trego County (Fig. 2); Wildcat Canyon (Sec. 16, T.14S, R.25W, Trego County); Castle Rock, Gove County (Fig. 3); Little Castle Rock (Sec. 17, T.15S, R. 26W, Gove County); Monument Rocks and the Sphinx (Secs. 33 and 34, T.14S, R.31W, Gove County); Chalk Bluff, Logan County (Fig. 4); Little Pyramids (Secs. 11 and 14, T.15S, R.33W, Logan County); and Goblin Hollow, Logan County (Fig. 5). This listing is not meant to detract from the very large number of other erosional features, including many unnamed cliff and badland areas, which afford so much delight to visitors.

General Geology. The Niobrara Chalk has long been classified as part of the Colorado Group, which in Kansas is subdivided as shown in Figure 6. Throughout the Kansas outcrop, Niobrara strata lie disconformably on the Carlile Shale (Hattin, 1975a). In the upper reaches of the Smoky Hill River, and locally along Prairie Dog Creek in northwestern Phillips County, the formation is overlain conformably by the Sharon Springs Member of the Pierre Shale. Elsewhere the Niobrara is overlain disconformably by the Ogallala Formation (Miocene and Pliocene) at a contact that truncates the formation from west to east, or by unconsolidated Quaternary deposits. The main part of the Niobrara outcrop lies in north-central and western Kansas, and underlies the eastern edge of the High Plains physiographic province (Schoewe, 1949, p. 276). The eastern edge of this province is marked by the Fort Hays (or Niobrara) escarpment, which is a bold topographic feature (Fig. 2) along major streams but has only subdued relief in interstream areas. The regional trend of this escarpment is nearly northeast, with major invaginations at each major stream where cliffs held up by the Fort Hays Member extend for many miles upstream in a generally westward direction. The escarpment is especially prominent along the Saline River in northern Ellis County and the Smoky Hill River in Trego County. Maximum relief along the escarpment is along the Saline River, where local relief is approximately 91 m (300 ft) in the Bemis-Shutts oil field area. Along the Smoky Hill River local relief is a maximum of 61 m (200 ft) in southeastern Trego County, near Cedar Bluff Dam. East of the main escarpment prominent buttes and mesas, capped by outliers of the Niobrara, are scattered along the area of Carlile Shale outcrop. Especially noteworthy are the Blue Hills of southwestern Mitchell County and a large number of similar hills in southeastern Osborne County.

In the type area the Smoky Hill Member contains few beds with erosional resistance that matches that of the Fort Hays Member. A group of bioturbated limestone beds, lying approximately 25 m (85 ft) above the base of the Smoky Hill, forms conspicuous low cliffs along Hackberry Creek and the Smoky Hill River in western Trego County. A thick unit of nearly massive chalk, lying 88.5 m (290 ft) above the base, forms the prominent caprock at Castle Rock (Fig. 3) and Monument Rocks in Gove County and is the caprock at Little Pyramids and Chalk Bluff (Fig. 4) in Logan County. These more resistant beds are scarcely evident in little-weathered exposures but form benches and overhanging, lichen-splotched ledges where highly weathered. A similar unit of nearly massive chalk lies near the top of the Smoky Hill elsewhere in Logan County but is less well exposed than that forming caprock on familiar landmarks of Smoky Hill River country. These major, resistant units correlate physically with the lower limestone unit and with the middle and upper chalk units, respectively, of the section at Pueblo, Colorado (Scott and Cobban, 1964). Numerous thinner, apparently bioturbated beds of tough chalk, which occur primarily in the upper half of the member, also form caprocks on erosional features, but on a much smaller scale.

Full thickness of the Smoky Hill is not exposed at any one locality in Kansas; rather, the section must be pieced from numerous exposures scattered across the outcrop. Mostly gentle dips, limited stratigraphic extent of individual exposures, mostly gentle topography, and locally extensive faulting make measurement of complete sections a major task. Composite sections of the entire Smoky Hill have been compiled only for Graham County (Virgil Cole, oral communication, 1962) and along the Smoky Hill River and its tributaries in southwestern Trego, Gove, and Logan counties. The latter comprises the type area of the Smoky Hill Member and the section exposed therein comprises the basis for this report.



FIGURES 2-5. **2,** Cedar Bluff and Cedar Bluff Reservoir, looking east from Sec. 6, T.15S, R.22W, Trego County, Kansas. The cliff is developed along a westward reentrant of the Fort Hays escarpment, and is held up by the Fort Hays Member, Niobrara Chalk. **3,** Famous exposure of Smoky Hill Member at Castle Rock, in Sec. 1, T.14S, R.26W, Gove County, Kansas. Note prominent caprock-forming unit at top of two pinnacles at left. **4,** Erosional pinnacles at Chalk Bluff, Sec. 25, T.14S, R.33W, Logan County, Kansas. Note caprock-forming unit at top of taller pinnacle. **5,** Exposure of Smoky Hill chalk at Goblin Hollow, Sec. 27, T.13S, R.35W, Logan County, Kansas.

The Smoky Hill composite section described here is based on natural exposures consisting of cliffs and badlands along the Smoky Hill River and several of its named and unnamed tributaries. At each of three localities (Pl. 1, Locs. 13, 19, 23), approximately 29 m (95 ft) of section were measured, but such extensive exposures are not numerous. Along Hackberry Creek (Pl. 1, Loc. 1) a section including the Fort Hays and lower part of the Smoky Hill Member is 38.3 m (125.6 ft) thick. This is apparently the thickest continuously exposed Niobrara Chalk section in the State.

In the Smoky Hill River area, structure at the base of the Niobrara is essentially a north to northeastwardly dipping homocline, with dip of approximately 3.5 m (11.7 ft) per kilometer to the northeast in Logan County, and approximately 2.3 m (7.3 ft) per kilometer slightly east of north in Gove County (based on Merriam, 1963, fig. 108). Anomalous dips occur locally, where small domal and anticlinal structures are reflected at the surface in Niobrara strata. Greatest reported concentration of these features is along the Smoky Hill River and its tributaries in Gove and Logan counties, where Lupton

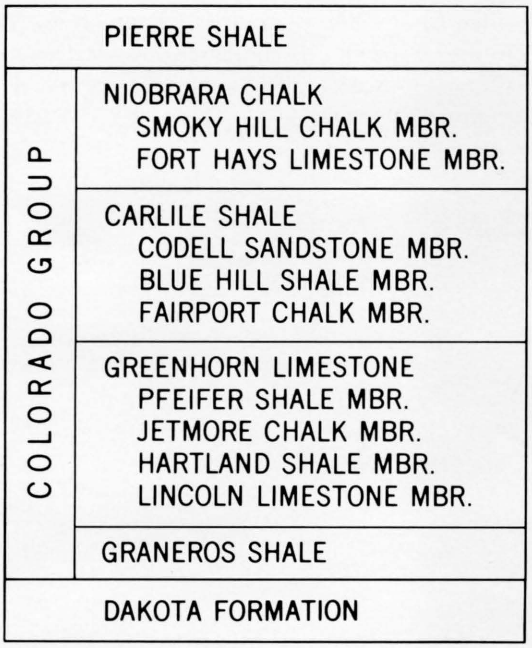


FIGURE 6. Stratigraphic classification of Upper Cretaceous rocks in west-central Kansas.

and others (1922) identified 18 structures of which at least eight are closed, with closure ranging from 15.2 m to 45.7 m (50-150 ft). In an analysis of some such features Twenhofel (1925, p. 1066) concluded that methods used to map several of these structures were inaccurate and the true structure bears little resemblance to that shown on maps.

Anomalous dips in Smoky Hill strata also occur adjacent to normal faults (Fig. 7), which have been recorded in abundance throughout the outcrop (e.g., Johnson, 1958, p. 30; Bass, 1926, p. 44; Prescott, 1955, p. 47). Although most of the faults are only a few hundred meters in length and involve little stratigraphic displacement, Johnson (1958, p. 30) mapped one Logan County fault that is 5.6 km (3.5 mi) long and believed that some fault displacements may be as much as 61 m (200 ft). In the field these faults are recognized readily, not only because of anomalous dips in adjacent strata (Fig. 7) and obvious stratigraphic displacement, but also because most are marked by masses of slickensided calcite, which litter the ground adjacent to faults or hold up elevated ridges along fault traces owing to differential erosion. Origin of these faults is uncertain but their erratic pattern and irregular distribution seem unrelated to regional structure. At a single elevation above sea level, chalk on either side of a fault may be weathered to greatly differing degrees, suggesting that faulting occurred after an episode of extensive weathering and that erosion later stripped the resulting much-weathered rock from the upthrown block, leaving only less-weathered rock situated beside highly weathered chalk of the downdropped block.

Chalk of the Smoky Hill Member has been quarried in many places for use as building stone (Risser, 1960, p. 89). Rock from the Smoky Hill has been used also for the manufacture of whiting. Smoky Hill strata have relatively low permeability and the unit is generally unsatisfactory as an aquifer. In the past quarter century the Smoky Hill has become a target for natural-gas drillers. Merriam (1958, p. 138) noted gas production from the basal Pierre and upper part of the Smoky Hill in the Goodland field (discovered 1938) at a depth of 1100 feet (335 m). Details of the productive horizon, the Beecher Island zone, which actually lies shortly beneath the Smoky Hill-Pierre contact, have been presented by Lockridge and Scholle (1978). The producing interval is approximately 6 to 15 m (20-50 ft) thick and has low permeability, but shallow depths and good prices have initiated a fair-sized play in the area. Additional note of this play, and its spread into northwestern Kansas, is made by Harris and Larsh (1979, p. 342).

In the Smoky Hill drainage basin, thickness of the Niobrara ranges widely. Johnson (1958, p. 36) reports a maximum thickness of 210 m (690 ft) in Logan County, and Hodson and Wahl (1960, p. 64-65) indicate about 203 m (665 ft) in northwestern Gove County. Farther north the formation has a maximum thickness of 184 m (605 ft) in Graham County (Prescott, 1955, p. 46-47) and 198 m (650 ft) in Phillips County (Landes and Keroher,

FIGURE 7. Exposure of uppermost part of Smoky Hill Member and lowermost part of Pierre Shale, Sec. 20, T.15S, R.32W, Logan County, Kansas. Cal James is pointing to the contact. Arrow indicates Marker Unit 23. Anomalous dip of strata owing to proximity of strata to a major normal fault.

1942, p. 286), adjacent to the Nebraska border. For the Smoky Hill Member some reported thicknesses are as follows: western Logan County, 168 m (550 ft) (Landes and Keroher, 1939, p. 23); Gove County, 183 m (600 ft plus) (Hodson and Wahl, 1960, p. 65); and Graham County, 183 m (600 ft) (Landes and Keroher, 1942, p. 286). According to Merriam (1957, p. 14), the Smoky Hill ranges in thickness from 122 m (400 ft) to more than 198 m (650 ft) along lines of cross sections prepared for the Kansas Mesozoic. In the composite section of the present report, based on field work in Trego, Gove, and Logan counties, thickness is 181.8 m (596.3 ft); however, marker-defined intervals have different thicknesses in sections separated by only a few kilometers, so the stated thickness is representative, rather than actual.

HISTORY OF STRATIGRAPHIC NOMENCLATURE

The earliest classification of Upper Cretaceous strata in the U. S. Western Interior region is that of Hall and Meek (1856), who divided the Missouri River section into units numbered from 1 through 5, in stratigraphically upward order (Table 1). These units were later (Meek and Hayden, 1861, p. 419) given the names Dakota, Fort Benton, Niobrara, Fort Pierre, and Fox Hills, respectively. The existence of chalk in Kansas, belonging apparently to the Niobrara division, was recognized in the 1850s, and Kansas strata comprising "light gray limestone with *Inoceramus problematicus*" were correlated with division No. 3 before the decade ended (Meek and Hayden, 1857, p. 130). The correctness of this correlation is in doubt, however, because in a later paper Hayden (1872, p. 67) described briefly "chalky limestone of the Niobrara Group filled with *Inoceramus problematicus,*" which he saw at Wilson's Station (= Wilson, Kansas), a place at which the Greenhorn Limestone, rather than the Niobrara Chalk, crops out. Nevertheless, Hayden (1872, p. 67) identified correctly as No. 3 (= Niobrara) the massive beds of yellow chalk that crop out at the summit of a bluff situated 12.8 km (8 mi) west of Hays City [sic], at a place that today is called Yocemento. Mudge (1876, p. 219) accepted Hayden's identification of Niobrara for the beds exposed near Wilson's Station and concluded, because these beds lie directly upon the Dakota, that the Fort Benton is not represented in the Kansas section. Mudge (1878, p. 218) proposed the name "Fort Hays division" for the massive stratum of limestone lying beneath chalk and chalky shales of the "Niobrara proper," and included also within this division all beds lying between the limestone and sandstones of the Dakota. He opined (p. 219) that the lower portion of the Fort Hays (i.e., beds below the massive limestone) may be equivalent to the upper portion of the Benton. In a later work, Mudge (1878, p. 65) included the massive limestone unit in the Benton, and seems to have discarded the name "Fort Hays division" altogether.

At the time of Mudge's earlier writing, the term "Colorado group" was proposed by Hayden (1876, p. 45) to embrace the Fort Benton, Niobrara, and Fort Pierre divisions. White (1878, p. 21) redefined the Colorado Group, for paleontological reasons, so as to include only the Fort Benton and Niobrara. This concept of Colorado Group has continued to the present day, but in Kansas and most of Colorado lithologic heterogeneity of included strata renders the group of questionable validity and of little practical value.

In a lengthy sketch of Kansas geology, St. John (1883, p. 589) implied that the heavy (= thick) limestone horizons in the upper Benton may belong to the Niobrara, noting that the top of this limestone unit (= top of Fort Hays Member) is "for the most part obscure and difficult to trace." An alternate interpretation of Benton-Niobrara relations was published by Hay (1889, p. 101) who recognized Dakota, Benton, and Niobrara divisions, but included in the Niobrara a thick shale succession containing concretions and "occasional intercalations of limestone" that is now assigned to the Carlile Shale (see Fig. 1).

On the basis of baculite specimens identified by F. B. Meek, deposits at McAllaster Buttes, Logan County, formerly ascribed to the Niobrara, were assigned to the Fort Pierre group by Williston (1893, p. 110), this being the first clear recognition of the group in Kansas. In the same paper, Williston also recognized the Niobrara and Benton, but included the Fort Hays, for which he also used the term "stratified beds," in the Benton.

A major revision of Cretaceous stratigraphic nomenclature in Kansas was presented by Cragin (1896), who gave the entire Upper Cretaceous section the name "Platte Series." In this paper, a number of new formational names are proposed, including Russell formation for strata now referred to the Graneros Shale, Greenhorn Limestone, and Fairport Chalk Member of the Carlile Shale; Victoria formation (or clay) for strata now assigned to the Blue Hill Shale Member of the Carlile Shale; Osborne limestone for beds referred to earlier as the Fort Hays division of the Niobrara; Smoky Hill chalk for the upper division of the Niobrara; Lisbon shales for what is now called Pierre Shale; and Arickaree shales for

TABLE 1. Historical summary of Upper Cretaceous stratigraphic nomenclature in Kansas, with detailed treatment of the Niobrara Chalk. Earliest uses of present geographic names applied to the formation and its divisions are shown by asterisks. 1, name abandoned; name not only preoccupied but another name has priority; 2, name abandoned, another name has priority; 3, name has priority; reason for abandonment not clear; 4, name abandoned; name preoccupied; 5, first official use of name by Kansas Geological Survey. The name "Niobrara Chalk" was used first by Beecher (1900, p. 267) in a short note concerning *Uintacrinus socialis* Grinnell.

WESTERN INTERIOR		KANSAS				
MEEK & HAYDEN 1856	MEEK & HAYDEN 1861	MEEK & HAYDEN 1857	HAYDEN 1872	MUDGE 1876	MUDGE 1878	ST. JOHN 1883
No. 5	Fox Hills beds			Absent in Kansas	Absent in Kansas	Absent in Kansas
No. 4	Fort Pierre Group					
No. 3	Niobrara* Division	No. 3 (lower part)	Niobrara Group	Niobrara: Niobrara proper	Niobrara	Niobrara
				Niobrara: Fort Hays* division (including beds equiv. to Benton)	Fort Benton	?—?—? Benton (lss. at top may be Niobrara)
No. 2	Fort Benton Group	No. 2 ?	Fort Benton Group			
No. 1	Dakota Group	No. 1	Dakota Group	Dakota group	Dakota group	Dakota

KANSAS						
HAY 1889	WILLISTON 1893	CRAGIN 1896	LOGAN 1897	WILLISTON 1897	MOORE & HAYNES 1917	JEWETT 1959
(Green sand and clay of uncertain age)	Not mentioned	Arickaree[1] shales	Absent in Kansas	(Not represented in Kansas)		
	Fort Pierre Group	Lisbon[1] Shales	Fort Pierre group	Fort Pierre beds	Pierre shale	Pierre Shale
Niobrara	Niobrara	Niobrara: Smoky Hill* chalk	Niobrara: Pteranodon beds or Smoky Hill chalk	Niobrara: Pteranodon beds: Hesperornis beds; Rudistes beds	Niobrara fm.: Smoky Hill chalk member[5]	Niobrara Chalk[5]: Smoky Hill Chalk Member
(incl. sh. w/concr.)	Benton: Fort Hays beds	Niobrara: Osborne limestone[2]	Niobrara: Fort Hays limestone	Niobrara: Fort Hays beds	Niobrara fm.: Fort Hays limestone mbr.[5]	Niobrara Chalk: Fort Hays Ls. Mbr.
Benton	Benton	Benton: Victoria shales[3]; Russell format.[4]	Benton	Benton	Benton formation	Carlile Shale; Greenhorn Ls.; Graneros Shale
Dakota	Dakota	Dakota	Dakota formation	(Not mentioned)	Dakota sandstone	Dakota Formation

Pierre beds that he believed equivalent to the lower part of Meek and Hayden's Fox Hills beds. Although three of Cragin's units—Osborne, Lisbon, and Arickaree—had valid formal names and the Russell formation was later divided among three other units, his divisions were based mostly on sound lithostratigraphic criteria, and the name "Victoria shale" certainly should have priority over the present Blue Hill for the upper part of the Carlile.

The Niobrara was accorded group status by Gilbert (1896, p. 566), who recognized two divisions in Colorado, the lower called Timpas and the upper called Apishapa. These names have since been abandoned in favor of Kansas terminology. The first detailed description of Upper Cretaceous strata in Kansas is by Logan (1897a), who recognized many of the Benton divisions to which formal names have been given subsequently. For the lower division of the Niobrara, Logan (1897a, p. 219) used the name "Fort Hays limestone," the upper division being called Pteranodon beds or Smoky Hill chalk. In the same volume, Williston (1897, p. 237 ff.) continued use of the name "Pteranodon beds," instead of Smoky Hill, for the upper division of the Niobrara, and divided these beds, on the basis of color differences, into lower Rudistes beds and upper Hesperornis beds. Logan (1899c) utilized the Williston (1897) classification of the Niobrara in a paper concerning correlation of Colorado formation subdivisions through much of the Great Plains and Black Hills areas. In this work, Logan (p. 91) correlated the Fort Hays limestone with the lower part of the Timpas beds of Colorado, and correlated the Pteranodon beds with the upper Timpas and Apishapa beds.

Moore and Haynes (1917) were first to rank the Kansas Niobrara as a formation, and gave member status to the divisions, namely Fort Hays limestone member and Smoky Hill chalk member. This classification has been in use in Kansas since that date, with the exception that the formational name has been changed to Niobrara Chalk (Jewett, 1959).

ADJACENT STRATIGRAPHIC UNITS

Fort Hays Limestone Member, Niobrara Chalk

In the Smoky Hill type area, the Smoky Hill Member is underlain conformably by cliff-forming chalky limestone of the Fort Hays Member. An excellent exposure of the Fort Hays is situated in bluffs along Hackberry Creek, Trego County (Fig. 1, Loc. 1), and extends upstream for approximately two kilometers from the confluence of that stream and the Smoky Hill River. A detailed stratigraphic description and graphic column of this section is presented by me (Hattin, 1965, p. 46, 65), and records a thickness of 21.9 m (71.9 ft). The Fort Hays comprises a sequence of thin to very thick beds of relatively resistant, massive, almost entirely bioturbated chalky limestone (Fig. 8). Contacts between these beds are marked commonly by reentrants, some of which formed along very thin partings of shaly chalk and a few of which, in the upper part of the member, are formed along bentonite seams. Part of the section consists of shaly weathering chalk beds, which form major reentrants on the Hackberry Creek cliff face. The sequence of Fort Hays limestone beds, which are probably time parallel, is remarkably consistent along the Smoky Hill River valley (Frey, 1970, p. 9; 1972, p. 14). Principal macroinvertebrate species of the Fort Hays Member are large, bowl-shaped inoceramids, which are invariably encrusted, at least in part, by crowded specimens of *Pseudoperna congesta.* The oyster *Pycnodonte aucella* (Roemer) occurs in the lower 8.6 m (28 ft) of the Hackberry Creek section (Loc. 1). *Inoceramus deformis* Meek ranges approximately from 1.1 m to 8.6 m (3.6-28 ft) above the base of the Fort Hays. *Inoceramus (Cremnoceramus) inconstans* Woods? ranges approximately from 7.9 to 14.9 m (25.9-48.8 ft) above the base at Locality 1. In the same section *Inoceramus (Cremnoceramus) browni* Cragin occurs in the interval 9.6 to 14.9 m (31.5-48.8 ft) above the base of the Fort Hays. In the interval from the uppermost occurrence of *I. (Cremnoceramus) browni* to the uppermost bed of the Fort Hays, fragmentary remains of bowl-shaped inoceramids are

FIGURES 8, 9. **8,** Typical exposure of Fort Hays Member. Cliff near mouth of Hackberry Creek, Sec. 25, T.14S, R.25W, Trego County, Kansas. Note massive beds of chalky limestone, which are characteristic of the member. **9,** Fort Hays-Smoky Hill contact, Sec. 24, T.14S, R.25W, Trego County, Kansas. Marge Hattin is standing on a prominent bench formed by the uppermost bed of the Fort Hays. Low slopes in background are formed by less resistant beds in lower part of Smoky Hill Member.

relatively sparse, and positive identification of the species represented has not been accomplished. The uppermost bed of the Fort Hays contains well-preserved articulated specimens referred tentatively to *Inoceramus (Volviceramus) koeneni* Müller.

The bed containing *Inoceramus (Volviceramus) koeneni* is uppermost in a continuous sequence of cliff-forming, bioturbated chalky limestone beds and forms a major bench along the cliff top at the Hackberry Creek site (Loc. 1). The top of this bed marks a conspicuous change in overall appearance of the stratigraphic section (Fig. 9) from ledge-forming chalky limestone to slope-forming, mostly laminated chalk and is designated as the Fort Hays-Smoky Hill contact (Hattin, 1965, p. 65).

Sharon Springs Shale Member, Pierre Shale

Beds of the Sharon Springs Member lie conformably and gradationally on the Smoky Hill. Near the top of the Niobrara section the Smoky Hill comprises chalky shale that grades upward into a calcareous shale interval that contains a few thin beds of noncalcareous gray shale. In the composite section, at Locality 21, the Smoky Hill-Sharon Springs contact is drawn at the stratigraphic horizon above which all of the shale is noncalcareous, and at which a distinctive color change is obvious (Fig. 7). As thus established, the contact lies approximately midway between two thin seams of bentonite, the lower 4.9 cm (0.16 ft) and the upper 4.5 mm (0.015 ft) in thickness. The upper of these bentonites forms a prominent white streak across the exposure.

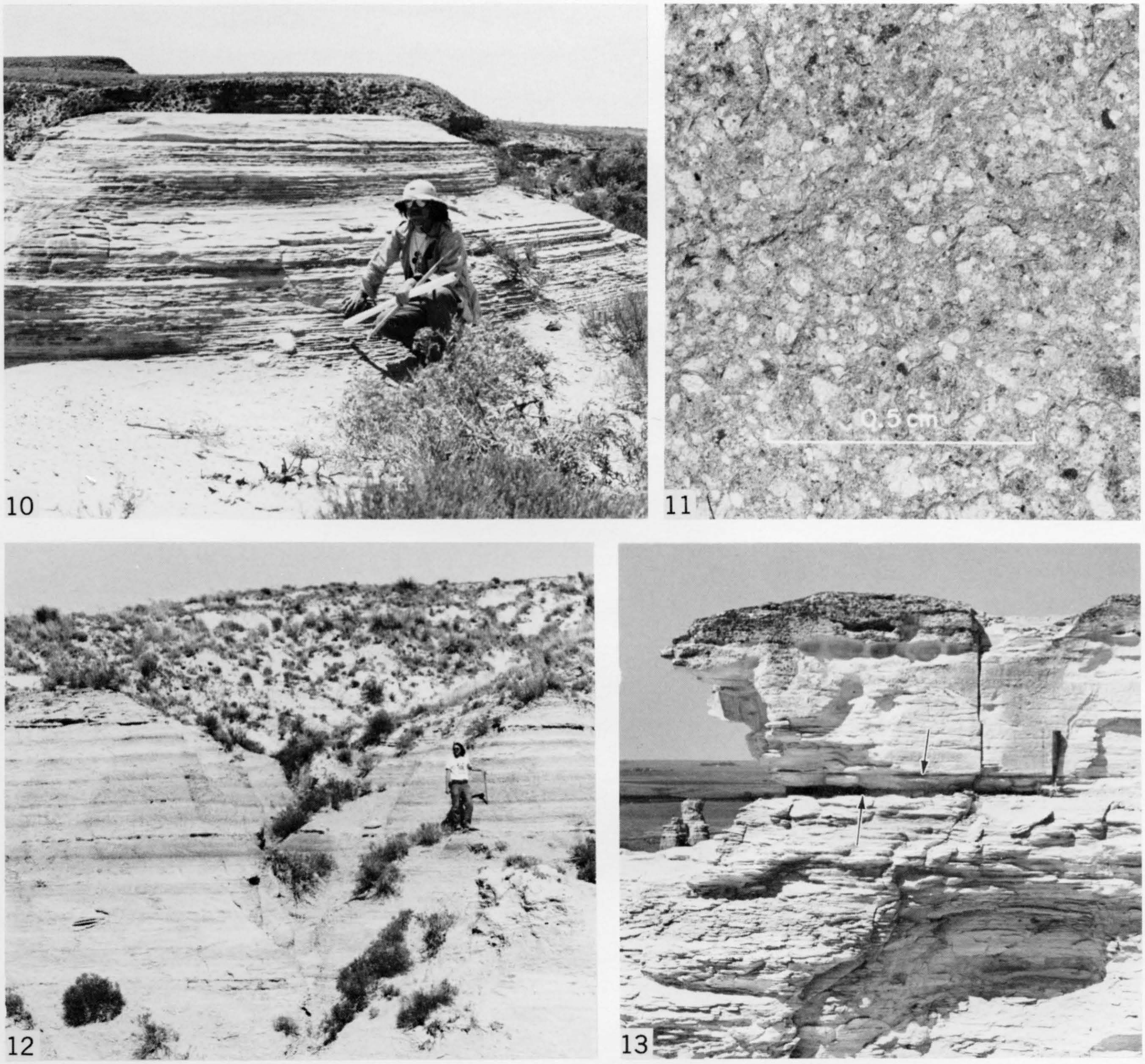
Lower strata of the Sharon Springs consist mostly of soft, dark gray, silty, flaky-weathering shale and the upper part comprises harder, buttress-forming, organic-rich dark gray shale overlain by a thin interval of phosphatic shale (Gill and others, 1972). Basal beds of the Sharon Springs Member contain almost no macroinvertebrate fossils. Field work and drilling suggest that the Sharon Springs is approximately 69 m (225 ft) thick (Gill and others, 1972, p. 7).

STRATIGRAPHY OF THE SMOKY HILL CHALK MEMBER

Lithology

Stratified Chalk. The Smoky Hill Member consists primarily of obscurely to well laminated, fissile, mostly white-speckled, shaly weathering chalk, which is predominantly olive gray (5Y4/1) and less commonly dark olive gray (5Y3/1) or olive black (5Y2/1) in color where least weathered. Partly weathered rock is lighter colored, being mostly medium olive gray (5Y5/1, 5Y4/2) or light olive gray (5Y6/1, 5Y5/2). Much-weathered chalk manifests wide color range, including very pale orange (10Y8/2) through dark yellowish brown (10YR4/2), pale grayish orange (10YR8/4) through moderate yellowish brown (10YR5/4), and pale yellowish orange (10YR8/6) through dark yellowish orange (10YR6/6) (colors from Goddard and others, 1948). Freshly exposed laminated chalk is tough, forms steep faces in cutbanks of streams, and has characteristically spally fracture. Much of the rock, especially in the lower half of the member, is thinly laminated (Fig. 10) but on gentle slopes and in highly weathered sections this feature is not everywhere obvious. Laminations are on a millimeter to centimeter scale. Units that lack obvious lamination in weathered exposure are usually observed to be moderately to well laminated in fresh exposure, as along cutbanks in gullied badlands. Lamination is owing primarily to vertical variations in abundance of fecal pellets (Hattin, 1975b), which have been compacted to oblate spheroidal shape and, because of great abundance, enhance fissility of the rock (Fig. 11). The upper half of the member, especially in the interval extending from 130 to 177 m (426-580 ft) above the composite section base, contains numerous beds of chalk that are neither bioturbated nor obviously laminated. Nevertheless, this chalk splits readily parallel to the general stratification and contains an abundance of fecal pellets. Throughout the section, beds that are well laminated are gradational with those that are obscurely laminated, which in turn are gradational with those lacking obvious lamination. Beginning at a horizon lying approximately 62 m (203 ft) below the top of the member, many units of shaly weathering chalk have thinly crinkled structure rather than lamination, and beds having this characteristic persist, with highly irregular spacing, to within 3 m (10 ft) of the Smoky Hill-Pierre contact. Alternation of darker, crinkled beds with lighter-colored beds of granular chalk (see below) produces a distinctly rhythmic stratification, most notably in the interval extending from 116 to 139 m (380-455 ft) above the Fort Hays-Smoky Hill contact (Fig. 12).

Weathered shaly chalk is friable, softer than little-weathered chalk, and breaks readily into small chips or flakes, which litter eroded slopes. In exposures where weathering has been most extensive the chalk may form relatively resistant ledges or cliffs of chalk that appears to be massive but splits readily along flat stratification planes that reflect original lamination (Fig. 13). Alteration of rock during weathering tends to obliterate lamina-

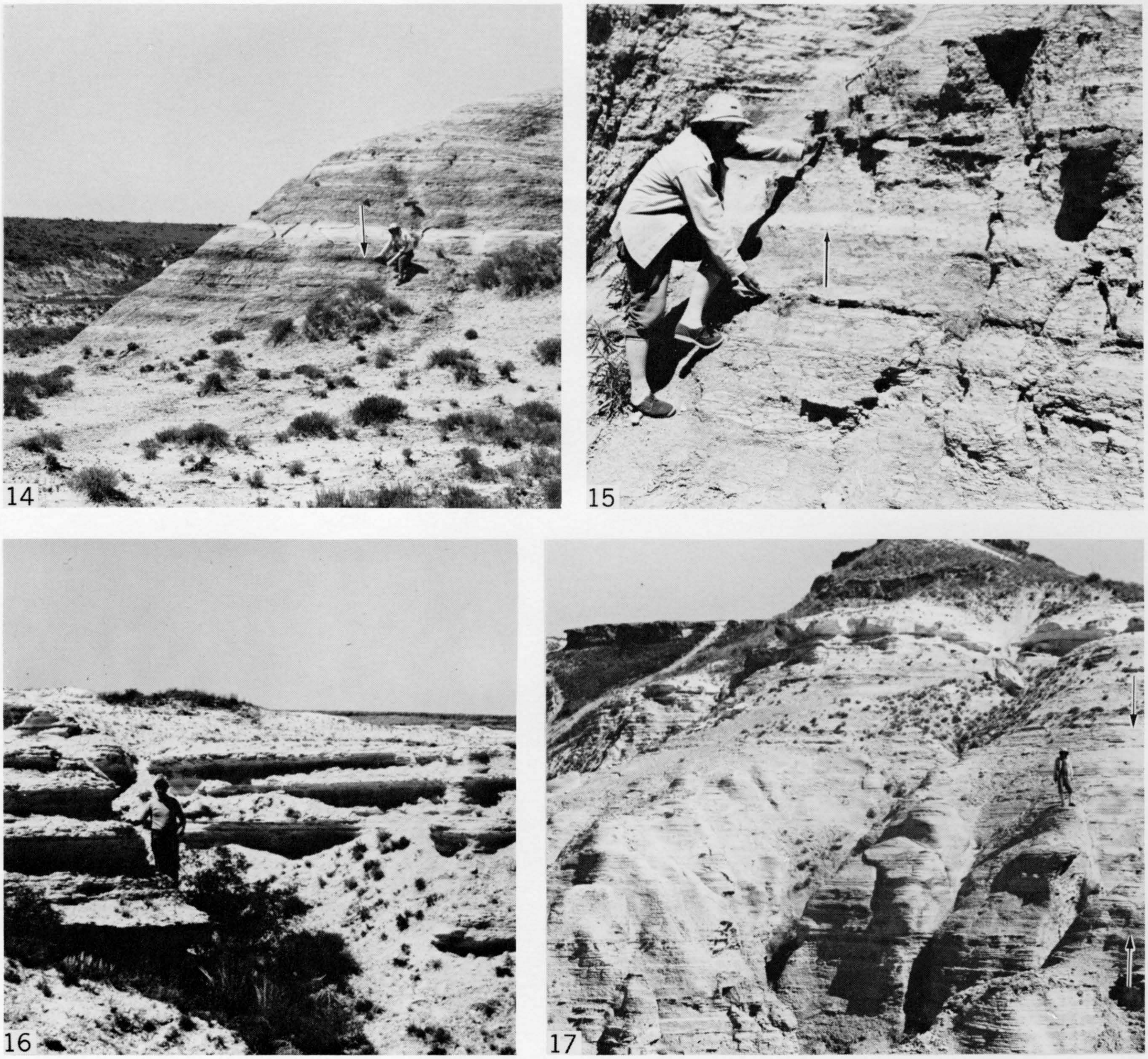


FIGURES 10-13. **10,** Exposure of Smoky Hill Member in Sec. 16, T.15S, R.34W, Logan County, Kansas, showing well-laminated character of chalk. **11,** Plan view of bedding surface of well-laminated chalk, showing abundance of coccolith-rich fecal pellets (light-colored grains). ×8. Sample from lower part of Smoky Hill Member in Sec. 16, T.14S, R.25W, Trego County, Kansas. **12,** Exposure of rhythmically stratified alternations of lighter-colored, granular chalk and darker-colored, crinkly chalk in Sec. 30, T.15S, R.32W, Logan County, Kansas. **13,** Bed (top of photo) of highly weathered, massive-looking chalk in Sec. 1, T.14S, R.26W, Gove County, Kansas. Rock splits easily along flat planes of bedding, but original laminations have been largely obliterated by weathering. Hammer is 28 cm (0.9 ft) long. Arrows indicate weathered bentonite seams, which comprise Marker Unit 12.

tion and causes thinning of units by as much as one third in exposures separated by just tens of meters from equivalent, unweathered rock.

A few intervals of mostly well laminated chalk contain conspicuously darker beds, which form prominent bands across little-weathered exposures (Fig. 14). Such beds are as much as 1.2 m thick. Four major beds of this kind lie in the interval 34 to 133 m (112-436 ft) above the base of the Smoky Hill in the composite section and are yellowish brown (10YR5/2) to dark yellowish brown (10YR4/2) in partly weathered exposures, which are most common. At one locality (Loc. 23, see Fig. 14) the next to uppermost of these four beds contains 5.8 percent organic carbon.

Bioturbated Chalk. Scattered irregularly through the Smoky Hill member are beds of mostly light olive gray (5Y2/1), resistant, nonlaminated chalk, which forms light gray to very light gray bands on little-weathered exposures (Fig. 15). In the lower 95 m of the Smoky Hill



FIGURES 14-17. **14,** Dark-colored band (arrow) of organic-rich chalk in Sec. 12, T.15S, R.32W, Logan County, Kansas. The organic-rich band is part of Marker Unit 14 and can be identified readily by its association with the light-colored band of granular chalk, which lies shortly above. **15,** Bed (arrow) of bioturbated chalk in Sec. 1, T.14S, R.26W, Gove County, Kansas. Allen Archer's hands are on two nearby bentonite seams, which together with the bioturbated chalk bed and associated chalk comprise Marker Unit 9. **16,** Resistant, ledge-forming beds of bioturbated chalk in Sec. 16, T.14S, R.25W, Trego County, Kansas. These beds comprise Marker Unit 3. **17,** Buttress-forming, partially bioturbated chalk of Marker Unit 10 in Sec. 1, T.14S, R.26W, Gove County, Kansas. This unit is the principal caprock in chalk badlands of Gove and Logan counties. Note that the buttress-forming unit (between arrows) is less well stratified than beds below.

such beds contain clear evidence of bioturbation, especially including deposit-feeder burrows referable to *Planolites* Nicholson. Bioturbated intervals range in thickness from a few centimeters to 30 or 40 cm (1.0-1.3 ft). Complete gradation exists between intervals in which bioturbation was extensive, and destroyed all traces of lamination, and those which were burrowed only partially and which preserve some or most of the primary lamination. Where least weathered, such beds form small shoulders or weakly developed benches on eroding slopes, and produce abundant brittle chips or small plates of irregularly fractured rock. In extensively weathered exposures these bioturbated beds exhibit the same color range as adjacent beds of well-stratified chalk, but are more resistant to erosion and form distinctive benches and overhanging ledges that are recognized readily (Fig. 16). These lighter-colored, bioturbated beds are especially useful as stratigraphic markers, and several of them are described in detail below.

An important example of partially bioturbated rock, which lies 88.4 m (290 ft) above the composite section base and is 6.7 m (22 ft) thick, is tough, poorly stratified compared with adjacent chalk beds, and forms prominent buttresses in little-weathered exposures (Fig. 17). This rock is gradational with laminated chalk and highly bioturbated chalk, and has a somewhat granular texture like rocks described in the next paragraph. The unit is the major caprock of erosional pinnacles and badlands in Gove and eastern Logan counties (Figs. 3, 4). Where least weathered this rock is medium olive gray (5Y5/1) and highly speckled throughout by fecal pellets.

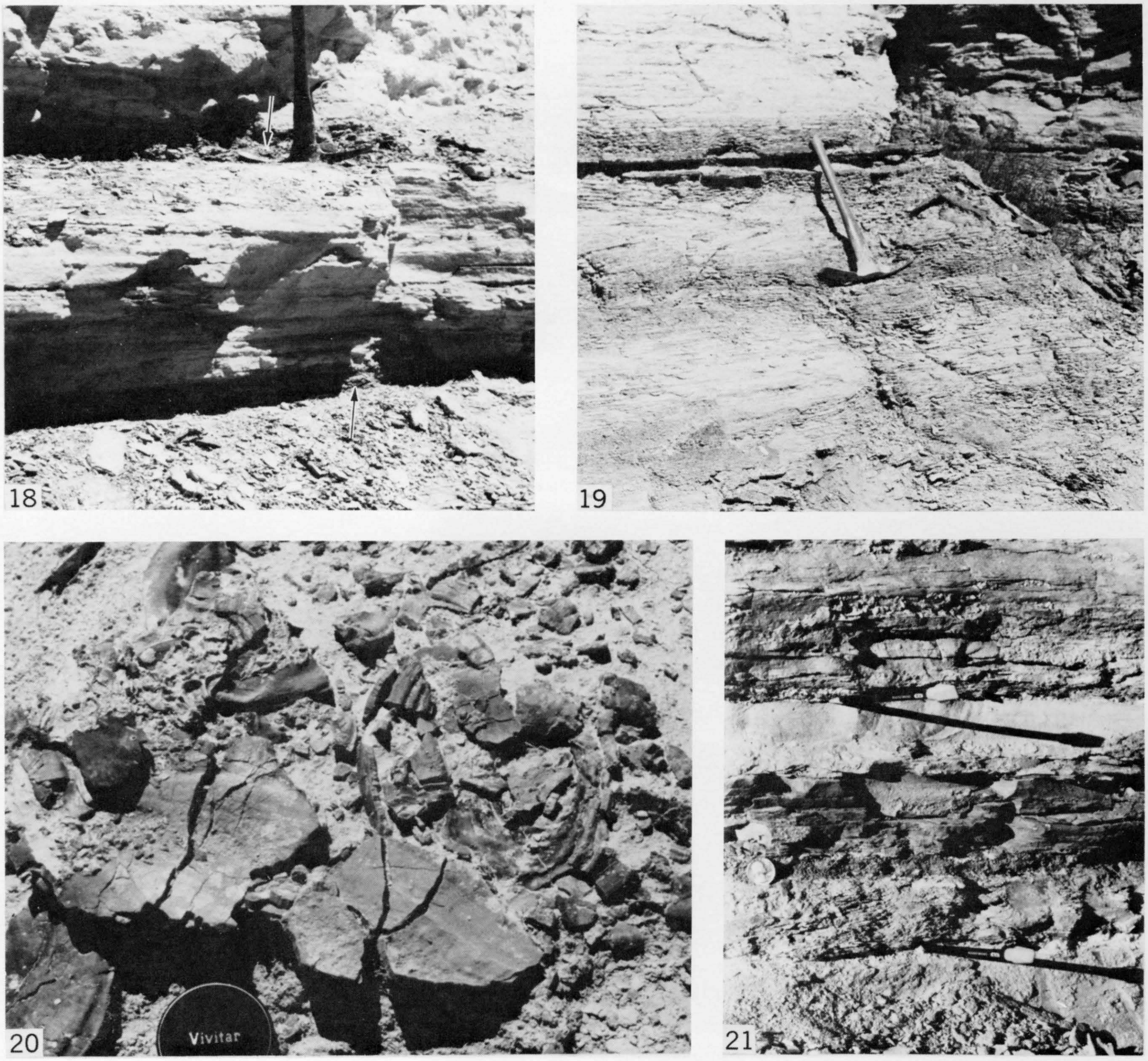
Granular Chalk. In the upper half of the Smoky Hill Member most beds of tough, more resistant, lighter-colored, poorly to nonstratified chalk have a somewhat granular texture, which is in marked contrast to that of adjacent, shaly weathering chalk beds. When viewed at a distance, some of these beds manifest thinly stratified appearance. Stratigraphic intervals consisting of granular chalk range from a few centimeters to as much as 0.76 m (2.5 ft) in thickness. This rock is apparently of similar origin to the bioturbated beds in the lower half of the member, but recorded burrow structures are sparse, very small, and detected mostly in thin sections. Granular chalk tends to form smoothly rounded shoulders on eroding slopes, and is a bench-forming caprock in much-weathered badlands. Where least weathered, the granular chalk is olive gray (5Y4/1) but the rock is more commonly medium olive gray (5Y3/1) to light olive gray (5Y5/2) and forms light-colored bands on the outcrop that stand out conspicuously against the background of adjacent, darker-colored stratified chalk (Figs. 12, 14). In highly weathered exposures the rock usually manifests a wide range of coloration, much the same as well-stratified chalks, but locally, near the top of the member, some such beds weather to moderate reddish orange. Granular chalk usually contains only sparse, fragmentary macroinvertebrate fossils but is highly speckled by nearly white fecal pellets.

Bentonite. Bentonite seams are a characteristic feature of Smoky Hill stratigraphy, and are scattered throughout the section (Fig. 18). The bentonites range in thickness from less than one mm to as much as 11.3 cm (0.37 ft). Bentonite color ranges widely, depending mostly upon the degree of weathering and partly on original mineral composition. Least-weathered seams are olive gray (5Y4/1), light olive gray (5Y6/1), medium gray (N5), and medium light gray (N6), with rare occurrences of light bluish gray (5Y7/1) and medium greenish gray (5GY6/1). Weathered bentonite is, in order of decreasing commonness, dark yellowish orange (10YR6/6), light brown (5YR5/6), very pale orange (10YR8/2) through dark yellowish brown (10YR4/2), yellowish gray (5Y8/1, 5Y7/2), and pale grayish orange (10YR8/4) through moderate yellowish brown (10YR5/4). Weathering colors of minor occurrence include pale shades of olive, gray, brown, yellow, and white, and for one seam only, pale grayish orange pink (5YR8/2). Most of the orange and brown coloration is owing to iron oxides, which nearly everywhere stain the more weathered seams. Iron mineralization has occurred in the form of oblate spheroidal marcasite nodules, as much as 0.7 m (2.3 ft) wide and 12 cm (0.4 ft) thick, usually altered to iron oxide, and as laterally continuous crusts (Fig. 19), which bound certain bentonite seams in some exposures and are as much as 3 cm (0.1 ft) thick. Gypsum has developed commonly as seams that bound the individual bentonite beds, and occurs also as fine powder, sand-sized crystals, or coarsely crystalline crusts in which selenite C axes are normal to bedding. Gypsum and iron oxide co-occur along many weathered bentonite seams. In the Smoky Hill composite section described below, more than 100 bentonite seams were identified. Yellowish-colored jarosite is also associated with iron oxide and gypsum along many of the weathered bentonite seams. Numerous seams consisting of iron oxide, commonly with associated gypsum, and usually less than 6 mm (0.02 ft) thick, probably represent highly weathered, originally very thin bentonite seams.

Thirty-five bentonite samples were analyzed by X-ray diffractometry. These samples, from 10 different localities, are representative of bentonite seams from most of the Smoky Hill composite section. In 23 samples the dominant clay mineral is kaolinite, whereas in nine samples the dominant mineral is smectite. In some kaolinite-dominated samples, smectite occurs as an accessory clay mineral, and vice versa. Quartz, usually in minor quantity, is an accessory mineral in 20 of the samples, occurring in both kaolinite- and smectite-dominated bentonites. Gypsum and calcite are the only other accessory minerals recorded commonly, and gypsum is the dominant mineral in two highly weathered bentonite seams in which no clay minerals were recorded.

Bentonite stratigraphy, including details of sequence, thickness of individual seams, clustering of seams within small stratigraphic intervals, and association with bioturbated or granular chalk beds was of primary importance in piecing together the composite section and has long been recognized (Russell, 1929) as a key factor in understanding the Smoky Hill Member.

Shelly Zones. Few beds of the Smoky Hill lack skeletal remains of benthic macroinvertebrates, although such fossils are very scarce in some beds, especially in the upper third of the member. Certain thin stratigraphic intervals, however, are characterized by enormous abundance of such fossils. Along the outcrop of these intervals the eroded slopes are littered with whole and broken skeletal remains of inoceramids and oysters (Fig. 20), and



FIGURES 18-21. **18,** Bentonite seams (arrows) separated by weathered chalk, Sec. 30, T.15S, R.32W, Logan County, Kansas. The two bentonite seams and intervening chalk comprise Marker Unit 18. **19,** Bentonite seam bounded by resistant crusts of iron oxide, Sec. 30, T.15S, R.32W, Logan County, Kansas. Hammer is 28 cm (0.9 ft) long. **20,** Skeletal debris on eroded surface of shelly zone, Sec. 16, T.14S, R.25W, Trego County, Kansas. Lens cap is 6.0 cm (0.44 ft) in diameter. **21,** Marker Unit 1, Sec. 25, T.14S, R.25W, Trego County, Kansas. Pencils mark top and bottom bentonite seams; coin (diam. 24 mm) marks central seam.

where these zones crop out on gentle slopes acres of the land surface may be almost completely paved with shelly debris. Important shelly intervals, none more than about 1.5 m (4.9 ft) in maximum thickness, lie 4.5 m (14.8 ft), 22.3 m (73.1 ft), 25.8 m (84.6 ft), 85.5 m (280.4 ft), and 114 m (374 ft) above the Fort Hays-Smoky Hill contact. In the best exposures of shelly zones, articulated, *in situ* specimens of inoceramids abound.

***Uintacrinus* Limestone.** Near the middle of the Smoky Hill Member, apparently in the zone of *Clioscaphites choteauensis* Cobban, are sparse, widely scattered, thin to very thin lenses of hard, brittle, crinoidal limestone composed largely of articulated and disarticulated remains of the free-swimming crinoid *Uintacrinus socialis.* The rock has suffered greatly from compaction as evident in compressed skeletal remains and numerous microstylolites resulting from pressure solution. Occurrence and morphology of the crinoids are described in great detail by Springer (1901) and localities where the crinoids have been collected are summarized by Miller and others

(1957). Despite many days of study in areas from which these crinoids have been collected, I have not been successful in locating any of the crinoidal lenses. Most of the readily accessible slabs containing crinoids were quarried during the nineteenth century and erosion since then has been insufficient to yield slabs of the quality once available in quantity.

Nodules. Iron sulphide nodules, variously altered to iron oxide and commonly including jarosite, occur throughout the Smoky Hill Member. Most such nodules have oblate spheroidal shape and occur along bentonite seams or enclose, at least in part, large flattened valves of inoceramid bivalves. Many nodules contain a partially decomposed core of powdery to splintery marcasite, which may yet retain the original metallic luster.

These nodules range in size from a few millimeters to as much as 0.7 m (2.3 ft) in breadth by 12 cm (0.4 ft) in thickness and are a conspicuous feature in all but a few intervals within the member.

Additionally, small polycuboidal pyrite nodules as much as 7 cm (0.23 ft) in diameter are scattered through several meters of section in a few intervals of the Smoky Hill, and especially in parts of the section exposed at Localities 13, 19, and 20 (see Pl. 1). Whereas most such nodules are of equant dimensions, very roughly spherical in shape, and have no connection with bentonite seams, some of those at Locality 13 have a well-defined median plane, which represents a very thin bentonite seam along which the nodules formed. The latter have top and bottom halves, commonly bluntly cylindrical or conical, that are essentially mirror images.

Nodular, usually stratiform masses of chert occur within the Smoky Hill at several places, e.g., at Locality 24, at several places in Graham County (Prescott, 1955, p. 47), and at Norton (Logan, 1897a, p. 220). At Locality 24 the nodules reach thicknesses as great as 15 cm (0.5 ft). Smoky Hill chert is associated with highly weathered chalk and occurs in the uppermost part of the exposure. According to Frye and Leonard (1949, p. 30), silicification took place at the same time as silicification in adjacent Ogallala (Miocene and Pliocene) beds.

Register of Localities

During the course of this study I visited numerous Smoky Hill exposures in Trego, Gove, Logan, Ellis, Rooks, and Graham counties. Sections were measured only in the Smoky Hill River drainage basin and, from these, 12 sections were selected as a basis for the composite reference section (Pl. 1). Descriptions of these sections are included in the appendix and locality data are furnished below, in stratigraphically upward order.

Locality 1. Bluffs and badlands on west side of Hackberry Creek, in west half Sec. 24 and NW¼ Sec. 25, T.14S, R.25W, Trego County, Kansas. Fort Hays Member (complete) and lower part of Smoky Hill Member.

Locality 17. Badlands and bluffs on west side of Hackberry Creek, in SW¼ Sec. 16, T.14S, R.25W, Trego County, Kansas. Smoky Hill Member.

Locality 12. Highly eroded bluff on west side of small southern tributary to Smoky Hill River, in SW¼ Sec. 16, T.15S, R.26W, Gove County, Kansas. Smoky Hill Member.

Locality 13. Highly eroded bluff and badlands on west side of small southern tributary to Smoky Hill River, in SE¼ Sec. 29, T.15S, R.26W, Gove County, Kansas. Smoky Hill Member.

Locality 19. Badlands along small southern tributary to Hackberry Creek, in NE¼ Sec. 2, T.14S, R.26W, Gove County, Kansas. Smoky Hill Member.

Locality 18. Bluff and adjacent erosional pinnacle directly south of Castle Rock, in SW¼ Sec. 1, T.14S, R.26W, Gove County, Kansas. Smoky Hill Member.

Locality 22. Gully in small badlands in NW¼ Sec. 18, T.15S, R.31W, Gove County, Kansas. Smoky Hill Member.

Locality 23. Bluffs along west side of small southern tributary to Smoky Hill River, in SW¼ Sec. 7, T.15S, R.31W, Gove County, Kansas, and SE¼ Sec. 12, T.15S, R.32W, Logan County, Kansas. Smoky Hill Member.

Locality 20. Highly eroded bluff on south side of Twin Butte Creek, in SW¼ Sec. 16, T.15S, R.34W, Logan County, Kansas. Smoky Hill Member.

Locality 24. Bluff on east side of Ladder Creek, in SW¼ Sec. 30, T.15S, R.32W, Logan County, Kansas. Smoky Hill Member.

Locality 25. Small butte situated northeast of bluff at Locality 24, in SE¼ Sec. 30, T.15S, R.32W, Logan County, Kansas. Smoky Hill Member.

Locality 21. Badlands along small southern tributary to Ladder Creek, in NE¼ Sec. 20, and NW¼ Sec. 21, T.15S, R.32W, Logan County, Kansas. Upper part of Smoky Hill Member and lower part of Pierre Shale.

Marker Units

General Statement. In the 1920s and 1930s geologists who were mapmaking in the Smoky Hill chalk country used bentonite seams as control points for determining surface structure (Virgil Cole, oral communication). In the only published work regarding utility of the bentonite sequence, Russell (1929) recognized 10 groups of seams, lettered A through J, but furnished few details of bentonite thickness, little on associated lithology, and nothing concerning fossils. Virgil Cole (oral communication, 1962) utilized 26 Smoky Hill markers, most of them bentonites, during the course of his work as an oil company geologist; in 1962 he communicated much of his knowledge to me during a brief trip through the Smoky Hill outcrop in Graham County.

My detailed study of the type Smoky Hill strata has served to identify numerous stratigraphic markers that can be used to determine with great precision position within the stratigraphic section. Some widely traceable bentonite seams are not included because they lack features necessary for positive identification. The described markers are those that can be recognized readily by persons not intimately acquainted with the area but whose sampling or fossil collecting requires accurate determination of stratigraphic position without measuring the entire member in detail. Knowledge of these markers is made especially necessary because at most localities less than 24 m (80 ft) of section, and usually less than 15 m (50 ft), are exposed. Furthermore, normal faulting has displaced the section in so many places that even exposures in closely spaced gullies or badlands tracts may belong to widely separated parts of the section.

In the Smoky Hill River section of the Niobrara Chalk, contact between the Fort Hays and Smoky Hill members lies at the top of a continuous sequence of massive, highly bioturbated chalky limestone beds. The uppermost of these limestone beds contains *Inoceramus koeneni* Müller and forms a prominent bench in bluffs overlooking Hackberry Creek at Locality 1. Above this bench the Niobrara section consists predominantly of thinly stratified chalk. In the following descriptions, thicknesses are given for marker units, intervals between marker units, and distance above the base of the composite Smoky Hill section. In general, thickness of a given marker unit and of the interval between two given markers is greater in the western part of the study area. However, in highly weathered sections markers and intervals between markers tend to be thinner than in little-weathered sections. From the base of the Smoky Hill Member to the base of Marker Unit 12, all thicknesses are based on exposures in western Trego and eastern Gove counties, whereas thicknesses from the base of Marker Unit 12 to the top of the composite section are based on exposures in western Gove and southern Logan counties. Details of individual marker units are presented in ascending order.

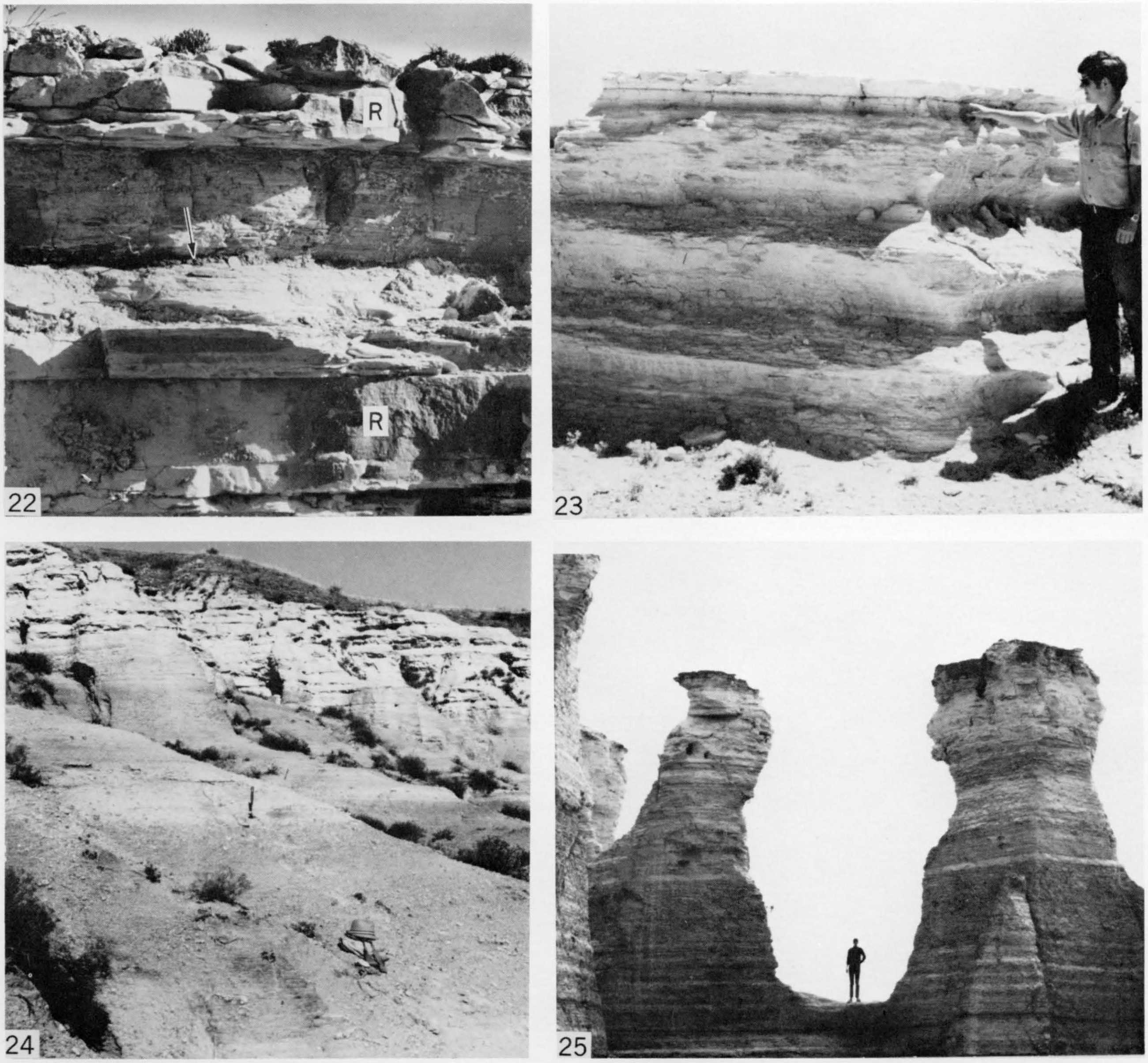
Marker Unit 1. Three bentonite seams in a 22 cm (0.72 ft) interval, separated by 5.2 cm (0.17 ft) and 12.8 cm (0.42 ft) beds of chalk (Fig. 21). Lowest bentonite 1.6 cm (0.05 ft), central bentonite 1.9 cm (0.06 ft), upper bentonite 0.6 cm (0.02 ft) thick (Fig. 21). A resistant bed of massive chalk 0.6 m (1.9 ft) thick lies above this marker unit and forms a bench. A rich concentration of *Inoceramus (Volviceramus) grandis* characterizes a 1.1 m- (3.5 ft) thick interval, which lies approximately 2.6 m (8.5 ft) above Marker Unit 1. This marker lies 1.6 m (5.3 ft) above the base of the composite section.

Marker Unit 2. A bentonite seam 2.5 cm (0.08 ft) thick, lying near the center of a 0.5 m- (1.6 ft) thick, nonresistant chalk interval, which is bounded above and below by lighter-colored chalk beds. The lower of these chalk beds is 19.8 cm (0.65 ft) thick and is bioturbated; the upper chalk bed is 21.4 cm (0.7 ft) thick and is laminated. In highly weathered exposures the lower chalk bed forms a resistant ledge, and the upper chalk bed forms a prominent bench (Fig. 22). A ferruginous gypsum seam 3 mm (0.01 ft) thick, probably a weathered bentonite, lies on the upper chalk bed and a bentonite seam 3 mm (0.01 ft) thick lies 0.55 m (1.8 ft) above this upper, resistant chalk bed. The marker bentonite lies 12.4 m (40.8 ft) above Marker Unit 1 and 14.3 m (46.8 ft) above the base of the Smoky Hill.

Marker Unit 3. Five subequally spaced beds of bioturbated chalk separated by beds of shaly chalk in an interval approximately 2.9 m (9.5 ft) thick. In little-weathered exposures the bioturbated chalk beds are lighter colored than adjacent laminated chalk beds and form minor shoulders on eroding slopes. In highly weathered exposures, the bioturbated chalk beds comprise a readily distinguishable bundle of resistant ledges, which hold up a small cliff and collectively form a major bench in large badlands areas (Fig. 16). The lowest bioturbated chalk bed is the thickest (0.49-0.55 m [1.6-1.8 ft]). The lower half of the marker unit is characterized by great abundance of inoceramid bivalve remains. A 0.6 m- (2.0 ft) thick interval rich in valves of *Inoceramus (Volviceramus) grandis* lies 2.9 m (9.6 ft) beneath the base of the marker. This marker unit lies 11.5 m (37.8 ft) above Marker Unit 2 and 25.8 m (84.7 ft) above the base of the Smoky Hill composite section.

Marker Unit 4. A bentonite seam 3 mm (0.01 ft) thick overlain by a bioturbated chalk bed 9.2 to 12.2 cm (0.3-0.4 ft) thick. In little-weathered exposures, the bioturbated chalk bed forms a conspicuous, very light colored band on the outcrop, whereas in highly weathered exposures the chalk bed forms a minor, though conspicuous bench (Fig. 23). The marker lies 6.7 m (21.9 ft) above Marker Unit 3, and 35.4 m (116 ft) above the base of the composite section.

Marker Unit 5. A partly bioturbated, partly laminated chalk bed 27.5 to 30.5 cm (0.9-1.0 ft) thick overlain by a bentonite seam, which is 6 mm (0.02 ft) thick. The chalk bed is lighter colored than adjacent olive gray laminated chalk, breaks into coarse chips upon weathering, and forms a minor bench (Fig. 24). In partly weathered exposures, the marker chalk bed forms a conspicuous, light gray band on the outcrop. Above the bentonite seam approximately 7.6 cm (0.25 ft) of chalk is also lighter colored than adjacent chalk beds and forms part of the conspicuous band. This marker lies 2.8 m (9.1 ft) above Marker Unit 4, and 38.1 m (125.1 ft) above the



FIGURES 22-25. **22,** Marker Unit 2, Sec. 24, T.14S, R.25W, Trego County, Kansas. The bentonite seam (arrow) lies within a bed of nonresistant, laminated chalk. More massive, resistant beds of chalk adjacent to the laminated bed are indicated by letter R. Upper resistant chalk bed forms bench at top of exposure. Coin is 2.1 cm in diameter. **23,** Marker Unit 4, Sec. 16, T.14S, R.25W, Trego County, Kansas. Cal James is pointing to bentonite seam that lies beneath bench-forming, bioturbated chalk bed. **24,** Marker Unit 5, Sec. 16, T.15S, R.26W, Gove County, Kansas. Hat is 14 cm tall. Note prominent light-colored band, formed by outcrop of marker, which extends across exposure. **25,** Erosional pinnacles in Smoky Hill at Monument Rocks, Sec. 34, T.14S, R.31W, Gove County, Kansas. Caprock is partially bioturbated, resistant chalk of Marker Unit 10.

base of the composite section.

Marker Unit 6. A bentonite seam 0.9 to 1.2 cm (0.03-0.04 ft) thick, which lies in the midst of a thick section of more or less laminated chalk. This marker lies shortly above the uppermost occurrences of *Inoceramus (Volviceramus) grandis,* and within the lower part of the range of *Inoceramus (Cladoceramus) undulatoplicatus* Roemer, which is readily recognizable because of the coarse radiating folds in its huge, snowshoe-like valves. The bentonite lies approximately 1.2 m (4.0 ft) above the first stratigraphic occurrence of pebble-sized polycuboidal pyrite nodules, which are common also through several meters of section directly above the marker. This marker unit lies 16.4 m (53.8 ft) above Marker Unit 5 and 54.9 m (180 ft) above the base of the composite section.

Marker Unit 7. A medium greenish gray (5GY5/1) to olive gray (5Y4/1) bentonite seam, which is 1.2 to 1.5 cm (0.04-0.05 ft) thick. Color and relatively large thickness are unusual for a bentonite in this part of the section. This bentonite seam can be identified positively by the presence 1.2 to 1.4 m (4.1-4.5 ft) lower in the section of two very thin bentonite seams, which are separated by 12 to 14 cm (0.4-0.45 ft) of laminated chalk. The lower of these two bentonite seams is 3 to 6 mm (0.01-0.02 ft) thick; the upper is 3 mm (0.01 ft) or less in thickness and consists of a persistent ferruginous seam that probably represents a highly altered bentonite. The two very thin bentonite seams lie directly above the uppermost known occurrence of *Inoceramus (Cladoceramus) undulatoplicatus.* A 0.6 cm- (0.02 ft) thick seam of bentonite lies 2.8 m (9.2 ft) above Marker Unit 7 and is separated from the latter by sparsely fossiliferous, laminated chalk. This marker lies 8.6 m (28.1 ft) above Marker Unit 6, and 63.4 m (208 ft) above the base of the composite section.

Marker Unit 8. A pale grayish orange pink (5YR8/2) to pinkish gray (5YR8/1) bentonite seam 0.6 to 1.2 cm (0.02-0.04 ft) thick. Another bentonite seam 3 mm (0.01 ft) thick lies an average of 2 m (6.5 ft) below the marker, and a bentonite seam 0.9 cm (0.03 ft) thick lies 1.9 m (6.1 ft) above the marker. Specimens of *Clioscaphites vermiformis* (Meek and Hayden) occur in a 0.76 m- (2.5 ft) thick interval the top of which lies approximately 1.5 m (4.9 ft) beneath the marker. The marker bentonite lies 17.1 m (56.2 ft) above Marker Unit 7, and 80.5 m (264 ft) above the base of the composite section.

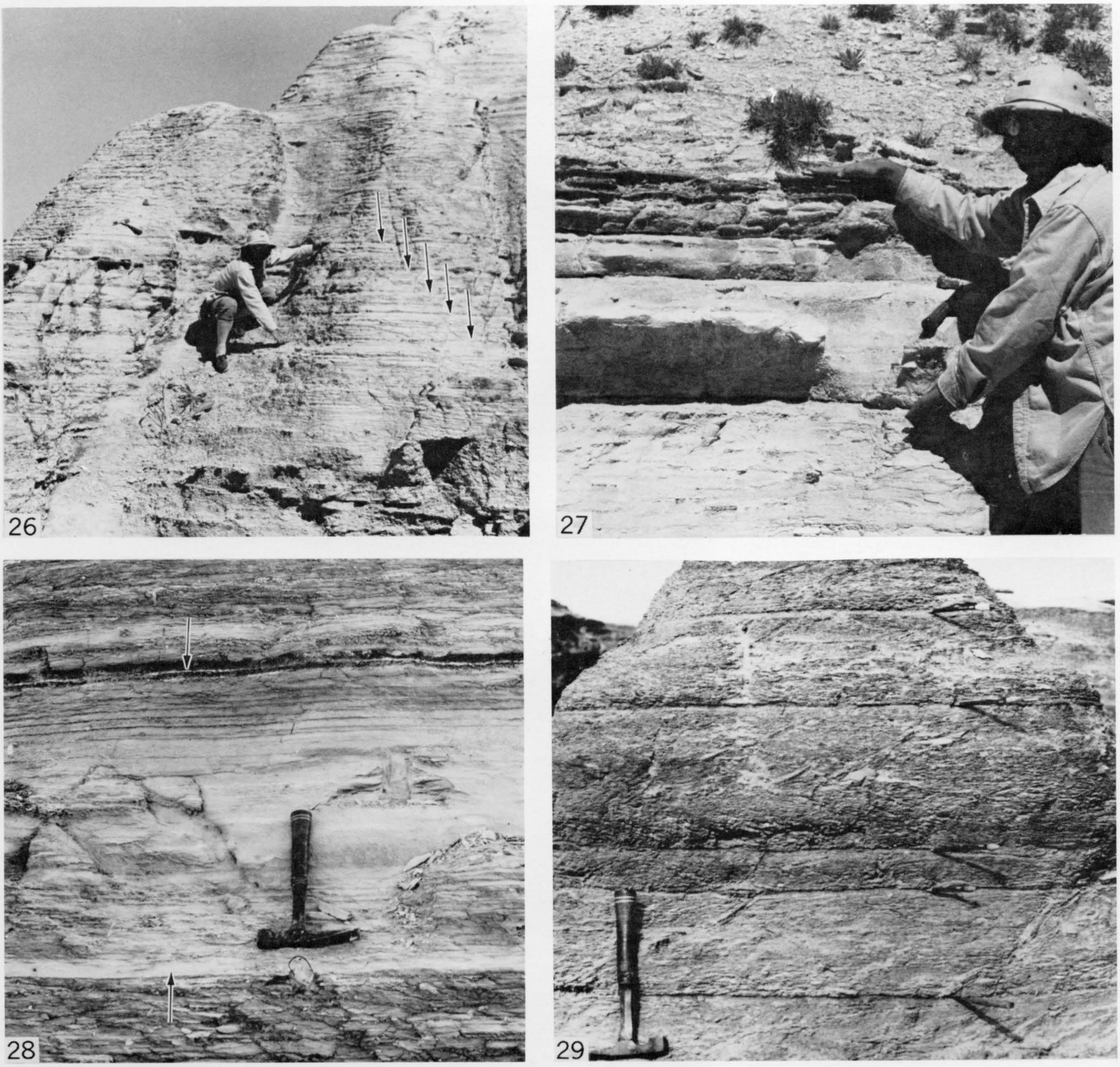
Marker Unit 9. Two bentonite seams separated by 0.71 to 1.0 m (2.35-3.28 ft) of poorly laminated chalk, in the middle of which lies a bioturbated chalk bed 9.2 cm (0.3 ft) thick (Fig. 15). In little- or partly weathered sections the bioturbated chalk bed forms a prominent white band on the outcrop (Fig. 15), and in much-weathered exposures forms a projecting ledge in cliff faces. The lower bentonite seam is 0.9 to 1.2 cm (0.03-0.04 ft) thick; the upper bentonite seam is 0.3 to 1.2 cm (0.01-0.04 ft) thick. The marker unit embraces the lower part of the ranges of *Clioscaphites choteauensis* and *Inoceramus balticus,* and is conspicuous for abundance of *Pseudoperna congesta* and *I. (Platyceramus) platinus,* which are also abundant in the first foot (1/3 m) of chalk above the marker unit. This marker lies 5.2 m (17 ft) above Marker Unit 8, and 85.8 m (281.4 ft) above the base of the composite section.

Marker Unit 10. Approximately 6.7 m (22 ft) of tough, poorly stratified, partly bioturbated, somewhat granular-looking chalk, which in little-weathered exposure forms a smooth, buttressed slope that is lighter colored than adjacent chalk beds (Fig. 17). In highly weathered exposures this unit forms very pale orange (10YR8/2) to grayish orange (10YR7/4) lichen-splotched, cavernously weathered caprocks on erosional remnants of the chalk. This unit is the main caprock-forming unit of the Smoky Hill Member and caps such well-known features as Castle Rock (Fig. 3), Monument Rocks (Fig. 25), the Sphynx and Cobra Rock in Gove County, and Chalk Bluff (Fig. 4) in Logan County. This marker is overlain directly by the distinctive bentonite cluster in Marker Unit 11 and is underlain by a sequence of five very thin, subequally spaced bentonite seams in a 0.8 m (2.7 ft) thickness of tough, poorly laminated chalk (Fig. 26). The thick caprock-forming marker unit contains the upper part of the range of the *Clioscaphites choteauensis* Range Zone. This marker unit lies 1.94 m (6.4 ft) above Marker Unit 9, and 88.5 m (290.3 ft) above the base of the composite section.

Marker Unit 11. Four bentonite seams in a 0.55 to 0.76 m (1.8-2.5 ft) thickness, separated by beds of tough, bioturbated chalk (Fig. 27). The thin, basal bentonite seam is 3 to 6 mm (0.01-0.02 ft) thick and is overlain by 0.29 to 0.43 m (0.95-1.4 ft) of massive chalk, which forms a minor ledge in some exposures. The second and third bentonite seams are also very thin (6-12 mm [0.02-0.04 ft]). The uppermost bentonite seam is locally as much as 2.7 cm (0.09 ft) thick, but together with associated iron oxide and gypsum the seam reaches 7.6 cm (0.25 ft) locally. The second, third, and fourth bentonite seams are separated by 9.1 to 12.2 cm- (0.3-0.4 ft) thick beds of tough, massive, bioturbated chalk. Marker Unit 11 is readily recognizable not only by the distinctive bentonite sequence but also by association with the main caprock-forming unit. The marker lies directly on Marker Unit 10, and 95.7 m (312.3 ft) above the base of the composite section.

Marker Unit 12. A pair of bentonite seams separated by 6.7 to 15.3 cm (0.22-0.5 ft) of laminated chalk, all in a total thickness of 8.8 to 22.5 cm (0.29-0.74 ft) (Fig. 13). The lower bentonite is the more prominent, and is 2.1 to 3.3 cm (0.07-0.11 ft) thick, but together with associated ferruginous and gypsiferous matter the seam may reach a total thickness of 6.7 cm (0.22 ft). The upper seam is merely a moderate reddish brown (10R4/6) to light brown (5YR5/6) ferruginous streak, probably a weathered bentonite, which is a maximum of 6 mm (0.02 ft) thick but in places is only a fraction of that thickness. This marker is not distinguished by associated fossils or adjacent bentonite seams, but a 0.27 to 0.43 m- (0.9-1.4 ft) thick bed of medium to dark yellowish brown (10YR5/2, 10YR4/2) laminated chalk lies shortly above the midpoint between Marker Unit 11 and Marker Unit 12. The latter lies 5.4 m (17.8 ft) above Marker Unit 11, and 101.2 m (331.9 ft) above the base of the composite section.

Marker Unit 13. Two seams of bentonite(?) and ferruginous and gypsiferous material, separated by 3.7 cm (0.12 ft) of laminated chalk. The lower seam is 1.8 cm (0.06 ft) thick and is composed mostly of iron oxide and gypsum. The upper seam is 1.2 cm (0.04 ft) thick and is



FIGURES 26-29. **26,** Group of five bentonite seams (arrows), which underlie buttress- and (above) caprock-forming chalk of Marker Unit 10, Sec. 1, T.14S, R.26W, Gove County, Kansas. Allen Archer's hands are on lowermost and uppermost seams. **27,** Group of four bentonite seams and intervening chalk beds that comprise Marker Unit 11, Sec. 1, T.14S, R.26W, Gove County, Kansas. Allen Archer's hands are on lowermost and uppermost seams. **28,** Marker Unit 15, Sec. 16, T.15S, R.34W, Logan County, Kansas, comprising light-colored band of granular chalk (lower arrow) and a bentonite seam (upper arrow), separated by interval of laminated and nonlaminated chalk. Hammer is 28 cm long. **29,** Marker Unit 17, Sec. 27, T.13S, R.35W, Logan County, Kansas. Knife (bottom) and four pencils mark the five bentonite seams.

also composed mostly of iron oxide and gypsum. Laminated chalk lying both below and above the marker, through a thickness of several meters, contains numerous distinctive specimens of *Inoceramus (Platyceramus) platinus,* which are usually less than 31 cm (1.0 ft) in maximum dimension and show particularly well the quadrate form of the shell. Peripheral portions of the valves, which are much thicker than the central portions, are abundant on eroding slopes adjacent to the marker unit. A very thin bentonite seam lies 2.3 m (7.4 ft) above the marker. Marker Unit 13 lies 10.3 m (33.9 ft) above Marker Unit 12 and 111.7 m (336.4 ft) above the base of the composite section.

Marker Unit 14. Two very thin seams of bentonite and a conspicuous bed of organic-rich chalk, which is darker colored than the adjacent laminated chalk beds, all in a 0.8 m- (2.6 ft) thick interval. The two bentonite seams are very thin (less than 3 mm [0.01 ft]), both seams consisting mostly of iron oxide and gypsum. Together with associated secondary mineral matter the lower seam is 0.6 to 1.5 cm (0.02-0.05 ft) thick and the upper ranges from less than 3 mm to 6 mm (0.01-0.02 ft) in thickness. The bentonite seams are separated by 18.3 to 21.3 cm (0.6-0.7 ft) of obscurely laminated chalk. The associated brown, organic-rich chalk lies 0.3 to 0.41 m (1.0-1.35 ft) above the upper bentonite seam. This darker-colored chalk bed forms a conspicuous dark band on eroded slopes (Fig. 14). In little-weathered exposures the marker unit is identified further by the presence 0.41 m (1.4 ft) above the organic-rich chalk bed of a prominent bed of tough, granular chalk 0.49 m (1.6 ft) thick, which is conspicuously lighter in color than the directly adjacent chalk. The dark-colored and light-colored beds together are visible from a considerable distance and can be traced readily across the outcrop (Fig. 14). Marker Unit 14 lies 6 m (19.5 ft) above Marker Unit 13, and 117.7 m (386.1 ft) above the base of the composite section.

Marker Unit 15. A 3.0 to 4.6 cm- (0.1-0.15 ft) thick bed of tough, granular chalk and a very thin, very light colored bentonite seam, separated by a 0.49 to 0.52 m- (1.6-1.7 ft) interval of both well-laminated, darker-colored chalk and granular, lighter-colored chalk (Fig. 28). The lower marker chalk bed forms a conspicuous, thin, nearly white band on little-weathered exposures. The bentonite seam is approximately 0.9 cm (0.03 ft) thick, white to very pale orange (10YR8/2), and is hard and brittle locally. Together with bounding crusts of associated iron oxide and gypsum the seam is locally as much as 5.5 cm (0.18 ft) thick. The intervening laminated chalk is darker-colored at the top and bottom, and lighter-colored, tough, and granular in the middle. A pair of very thin bentonite seams, separated by 12.3 to 15.3 cm (0.4-0.5 ft) of chalk, lies 1.6 to 1.8 m (5.3-6.0 ft) above the marker unit and aids in identification of the marker. Chalky strata lying adjacent to the marker contain few macroinvertebrate fossils. Marker Unit 15 lies 13.7 m (45 ft) above Marker Unit 14, and 132.2 m (433.7 ft) above the top of the composite section.

Marker Unit 16. Two bentonite seams and a ferruginous seam in an interval that is 0.27 to 0.37 m (0.9-1.2 ft) thick and lies near the top of a thick chalk interval that is conspicuously light- and dark-banded (Fig. 12). The lowest bentonite seam is as much as 1.8 cm (0.06 ft) thick and is separated from the second bentonite seam by 6.1 to 7.6 cm (0.2-0.25 ft) of chalk. The second bentonite seam is 0.6 to 1.5 cm (0.02-0.05 ft) thick, consists largely of ferruginous and gypsiferous material, and is overlain by 18.3 to 24.4 cm (0.6-0.8 ft) of chalk. The top of this marker is a ferruginous seam, probably a highly weathered, very thin bentonite seam, which is 0.3 to 0.9 cm (0.01-0.03 ft) thick. Identification of this marker is aided by association with conspicuously light- and dark-banded chalk and by the presence of two additional bentonite seams, separated by 0.29 to 0.34 m (0.95-1.1 ft) of chalk, the upper of which is the thicker and lies 1.4 to 1.6 m (4.6-5.4 ft) below the marker unit. This part of the section contains very few macroinvertebrate fossils. The marker unit lies 11.9 m (39.1 ft) above Marker Unit 15, and 145 m (474.5 ft) above the base of the composite section.

Marker Unit 17. Five very thin seams of bentonite in an interval of mostly crinkly bedded chalk 0.37 to 0.61 m (1.2-2.0 ft) thick. The bentonite seams are subequally spaced through the interval, with the second and third seams being closest together. The seams may be associated with ferruginous and/or gypsiferous material, and locally contain no discernable flakes of bentonite. In eroding badlands the five bentonite seams form a group of distinctive reentrants that can be traced as a group across the outcrop (Fig. 29). Two prominent bentonite seams lying 0.4 to 0.49 m (1.3-1.6 ft) apart, and separated by a chalk interval that contains a very thin seam of bentonite in its upper half, lie shortly higher in the section, and aid in identification of the marker unit. The lower of these two bentonite seams lies 0.78 to 1.1 m (2.5-3.7 ft) above the marker unit and is thinner than the upper bentonite, which is 3.0 to 4.6 cm (0.1-0.15 ft) thick. The marker unit lies at the base of a 3 m- (10 ft) thick interval that contains at least 13 bentonite seams. Marker Unit 17 lies 2.6 to 3.0 m (8.6-9.8 ft) above Marker Unit 16, and 147.6 m (484 ft) above the base of the composite section.

Marker Unit 18. Two relatively thick and prominent bentonite seams, separated by 0.34 to 0.49 m (1.1-1.6 ft) of obscurely laminated to laminated chalk, which forms a minor resistant ledge in highly weathered exposures (Fig. 18). The lower bentonite seam is 3.3 to 6.1 cm (0.11-0.2 ft) thick; the upper seam is 7.0 to 11.6 cm (0.23-0.38 ft) thick. These are among the thickest bentonite seams in the entire Smoky Hill Member, and the only two of such large thickness that are so close together stratigraphically. A bentonite seam 1.5 to 2.4 cm (0.05-0.08 ft) thick lies 0.98 to 1.2 m (3.2-3.9 ft) below the marker unit, and a pair of very thin bentonite seams, separated by 5.5 cm (0.18 ft) of chalk, lie 0.39 to 0.7 m (1.3-2.3 ft) above the marker. The upper of these two bentonites is the thicker; in places the lower seam is represented only by a seam of iron oxide. Marker Unit 18 lies 4.5 to 5.4 m (14.6-17.8 ft) above Marker Unit 17, and 152.4 m (499.8 ft) above the base of the composite section.

Marker Unit 19. Five very thin bentonite seams in an interval 1.0 to 1.1 m (3.2-3.6 ft) thick and separated by beds of rather massive chalk. The lowest two seams are a maximum of 6 mm (0.02 ft) thick and are separated by 2.1 cm (0.07 ft) of chalk. This pair of bentonites lies 0.73 to 0.82 m (2.4-2.7 ft) below the third bentonite seam, which is also 6 mm (0.02 ft) or less in thickness. The fourth bentonite is 3 to 6 mm (0.01-0.02 ft) thick and is separated from the third bentonite seam by 18.3 to 19.8 cm (0.6-0.65 ft) of chalk. The uppermost of the five bentonite seams is 0.9 cm (0.03 ft) thick and is separated from the fourth seam by 3.6 cm (0.12 ft) of chalk. The distinctive pairing of the lowest two and upper two seams in such a small stratigraphic interval is unique in the Smoky Hill Member and serves, together with the central bentonite seam, to identify the marker unit. Poor stratification of associated chalk beds and paucity in them of macroinvertebrate fossils are further characteristics of the marker. This marker unit lies 5.6 m (18.5 ft) above Marker Unit 18, and 158.7 m (520.5 ft) above the base of the composite section.

Marker Unit 20. Four seams of bentonite in a 0.82 m (2.7 ft) interval, separated by beds of tough, ledge-forming chalk or chalky limestone (Fig. 30). The lowest two seams are 0.6 and 1.5 cm (0.02 and 0.06 ft) thick, respectively, and are separated by 1.5 cm (0.06 ft) of chalk. The third bentonite is 9 mm (0.03 ft) thick and is separated from the second bentonite by 0.52 cm (1.7 ft) of chalk, which contains a 3 mm (0.01 ft) seam of powdery gypsum 9.1 cm (0.3 ft) above its base. This thicker chalk bed has been quarried locally for building stone (see Merriam, 1963, pl. 3C). In highly weathered sections the powdery gypsum seam appears only as a small reentrant on the chalk face. The fourth bentonite seam is 9 mm (0.03 ft) thick and is separated from the third seam by 24.3 cm (0.79 ft) of chalk. The pairing of the two lowest bentonites, the distinctive spacing of all four seams, and the resistant character of associated chalk or chalky limestone beds is unique in the Smoky Hill Member. This interval contains few macroinvertebrate fossils. Marker Unit 20 lies 2.1 m (7.0 ft) above Marker Unit 19, and 161.9 m (531.1 ft) above the base of the composite section.

Marker Unit 21. A 2.2 m- (7.3 ft) thick bed of tough, granular chalk or chalky limestone that is only crudely stratified and tends to form a smooth, buttress-like slope where partly weathered, and is a distinctive moderate reddish orange (10R6/6) color where highly weathered. The uppermost part of this interval is a major bench former in badlands. From a distance the unit appears thinly stratified, but the rock is not well laminated. The upper part of this unit contains molds of a very large, smooth species of *Baculites* and large specimens of *Inoceramus balticus* Böhm. A similar unit, 2.0 m (6.7 ft) in thickness, overlies the marker bed but from a distance appears distinctly laminated and the rock weathers shaly in part. The marker unit lies directly on a 9 mm- (0.03 ft) thick seam of ferruginous and gypsiferous bentonite. A similar seam, 2.7 cm (0.09 ft) in thickness, lies 2.0 m (6.7 ft) above the marker. Marker Unit 21 lies 2.7 m (9.0 ft) above Marker Unit 20, and 165.5 m (542.8 ft) above the base of the composite section.

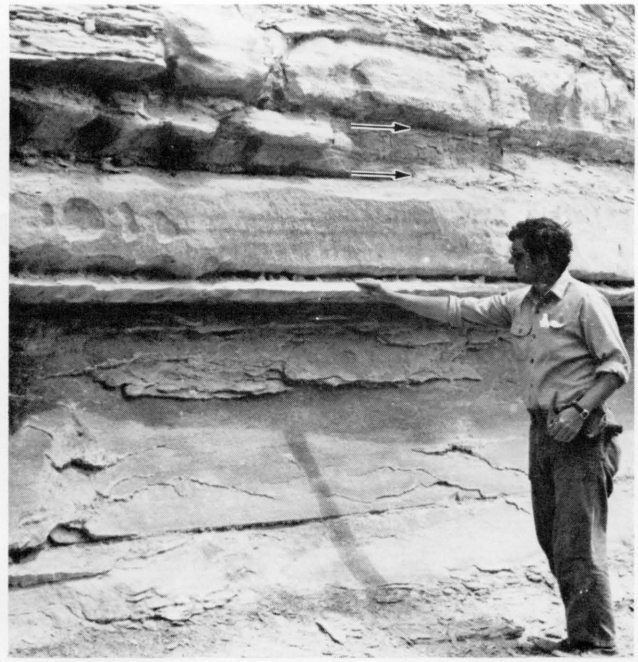


FIGURE 30. Marker Unit 20, Sec. 20, T.15S, R.32W, Logan County, Kansas. The pair of very thin bentonite seams at base of marker interval is beneath the lowest overhanging ledge, just below Cal James' hand. The third and fourth bentonite seams are indicated by arrows. A powdery gypsum seam lies just above Cal's hand, and forms a prominent reentrant.

Marker Unit 22. A medium dark gray (N4) bentonite bed 11.6 cm (0.38 ft) thick and lying in the midst of a soft-weathering chalk interval that is characterized by abundance of beds with crinkly structure. A very thin bentonite seam lies 0.64 m (2.1 ft) below the marker and another bentonite seam 2.4 cm (0.08 ft) thick lies 0.4 m (1.3 ft) above the marker. This marker lies 6.25 m (20.5 ft) below the Smoky Hill-Pierre contact, and Smoky Hill strata above the marker are characterized by no less than 11 additional bentonite seams, which are spaced at intervals ranging from 0.2 to 0.76 m (0.65-2.5 ft). The marker is the only relatively thick bentonite seam in the upper 7.6 m (25 ft) of the Smoky Hill. Marker Unit 22 lies 6.4 m (21 ft) above Marker Unit 21, and 174.1 m (571.1 ft) above the base of the composite section.

Marker Unit 23. A bentonite seam 4.9 cm (0.16 ft) thick that lies 24.4 cm (0.8 ft) below the Niobrara-Pierre contact (Fig. 7). Beginning approximately 3.9 m (10.0 ft) below the top of the Smoky Hill, the member grades stratigraphically upward from predominantly flaky-weathering, crinkly chalk through chalky shale into calcareous shale that contains a few thin intervals of noncalcareous shale. The marker unit can be identified by association with this less calcareous part of the member and by proximity to the Pierre Shale. The Smoky Hill-

Pierre contact lies at the top of the calcareous sequence, overlying Pierre strata consisting of olive black to dark olive gray (5Y2/1, 5Y3/1), silty, flaky-weathering, noncalcareous shale. A very thin, nearly white seam of bentonite, 6 mm (0.02 ft) thick, lies 0.32 m (1.05 ft) above the base of the Pierre Shale and makes a conspicuous white band on eroded slopes. Marker Unit 23 lies 7.2 m (23.7 ft) above Marker Unit 22, and 181.5 m (595.2 ft) above the base of the composite section. Total thickness of the composite section is 181.8 m (596.3 ft).

Physical Correlation

Detailed published information for the entire Smoky Hill is available for only one other complete stratigraphic section, that of Scott and Cobban (1964) for exposures along the Arkansas River valley at and shortly west of Pueblo, Colorado. The Pueblo section contains numerous bentonite seams and very thin ferruginous seams (probably weathered, very thin bentonites) not recorded by Scott and Cobban, so the reported bentonite sequence cannot at this time be matched precisely with that of the Kansas Smoky Hill. However, my own examination of the Pueblo section confirms direct correlation of several composite-section marker units, as follows:

1. The lower part of the lower limestone unit, including beds 1 through 9 of Scott and Cobban (1964, p. 13) are equivalent to Marker Unit 3 of Kansas.
2. Beds 21 and 22 of the lower limestone unit (Scott and Cobban, 1964, p. 13) are equivalent to Marker Unit 4 of Kansas.
3. Beds 1 and 2 of the middle chalk unit (Scott and Cobban, 1964, p. 17) are equivalent to at least the upper half of Marker Unit 10 of Kansas.
4. Beds 3 through 6 of the middle chalk unit (Scott and Cobban, 1964, p. 17) are equivalent to most of Marker Unit 11 of Kansas.
5. Beds 47, 48, and 49 of the upper chalky shale unit (Scott and Cobban, 1964, p. 20) are equivalent to Marker Unit 18 of Kansas.
6. The upper chalk unit (Scott and Cobban, 1964, p. 21) is equivalent to Marker Unit 21 of Kansas.
7. At Pueblo, Colorado, the basal part of the Pierre Shale comprises calcareous shale through which are scattered several seams of bentonite. Called "unnamed transition member" of the Pierre by Scott and Cobban (1964, p. 23), these strata are equivalent to Smoky Hill strata lying above Marker Unit 21 of Kansas. A seam of bentonite 12.2 cm (0.4 ft) thick, and lying 5.9 m (19.2 ft) above the base of the transition member, is equivalent to Marker Unit 22 of Kansas.

In addition to the above, beds 11 through 20 of the lower shale unit (Scott and Cobban, 1964, p. 11) include two closely spaced limonite seams and two bentonite seams, which represent Marker Unit 2 of Kansas.

Collectively these physical correlations of the Kansas and Pueblo sections furnish a chronological framework that reinforces correlations based on macroinvertebrate fossil zones. Further study of the thick middle shale unit of Scott and Cobban (1964, p. 13) should serve to identify additional markers in the interval that correlates with that part of the Kansas section containing Marker Units 5 through 9.

BIOSTRATIGRAPHY

Western Interior Standard Zonation

Intensive study of Cretaceous macroinvertebrate fossils has brought biostratigraphic subdivision of U.S. Western Interior strata to a high degree of refinement. In a classic contribution to Western Interior stratigraphy, Cobban and Reeside (1952) established a zonal scheme that has wide application in marine beds of this richly fossiliferous region. The standard zonal sequence has been revised several times since that date, the more important contributions to Niobrara biostratigraphic refinement being those by Cobban and others (1962), Scott and Cobban (1962), Cobban (1962, 1964, p. 24, 1969), Scott and Cobban (1964, p. 24), Gill and Cobban (1966, p. 35), and Kauffman (1975, 1977, p. 82, 83). The standard Western Interior zonation, embracing strata of the Niobrara Chalk (= Niobrara Formation of Colorado), is shown in Table 2.

Chronologic Comparison of Pueblo, Colorado, and Kansas Sections

Both base and top of the Niobrara are regionally diachronous (e.g., Cobban, 1964; Hattin, 1975a) so that different zonal indices occur in lowermost and uppermost beds, depending upon geographic location. In the Pueblo, Colorado, section, Scott and Cobban (1964) recorded *Inoceramus* aff. *I. perplexus* (uppermost Turonian) in basal beds of the formation, whereas in central Kansas the basal beds contain *Inoceramus deformis (Scaphites depressus* Range Zone—Lower Coniacian) and in northeastern Nebraska the basal beds contain *I. (Volviceramus) grandis* (Hattin, 1975a). The base of the formation therefore ascends chronologically from southwest to northeast. Similarly, the top of the Niobrara ascends chronologically in a southeastward direction from central Montana and north-central Wyoming to the Black Hills area and

TABLE 2. Standard Western Interior biostratigraphic zones for the Niobrara and equivalent strata.

STAGES		ZONAL INDICES	ASSOCIATED SPECIES*
Campanian	Lower (part)	*Haresiceras natronense*	*Scaphites hippocrepis* (fine-ribbed form)
		Haresiceras placentiforme	*Scaphites hippocrepis* (coarse-ribbed form)
		Haresiceras montanaense	*Scaphites hippocrepis* (coarse-ribbed form)
Santonian	Upper	*Desmoscaphites bassleri*	*Haresiceras mancosense* (late form)
		Desmoscaphites erdmanni	*Haresiceras mancosense* (early form) *Clioscaphites novimexicanus*
	Middle	*Clioscaphites choteauensis*	*Inoceramus (Endocostea) balticus**
		Clioscaphites vermiformis	*Inoceramus cordiformis**
		Clioscaphites saxitonianus	*Inoceramus (Cladoceramus) undulatoplicatus**
	Lower	*Scaphites depressus*	*Protexanites shoshonensis, Scaphites binneyi, Inoceramus stantoni**
Coniacian	Upper	*Scaphites ventricosus*	*Inoceramus (Volviceramus) grandis**
	Lower	*Scaphites preventricosus*	*Inoceramus deformis*
			Inoceramus erectus (late form)
		Barroisiceras, Peroniceras	*Inoceramus erectus* s.s.
Turonian	Upper part	*Scaphites corvensis*	*Prionocyclus quadratus* *Inoceramus* aff. *I. perplexus*

* Associated species marked * are not restricted to the zone.

beyond (Cobban, 1964), the uppermost beds climbing in that region from the zone of *Desmoscaphites erdmanni* (lower Upper Santonian) to the zone of *Haresiceras placentiforme* (Lower Campanian). Physical evidence demonstrates that the Niobrara-Pierre contact also ascends chronologically from Pueblo, Colorado, to the Smoky Hill River outcrop. At Pueblo, the unnamed transition member of the lower Pierre Shale contains a bentonite seam, which in Kansas lies within chalk of the Smoky Hill, well below the Niobrara-Pierre contact. Furthermore, beds equivalent to the uppermost Niobrara at Pueblo (upper chalk unit of Scott and Cobban, 1964) lie 12.8 m (42 ft) below the Niobrara-Pierre contact in the Smoky Hill composite section of Kansas.

At Pueblo (Scott and Cobban, 1964) the Fort Hays-Smoky Hill contact lies within the zone of *Inoceramus deformis* but in the Smoky Hill composite section this contact lies approximately at the base of the *I. (Volviceramus) grandis* Range Zone, which is separated from that of *I. deformis* by the zones of *Inoceramus (Cremnoceramus) browni* and *Inoceramus koeneni*. This places the contact close to the Lower/Upper Coniacian boundary. Sixty-five km (40 mi) east of Pueblo, *Haresiceras placentiforme* occurs near the top of the Smoky Hill Member (Scott and Cobban, 1964, p. 20), which indicates an Early Campanian age. The upper chalk unit of Scott and Cobban (1964, p. 21) and overlying unnamed transition member of the Pierre Shale have not yielded diagnostic fossils in southeastern Colorado, nor have equivalent parts of the Smoky Hill Member in Kansas, but these beds are also assignable to the Lower Campanian because in both areas Lower Campanian fossils are known in slightly younger strata of the Pierre.

Biostratigraphy of Smoky Hill Member in Kansas

Except for smooth molds of *Baculites,* ammonites have been recorded only sparingly in the Kansas Smoky Hill. Of the standard zonal indices only *Clioscaphites vermiformis* and *C. choteauensis* have been identified positively, and the former is known only from a few imperfect specimens. Comparison of the Kansas section with the Western Interior biostratigraphic standard is thus based largely on the sequence of inoceramid bivalve species, most of which are well preserved and relatively common. A listing of the most useful Kansas zone fossils, together with associated species, is presented in Table 3. Known ranges of Smoky Hill macroinvertebrate species are depicted in Figure 31. Species recorded in the field during the course of this study are illustrated in Plates 2-9.

Apparent absence of eight scaphite zonal indices in Kansas could be owing to (1) incomplete field data, (2) lack of preservation, or (3) lack of scaphites in western Kansas during much of Smoky Hill deposition. The Smoky Hill Member has been the object of fossil searches for generations, but only *Clioscaphites choteauensis* has been recorded reliably in previous literature (Miller, 1968, p. 45). The single specimen (now lost) of *Clioscaphites vermiformis* reported by Morrow (1931) was from the Monument Rocks exposure in Gove County. Beds at that locality are in the zone of *Clioscaphites choteauensis,* to which species Morrow's specimen probably belonged. I have visited repeatedly exposures that are the basis for the Smoky Hill composite section, and have tried systematically to examine bedding surfaces through all measured units. The poor record of scaphites thus seems not to be

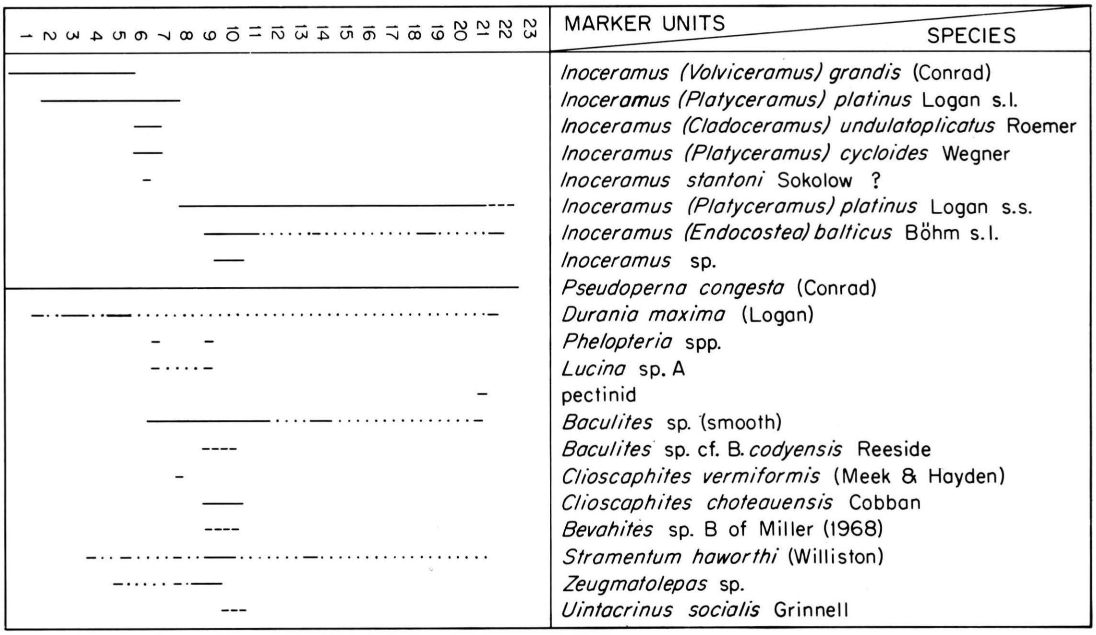


FIGURE 31. Species ranges of macroinvertebrate body fossils in the Smoky Hill type area. Only species for which sound stratigraphic evidence is available are plotted on this chart. Dotted parts of ranges designate intervals for which no specimens were recorded. Dashed ranges or parts of ranges indicate uncertainty regarding exact extent of range. Ranges of *Baculites* sp. cf. *B. codyensis, Bevahites* sp. B, and upper part of *Lucina* sp. range are based on Miller (1968). Range of *Uintacrinus socialis* is based on statements by Williston (1897) and Springer (1901). Extension of *Stramentum haworthi* range above Marker Unit 13 is based on specimens in pink chalk, from upper part of member, in collection of Sternberg Memorial Museum, Fort Hays Kansas State University. All other data are based on observations by the author. Range for *Pseudoperna congesta* embraces all small epizoic oysters recorded by the author; very small numbers of specimens have been attributed to two other species (Miller, 1968), for which stratigraphic data are not available.

TABLE 3. Biostratigraphic zonation of the Smoky Hill Member in Kansas.

STANDARD ZONATION	KANSAS ZONATION	ASSOCIATED SPECIES
Haresiceras natronense *Haresiceras placentiforme* *Haresiceras montanaense* *Desmoscaphites bassleri* *Desmoscaphites erdmanni*	*Inoceramus (Endocostea) balticus* s.l.	*I. (Platyceramus) platinus* *Baculites* sp. (smooth)
Clioscaphites choteauensis	*Clioscaphites choteauensis*	*Baculites* sp. (smooth) *Phelopteria* sp. *I. (Platyceramus) platinus* *I. (Endocostea) balticus* s.l.
Clioscaphites vermiformis	*Clioscaphites vermiformis*	*Baculites* sp. (smooth) *Inoceramus (Platyceramus) platinus*
Clioscaphites saxitonianus	*Inoceramus (Cladoceramus) undulatoplicatus*	*I. stantoni* *I. (Platyceramus) cycloides* *I. (Platyceramus) platinus* s.l.
Scaphites depressus *Scaphites ventricosus*	*Inoceramus (Volviceramus) grandis*	*I. (Platyceramus) platinus* s.l.

the result of poor collecting. In Kansas *Clioscaphites choteauensis* is not only common through several meters of strata that represent its zone but is also preserved excellently (Pl. 8, 6). In contrast, *C. vermiformis,* whilst reasonably well preserved, is much less common than *C. choteauensis*. Paucity of the former thus seems related more to originally small numbers of specimens than to poor preservation. The excellent preservation of *Baculites* molds in many intervals between the base of the *C. choteauensis* zone and Marker Unit 22 demonstrates the preservability of originally aragonitic ammonites at least in some strata where scaphites might be expected. The general absence of scaphites is, therefore, not attributed to lack of preservation. From stratigraphic evidence now available, I conclude *tentatively* that conditions in the water column were favorable for scaphitid ammonites only during deposition of the *S. vermiformis* and *C. choteauensis* zones, and that near absence of scaphitids, and indeed most other ammonites, through most of the Smoky Hill, is owing to environmental factors in the water column. It must be noted, however, that the Smoky Hill lacks the sort of hard limestone beds and concretions in which scaphites are so commonly preserved in the Western Interior, and that even the common species *C. choteauensis* was not recorded in Kansas until 1958 (Miller). Further search may yet serve to turn up some of the other zonal species of scaphites.

Not shown on the range chart (Fig. 31) or on Plates 2-9 are many named macroinvertebrate species for which little or no stratigraphic data are available. Most of these forms are described and illustrated in the work of Miller (1968) and include:

- *Ostrea exogyroides* Logan
- *Ostrea rugosa* Logan
- *Pecten bonneri* Miller
- *Spinaptychus sternbergi* Fischer and Fay
- *Actinocamax* sp. aff. *A. laevigatus* Arkhangelsky
- *Actinocamax sternbergi* Jeletzky
- *Actinocamax walkeri* Jeletzky
- *Tusoteuthis longa* Logan
- *Niobrarateuthis bonneri* Miller
- *Niobrarateuthis walkeri* Green
- *Calantica (Titanolepas) martini* Withers
- *Serpula intrica* White
- *Serpula tenuicarinata* Meek & Hayden

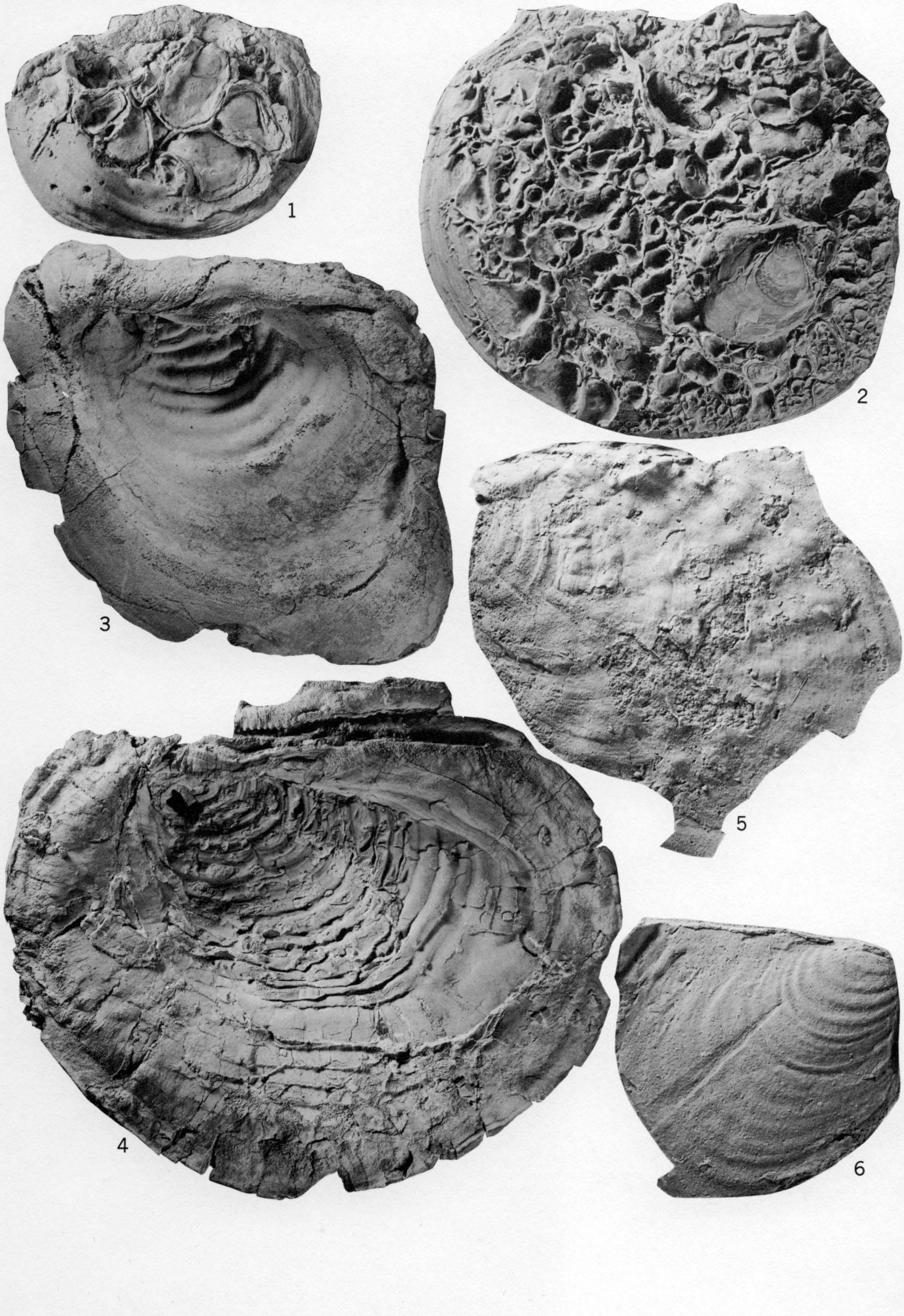
All of the above-named species are rare, some are known from only a single specimen, and for some the locality data are unknown.

EXPLANATION OF PLATE 2

Inoceramids of the Smoky Hill Member

1-4, *Inoceramus (Volviceramus) grandis* (Conrad). **1,** Exterior view of upper valve of juvenile, ×1, KU153992, upper part of section at Locality 1. Note encrustation by *Pseudoperna congesta* (Conrad) and circular sponge borings (lower left). **2,** Exterior view of upper valve, ×1, KU153994, upper part of section at Locality 12. Note heavy encrustation by *Pseudoperna congesta* (Conrad). **3,** Interior view of upper valve, ×0.70, KU153990, lower part of Smoky Hill Member at Locality 1. **4,** Interior view of upper valve, ×0.5, KU154027, middle part of section at Locality 17.

5,6, *Inoceramus (Cladoceramus) undulatoplicatus* Roemer. **5,** Internal mold of left valve, ×1.25, KU153998, upper part of section at Locality 13. **6,** Internal mold, right valve of juvenile specimen, ×1.5, KU154008. Note mold of *Endocostea*-like feature.



EXPLANATION OF PLATE 3

Inoceramids of the Smoky Hill Member

1, *Inoceramus (Volviceramus) grandis* (Conrad). External view of upper valve and outer rim (at right) of lower valve of articulated specimen, ×1, KU153991, lower part of Smoky Hill Member at Locality 1.

2, *Inoceramus (Cladoceramus) undulatoplicatus* Roemer. External view of fragment of valve margin, ×0.5, KU153996, middle part of section at Locality 19.

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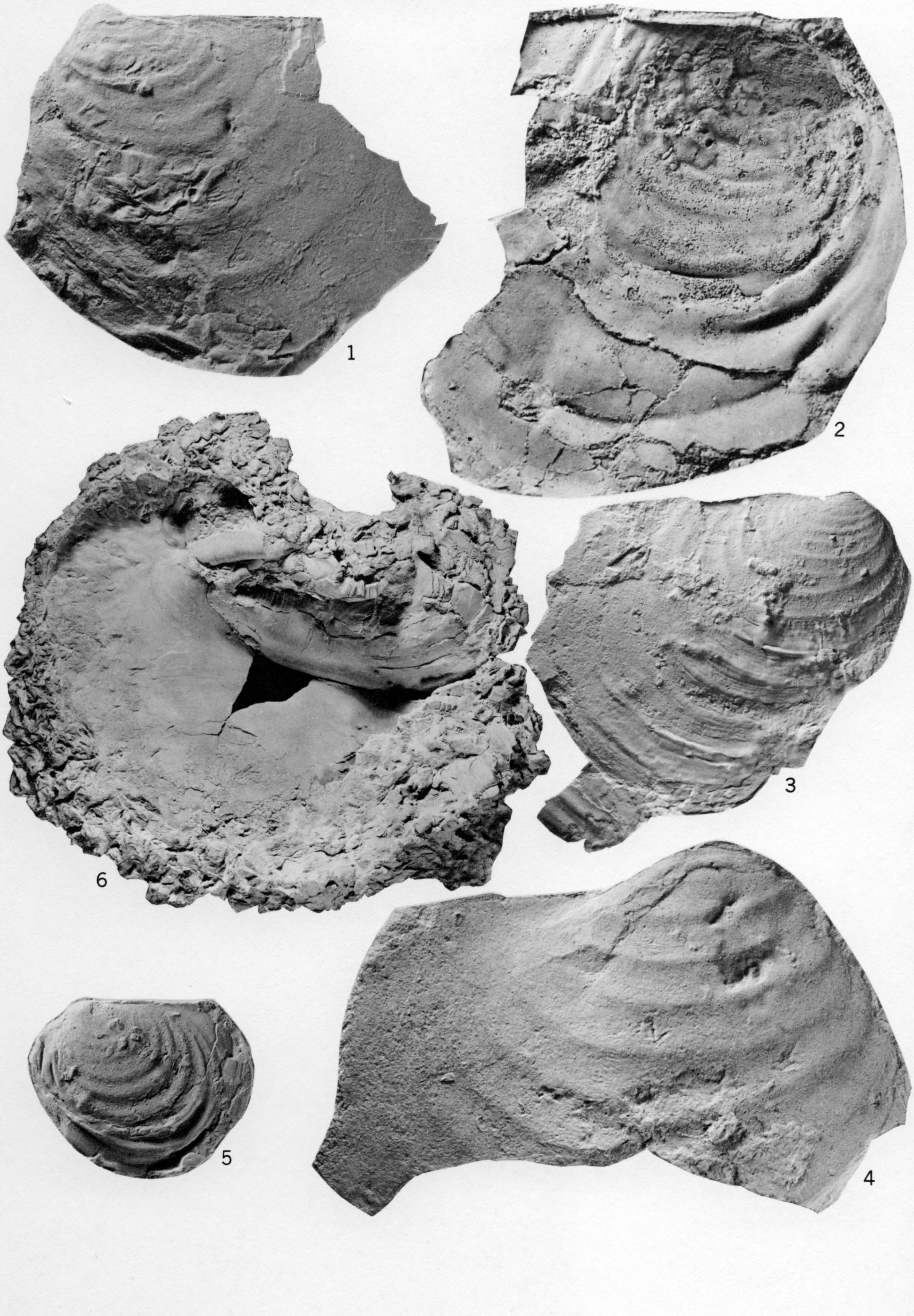
EXPLANATION OF PLATE 4

Inoceramids of the Smoky Hill Member

1-5, *Inoceramus (Endocostea) balticus* Böhm. **1,** Internal mold of left valve, with bits of shell attached (lower left), ×1, KU 154004, middle part of Smoky Hill Member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas. **2,** Interior view of left valve, ×1, KU154003, middle part of section at Locality 21. **3,** Internal mold of right valve, ×⅔, KU154007, middle part of section at Locality 25. **4,** Internal mold of right valve, coarsely ribbed specimen, ×1, KU154006, middle part of section at Locality 25. **5,** Internal mold of left valve, with portion of valve preserved at periphery, ×1, KU154005, middle part of Smoky Hill Member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas.

6, *Inoceramus (Volviceramus) grandis* (Conrad). Interior view of articulated specimen, ×⅓, KU153993, float from slope beneath bed equivalent to unit 12-15, 0.8 km (0.5 mile) south of Locality 12. Neither valve is complete. Note encrustation of external surfaces by *Pseudoperna congesta* (Conrad) all around periphery of specimen.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EXPLANATION OF PLATE 5

Bivalves of the Smoky Hill Member

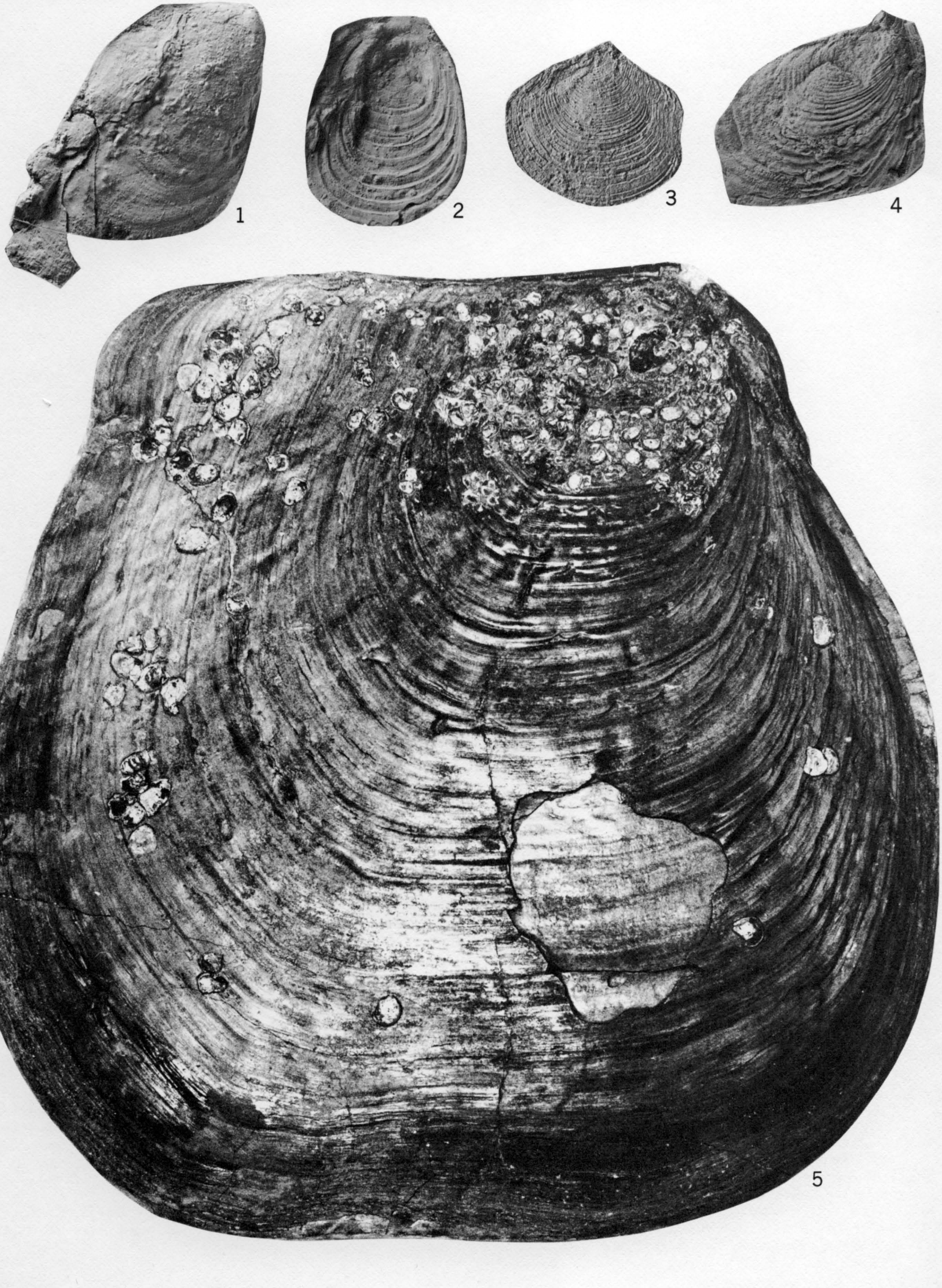
1, *Inoceramus stantoni* Sokolow? Internal mold of right valve, with portion of valve preserved along posterior margin, ×1.5, KU154002, middle part of section at Locality 13.

2, Interior view of valve, unidentified species of pectinid, ×3, KU153997, middle part of section at Locality 21.

3, *Lucina* sp. A. Compressed mold, ×3, KU154018, upper part of section at Locality 13.

4, *Inoceramus* sp. Fragmentary shell and internal mold of right valve, ×1.5, KU154009, middle part of Smoky Hill Member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas.

5, *Inoceramus (Platyceramus) platinus* Logan. Right valve (not coated) of nearly perfect specimen from Sternberg Museum, Fort Hays Kansas State University, approximately ×0.25, FHKSU2086. Specimen collected by G. F. Sternberg.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EXPLANATION OF PLATE 6

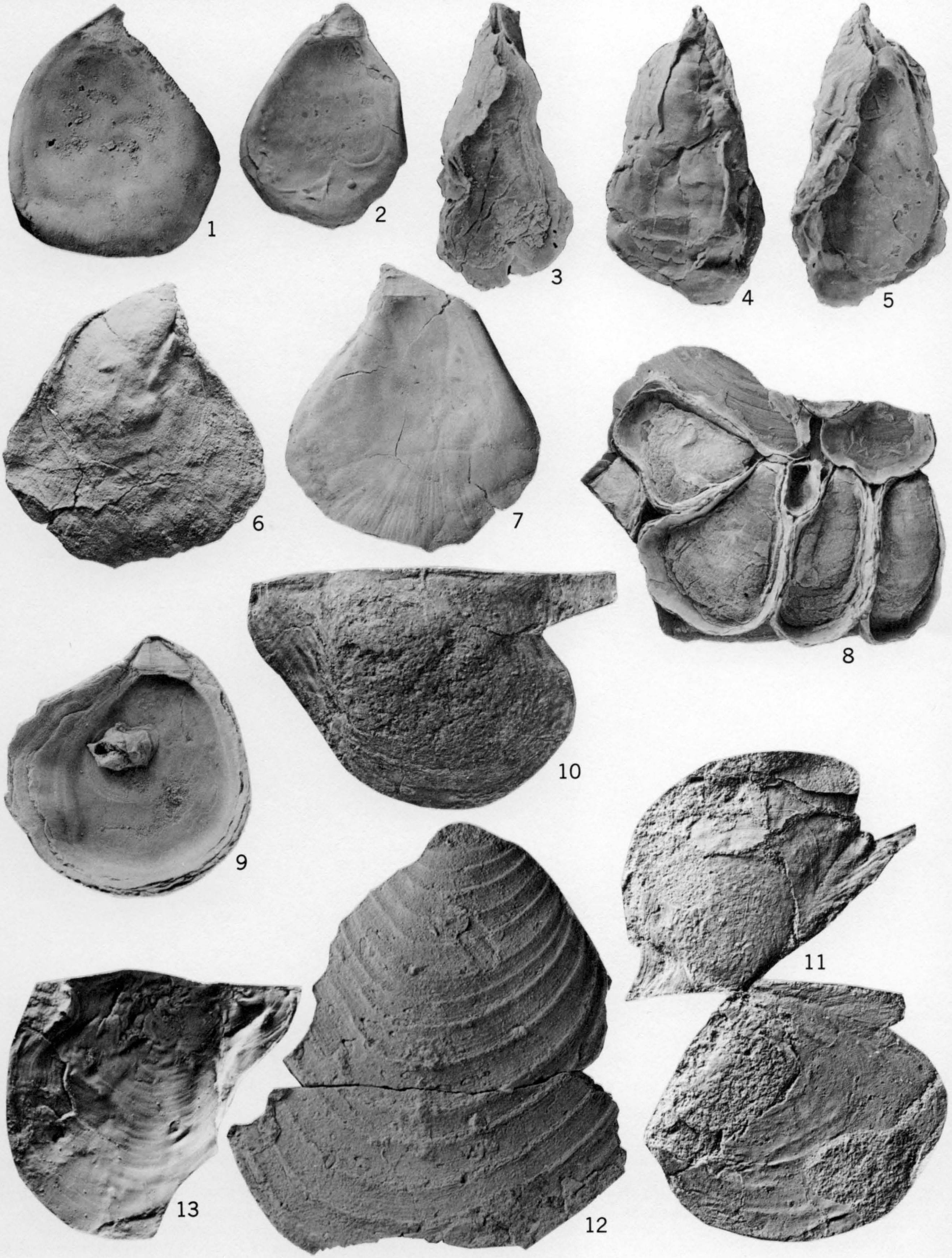
Bivalves of the Smoky Hill Member

1-9, *Pseudoperna congesta* (Conrad). **1,** Interior view of right valve, ×2, KU154012, near middle of section at Locality 18. **2,** Interior view of right valve, ×1, KU154026, float from middle part of member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas. **3,** Right-hand view of articulated specimen, ×1, KU154013, from middle part of member in section exposed in Sec. 15, T.14S, R.26W, Gove County, Kansas. Specimen was attached to a small shell fragment and developed elongate shape as substrate sank into sea-floor ooze. **4,5,** Left-hand (4) and right-hand (5) views of articulated specimen, ×1, KU154014, from same exposure as number 3. Elongate shape as in number 3. **6,7,** Exterior (6) and interior (7) views of right valve, ×2, KU154011, middle part of section exposed at Locality 18. **8,** Cluster of crowded, articulated specimens attached to fragment of inoceramid bivalve, ×1, KU154010, from lower part of member in section exposed in Sec. 21, T.15S, R.26W, Gove County, Kansas. **9,** Interior view of left valve, ×1.5, KU154015, upper part of Smoky Hill section exposed at Locality 1.

10,11, *Phelopteria* sp. B. **10,** Internal mold of left valve, ×3, KU154020, upper part of section at Locality 13. **11,** Internal molds of paired valves, with small bits of shell, ×2, KU154019, upper part of section at Locality 13.

12, *Inoceramus (Platyceramus) cycloides* Wegner. Internal mold of right valve, ×1, KU153999, upper part of section at Locality 13.

13, *Phelopteria* sp. A. Interior view of left valve, ×1, KU154017, middle part of Smoky Hill Member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas.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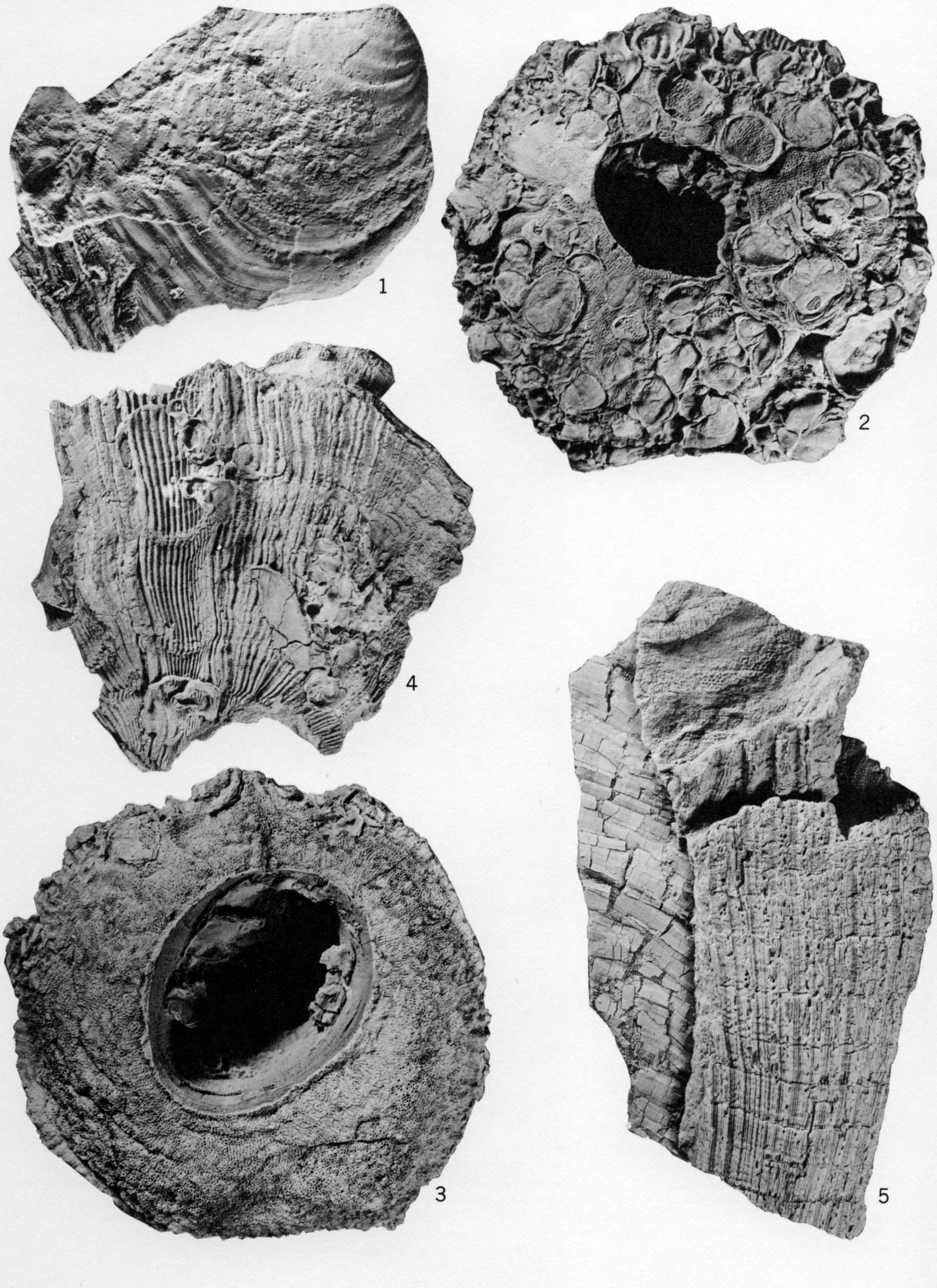
EXPLANATION OF PLATE 7

Bivalves of the Smoky Hill Member

1, *Inoceramus (Platyceramus) platinus* Logan. Internal mold of right valve, with part of shell attached (lower left), ×0.5, KU153995, middle part of Smoky Hill Member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas.

2-5, *Durania maxima* Logan. **2,** Ventral and **3,** dorsal views of small, short specimen of lower valve, ×1, FHKSU4094, from middle? part of Smoky Hill Member, several miles south of Castle Rock in Trego? County, Kansas. Note heavy encrustation of lower surface (2) by *Pseudoperna congesta,* and smaller numbers of the same oyster on the dorsal and interior surfaces (3). **4,** Lateral view of lower valve, ×1, KU154028, middle part of section exposed at Locality 17. **5,** Lateral view of lower valve fragment, ×0.75, KU154016, from bed equivalent to unit 21-32, in section exposed in Sec. 16, T.15S, R.32W, Logan County, Kansas. Note abundant borings of acrothoracican cirripeds.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EXPLANATION OF PLATE 8

Ammonoids and cirripeds of Smoky Hill Member

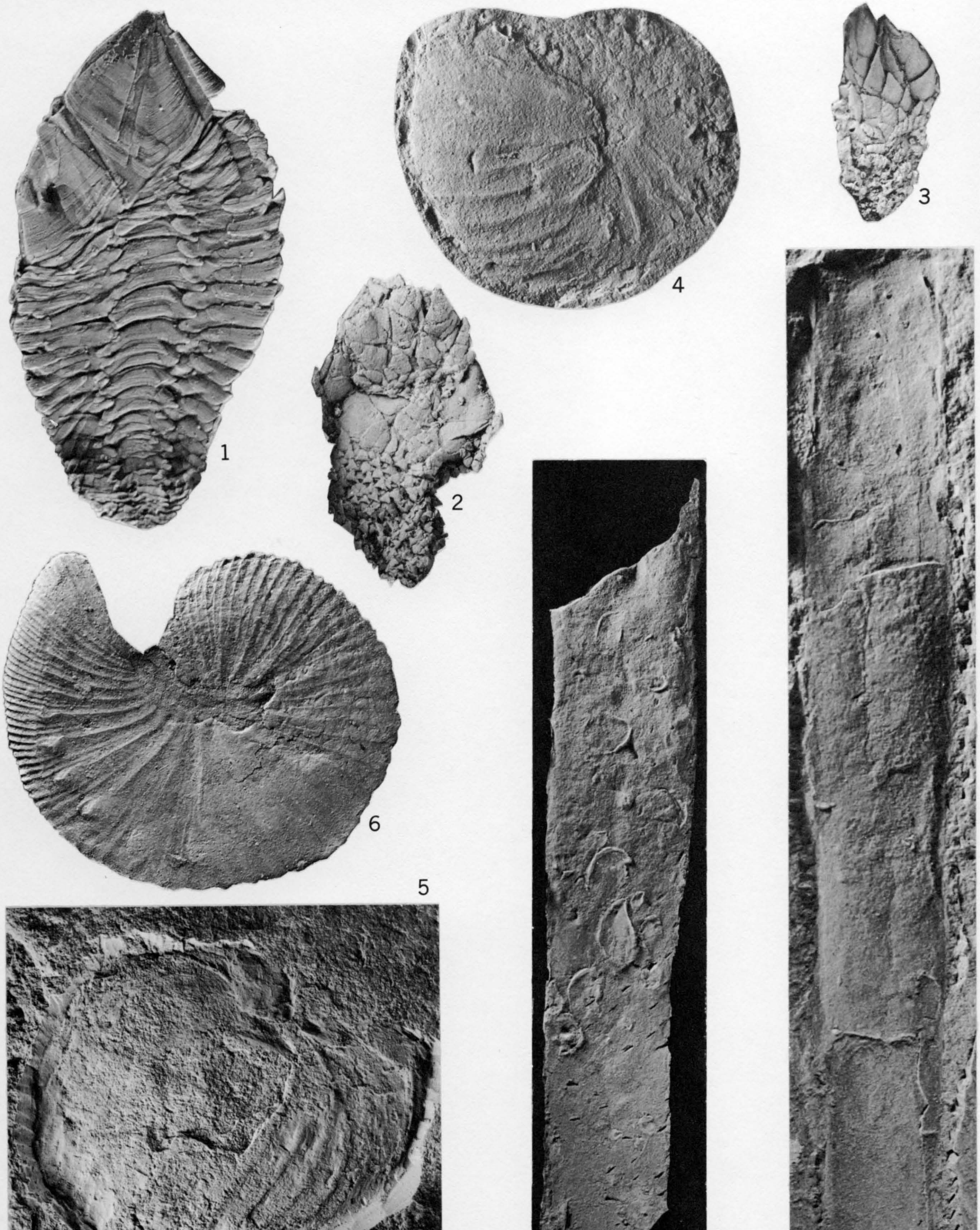
1, *Stramentum haworthi* (Williston). Holotype, ×4, KU8323, from near Gove City, Gove County, Kansas, probably from middle part of Smoky Hill Member.

2,3, *Zeugmatolepas* sp. **2,** Pair of specimens, ×5, KU154000, middle part of section at Locality 12. **3,** Single specimen, ×5, KU154001, middle part of section at Locality 12. All specimens are epizoic on right valves of *Pseudoperna congesta,* which in turn is epizoic on an adult upper valve of *Inoceramus (Volviceramus) grandis* (Conrad).

4,5, *Clioscaphites vermiformis* (Meek and Hayden). **4,** Mold of living chamber, ×1, KU154024, upper part of section at Locality 19. **5,** Obliquely deformed specimen, ×1.25, KU154025, upper part of section at Locality 19.

6, *Clioscaphites choteauensis* Cobban. Lateral view of internal mold, ×1, KU154023, from middle part of Smoky Hill Member in section exposed in Sec. 9, T.6S, R.19W, Rooks County, Kansas. Specimen collected by M. V. Walker.

7,8, *Baculites* sp. (smooth). **7,** Lateral view of compressed mold, ×1, KU154022, middle part of Smoky Hill Member in section exposed in Sec. 33, T.14S, R.31W, Gove County, Kansas. Note small epizoic oysters. **8,** Lateral view of compressed mold, ×1, KU154021, middle part of Smoky Hill Member in section exposed in Sec. 25, T.14S, R.33W, Logan County, Kansas.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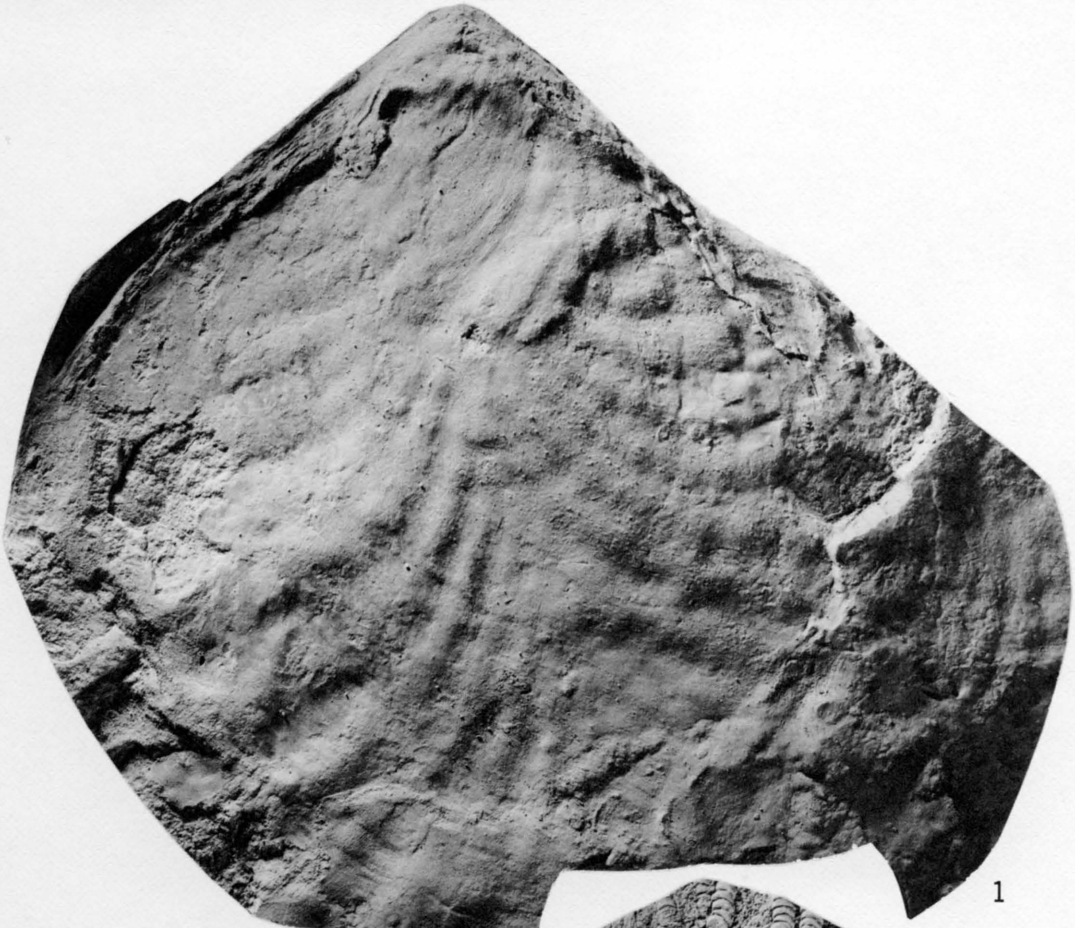
EXPLANATION OF PLATE 9

Bivalve and crinoids of the Smoky Hill Member

1, *Inoceramus (Cladoceramus) undulatoplicatus* Roemer. Internal mold of right valve with some shell attached, ×1, KU154029, 2.0 m (6.6 ft) below Marker Unit 7 at Locality 13.

2, *Uintacrinus socialis* Grinnell. Underside of thin slab showing portions of two articulated specimens, ×1, FHKSU14063, NW¼ Sec. 22, T.14S, R.32W, Logan County, Kansas.



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PETROLOGY OF THE SMOKY HILL MEMBER

Stratified Chalk

The Smoky Hill Member consists primarily of obscurely to well laminated, shaly weathering chalk that is mostly foraminiferal pelmicrite with packstone or, less commonly, wackestone texture (Figs. 32, 33). The pellets are much compacted, and thus present fusiform outlines in thin sections cut normal to bedding. These pellets are composed almost entirely of coccoliths, contain little evidence of interstitial cementation, have only modest indications of aggrading neomorphism, and show little or no etching of individual coccoliths (Fig. 34). In a sample of laminated chalk from Locality 13 the average maximum dimension of 100 pellets is 0.12 mm (Hattin, 1975b). Contrasting sharply with these pellets is the adjacent matrix, which comprises a heterogeneous mixture of coccoliths, crystals of secondary calcite, and noncarbonate particles (Fig. 35). Textural differences between pellets and matrix are consistent throughout the composite section, regardless of whether the chalk is laminated, bioturbated, granular, or organic-rich, and has been reported also from pellet-rich rocks of the Greenhorn Limestone and Alberta Shale (Hattin, 1975b).

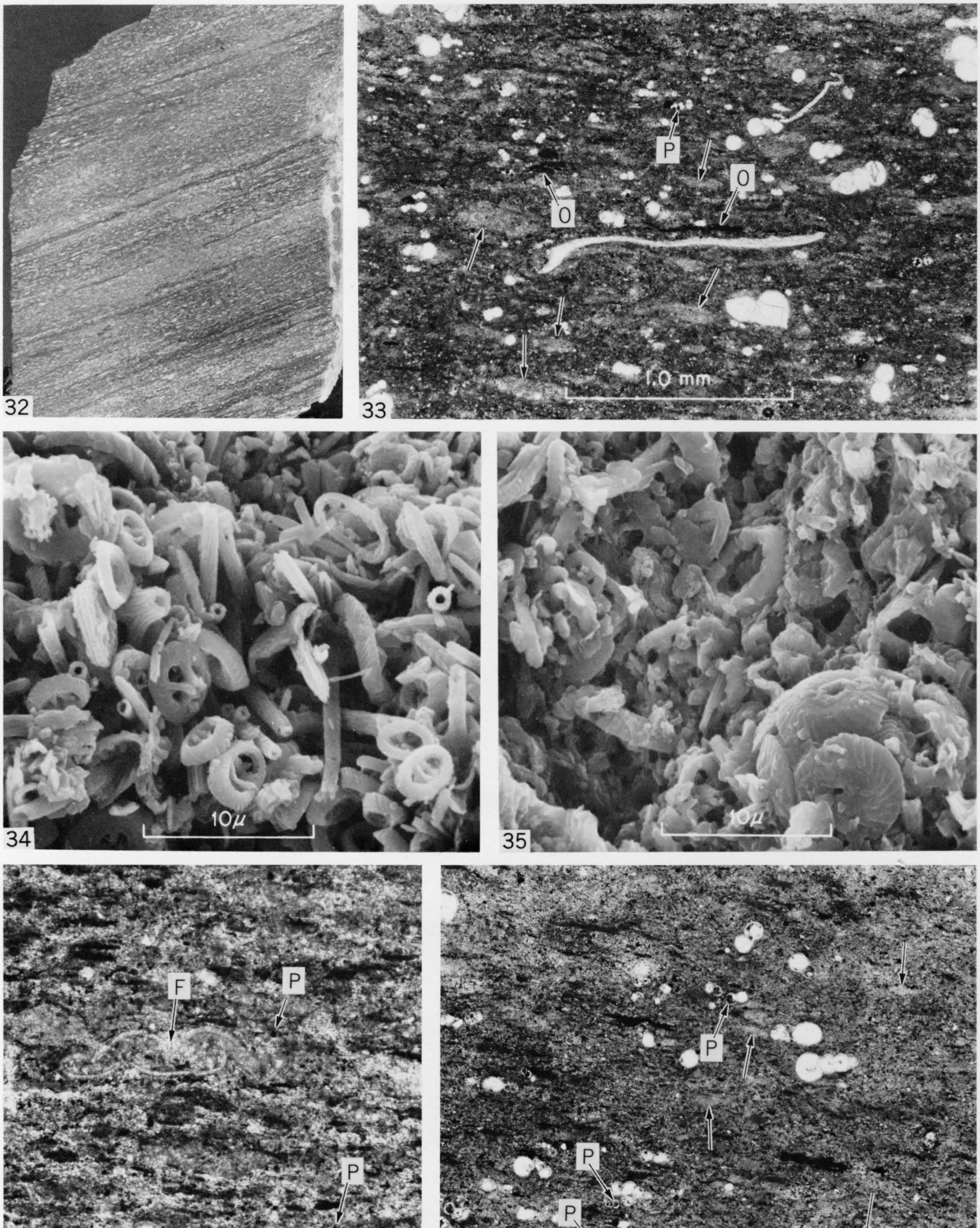
Planktonic foraminiferal tests are also ubiquitous in samples of stratified chalk, with usual maximum dimension in the range 0.3 to 0.4 mm. Most commonly, test walls are preserved with the radial structure essentially intact. In many specimens the inner and outer surfaces of the walls bear minute overgrowths of syntaxial calcite. Less common are foraminifers in which the test walls have been partly corroded or even removed entirely by dissolution. Test chambers are filled usually by one to a few blocky crystals of low-magnesium calcite, which does not manifest centripetal growth or enlargement. Rarely, a chamber may be floored with micrite, with overlying space filled by blocky calcite. Outer surfaces of large calcite crystals may bear the imprint of much smaller syntaxial calcite crystals, but more commonly bear casts of wall pores. Foraminiferal test chambers are generally globular but in most thin-sectioned samples some tests have been crushed by compaction (Fig. 36). Such tests are filled with fine, microsparry calcite (Fig. 36) or undistorted blocky calcite. Dark coloration of little-weathered chalk is owing largely to content of organic carbon, which comprises from 0.5 to 5.8 percent of analyzed samples, and to presence of finely crystalline pyrite. The latter occurs within the matrix and within foraminiferal chambers (Fig. 33), mostly as spherical framboids less than 40 μm in diameter (Figs. 33, 36), or less commonly as a skeletal replacement mineral. The organic matter is black, having the appearance of charcoal in reflected light, and occurs as angular, silt-sized grains and as wispy streaks (Fig. 33) or flakes that lie parallel to bedding. Beds richest in organic carbon have a characteristic brownish color. Framboidal pyrite occurs commonly within the wispy concentrations of organic matter. Association of pyrite and organic matter in these rocks indicates that reducing conditions prevailed in the chalk-forming muds. Most thin sections also contain wispy streaks of reddish-colored iron oxide, some of which is concentrated along incipient microstylolites (Fig. 36) or along borders of fecal pellets.

All samples of stratified chalk contain fish bones or scales, usually in amounts totaling less than one percent of the rock. In most samples, macroinvertebrate skeletal grains are sparse but include fragments and prisms derived from inoceramid valves and fragments of oyster valves. Although common in certain strata of the Kansas Greenhorn (Hattin, 1975c), calcispheres are rare in chalk samples from the Smoky Hill composite section.

Stratified chalks have strongly preferred orientation, parallel to bedding, of tabular grains such as compressed fecal pellets, fish scales, bivalve fragments, and organic flakes. Owing to compaction, the stratified rock fabric is deformed around larger biogenic grains. Lamination of well-stratified chalks is on a millimeter to centimeter scale, and is largely a result of vertical differences in fecal pellet abundance. In fact, the great abundance of fecal pellets along some bedding planes enhances fissility of these chalks. Thinner, darker-colored laminae (Fig. 32) are generally deficient in fecal pellets. Burrow structures, which are sparse in the well-stratified chalk, truncate laminae locally. Extensive weathering tends to diminish or obscure the visibility of primary laminations, but such rock still splits readily along original bedding planes.

Weathered chalk has lost its original dark coloration, owing to oxidation of organic matter and pyrite. The weathered rock is various shades of pale yellow and orange, the result of iron oxide staining.

In the upper part of the Smoky Hill, especially at Localities 21 and 24, are numerous beds of relatively hard and brittle, spally to shaly weathering chalk that lacks evidence of bioturbation and is not obviously laminated, but which splits readily along original bedding planes. Where partially weathered this rock is harder, may form projecting ledges, and has the general character of chalky limestone. Just as in well-stratified chalk, the nonlaminated chalk is highly speckled by compacted fecal pellets and weathering produces the same coloration. Except for sparse oysters and rare inoceramids this variety of chalk contains few macroinvertebrate fossils. As seen in thin sections the nonlaminated chalk is very similar to laminated chalk, comprising foraminiferal pelmicrite with packstone or, less commonly, wackestone texture, and the principal constituents are the same (Fig. 37). The fecal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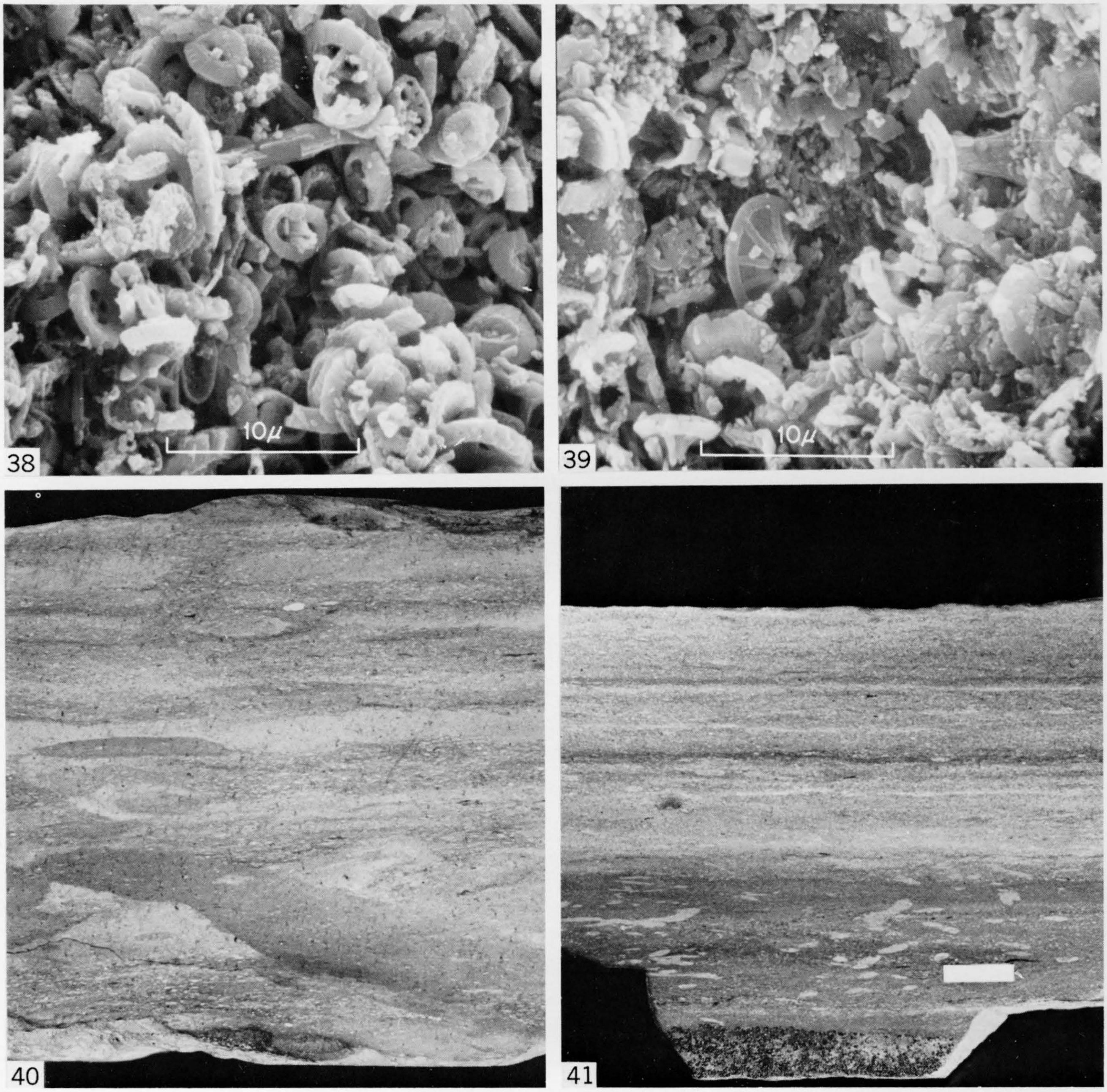
pellets are greatly compacted, and many have etched borders. Foraminiferal test walls are mostly intact or only partly corroded, and chambers are mostly filled with one to a few blocky crystals of sparry calcite that lacks evidence of centripetal growth or enlargement. All samples contain foraminiferal tests that have been crushed by compaction. Dark coloration of this chalk is owing in part to relatively high content of organic matter, which, like that in stratified chalk, occurs as wisps or flakes and as angular, silt-sized grains. Also contributing to dark coloration is abundant framboidal pyrite, which occurs inside foraminiferal chambers as well as in the matrix. Elongated grains have strongly preferred orientation parallel to bedding planes, and serve to enhance fissility. Scanning electron micrography of pellet and matrix areas reveals the same microtextural differences recorded above for stratified chalk (Figs. 38, 39). The pellets show minimal evidence of aggrading neomorphism or interstitial cementation, whereas both features are better developed in the matrix. These nonbioturbated, nonlaminated chalk beds are related genetically to and are gradational lithologically with the stratified chalk, differing primarily in the lack of well-defined laminae in fresh exposures, paucity of macroinvertebrate body fossils, smaller number of planktonic foraminiferal tests, and smaller maximum size (0.03 mm) of foraminifers. This genetic and gradational relationship is emphasized by scattered occurrence of such chalk beds within the lower 130 m of the composite section, where most chalk beds are more or less laminated, and by scattered occurrence of laminated chalk beds in the upper part of the member.

X-ray diffractometry of laminated and nonlaminated chalk samples indicates that the chalk is composed primarily of low-magnesium calcite. Quartz, in amounts usually less than five percent, was detected in all but one analyzed sample. Dolomite (four samples), gypsum (one sample), and smectite? (one sample) were detected only in trace quantities. Selected samples of both laminated and nonlaminated chalk samples were analyzed by chemical methods (Table 4). The lime is chiefly that of calcite. The silica is partly that of quartz and partly that of other silicate minerals (principally clays). The ferrous iron and most of the sulphur are attributed to pyrite, the ferric iron representing oxidized pyrite. Ubiquitous occurrence of vertebrate remains in the chalk is reflected by phosphate content of the samples. Reported carbon is organic carbon, which occurs in all little-weathered samples, and is indicative of a larger total quantity of organic matter. Among 31 samples selected so as to represent all but the uppermost four meters of the composite section, insoluble residue content ranges from 15.8 to 52.5 percent, averaging 31.4 percent ($\sigma = 10.4$). Most of the residues consist mainly of quartz, kaolinite, and mixed layer illite-montmorillonite. Accessory minerals include pyrite, feldspar, alunite, and gypsum. Chemical and residue data show that most Smoky Hill strata are impure chalks, and that some beds are best termed chalky marl.

Bioturbated and Granular Chalks

The Smoky Hill composite section contains numerous, irregularly distributed beds of relatively resistant, nonlaminated chalk, which forms light-colored (light olive gray to very light gray) bands on surfaces of little-weathered exposures (Fig. 15). In the lower 95 m of the member such beds contain clear evidence of bioturbation, including discrete, deposit-feeder burrows of the sort referred usually to *Planolites* Nicholson (Fig. 40) or *Chondrites* von Sternberg. These bioturbated intervals range in thickness from as little as one or two cm to as much as 30 or 40 cm. The thicker beds weather so as to produce prominent projecting ledges (Fig. 16). The thinner beds form minor shoulders on eroding slopes and produce a surface litter of brittle, light-colored chips. In some burrowed intervals bioturbation was sufficiently extensive to destroy all laminae; partially burrowed beds preserve some or most laminae. Complete gradation exists between nonburrowed and highly bioturbated beds of chalk (Fig. 41). Bioturbated chalks are mainly foraminiferal and pelletal micritic wackestones, but some of the rocks are packstones (Fig. 42). Because of bioturbation, fecal pellets are less abundant than in nonbioturbated chalk, and surviving pellets commonly have indistinct boundaries. Most fecal pellets are in the size range 0.1 to 0.15 mm. Qualitative contrasts with nonbioturbated chalk include presence of less-compacted

FIGURES 32-37. **32,** Polished surface of well-laminated chalk from lowermost unit of section in Sec. 2, T.14S, R.26W, Gove County, Kansas. Light-colored specks are mostly fecal pellets. Note alternation of mostly thicker, lighter-colored, fecal-pellet-rich laminae and thinner, darker-colored, fecal-pellet-poor laminae. ×2. **33,** Photomicrograph of laminated chalk from lower part of section in Sec. 28, T.15S, R.26W, Gove County, Kansas, showing abundance of fecal pellets (arrows), tests of planktonic foraminifers, pyrite framboids in foram (P), and black organic matter (O). Note well-stratified grain fabric. Crossed Nicols, ×40. **34,** Scanning electron micrograph of fecal pellet from laminated chalk, showing abundance of well-preserved coccoliths. Sample from lower part of exposure in Sec. 16, T.14S, R.25W, Trego County, Kansas. ×3000. **35,** Scanning electron micrograph of matrix in laminated chalk, showing conspicuous amount of secondary calcite and a coccosphere. Same sample as in Figure 34. ×3000. **36,** Photomicrograph of laminated chalk, showing crushed foraminifer (F) filled with fine microsparry calcite. Note pyrite framboids (P) in matrix, and concentrations of iron oxide along incipient microstylolites. Lower part of section exposed in Sec. 16, T.15S, R.26W, Gove County, Kansas. Plane-polarized light, ×80. **37,** Photomicrograph of nonlaminated, nonbioturbated chalk from lower part of section exposed in Sec. 21, T.15S, R.32W, Logan County, Kansas. Note sparry calcite fill of foraminifers, framboidal pyrite (P) inside foraminifer chambers, and fecal pellets (arrows). Plane-polarized light, ×40.



FIGURES 38-41. **38,** Scanning electron micrograph of fecal pellet from nonlaminated, nonbioturbated chalk in lower part of section exposed in Sec. 21, T.15S, R.32W, Logan County, Kansas, showing abundance of well-preserved coccoliths and only small amounts of secondary calcite. ×3000. **39,** Scanning electron micrograph of matrix in nonlaminated, nonbioturbated chalk, showing smaller number of well-preserved coccoliths than in pellets (Fig. 38), and relatively large amount of secondary calcite. Same sample as in Figure 38. ×3000. **40,** Sample of bioturbated chalk from lower part of exposure in Sec. 16, T.15S, R.26W, Gove County, Kansas, showing sediment-filled burrow structures of kind usually attributed to *Planolites*. ×2. **41,** Polished surface, cut normal to bedding, of partly laminated, partly bioturbated chalk from lower part of exposure in Sec. 29, T.15S, R.26W, Gove County, Kansas. Note stratification differences between bioturbated and nonbioturbated parts of sample. Bar scale = 1 cm.

fecal pellets, generally smaller number of crushed foraminiferal tests, greater abundance of foraminiferal fragments, occurrence (sparse) of foraminiferal tests that have breached walls and a filling of micrite/microsparite, more common alteration of foraminiferal walls, usually smaller amount of optically visible organic matter, and paucity in many samples of wispy iron oxide streaks. Especially apparent in the most highly bioturbated rocks is the lack or near lack of bed-parallel orientation among elongated and tabular grains (Fig. 42). Minute pyrite framboids, or their oxidized counterparts, occur commonly inside foraminiferal chambers, but tend to be less abundant in the

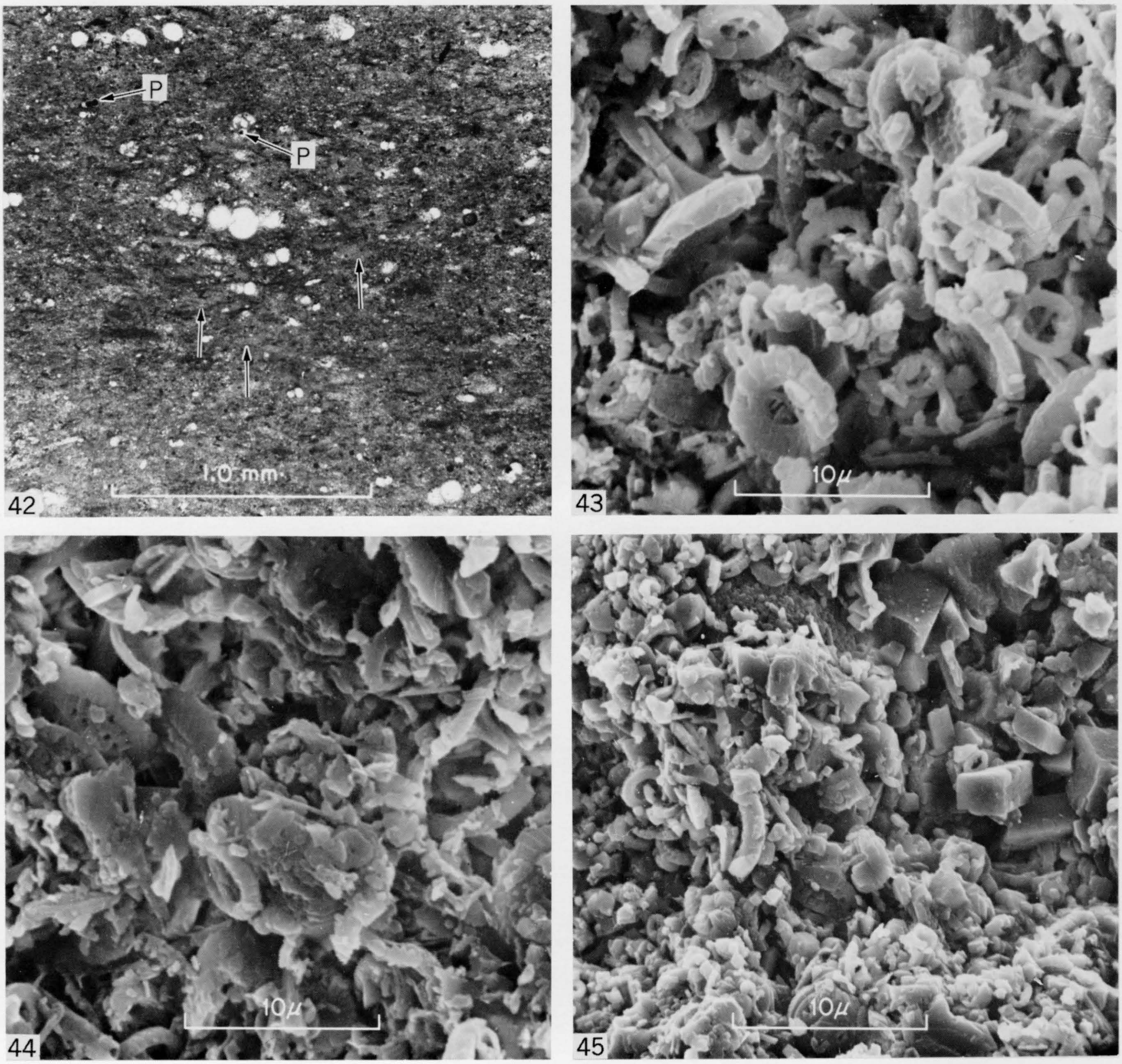
TABLE 4. Chemical analyses of nonbioturbated chalk samples from Smoky Hill Member of Niobrara Chalk. Samples are arranged stratigraphically, with oldest sample at top of table. Sample KN-23-26 contains the highest percentage of organic carbon and is from a distinctively dark-colored bed, which is a good stratigraphic marker. In sample codes, first number is the locality, as listed in the register of localities. Localities not listed in the register are KN-14 (SW¼ Sec. 21, T.15S, R.26W, Gove Co., Kansas) and KN-2 (E½ Sec. 27, T.12S, R.35W, Logan Co., Kansas).

SAMPLE NO.	SiO_2	Al_2O_3	Fe_2O_3	FeO	TiO_2	CaO	MgO	P_2O_5	S	SO_3	CO_2	C	H_2O(-)	H_2O (110°-200°C)
KN-1-CCC	13.2	5.55	0.46	1.14	0.18	40.4	0.70	0.083	0.15	0.64	30.5	2.1	1.32	0.62
KN-17-1	16.9	6.36	0.62	1.14	0.32	37.7	0.99	0.071	0.48	0.30	28.1	0.5	1.29	0.58
KN-17-5	22.3	8.66	0.87	1.29	0.38	32.3	1.41	0.061	0.53	1.14	27.1	2.7	1.50	0.49
KN-14-7	18.1	7.23	0.70	1.14	0.39	31.2	0.96	0.088	0.55	0.38	25.2	1.6	1.38	0.50
KN-12-3	10.5	4.37	0.09	1.14	0.16	43.6	0.95	0.088	0.22	0.44	33.4	2.2	0.78	0.27
KN-12-15	18.4	6.79	0.62	1.21	0.30	35.5	1.24	0.11	0.30	0.46	26.5	3.2	1.28	0.48
KN-13-3	14.6	5.84	0.02	1.46	0.22	38.6	1.31	0.10	0.63	0.86	30.2	2.0	0.49	0.26
KN-13-5	12.4	4.71	N.D.	1.37	0.17	41.4	0.77	0.097	0.59	0.67	32.5	2.0	0.71	0.20
KN-13-9	16.9	6.43	0.85	0.97	0.16	37.4	1.24	0.095	0.30	0.32	29.8	1.7	0.96	0.39
KN-13-13	22.6	8.38	1.09	1.21	0.29	32.0	1.36	0.12	0.42	0.41	25.8	2.9	1.14	0.48
KN-19-3	19.8	7.62	0.13	1.78	0.22	34.1	1.11	0.11	0.60	0.30	26.3	2.9	1.10	0.34
KN-19-11	18.9	7.00	0.84	0.89	0.22	34.6	1.14	0.11	0.59	0.27	28.4	3.0	0.93	0.35
KN-19-19	24.6	9.23	0.62	1.61	0.31	29.3	1.28	0.13	0.73	0.81	23.7	3.3	1.18	0.36
KN-19-23	18.2	6.63	0.63	1.05	0.20	35.8	0.88	0.11	0.42	0.45	27.5	3.7	0.91	0.33
KN-18-5	18.0	6.47	0.45	1.29	0.21	35.6	0.94	0.12	0.44	0.62	27.5	2.9	1.15	0.56
KN-18-11	15.5	5.55	0.86	1.05	0.18	38.3	0.64	0.12	0.33	0.31	29.8	2.9	0.92	0.47
KN-18-27	7.02	2.50	0.30	0.65	0.050	45.9	0.25	0.068	0.26	1.19	34.8	2.4	0.92	0.43
KN-23-26	21.3	8.54	1.60	1.22	0.24	29.2	0.62	0.12	0.98	0.21	23.6	5.84	1.71	0.70
KN-2-1	9.44	3.29	1.64	0.97	0.14	39.9	0.63	0.086	0.19	5.70	29.1	3.3	2.07	1.11
KN-2-11	8.58	3.43	2.66	1.46	0.11	37.9	0.47	0.082	0.66	7.02	27.2	3.9	2.13	1.48
KN-2-19	6.36	2.86	3.34	0.57	0.15	40.4	0.42	0.079	N.D.	6.78	29.0	3.3	1.74	1.83
KN-2-23	8.98	4.15	2.36	1.29	0.082	38.6	0.48	0.075	N.D.	6.80	27.6	3.9	2.73	0.97
KN-21-1	5.06	2.18	3.45	0.97	0.057	42.0	0.32	0.088	1.74	6.41	30.5	3.5	2.56	0.52
KN-21-37	10.7	4.65	3.37	1.29	0.13	37.5	0.45	0.10	2.64	3.31	27.6	2.9	1.77	0.59

adjacent matrix than in nonbioturbated chalk. Bioturbated chalk fecal pellets are composed mostly of coccoliths, but overgrowths of neomorphic calcite are more common than in nonbioturbated chalk pellets (Fig. 43). As compared to nonbioturbated chalk, the matrix of bioturbated chalk contains generally greater evidence of interstitial cementation and neomorphism (Fig. 44). Microtextural differences between laminated and bioturbated chalk apparently resulted largely from burrowing activity in the latter. This conclusion is supported by evidence from bioturbated limestones of the underlying Fort Hays Member, which also contains more secondary calcite than the laminated chalk deposits (Fig. 45). In degree of alteration by neomorphic overgrowths on coccoliths and amount of interstitial cement, complete gradation exists between soft, laminated chalks and the hardest, most thoroughly bioturbated chalky limestones. This relationship is true also for the older Greenhorn Limestone of Kansas (Hattin, 1971, 1975c). In massive, chalky limestones of the Fort Hays and in chalky limestones of the Greenhorn, all of which are highly bioturbated, surviving fecal pellets and macroinvertebrate body fossils are little flattened by compaction, suggesting that the bioturbated beds became lithified earlier than the nonbioturbated chalks. Greater purity of chalk-forming muds and better circulation of interstitial fluids during burrowing activity played important roles in early lithification of bioturbated beds, as suggested also by Bathurst (1971, p. 402) for the Bioturbation Chalk of Northern Ireland, by Bromley (1975, p. 409) for chalk hardgrounds, and by Milliman (1966, p. 966) for deep-sea pelagic oozes. Bioturbated beds of the Smoky Hill Member are less pure than chalky limestones of the Greenhorn and Fort Hays. Accordingly, the Smoky Hill beds are less well cemented and suffered greater compaction than did chalky limestones of the two older Kansas units.

Marker Unit 10 is the most prominent example of partially bioturbated rock in the composite section. This unit, which is 6.7 m thick at Locality 18, comprises tough, partially stratified chalk with petrologic features intermediate between those of nonbioturbated and highly bioturbated chalk (Fig. 17). The rock is a foraminiferal pelmicrite with packstone texture, and contains scattered burrow structures, some of which contain fragmented tests of planktonic foraminifers. This chalk is mostly similar to the laminated and nonlaminated chalks, but parts that have been burrowed are texturally like typical bioturbated chalks.

In the upper half of the composite section most light-colored, tough, relatively resistant beds of chalk have a rather granular appearance (Fig. 14). In thin sections, fecal pellets and silt-sized grains of black organic matter are aligned essentially parallel to bedding planes, but lesser compaction of fecal pellets, smaller number of



FIGURES 42-45. **42,** Photomicrograph of bioturbated chalk from middle part of section exposed in Sec. 2, T.14S, R.26W, Gove County, Kansas. Note lack of stratified grain fabric, less compacted fecal pellets (arrows) and framboidal pyrite (P) inside foraminifer tests. Plane-polarized light, ×40. **43,** Scanning electron micrograph of fecal pellet in bioturbated chalk sample from lower part of section exposed in Sec. 16, T.15S, R.26W, Gove County, Kansas. Note neomorphic calcite overgrowths on coccoliths. ×3000. **44,** Scanning electron micrograph of matrix in sample of bioturbated chalk, showing large amounts of secondary calcite cement. Same sample as in Figure 43. ×3000. **45,** Scanning electron micrograph of bioturbated chalk sample from upper part of Fort Hays Limestone Member, Sec. 24, T.15S, R.25W, Trego County, Kansas. Note extensive development of secondary calcite as overgrowths on coccoliths and as interstitial cement. ×3000.

crushed foraminifers, and paucity of wispy organic matter and iron oxide have produced a less well stratified appearance than is typical for nonbioturbated chalk. In natural exposures, burrow structures were recorded only sparingly in the granular chalk beds. Thin sections contain a few ovoid burrow structures, which contain micrite or microspar and are about 0.5 mm in diameter. Thin sections also reveal sparse, scattered, minute ovoid bodies of grayish to brownish color, which may also be filled burrows. Thus, beds of granular, nonstratified, or only poorly stratified chalk appear to have resulted from bioturbation, but apparently were burrowed by organisms that were smaller and less abundant than those that burrowed the more obviously bioturbated chalks. These granular beds range in thickness from a few centimeters to as much as 0.76 m, and, because of superior resistance to erosion, form caprocks in chalk badlands. The granular chalks are mainly foraminiferal and pelletal micrites, with wackestone texture (Fig. 46); a few are foraminiferal pelmicrite packstones. Except for the nature of the burrow-like features, the petrographic character of granular chalk differs in no major way from that of the bioturbated chalk.

X-ray diffractograms of bioturbated and granular chalks are nearly identical. Low-magnesium calcite is the predominant mineral component, as in laminated chalk, and trace to moderate amounts of quartz occur in all analyzed samples. Where recorded in this section the quartz occurs as widely scattered grains of angular silt. Traces of kaolinite (one sample) and gypsum (two samples) are the only other minerals detected by X-ray methods.

A few samples of bioturbated and granular chalk were analyzed chemically (Table 5). These rocks have a higher content of $CaCO_3$ than is normal for nonbioturbated chalk, which observation is supported by insoluble residue data. Among 18 samples of bioturbated and granular chalk digested in formic acid, the average residue is 22.5 percent ($\sigma = 8.2$).

Skeletal Limestone

In the Smoky Hill composite section, I recorded no well-washed biosparite or biosparrudite such as characterizes parts of the older Greenhorn and Fairport (Fig. 6) chalky units. However, small, very thin lenses of biomicrite and biomicrudite composed mostly of fragmented inoceramid valves are scattered sparingly through the section (Fig. 47). Isolated occurrences and presence of a micritic matrix suggest that such lenses formed by *in situ* disintegration of bivalves under quiet-water bottom conditions, which characterized nearly all of Smoky Hill deposition.

On the south side of Plum Creek, Gove County, in SE ¼ Sec. 1, T.14S, R.31W, the chalk lying approximately midway between Marker Units 21 and 22 contains a single lens of fine-grained, pale yellowish brown skeletal limestone. When freshly broken, the rock emits a strong hydrocarbon odor. The lens is approximately 3.2 m (10.5 ft) wide and 2 to 3 cm (0.07-0.1 ft) thick, with protuberances on the lower surface that expand the thickness to 5.5 cm (0.18 ft) locally. This lens has been thoroughly bioturbated, as evident in plentiful casts of simple, horizontal burrows, and lacks internal stratification. Principal grain types, listed in order of decreasing abundance, are *Inoceramus* debris, tests of planktonic foraminifers, fish bones and scales, fragments of small oysters, and angular quartz sand (sparse). The rock is grain supported and bound mostly by micrite, and is therefore a biomicritic packstone. Inoceramid remains consist mostly of isolated calcitic prisms and scattered small fragments of the prismatic shell layer. Foram tests are intact or broken, and the walls are either well preserved or somewhat altered. Foram chambers are filled by one to a few blocky crystals of sparry calcite, which shows no evidence of centripetal growth or crystal enlargement. Sparry calcite occurs also as minute overgrowths on some foraminifer tests, as the filling in void spaces within bone fragments, and as local interstitial fill between allochems. Minute pyrite framboids, or the oxidized equivalent thereof, are common within foram chambers and occur sparingly within the micritic matrix.

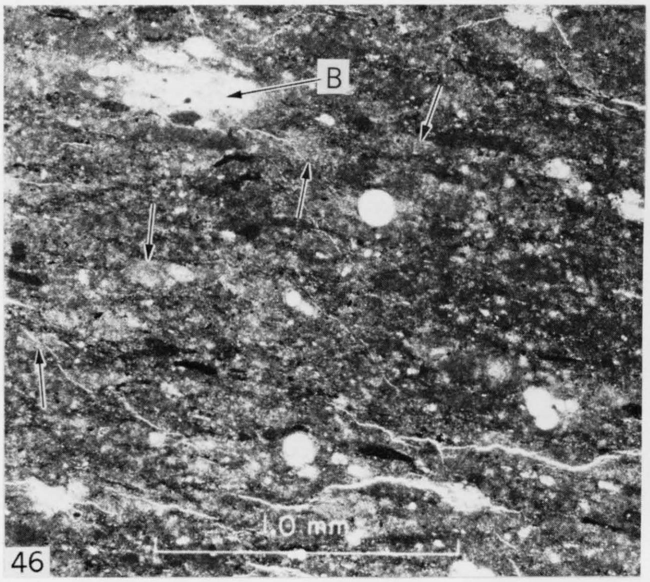
In or adjacent to the zone of *Clioscaphites choteauensis* are very sparse, thin to very thin lenses (maximum ca. 5 cm thick) of hard, brittle limestone composed chiefly of remains of the free-swimming crinoid *Uintacrinus socialis.* Both articulated and disarticulated crinoidal material has been distorted by compaction. Abundant microstylolites, which occur along grain boundaries, are evidence of extensive pressure solution at grain-to-grain contacts (Fig. 48). Crinoid skeletal parts have been converted almost entirely to coarse microspar (Fig. 49), and the original high-magnesium calcite has been altered to low-magnesium calcite, which is the only mineral I detected by X-ray methods. Alteration of the skeletal elements to microsparite has been attributed by Neugebauer (1978a) to the effects of partial dissolution, and is an example of crystal diminution.

Diagenesis

Although the Smoky Hill chalk is relatively soft and friable, especially in weathered exposures, all samples contain evidence of post-depositional alteration. The

TABLE 5. Chemical analyses of bioturbated and granular chalk samples from Smoky Hill Member of Niobrara Chalk. Samples are arranged stratigraphically with oldest sample at top of table. *Sample of chalky limestone that has suffered little compaction but lacks obvious burrow structures.

SAMPLE NO.	SiO_2	Al_2O_3	Fe_2O_3	FeO	TiO_2	CaO	MgO	P_2O_5	S	SO_3	CO_2	C	H_2O(-)	H_2O (110°-200°C)
KN-18-13	7.06	2.54	0.41	0.65	0.022	45.3	0.33	0.065	0.096	2.81	34.2	2.3	1.32	0.57
KN-18-19	7.42	2.47	0.47	0.49	0.075	45.0	0.44	0.062	0.24	1.73	34.3	2.8	1.14	0.54
KN-21-15*	1.24	0.69	0.27	0.81	0.017	52.0	0.22	0.044	0.51	1.27	40.6	1.7	0.53	0.08
KN-21-27	1.96	0.98	0.92	0.59	N.D.	49.4	0.24	0.049	N.D.	3.56	37.1	1.4	1.45	0.41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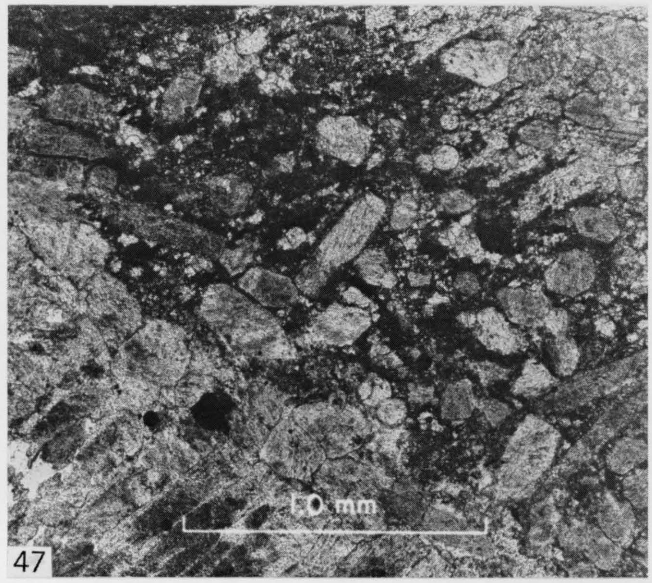
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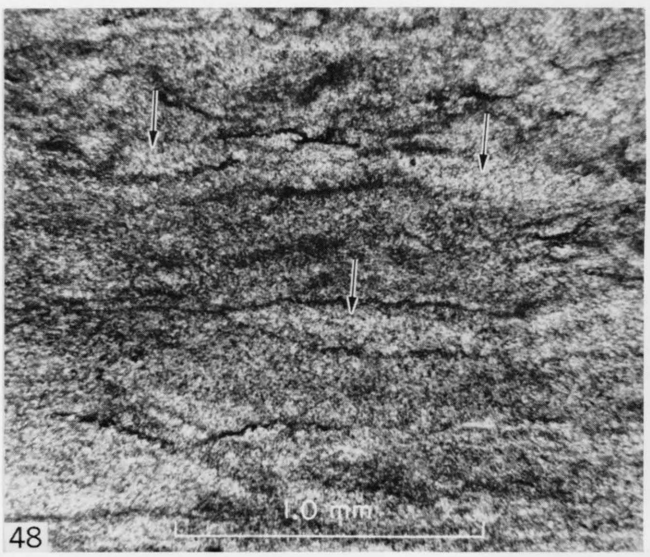
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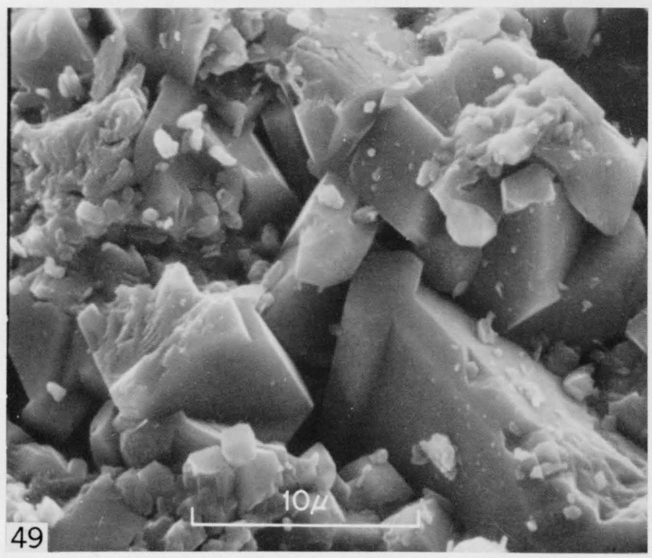
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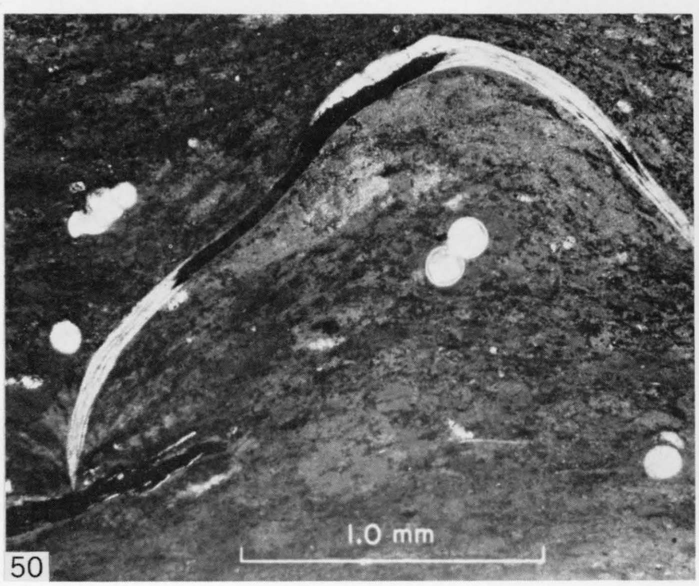
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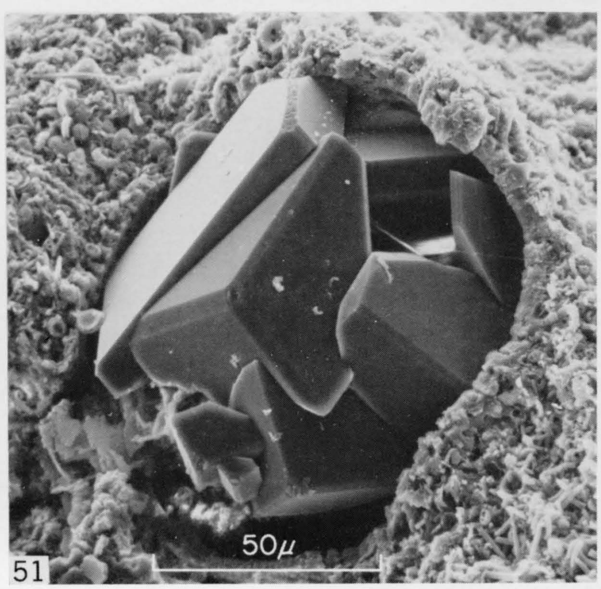
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most obvious diagenetic feature is compaction, which is evident in the shape of crinoidal elements (Fig. 48); flattened valves of inoceramids, bakevelliids, and some oysters; deformation of inoceramid valves around their epizoic oysters; and flattened molds of cephalopods (*Baculites, Clioscaphites,* collignoniceratids) and bivalves (*Lucina*). Despite theoretically great resistance of spherically shaped structures to compaction, in many specimens of planktonic foraminifers the globular chambers have been crushed by compaction (Fig. 36). Compaction is also manifest where rock fabric arches over or bends downward beneath large allochems, such as oysters or inoceramid fragments (Fig. 50). Fecal pellets also have been compacted, most especially in the nonbioturbated chalk, and present conspicuously fusiform or elongate-elliptical outlines as viewed in hand specimens and thin sections (e.g., Figs. 33, 37). In all nonbioturbated rocks the preferred orientation of tabular grains is owing in part to the grain attitude at the time of deposition, in part to rotation of grains in response to compactional stresses, and in part to compactional flattening of the grains. Although compaction in carbonate grainstones is not common, and the lack of compaction in some Cretaceous chalks has been noted (e.g., Mapstone, 1975, p. 609; Kennedy and Garrison, 1975, p. 342; Mimran, 1978), compaction in chalk is actually a widespread phenomenon (e.g., Hattin, 1962, 1975c; Schlanger and Douglas, 1974; Kennedy and Garrison, 1975; Garrison and Kennedy, 1977). Scholle and Cloud (1977, p. 257) note that all chalk is subject to mechanical and chemical compaction, the principal mechanisms being the stress of overburden, tectonics, and pore-fluid pressure. Only the first of these was significant in compaction of the Smoky Hill carbonate muds because the area is tectonically stable and burial depths never reached sufficient depths for pressure solution to have become pervasive.

In intervals of bioturbated chalk the primary fabric was homogenized by burrowing organisms, most of which were apparently worms. Their sediment-ingesting activities also caused fragmentation of foraminiferal tests, clustered fragments of which are preserved locally within burrow fill.

In general, Smoky Hill chalk beds are not well cemented, which explains the friability of even the little-weathered chalk. Nonetheless, most samples examined by scanning electron microscopy contain evidence of calcitic overgrowths on coccoliths and of interstitial cement consisting of minute calcite rhombs within the chalk matrix (Figs. 35, 39, 44). This calcite reflects inception of the lithification process, which, if sufficiently extended, would have resulted in gradual obliteration of primary microtextural features. In the older Greenhorn Limestone, highly bioturbated beds of chalky limestone did undergo more extensive neomorphism and cementation, and now consist primarily of microsparry calcite (Hattin, 1971, 1975c). With few exceptions the matrix of Smoky Hill chalk samples contains greater abundance of secondary calcite than do the fecal pellets, which implies that the pellets were protected somehow from diagenetic alteration, perhaps because of an original mucilaginous coating. Neugebauer (1974) suggests that during chalk lithification cement precipitation on coccoliths is retarded because of their small size or geometric shape, but notes (Neugebauer, 1975a) the common occurrence of overgrowths on coccoliths of the Kansas chalk. Adelseck and others (1973) and Roth and Berger (1975) determined that during diagenesis the smallest ($<1\mu m$) coccoliths may be dissolved selectively, whereas secondary calcite overgrowths commonly develop on the larger ones. In addition to overgrowths on coccoliths, syntaxial overgrowths have been recorded also in foraminifera (Neugebauer, 1975b; this paper), crinoidal limestone (Neugebauer, 1978a), and inoceramid prisms (Neugebauer, 1978b) of the Smoky Hill chalk.

In Smoky Hill chalks, just as in the older Greenhorn and Fairport chalks (Hattin, 1962, 1975c), much secondary calcite was precipitated within planktonic foraminiferal chambers, usually as only one to a few large crystals (Fig. 51). This calcite may fill most or nearly all of the original void space of the chamber or, rarely, the space above a floor of geopetal micrite. None of this chamber-filling blocky calcite contains evidence of centripetal growth or crystal-size increase. Similar sparry calcite has been reported in chambers of modern foraminifers from deep-sea chalk (Schlanger and others, 1976, p. 167). Some Smoky Hill thin sections contain a

FIGURES 46-51. **46,** Photomicrograph of granular chalk from upper part of exposure in Sec. 12, T.15S, R.32W, Logan County, Kansas. Sample from light-colored bed above dark, organic-rich bed illustrated in Figure 14. Note poor definition of stratification, burrow-like structure (B), and fecal pellets (arrows). Plane-polarized light, ×40. **47,** Photomicrograph of biomicrudite from lower part of section exposed in Sec. 1, T.14S, R.26W, Gove County, Kansas. Interstitial micrite (dark) between prisms and fragments of inoceramids suggests essentially *in situ* accumulation of disintegrated bivalve debris. Plane-polarized light, ×40. **48,** Photomicrograph of *Uintacrinus*-rich limestone from middle part of Smoky Hill Member in Sec. 27, T.14S, R.32W, Logan County, Kansas. Note fusiform shape of compactionally distorted crinoidal elements (arrows), and microstylolites (dark, crinkly lines) along grain-to-grain contacts. Plane-polarized light, ×40. **49,** Scanning electron micrograph of crinoid skeletal element, showing recrystallization of original unit crystal to microsparite. Specimen from Sec. 27, T.14S, R.32W, Logan County, Kansas. ×3000. **50,** Photomicrograph of partially bioturbated chalk from Marker Unit 10 in Sec. 1, T.14S, R.26W, Gove County, Kansas, showing deformation of grain fabric around an oyster valve. Plane-polarized light, ×40. **51,** Scanning electron micrograph of planktonic foraminifer test, showing large crystals of low-magnesium calcite that nearly fill the chamber. Chambers containing only one crystal (very common) are usually filled completely. Sample from lower part of section exposed in Sec. 16, T.14S, R.25W, Trego County, Kansas. ×600.

few foraminifers whose chambers are filled with micrite and/or microsparite that represents infiltration of carbonate ooze through fractured or breached test walls. Severely crushed foraminiferal tests are usually filled with microsparite (Fig. 36), but a few are filled with blocky calcite. Presence of large sparry crystals in most Smoky Hill foraminifers reflects slow growth, and is believed to have occurred during burial diagenesis (see Folk, 1974, p. 47). If the blocky calcite had crystallized during early diagenesis, as the minute syntaxial overgrowths apparently did, fewer foraminifera would have been crushed by compaction. Among partially crushed foraminifers are many in which remaining void space is filled with blocky crystals of sparry calcite, which shows no evidence of strain and was therefore emplaced after compaction of the tests.

One possible source of early diagenetic calcite is the metastable aragonite of bivalves and cephalopods. Several authors (e.g., Bathurst, 1971, p. 442; Neugebauer, 1973, p. 224; Kennedy and Garrison, 1975, p. 370; Scholle, 1977, p. 991) have mentioned this possibility, but have generally considered such a source as minor on the grounds that aragonitic skeletal remains were rare in chalk-forming muds. In addition, Kennedy and Garrison (1975, p. 370) and Hancock (1975, p. 512) state that cementation of the hardest English chalks preceded skeletal aragonite dissolution because molds of aragonitic skeletons are preserved therein. Contrary to such arguments, the Smoky Hill chalks almost nowhere preserve skeletal aragonite, and dissolution of such remains occurred while the muds were still relatively soft because, *without exception,* potential void spaces left by removal of aragonite have been closed by compaction. Finally, the abundance and distribution of inoceramids alone imply that substantial amounts of secondary calcite could have been derived from aragonitic skeletal sources. One must remember further that Smoky Hill chalks are *not* well cemented, and only minor volumes of $CaCO_3$ were required to effect the observed degrees of neomorphism and cementation. As Wise (1977, p. 718) has noted, wherever aragonitic skeletons do occur in chalk-forming muds "they should be considered as important potential donors of carbonate for cementation."

An additional source of secondary calcite in Smoky Hill chalks is that derived from pressure solution (=solution transfer) during burial diagenesis—a mechanism of chalk cementation favored by many workers (e.g., Neugebauer, 1974; Mapstone, 1975, p. 611; Hancock, 1975, p. 524; Scholle, 1977; Garrison and Kennedy, 1977, p. 130). Thin sections of many Smoky Hill chalk samples contain numerous incipient microstylolites, which occur especially along margins of fecal pellets but also occur sparingly along grain-to-grain contacts. Correlation between abundance of well-developed microstylolites and degree of cementation is illustrated by the *Uintacrinus* limestone (Fig. 48). However, well-developed microstylolites are not common in the Smoky Hill, nor are incipient microstylolites usually developed on a large scale. The Smoky Hill lacks such features as the clay pellicles reported by Haakansson and others (1974, p. 224) or the flaser chalks described by Garrison and Kennedy (1977). Additionally, the maximum overburden in Kansas seemingly did not reach the 1000-m thickness regarded by Neugebauer (1974, p. 156) as necessary to the generation of large amounts of cement through pressure solution. Collectively, the evidence suggests that pressure solution does not account for a large volume of secondary calcite in Smoky Hill chalks.

Adelseck and others (1973, p. 2760) and Roth and Berger (1975, p. 92) have suggested that the smallest coccoliths tend to be dissolved preferentially, and supply the calcium carbonate necessary for overgrowths on large coccoliths. Most Smoky Hill coccoliths show little evidence of etching, thus contrasting markedly with etched coccoliths of the North Pacific oozes reported by Matter and others (1975). Etching of coccoliths appears to have been an insignificant source of secondary calcite in Smoky Hill chalks.

Tests of Smoky Hill planktonic foraminifers exhibit a wide range of diagenetic effects. Some preserve details of original microstructure, whereas others have been recrystallized. Many have minute secondary overgrowths of syntaxial calcite, whereas others have been corroded, even to the point where test walls have been largely destroyed. The timing of processes that altered these foraminifers is uncertain but it is apparent that some were donors of calcite for secondary mineralization, and some were the objects of secondary calcite overgrowth. This problem is worthy of further study. Neugebauer (1975b) has described in great detail the processes of test alteration in Niobrara foraminifers and concludes that the extensive overgrowths on wall crystals resulted from the large surface areas presented for diagenetic reactions. Neugebauer (1978a,b) has shown also that the calcite of echinoderms and the prismatic layer of inoceramids from the Niobrara chalk show effects of partial dissolution. However, the small quantities of $CaCO_3$ from these sources seems to have been consumed in cementation of the *Uintacrinus* limestone and development of calcite overgrowths on *Inoceramus* prisms rather than in cementation of adjacent chalk. These skeletal sources therefore were apparently of small significance as compared to aragonitic sources of $CaCO_3$.

That bioturbation had an influence on the degree of chalk cementation is now well documented (Hattin, 1971, 1975c, 1981). Kansas chalks that are most highly bioturbated are those that have undergone the greatest amount of diagenetic alteration and contain evidence—fossils preserved in-the-round, noncompressed burrows and fecal pellets—for precompactional lithification. Except for a few beds within the Fort Hays Member, none of these better-lithified chalks contains flasers (see Garrison and Kennedy, 1977), microstylolites, or other compelling evidence of pressure solution. Carbonate cement for these early-lithified units is judged to have come partly from aragonitic skeletal remains, but most is the result of improved circulation of $CaCO_3$-saturated water during bioturbation.

In summary, several possible mechanisms may account for observed calcite overgrowths, interstitial cement, and void-filling calcite in Smoky Hill chalks. In answer to the question, "Are these sources sufficient to furnish the needed amounts of secondary calcite," I remind the reader that these rocks are poorly cemented, and large volumes of secondary calcite were not needed to produce the observed effects.

Diagenetic framboids of pyrite, ranging from 5 to 40 μm, are nearly ubiquitous in Smoky Hill chalks, and are most abundant in nonbioturbated strata. Presence of conspicuous quantities of pyrite is clear evidence of interstitial reducing conditions, which are in harmony with occurrences in the chalks of appreciable amounts of organic matter. Smaller quantities of both pyrite and organic matter in the more extensively bioturbated beds suggest that burrowing activity circulated oxygenated water through the sediment and thereby retarded development of a reducing microenvironment within the carbonate mud. Despite effects of bioturbation, reducing microenvironments were maintained within foraminiferal chambers, where framboids are approximately as common as in nonbioturbated chalks, as well as locally within the adjacent matrix. Organic carbon content of nonbioturbated Smoky Hill chalks ranges from 0.5 to 5.8 percent, averaging 2.8 percent for 25 samples (Table 4), whereas four samples of bioturbated and granular chalk have organic carbon content ranging from 1.4 to 2.8 percent, averaging 2.0 percent. The difference between the two groups of rock samples is smaller than that reported by Hattin (1971) for the bioturbated and nonbioturbated Greenhorn chalks and is explained by the smaller amount of bioturbation in most burrowed beds of the Smoky Hill.

Smoky Hill organic matter occurs as black, silt-sized grains and as wispy streaks or flakes in which small amounts of pyrite are common. The reddish-colored streaks of iron oxide that occur most commonly in nonbioturbated chalks have similar size and shape as the organic wisps, and may be their oxidized equivalent. Samples of yellow- or orange-colored chalk contain only the reddish-colored wisps, the pyrite and organic matter having been oxidized during weathering.

A postdepositional feature recorded primarily in the upper half of the composite section consists of closely spaced, wispy crinkles (Fig. 52), which occur in mostly thin zones within beds of dark-colored, nonlaminated chalk. The crinkles are irregular fractures, lying roughly parallel to stratification, and are filled with sparry selenite. Although these crinkles have the appearance of chalk flasers (Garrison and Kennedy, 1977), concentrations of clay and other insoluble minerals are lacking, so the features are not the result of pressure solution. Presence of gypsum suggests that these crinkles are an epigenetic phenomenon that developed by near-surface evaporation and precipitation from sulphate-rich waters during weathering of the section. I have recorded selenite in chambers of planktonic foraminifers occurring in weathered chalk samples, so the presence of gypsum in the crinkly fractures does appear related to weathering. The weathering hypothesis requires testing by comparison of the surface phenomena with unweathered chalk from equivalent beds in the nearby subsurface, where the crinkles presumably would be absent.

The Smoky Hill chalk manifests a wide variety of diagenetic features, none of which was sufficient to produce hard, well-cemented chalk. Hardgrounds, such as those recorded commonly in European chalk deposits, are lacking.

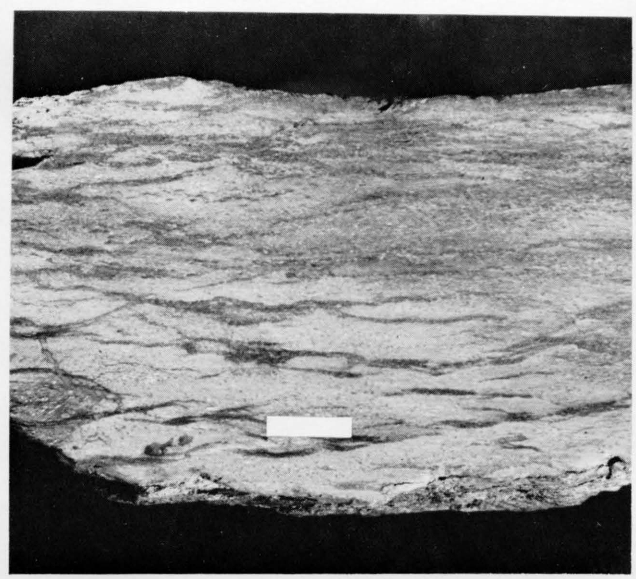


FIGURE 52. Polished surface of chalk, cut normal to bedding, showing gypsum-filled wispy crinkles. These structures lack insoluble detritus and iron oxide and were not produced by pressure solution during burial diagenesis. Sample from middle part of exposure in Sec. 20, T.15S, R.32W, Logan County, Kansas. Bar scale = 1 cm.

DEPOSITIONAL ENVIRONMENT

Regional Setting and Stratigraphic Framework of Smoky Hill Deposition

The Smoky Hill Member of Kansas was deposited in the eastern part of a broad seaway, which in Late Cretaceous time extended from the Gulf of Mexico to Arctic Canada. The subsiding trough containing these waters has been called the Rocky Mountain Geosyncline by many authors (e.g., Gilluly, 1963, p. 146; Armstrong, 1968, p. 432; Gill and Cobban, 1973, p. 1) although in recent years the name "Western Interior basin" (e.g., Kauffman, 1969, p. 227; Kauffman and others, 1977, p. 6) has come into regular use. In tectonic terms the trough is a retroarc foreland basin (Dickinson, 1976, p. 1278). Throughout the U.S. Western Interior region, subsidence was greatest near the western edge of this structural depression. Locally, as in southwestern Wyoming and central Utah, Upper Cretaceous deposits alone reach thicknesses between 5490 and 6100 m (18,000-20,000 ft) (Reeside, 1944). In general, Cretaceous deposits are coarser grained toward the western margin of the basin (Reeside, 1957, p. 508) where, in complexly intertongued relationships, fine-grained offshore marine shales give way to nearshore and marginal marine sandstones and these, in turn, pass westwardly into nonmarine deposits of coastal swamps, fluviatile systems, and piedmont areas (see Pike, 1947; Spieker, 1949; Weimer, 1970, p. 273; McGookey and others, 1972, maps). Along the western margin of the basin, distribution of lithofacies delineates clearly a major western source for trough-filling terrigenous detritus. This detritus was derived from tectonic highlands, the Sevier orogenic belt of Armstrong (1968, p. 435), which were raised within the area embraced formerly by the Cordilleran geosyncline (Gilluly, 1963, p. 146; Armstrong, 1968, p. 432; King, 1977, p. 95). As a part of the stable craton, the area lying east of the seaway was low and flat (Reeside, 1957, p. 509) and during most of Late Cretaceous time was not an important source for terrigenous detritus that entered the basin (Weimer, 1970, p. 273; McGookey and others, 1972, p. 195; Tourtelot and Cobban, 1968, p. 7).

Across most of the Western Interior basin, late Cretaceous strata manifest marked cyclicity; nowhere is this cyclicity marked more clearly than along the western side of the former seaway, where dark-colored shales and light-colored sandstones are intertongued complexly. Pike (1947, p. 15) has reviewed two major hypotheses that have been advanced to account for such intertonguing, namely (1) repeated vertical oscillation within the seaway during deposition, and (2) alternation of transgression caused by downward movements of the crust and regression resulting from subsequent infilling of the basin margin by terrigenous detritus. The latter hypothesis was favored by Sears and others (1941), Pike (1947), and Weimer (1960). Such a simple explanation of this cyclicity is probably rendered untenable by present-day understanding of Cretaceous global sea-events. For example, Mörner (1980) has noted the influence of tectono-eustacy or geoidal eustacy in causing major Cretaceous transgressions and regressions.

Details of cyclic deposition in the Four Corners area and in central Utah have been elaborated in classic papers by Pike (1947) and Spieker (1949), respectively, and Weimer (1960) has documented on a regional basis four major Late Cretaceous depositional cycles that can be recognized through much of the Rocky Mountains and adjacent Great Plains regions. These cycles are named for peak-transgressional units, which are (ascending) Greenhorn, Niobrara, Claggett, and Bearpaw. Kauffman (1977) claims that these four cycles, and possibly two others of Late Cretaceous age, are widely correlative around the world and are the result of eustatic fluctuations of sea level related to plate-tectonic movements (=tectono-eustacy). Jeletzky (1977, 1978) has issued a major challenge to this interpretation on the basis of stratigraphic data from several western and Arctic Canadian basins in which sea-level curves show little correspondence to Kauffman's scheme or to each other. Jeletzky (1977, 1978) states that the major control of such cyclic fluctuations is local, regional, or interregional tectonic movement. Perhaps Jeletzky's view is confirmed best by the work of Peterson and Kirk (1977), who recognized *nine* transgressive-regressive cycles in four basins situated in the southern part of the Colorado Plateau, and by Gill and Cobban (1966, p. 45), who concluded that their extensive studies of the Pierre Shale had failed to yield a clear-cut example of transgression and regression that could be "unquestionably related to anything other than local subsidence and uplift." Similarly, Gill and Cobban (1973, p. 21) report that the westwardly directed Bearpaw transgression of western Montana was synchronous with marine regression across eastern Wyoming, which demonstrates the significance of local tectonic events in determining strandline movements. For the Montana area, these authors (p. 33) believe that crustal instability, combined with varying rates of detrital influx, is the best explanation for the transgressive and regressive events. Discrepancies in number and timing of Western Interior Late Cretaceous depositional cycles emphasize the need to view with great caution any generalizations concerning their relationship to worldwide events. The stratigraphic section in each area must be interpreted on its own specific features, coupled with data deriving from studies of global sea-level events. Good recent discussions of Western Interior cyclicity have been presented by Gill and Cobban (1973), Ryer (1977), Kauffman (1977), Cooper (1977), and Hancock and Kauffman (1979).

Although global eustacy undoubtedly accompanied plate-tectonic events such as late Cretaceous widening of the North Atlantic, serious doubt has been cast on the premise that eustacy alone could account for aggregate thicknesses of marine strata of the Western Interior region (Bond, 1976; Cross and Pilger, 1978). These authors point out that subsidence must have been greater than can be attributed solely to supracrustal loading. This excess of subsidence has been attributed to low-angle subduction of a Pacific oceanic plate (Dickinson, 1976; Cross and Pilger, 1978). Aside from causative factors, it is evident that for much of the Western Interior region the dominant crustal movement was, in fact, downward. How else could we explain the widespread accumulation of marine strata to a thickness commonly much greater than 1000 m, with only minor unconformities?

Depositional cycles in the Western Interior Late Cretaceous are most evident along the western side of the basin, where transgressive events are recorded in westwardly directed tongues of offshore marine shale and regressions are marked by eastwardly directed tongues of nearshore and marginal marine sandstone. The youngest of the regressive sandstone bodies corresponds to the Fox Hills Sandstone of the classic Western Interior section, and before the advent of Tertiary erosion may have extended eastward into Kansas. Because other major western sand tongues did not approach Kansas even closely, the pattern of cyclicity there differs greatly from that in the Four Corners area, central Utah, etc. In Kansas the lower part of the Upper Cretaceous section contains a complete marine cyclothem (Hattin, 1964), and corresponds to the first transgressive-regressive cycle documented by Weimer. Uppermost strata of the Greenhorn cyclothem comprise sandy or silty beds known as the Codell Sandstone Member of the Carlile Shale, which nearly everywhere in Kansas is overlain sharply by chalky limestone belonging to the Fort Hays Limestone Member, Niobrara Chalk. Unlike the Greenhorn cyclothem, basal marine beds of which are marginal marine sandstones and sandy or silty shales, the second (Niobrara) transgressive sequence commences with offshore chalky limestone. The Codell and Fort Hays are separated by a northeastwardly widening lacuna, and the base of the Fort Hays is demonstrably diachronous, ascending biostratigraphically in the direction of transgression (Hattin, 1975a). At the Codell-Fort Hays contact evidence of subaerial erosion or nonmarine deposition is lacking. This has prompted the conclusion (Hattin, 1975a) that during the regressive part of the Greenhorn cycle marine waters were not withdrawn from the Kansas area. Lack of terrigenous detrital units at the base of the Niobrara transgressive sequence indicates remoteness of the eastern shoreline at the time Fort Hays deposition was initiated. Assuming that the purest Niobrara carbonates represent peak transgression in the second late Cretaceous cycle, the transgressional maximum apparently occurred sometime during deposition of the Fort Hays Member (Fig. 53). Less pure carbonates of the Smoky Hill Member thus are deposits of a protracted regressional episode that was marked by occasional minor incursions (Coates and others, in press). Smoky Hill strata lack uniform carbonate content, some intervals being noticeably less chalky than others (e.g., middle part of section exposed at Locality 19). These differences manifest variable rates of terrigenous detrital influx against relatively uniform, dominantly carbonate production. Times of least detrital deposition are marked by bioturbated or granular chalk intervals. Near the top of the Smoky Hill, impure chalk gives way to chalky shale, then to calcareous shale, which is followed upward by noncalcareous shale of the Sharon Springs Shale Member, Pierre Shale. In the Pueblo area of Colorado, chalky and calcareous shales assigned to the basal, unnamed transition member of the Pierre (Scott and Cobban, 1964) are overlain by the Apache Creek Sandstone Member. The latter unit represents terminal deposits of the Niobrara cyclothem. Although not developed in Kansas, the Apache Creek Member is equivalent to dark noncalcareous shales belonging to the lower part of the Sharon Springs Member of Kansas (Gill and

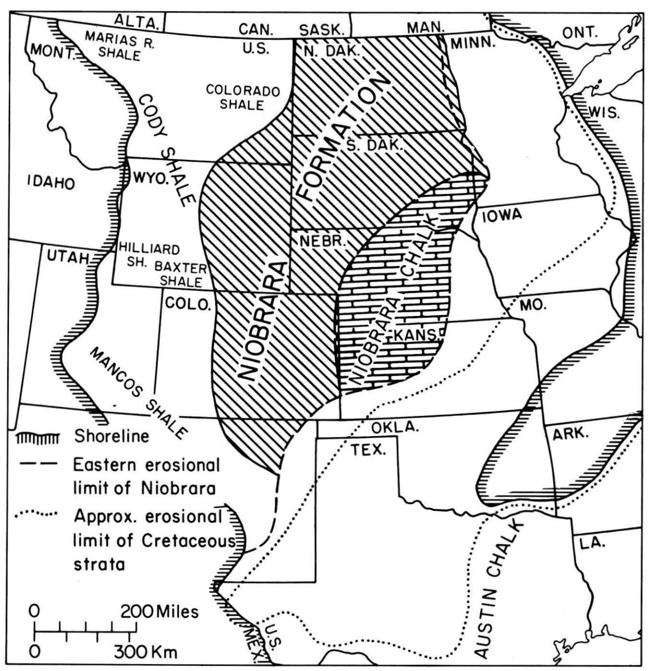


FIGURE 53. Map showing paleogeography at peak of Niobrara transgression, regional distribution of Niobrara Chalk (Formation), and nomenclature of laterally contiguous marine units. Position of eastern shoreline is conjectural. Compiled from numerous sources.

others, 1972). Overlying beds of the Sharon Springs are transgressive deposits of the Claggett cycle, the peak of which is represented by organic-rich shales belonging to the middle, buttress-forming unit of the Sharon Springs in Kansas (Gill and others, 1972, p. 8).

Carbonate-rich units of the Greenhorn Limestone and Niobrara Chalk are tongue-like bodies sandwiched between dark-colored clayey shales of a huge clayey shale lithosome that includes such units as the Mancos Shale, Lewis Shale, Pierre Shale, Graneros Shale, Blue Hill Shale Member of the Carlile Shale, Claggett Shale, and Bearpaw Shale. Along the western side of the basin this lithosome is intertongued with the sandstone bodies mentioned above. The western side of the basin was the locus of maximum subsidence and development of greatest statigraphic thicknesses, whereas deposits along the eastern side are much thinner and evince subsidence of much smaller magnitude. The basin can be divided structurally into two broadly defined zones, namely a western, axial zone, in which tectonism was most active, and a broad, stable eastern shelf (Fig. 54). Kauffman (1977, p. 84) has suggested a fourfold division, including a broad "hinge" zone between the stable shelf of Kansas-Nebraska-Iowa and the actively subsiding parts of the basin. However, lateral changes of facies across the so-called "hinge zone" are very gradual and do not suggest an abrupt change in slope of the sort associated with tectonic hinges. For example, individual limestone beds of the Kansas Greenhorn can be traced to westernmost New Mexico, and the Niobrara changes facies gradually westward from chalk, to chalky shale, to calcareous shale and is thus recognizable as far west as the Four Corners area, north flank of the San Juan Mountains, and northwestern Colorado. Such persistence suggests that the stable shelf extended far to the west, and that the hinge zone lay for the most part west of the Southern Rocky Mountains. The model proposed by Weimer (1978, fig. 2) is a more acceptable interpretation.

The Niobrara Chalk of Kansas represents deposition of carbonate-dominated muds far from the major, western sources of terrigenous detritus. Detrital content of the Niobrara increases gradually westward, apparently reflecting western source areas. At the eastern (erosional) limit in Kansas the Niobrara has its highest carbonate content, suggesting that the eastern shoreline was far removed from the present outcrop, and that the eastern detrital source areas had little influence on Niobrara deposition in Kansas. Because the Niobrara is truncated erosionally along the entire eastern outcrop, position of the shoreline is conjectural. In contrast, the excellent stratigraphic record in the axial zone of the basin permits definition of the western shoreline with considerable accuracy (Fig. 53).

The names Niobrara Chalk and Smoky Hill Chalk Member are used only in Kansas, Nebraska (Condra and Reed, 1943), and southeastern South Dakota (Robert Stach, oral communication, 1980). Niobrara strata are traceable southwestward across Colorado and northern New Mexico to the San Juan basin, where they pass into shale and sandstones of the Mancos Shale (Molenaar, 1973), and where the name "Niobrara Shale Member" is used locally (e.g., Lamb, 1968). In southern Colorado (e.g., Dane and others, 1936; Scott and Cobban, 1964) and northeastern New Mexico (e.g., Griggs, 1948; Pillmore and Eicher, 1976) the formal name is Niobrara Formation. In both areas the upper member is known as Smoky Hill Marl Member (Dane and others, 1936; Griggs, 1948) or Smoky Hill Shale Member (Gill and Cobban, 1964; Pillmore and Eicher, 1976). In southern New Mexico the Niobrara equivalent is assigned to the Mesa Verde Formation (or Group) (Cobban and Reeside, 1952, chart 10b). In western Colorado the Niobrara passes into calcareous beds of the Mancos Shale (Fisher and others, 1960) and in east-central Utah is represented by the Bluegate Shale Tongue of the Mancos (McGookey and others, 1972). In a broad area embracing northern Colorado (e.g., Kent, 1967a), southern Wyoming (e.g., Frerichs and others, 1975), the Black Hills (Robinson and others, 1964; Tourtelot and Cobban, 1968), eastern Montana (Montana Geological Society, 1969, p. 9),

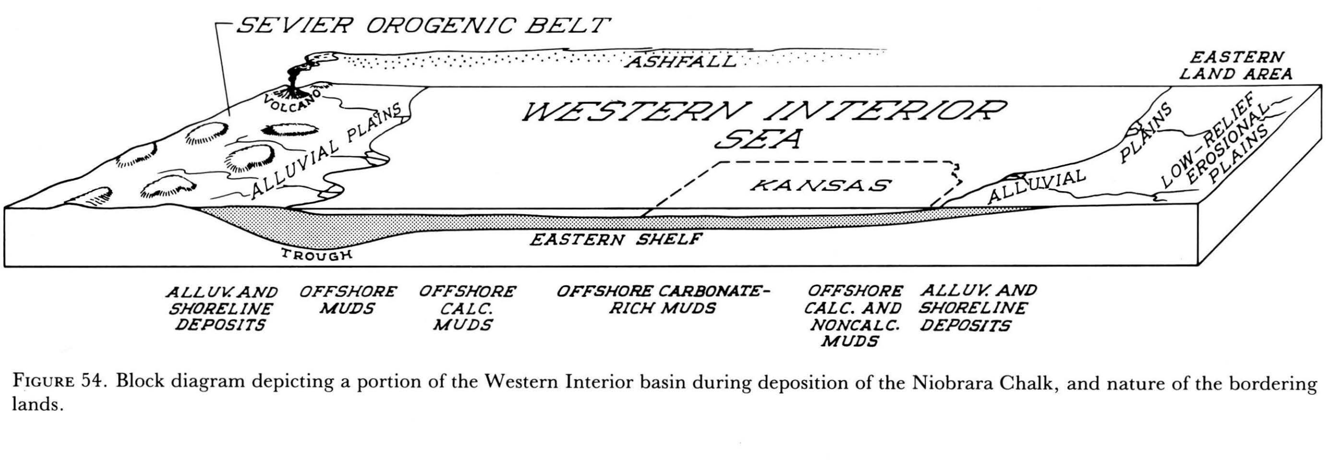


FIGURE 54. Block diagram depicting a portion of the Western Interior basin during deposition of the Niobrara Chalk, and nature of the bordering lands.

western South Dakota (Robert Stach, oral communication, 1980), North Dakota (Gries, 1954; Carlson, 1964), and Minnesota (Shurr and Cobban, 1979), the name "Niobrara Formation" is in general use; and the upper member, where recognized formally, is the Smoky Hill Chalk Member in South Dakota (Agnew and Tychsen, 1965, p. 171; Robert Stach, oral communication, 1980) and Smoky Hill Member in northern Colorado (Trexler, 1967; Weimer, 1978). Northward in Montana the Niobrara equivalent is known as the First White Specks interval of the Colorado Group or Colorado Shale (Montana Geological Society, 1969, p. 9), and in southern Canada as the First White Specks zone of the Alberta Group (Williams and Burke, 1961), Thistle Member of the Wapiabi Formation (Stott, 1963, p. 114), or Boyne Member of the Vermillion River Formation (Wickenden, 1945, p. 3). For the Manitoba escarpment section McNeil and Caldwell (1981, p. 62) have recently abandoned the name "Boyne Member" in favor of the term "Niobrara Formation." In the central and northern Rocky Mountains the Niobrara equivalent is embraced by the Cody Shale of south-central Montana and north-central and northwestern Wyoming, and by parts of the Baxter Shale and Hilliard Shale (Cobban and Reeside, 1952, chart 10b; McGookey and others, 1972). Regional distribution of the Niobrara and its equivalents is depicted in Figure 53.

Origin of Chalk Components

The principal component of most Smoky Hill strata is calcium carbonate, nearly all low-magnesium calcite, which occurs in several forms. Examination of samples in the field and of thin sections and scanning electron micrographs (Hattin, 1971, 1975b, 1981) has permitted identification of nearly all carbonate components. Laminated and nonlaminated chalk, the most abundant lithotypes in the member, consist largely of coccoliths and coccolithophorid debris. These minute plant fossils are skeletal remains of coccolithophores, members of the Chrysophyceae (golden-brown algae), modern examples of which are planktonic forms occurring mainly in open-ocean waters of normal salinity. As coccoliths are shed from the living algae, or when coccolithophores die, the skeletal remains sink directly toward the sea floor, where the tiny skeletal plates may accumulate as part of the sea-floor ooze.

Alternatively, coccolithophores may be eaten by pelagic organisms, such as copepods and salps, in which case the skeletal remains sink more rapidly to the sea floor in fecal pellets (Lohmann, 1902; Honjo, 1975; Bathurst, 1971, p. 267; Hattin, 1975b). Coccolithophores were exceedingly abundant in Cretaceous seas because widely distributed chalk deposits of that system are generally rich in coccoliths (e.g., Sorby, 1861; Cayeux, 1935, p. 35; Black, 1953; Hancock and Kennedy, 1967; Hattin, 1971, 1975c; Scholle, 1977). In the Smoky Hill chalks, coccoliths are concentrated in fecal pellets, which are abundant to profuse in all chalks examined by me, and occur in more scattered fashion in the chalk matrix. I conclude, therefore, that coccoliths were transported to the sea floor in pellets *and* as individual plates or coccospheres not associated with pellets.

Also abundant in Smoky Hill rocks are tests of calcareous foraminifers, most of which are remains of planktonic forms belonging to the families Globotruncanidae, Marginotruncanidae, Heterohelicidae, and Planomalinidae (Frerichs and Dring, 1981). Like coccoliths, the pelagic foraminifers sank upon death to the sea floor, where their tests contributed importantly to accumulation of carbonate mud. Diverse species of calcareous benthic foraminifers have been reported from the Niobrara and its equivalents (e.g., Loetterle, 1937; Kent, 1967a) but are an insignificant element in Smoky Hill thin sections examined by me.

Chalky carbonates and certain calcisiltites of the Kansas Greenhorn contain conspicuous quantities of calcispheres, which are the spheres, or oligosteginas, of European chalk literature. Few structures in Smoky Hill thin sections can be identified with certainty as calcispheres, which therefore are a negligible component in the member.

Nearly all chalky strata of the Smoky Hill contain abundant, vertically compacted ellipsoidal calcareous pellets composed of micritic carbonate. These structures are also abundant in chalky beds of the Greenhorn Limestone (Hattin, 1975b,c) and Fairport Member of the Carlile Shale (Hattin, 1962). I concluded (Hattin, 1962, p. 106; 1975b) that these are the fecal pellets of coccolithophore-eating organisms. Scanning electron micrographs of pellets show them to be composed almost entirely of coccolithic material. Pellets everywhere contain richer concentrations of coccoliths than the adjacent matrix of nonpelleted micrite.

Other carbonate constituents apparently are of benthic or diagenetic origin. Inoceramid valves, valve fragments, and isolated prisms are principal among benthic allochems of Smoky Hill chalks. Although unbroken inoceramid valves are nearly ubiquitous, fragmented material is common through the entire section. Fragmentation occurred most probably by preburial decay of the organic binding (Tarr, 1925, p. 259), which occurs within both nacreous and prismatic layers of living bivalves (Wilbur, 1964). Presence in the Smoky Hill of teeth deriving from shell-crushing sharks such as *Ptychodus* suggests that these predators may have broken up the skeletons of larger benthic invertebrates; however, evidence of bite marks on inoceramid valves was not recorded during this study, and fragments of inoceramid valves were observed in only two of the many coprolites that were examined. Most fragmental remains of Smoky Hill inoceramids are disposed so as to indicate *in situ* disintegration rather than the ravages of predator attack. The only significant exception is the lens of biomicrite that lies between Marker Units 21 and 22 in SE¼ Sec. 1, T.14S, R.31W, Gove County, which probably resulted from a brief, localized episode of gentle sea-floor scour.

In Smoky Hill strata, shells of ostreid bivalves probably outnumber those of inoceramids. Although some species of the latter lack epizoic oysters, large forms such as *Inoceramus (Volviceramus) grandis* and *I. (Platyceramus) platinus* are generally encrusted by scores to hundreds of *Pseudoperna congesta* specimens, and these oysters occur also as isolated, articulated specimens or even as single valves. Collectively, the oysters are an important carbonate component in much of the Smoky Hill section, especially in the lower half, below Marker Unit 11.

Other calcitic skeletal remains, including those of stalked cirripeds, rudists, and various poorly represented bivalve groups, are responsible for most other primary carbonate material in the Smoky Hill.

The soft, porous character of most Smoky Hill rocks attests to generally poor cementation. These rocks usually contain only small amounts of secondary overgrowths on coccoliths, inoceramids, and foraminifers, and crystals of interstitial cement. The bioturbated and granular chalk units are generally harder, more resistant to weathering, and in general contain larger amounts of secondary calcite. A logical source for this secondary calcite is originally aragonitic skeletal material, such as that derived from ammonite conchs and the nacreous layer of inoceramids. Aragonitic skeletal matter is virtually nonexistent in the Smoky Hill chalks, and potential void spaces that may have been left by its removal have invariably been closed by compaction. This suggests early diagenetic dissolution and precipitation elsewhere, probably as neomorphic overgrowths on skeletal remains and as interstitial cement. The greater degree of textural alteration in bioturbated chalk beds indicates that burrowing activity enhanced neomorphism by improving the movement of interstitial fluids.

The calcite that now fills or nearly fills most foraminiferal chambers consists of large, sparry crystals that lack evidence of centripetal growth. Even partially crushed tests commonly contain undeformed calcite crystals, which shows that crystal growth occurred after the tests were compacted. Incipient microstylolites, representing pressure solution during deeper burial diagenesis, suggest a possible source for sparry calcite now preserved in foraminiferal tests. Support for this interpretation comes from the lenses of *Uintacrinus* limestone, which not only contain the most numerous and best-developed microstylolites in the Smoky Hill, but are also the best-cemented rocks in the entire section!

Skeletal grains deriving from vertebrates, especially including fish scales and small bone fragments, are essentially ubiquitous in Smoky Hill chalk samples. These grains are scattered throughout the section, and except for a single lens in SE¼ Sec. 1, T.14S, R.31W, are not concentrated as in skeletal calcarenites and calcirudites of the older Greenhorn Limestone. The Smoky Hill Member is renowned as a natural repository for well-preserved, articulated vertebrate skeletons; however, evidence of predation, especially in the form of skeletal fragments in coprolites, is common. Predation and disintegration of carcasses on the sea floor or floating in the water column, coupled with gentle current action, could account easily for occurrence of vertebrate skeletal debris throughout the Smoky Hill composite section. Except for rare, nonaquatic-dinosaur skeletons, the animals that contributed the vertebrate debris were inhabitants of the sea in which Smoky Hill deposits accumulated.

Nearly all thin sections of little-weathered Smoky Hill chalk contain wisps or flakes and angular silt-sized grains of opaque, black organic matter. This material is interpreted as plant debris, derived possibly from distant land sources and transported as small particles, or may in part represent fragments produced by disintegration of large floating or waterlogged tree trunks and limbs. Fossilized logs have been reported from the Smoky Hill (Williston, 1897, p. 243) and carbonized logs were recorded during my investigation. Total organic carbon content of chemically analyzed Smoky Hill samples ranges to as much as 5.8 percent (Table 4). This is much higher than indicated by abundance of microscopically visible grains, which indicates that much of the organic carbon was derived from the organic matter of marine organisms, i.e., from decay of foraminifers, coccolithophores, bivalves, fish, algae, etc., on the sea floor. This interpretation is supported by isotopic evidence presented recently by Arthur and others (1981). Preservation in Smoky Hill muds of so much organic matter is clear evidence for reducing conditions below the mud-water interface, and helps to account for olive gray coloration in most of the little-weathered chalk. Highly weathered samples of chalk contain no visible evidence of organic carbon, presumably because of oxidation during weathering.

All analyzed Smoky Hill chalk samples contain terrigenous detritus comprising silt and finer-grained quartz, kaolinite, and mixed-layer illite-montmorillonite. A few samples contain trace amounts of feldspar. Some of the quartz is visible in thin sections, but the other minerals, and most of the quartz, were detected by X-ray diffraction. This indicates that the bulk of terrigenous detritus is clay-sized material and is mostly disseminated throughout the rock rather than being concentrated in detritus-rich laminae. The gradual decrease in purity of Smoky Hill carbonate rocks in a westward direction from

Kansas to western Colorado and northwestern New Mexico suggests progressively greater dilution of pelagic carbonate muds in that direction, presumably by detritus derived from the Sevier orogenic belt.

Insoluble residue content of nonbioturbated chalk samples from throughout the composite section averages 31.4 percent of the rock. This is far greater than can be accounted for by terrigenous detritus and organic carbon. Secondary minerals, including gypsum, alunite, iron oxide, and especially pyrite, make up much of the remaining residue material. Pyrite, which occurs mostly as minute framboids, but locally replaces skeletal calcite, formed diagenetically during decay of organic matter in a reducing environment that existed below the mud-water interface.

Physical Aspects of the Environment

General Statement. Speculation on the depositional environment of Cretaceous chalk deposits has occupied many pages in the geological literature, but most of the work pertains to the strata in England and northwestern Europe. Quite recently, however, the American chalk formations have received increased attention, partly because the field for environmental investigation is fertile and partly because of growing interest in chalk deposits as oil and gas reservoirs. Some of the more embracive contributions to depositional environments of Western Interior chalks include works by Reeside (1957), Miller (1958, 1968), Hattin (1962, 1971, 1975c, 1981), Asquith (1970), King (1972), Frey (1972), Kauffman (1967, 1969, 1977), Eicher (1969), Frush and Eicher (1975), and Baldwin (1976). The flood of recent papers concerned with chalk genesis and inhabitation of soft substrates by marine benthic organisms, coupled with lithologic and stratigraphic information for the entire composite section, makes possible an embracive environmental synthesis of the Smoky Hill Member in Kansas. In the following sections pertinent environmental parameters are examined on the basis of inorganic and biological evidence. Paleoecology of the major macroinvertebrate groups is treated separately.

Depth of Deposition. In Kansas Geological Survey Bulletin 209 (Hattin, 1975c), I presented an historical account of the controversy regarding depth of deposition of Cretaceous chalk deposits. From extensive reports of the Deep Sea Drilling Program we know with certainty that chalk is a common result of diagenetic processes that alter nannoplankton oozes beneath the deep-sea floor. For more than a century, debate has waxed and waned as to whether or not Cretaceous chalk deposits are an ancient analog of deep-sea oozes or the product of considerably shallower depositional settings. As noted by Hancock (1975, p. 517), "it is a subject about which a fair amount of nonsense has been written." With apologies to Jake, and with minor emendations and additions, my review is repeated here.

The abundance, or apparent abundance, of planktonic foraminifera in some chalk deposits led many early authors to conclude in favor of oceanic depths for deposition of the British and European chalks (e.g., Huxley, 1858; Fuchs, 1883; Hume, 1894). At that time only Cayeux (1897, p. 527) argued forcefully against the deep-water interpretation, stating that the maximum depth of chalk deposition in the Paris Basin was less than 150 fathoms (275 m). In their classic monograph of the British Chalk, Jukes-Browne and Hill (1903, 1904) concluded, principally on foraminiferal evidence supported by evidence from other fossil groups, that the Lower Chalk was deposited at depths of 400 to 500 fathoms (732-915 m) (1903, p. 358), the Middle Chalk at depths that usually exceeded 500 fathoms (915 m) (1903, p. 557) and probably reaching a maximum of approximately 650 fathoms (1185 m), and the Upper Chalk at depths as great as 700 fathoms (1281 m) (1904, p. 377). The evidence from foraminifera has been reviewed extensively by Earland (1939), who fairly well dispelled the notion that the Cretaceous chalk is to be compared with deep-sea deposits. He concluded (1939, p. 20) that foraminifera and other fossils of the British Chalk suggest deposition at depths to 50 fathoms (92 m) or less (for impure deposits near the base of the Chalk) to a maximum of 300 fathoms (549 m). Earland reviewed the work of Jukes-Browne and Hill (1903, 1904) and pointed out many errors in depth interpretation based upon foraminifers.

Sorby (1861, p. 197) was aware that foraminifers may be comparatively rare in chalk and that coccoliths are the chief constituent of the chalk matrix, and on the basis of coccolith abundance he implied that the Chalk is a Cretaceous analog of modern deep Atlantic muds. Quite recently, however, Hay and others (1967, p. 431) mentioned the considerable abundance of coccoliths in shallower shelf deposits. Furthermore, Scholle and Kling (1972) have reported concentrations of coccoliths that comprise as much as 20 percent of the deposits in lagoonal environments off British Honduras (= Belize) at depths no greater than 140 feet (43 m). Black (1965) notes that in modern tropical waters the maximum concentration of coccolithophorids is commonly at about 50 m (164 ft) whereas around the British Isles the maximum concentration is at depths of only 10 to 20 m (33-66 ft).

In a summary of chalk genesis, Tarr (1925, p. 253) cited conclusions of workers who favored the idea of great depositional depth but noted that much of the chalk may have been deposited in water depths less than 20 fathoms (37 m). In the past few decades, opinion has shifted in favor of shallower water origin for the European chalk. Boswell (1933, p. 201) wrote, "Conclusions as to the evidence of fossils would have been stated more boldly in favor of shallow depths but for considerations of the early globigerina ooze analogy." More recent study of planktonic foraminiferal percentages (Barr, 1961) suggests that the British Chalk need not have been deposited at depths much greater than 90 m (295 ft). By use of discriminant functions to maximize differences in foraminiferal assemblages, and by comparing Chalk Marl foraminifers with comparable living forms, Burnaby (1961) concluded that depth fluctuations occurred, with definite deep- and shallow-water phases. For the latter he estimated depths as little as 5 fathoms (9 m). For a higher part of the British section, and on the basis of comparison with modern sponge bathymetry, Reid (1962) concluded that the Late Turonian Chalk Rock was deposited in water not less than 50 fathoms (92 m) deep and not necessarily more than 110 fathoms (201 m). For the Chalk as a whole he (Reid, 1968, p. 558) stated that the hexactinellid sponge evidence indicated depths of at least 100 m (328 ft) but not necessarily more than 200 to 300 m (656-984 ft). Continental geologists have also been revising to smaller figures the maximum depositional depth of the Late Cretaceous European chalks. Nestler (1965, p. 113) concluded that the benthos of the German Rügen Chalk could have lived at depths ranging from 100 to 250 m (328-820 ft). This is in marked contrast to estimates of Voigt (1929) who, on the basis of bryozoan abundance, concluded that the Rügen Chalk was deposited at depths ranging from 300 to 1000 m (984-3280 ft) or more. Steinech (1965, p. 195) believed that this formation was deposited at depths not greater than 300 m (984 ft), on the grounds of comparison with modern depth ranges of some brachiopod genera found in the Rügen Chalk.

Hudson (1967) concluded that the softness of the English Chalk is related to initial absence of aragonite in chalk-forming muds. He interpreted this as the result of aragonite solution in a bathymetric range where particulate calcite is not dissolved. He stated that this would occur between depths of 150 m and 280 m (492-918 ft).

European and British chalk deposits contain numerous hardgrounds—nodular beds of chalk formed by lithification at or just beneath the sea floor. Kennedy and Garrison (1975) have summarized the main factors regarding hardground development. Many authors have stated that hardgrounds represent subaerial exposure of carbonate muds, whereas others have concluded that hardgrounds represent submarine lithification during periods of shallowing and depositional stillstand when the sea floor had become sufficiently shallow to be affected by wave and current action. The occurrence of numerous, closely spaced incipient to fully developed hardgrounds, as in the section at the east cliff, Dover, England, suggests that the sea floor was subjected repeatedly to shallow-water conditions. The origin of hardgrounds during episodes of shallowing is a view shared by Bromley (1967a, p. 507). For the well-known English hardground known as Chalk Rock he suggested that glauconitization occurred during shallowing to depths not less than 100 m (328 ft) and that phosphatization in this bed occurred during shallowing to depths not less than 50 m (164 ft). Kennedy and Garrison (1975, p. 321) estimated depositional depth of "clearly shallow water horizons" of the British Chalk, including the Chalk Rock hardground, to have been on the order of 50 m (164 ft) or less. Part of their evidence consisted of enterolithic algal borings, which have also been reported from the Chalk Rock by Bromley (1968, p. 250), indicating photic-zone depths. According to Scholle (1974, p. 181) most of the Chalk contains little or no evidence of algal growth, thus suggesting deposition below the photic zone, which probably extended to depths of at least 150 to 200 m (492-656 ft). The minimum depth for normal chalk deposition was thus on the order of 200 to 300 m (656-984 ft), and was probably not much in excess of the latter figure (Scholle, 1974, p. 181). On the basis of his literature review, Hancock (1975, p. 519) concluded in favor of a greater maximum depth, 600 m (1968 ft), but as noted by Scholle (1974, p. 181) depths on this order are difficult to envisage over broad continental platforms.

The preponderance of recent opinion favors deposition of the English and European white chalk facies at depths not significantly exceeding 300 m (984 ft), with the sea in some places, or at times of hardground formation, having been less than 50 m (164 ft) deep. However, in his recent summary of the topic, Hancock (1975, p. 519) concluded that the collective evidence suggests that deposition of chalk-forming muds occurred at depths ranging from 100 to 600 m (328-1968 ft). Obviously, the depositional depth of the white chalk facies was not uniform throughout the area of deposition. Depositional depths were thus compatible with the epicontinental shelf or platform tectonic settings.

Relatively few estimates have been made for depth of deposition of Upper Cretaceous chalk units of the Western Interior and adjacent seas of North America. On the basis of ammonite morphology, Scott (1940, p. 322) suggested probable bathymetric ranges of 20 to 80 or 100 fathoms (37 to 146 or 183 m) for the Eagle Ford and Austin groups of Texas. On the basis of Austin Chalk faunal and stratigraphic data, Dravis (1979, p. 58) postulated a depositional depth of 10 m (33 ft) or less for the area embracing San Antonio and Austin, Texas. Dravis (1979, p. 59) suggested southward deepening of water in the Austin depositional environment to more than 100 m (328 ft) in the present-day Texas subsurface. In a comparison of overall faunal characteristics of the Austin Chalk and Taylor marl of Texas, Clark and Bird (1966, p. 323) stated that the depth range for deposition of carbonate-rich muds could have been from 200 ft to 6000 ft (61-1830 m) but this range was reduced to between 200 and 1600 ft (61 and 488 m) on the basis of associated lithotypes. The Annona Formation of Arkansas contains an offshore, deeper-water shelf chalk facies, which was deposited at depths between 75? m and 125? m (246-410 ft), according to Bottjer (1978, p. 211). His estimate is based on embracive stratigraphic, petrologic, and paleoecologic characters.

In the Western Interior region chalky strata are assigned to two formations, the Greenhorn and Niobrara. For the Greenhorn Limestone, Kauffman (1969) has suggested depositional depths ranging from 100 to 500 ft (31-153 m), based mainly on comparative analysis of recent and fossil faunal elements. Much greater depths were postulated by Eicher (1969), who concluded from foraminiferal evidence that the central (eastern Colorado) part of the seaway during Greenhorn deposition was 1640 ft (500 m) or more in depth. From determinations of paleoslope over which the Greenhorn transgression occurred, Eicher (1969) postulated maximum depth between 2000 and 3000 ft (610-915 m). Even by combining the effects of maximum eustatic sea-level rise (see Bond, 1976) and isostatic compensation for water load, adjusted for shallowing caused by accumulation of upper Cretaceous deposits laid down prior to the transgressional peak, the minimum depth suggested by Eicher's paleoslope model could not have been attained without substantial tectonic subsidence. Disregarding the possibility of tectonic subsidence, the maximum depth at the peak of Greenhorn deposition could have been no greater than approximately 380 m (1246 ft). However, total thickness of the predominantly marine upper Cretaceous section in western Kansas was originally in excess of 760 m (2500 ft), so tectonic subsidence must have occurred at some time in order to accommodate the observed marine sequence. The maximum depth for Greenhorn deposition thus could have been in excess of 500 m (1640 ft).

Depth estimates for Niobrara deposition also have broad range. Without stating specific evidence, Miller (1968, p. 18) estimated the depth of Smoky Hill deposition to have been shallow, probably about 40 m (131 ft), with Fort Hays deposition occurring at even shallower depth. By comparing fossil and living macroinvertebrates, Kauffman (1967) implied a depth range of 50 to 500 ft (15-152 m) for Niobrara deposition, but suggested later (Kauffman, 1969, p. 227) that central basin carbonates of the Western Interior were deposited at depths of 100 to 200 ft (30-61 m), mostly within the photic zone. In a comparison of Niobrara and modern foraminifers, Kent (1967b) concluded that the Niobrara was deposited at depths of approximately 200 m (656 ft). Mainly on the basis of Kauffman's analysis, Frey (1972, p. 48) noted a deepening trend during Fort Hays deposition and stated that the trend continued during Smoky Hill deposition. This trend was also determined by Baldwin (1976, p. 24, 27), who suggested a minimum depth for Fort Hays deposition of 20 m (66 ft), and a maximum depth of 200 m (656 ft) at the top of the member. A markedly different interpretation of Niobrara depositional depth, at least in the Wyoming area, is presented by Asquith (1970), whose study of depositional topography in the west-to-east shelf-slope-basin setting suggests that the water at times exceeded a depth of 2000 ft (609 m). Depths of this order would have required considerable contemporaneous tectonic subsidence.

In their study of eustatic rise of sea level in relation to plate tectonics, Hays and Pittman (1973, p. 20) concluded that the depths of Cretaceous epeiric seas would have been generally less than 500 m (1640 ft) and possibly only 100 to 200 m (328-656 ft). Bond (1976) gave an overestimated maximum of 310 m (1017 ft) for Late Cretaceous eustatic sea-level rise. Neither of these estimates includes possible added depth owing to isostatic adjustments during transgression or to contemporaneous subsidence. Therefore, maximum depth could have been considerably in excess of these estimates.

The Niobrara of Kansas is part of a major depositional cycle, which is widely manifest in Coniacian and Santonian marine strata of the U.S. Western Interior, and is also represented by the Austin Chalk of Texas and the First White Specks zone of western Canada. During Niobrara deposition a white chalk facies was being deposited across a broad area of northwestern Europe and the British Isles. The broad distribution of a relatively deep-water chalky facies suggests that extra-basinal control, i.e., eustacy, was a major factor leading to transgression during the Niobrara cycle (see Mörner, 1980). In Kansas, initial deposits of the Niobrara are sandy basal beds of the Fort Hays Member, which lie with regional disconformity upon the Carlile Shale. The post-Carlile surface was produced (Hattin, 1975a) during an episode of nondeposition and sublevation upon which Niobrara deposition was initiated when transgressional waters deepened sufficiently to permit accumulation of permanent carbonate muds. Water depth during the stillstand can only be surmised. King (1963, p. 248) estimated that sand or gravel cannot be moved solely by waves at depths greater than 30 to 40 ft (9-12 m), but noted that the action of tidal currents extends to much greater depths on modern shelves. The evidence for tidal action in the Western Interior Cretaceous is rather extensive (Klein and Ryer, 1978), so that the minimum depth for movement of basal Fort Hays sand and local phosphate pebbles apparently exceeded the maximum depth of wave transport suggested by King (1963). According to Gross (1977, p. 122) the accumulation of silt and clay particles, which would include nannoplankton-rich carbonate muds, occurs on many modern shelves at depths of 50 to 150 m (164-492 ft). Assuming less physical rigor on the Western Interior carbonate shelf than on modern open-ocean shelves, the lower end of this range (50 m) is regarded as closer to the depth at which Niobrara muds may have begun to accumulate. This figure exceeds that for minimum depth (15 m) indicated by Kauffman (1969, p. 238) for gryphioid pycnodont oysters, which occur in lowermost Fort Hays beds, and that (20 m) indicated by Baldwin (1976) on the basis of foraminiferal data. In summary, initial deposits of the Fort Hays may have been deposited in waters no more than 50 m (164 ft) deep, and possibly as little as 15 m (49 ft) deep. Progressive deepening during Fort Hays and Smoky Hill deposition has been noted above. Just how deep these waters became is a matter of speculation. As Smoky Hill deposition proceeded, water depth apparently became gradually greater, and bottom circulation of this water decreased, possibly because of density stratification. During final phases of deposition, as represented especially by strata at Localities 21 and 24, benthic macroinvertebrates became scarce, suggesting that depth was near the lower limit of the vital isostrate, which Byers (1979a) suggests was at 150 m (492 ft) in poorly circulated interior basins. However, flat depositional topography and the huge regional extent of the Niobrara depositional environment suggest that circulation probably affected the bottom at depths greater than 150 m. Overlying beds of the Sharon Springs Member, Pierre Shale, represent a lethal isostrate (Byers, 1979b, p. 22), indicating that the water was even deeper than during terminal Smoky Hill deposition. Inoceramids and oysters occurring in the Smoky Hill were interpreted by Kauffman as indicating depths of 200 to 500 ft (61-152 m), the larger figure according well with the lower limit suggested by Byers' work. Despite Kauffman's implication (1969) that deposition occurred mostly within the photic zone, I have not detected endolithic algae in any thin sections of Smoky Hill macroinvertebrate shells. For clear water, absence of endolithic algae indicates water depths of at least 150 to 200 m (492-656 ft) (Hancock, 1975, p. 518).

If the maximum possible (310 m) eustatic rise in sea level postulated by Bond (1976) did occur during the Niobrara transgression, and did prevail during most or all of Smoky Hill deposition, then it is possible to estimate water depth from non-biologic considerations. A 310 m sea-level rise would involve an additional 93 m (305 ft) of depth increase owing to isostatic adjustment for water load (Bloom, 1967; Eicher, 1969), bringing total depth to 403 m. This depth must be adjusted for the shallowing effect of deposition during transgression, and for subsidence under the sediment load. Thickness of the partially compacted Niobrara section was approximately 300 m, and would have depressed the crust isostatically approximately 200 m (Eicher, 1969, p. 1087). This means a possible maximum water depth on the order of 300 m. This figure does not include an allowance for tectonic subsidence, which would have caused greater deepening, and is based also on the assumption that maximum eustatic rise in sea level prevailed during deposition of the upper Smoky Hill, which seems unlikely (see Kauffman, 1977, p. 85). Although Smoky Hill muds accumulated during a time of regional regression, lithologic and faunal evidence indicate that greatest water depth occurred near the close of Smoky Hill deposition. This suggests that in western Kansas, at least, depth was indeed influenced by tectonic subsidence, and not solely by eustacy and isostatic adjustment of the crust. Based on all of the factors discussed above, the depth of Smoky Hill deposition appears to have ranged from a minimum of 150 or 200 m (492-656 ft) to a maximum in excess of 300 m (984 ft).

Temperature. Early in the twentieth century, knowledge of climatically controlled latitudinal variations of Cretaceous biotas was understood sufficiently to be summarized in some detail by Dacqué (1915, p. 423-426). At that time paleontologists recognized in the Northern Hemisphere a warm-water Tethyan or Mediterranean belt, in which deposits are characterized by rudists, corals, actaeonellids, nerineids, and larger benthic foraminifers, and a cool-water Boreal belt, in which deposits are characterized by belemnites. Reeside (1957, p. 512) concurred that the Mediterranean realm had a warm or perhaps tropical climate but noted that the more northerly realm had a temperate, possibly cold-temperate, but not Arctic climate. Jeletzky (1971, p. 12-13) opined that the term "boreal" is misleading because fossil evidence from higher latitudes indicates at least a warm-temperate climate "everywhere in the 'Boreal' Realm." Accordingly, Kauffman (1973, p. 367) has substituted the term "north-temperate realm" and noted that this realm contains no truly Arctic faunas and has few cold-temperate bivalves.

In his review of biogeographic data on Cretaceous foraminifers, Bergquist (1971, p. 1567, 1578) postulated for North America a climatic zonation comprising tropical, warm-temperate, mild-temperate, cool-temperate, and cold zones. In this scheme the warm-temperate zone includes the area of the present Gulf Coastal Plain, the mild-temperate zone embraces the southern part of the Western Interior region (including Kansas), the cool-temperate zone includes the northern part of the U.S. Western Interior and all of western Canada, and the northern cold zone includes the Arctic portion of Alaska and Canada. An alternate zonation was proposed by Sohl (1971, p. 1611), who stated that through most of Cretaceous time North America was characterized by three main biotic provinces, including (1) a Caribbean-Central American-Baja Californian province having a warm-water fauna of Tethyan affinity, (2) a Coastal Plain-southern Western Interior province having subtropical to warm-temperate assemblages, and (3) a Californian-northern Western Interior province having a Boreal fauna. This scheme has been modified recently by Coates and others (in press), who recognize within the U.S. Western Interior three climatic belts, including Southern Interior, Central Interior, and Northern Interior provinces. Of these, the Central Interior Subprovince extended normally from Kansas, Central Colorado, and Utah northward to Montana and South Dakota. These authors (Coates and others, in press) imply that waters of these subprovinces were warm-, mild-, and cool-temperate, respectively, but that boundaries of the three subprovinces migrated both northward and southward, at times establishing marginal Tethyan influence in the Central Interior Subprovince, which included Kansas. Such fluctuations apparently account for occurrence, at some levels in the Kansas Cretaceous, of such typical Tethyan forms as *Vascoceras* and *Desmoceras* (Greenhorn Limestone), *Durania* and *Texanites* (in Kansas represented by the jaw apparatus, *Spinaptychus*) (Niobrara), *Trachyscaphites* (Pierre Shale), and keeled planktonic foraminifers. Although these, as well as other subtropical forms, are widespread at certain levels within the Central Interior Subprovince, at few places are they abundant elements of the local fauna. Similarly, a few horizons in the Kansas Cretaceous contain sparse representation of faunal elements more usually associated with the cool water (e.g., *Dunveganoceras* in the Greenhorn Limestone, belemnites in the Fairport and Smoky Hill chalks), and which probably migrated southward from the Northern Interior Subprovince. Unfortunately, the horizons at which Smoky Hill belemnites occur are not known. Theoretically, such fossils should occur in beds lying between those containing rudists, but mixing of Tethyan elements and belemnites has been recorded (e.g., Campanian of Sweden; Surlyk and Christensen, 1974), which casts a certain suspicion on the validity of climatic zonation schemes that have narrow divisions. Valentine (1967) stated that latitudinal ranges of individual species are narrow at times of increased climatic zonation, but several Niobrara species have wide latitudinal distribution, suggesting that climatic zonation was not quite as narrow and well defined as implied by Coates and others (in press). Examples of Smoky Hill species that have broad latitudinal distribution include *Inoceramus (Volviceramus) grandis* (New Mexico to Alberta), *Inoceramus stantoni* (New Mexico to northwestern Montana), *Scaphites depressus* (southern Colorado to central Alberta), *C. choteauensis* (southern Colorado to southern Alberta?), *Desmoscaphites bassleri* (northwestern New Mexico to northwestern Montana), and *Scaphites hippocrepis* (central Texas to Saskatchewan). These distributions suggest rather broad climatic zonation of the Western Interior Sea during much of Smoky Hill deposition. Nevertheless, distinct south-to-north differences in Western Interior faunas have been documented (e.g., Kent, 1969; Sohl, 1971; Bergquist, 1971; Jeletzky, 1971; Coates and others, in press), and climate, i.e., temperature, is accepted generally as the principal controlling factor.

Rudists have been recorded sparingly in the Kansas Smoky Hill (see Fig. 31), aptychi of *Texanites* are sparse (Miller, 1968), and keeled planktonic foraminifers extend geographically well to the north of Kansas (Kent, 1969). Based on the evidence of these few forms, Tethyan influence was very small in Kansas during deposition of the Smoky Hill chalk, and as noted by Coates and others (in press) was sporadic rather than continuous. Likewise, belemnites are rare in the Smoky Hill, suggesting that Kansas lay mostly below the southern geographic limit of these forms. A warm- or mild-temperate climatic belt is thus suggested for the Kansas area during most of Smoky Hill deposition.

Only sparse foraminiferal data are available for determining temperature during Smoky Hill deposition. The keeled planktonic foraminifer *Globotruncana* is a tropical form, the northern geographic limit of which was the 20°C isotherm (Bandy, 1960). This genus has been recorded widely in strata of Niobrara age in the Western Interior, including an area that lies well to the north of Kansas (Kent, 1969), suggesting minimum temperatures of 20°C for the upper part of the water column during at least part of Smoky Hill deposition. Another Niobrara keeled planktonic foraminifer, *Praeglobotruncana,* likewise of tropical affinity, has been recorded even farther to the north than *Globotruncana* (Kent, 1969; Bergquist, 1971). According to Bergquist (1971, p. 1594) the occurrence of *Marginotruncana marginata* Reuss in the Niobrara of Kansas, Colorado, and New Mexico suggests a moderate temperature for a large area of the Western Interior Sea. From these interpretations one can also conclude that during Niobrara deposition water temperature fluctuated between mild-temperate and subtropical.

Lowenstam (1964) has summarized oxygen-isotopic data that confirm the low- to high-latitude decline of Cretaceous paleotemperatures in the Northern Hemisphere. Isotopic methods have been utilized by Scholle and Kauffman (1977) to demonstrate climatic fluctuations from warm-temperate to subtropical in the U.S. Western Interior, but their data remain unpublished.

Substrates and Bottom Conditions. During Smoky Hill deposition carbonate muds accumulating on the sea floor were mainly soft oozes, and were perhaps even soupy. Such interpretation is suggested by modern deep-sea nannoplankton-rich muds, which have original porosity in the range 70 to 80 percent (Scholle, 1977, p. 987), and in some instances have porosity as high as 94 percent (Cook and Cook, 1972, p. 945). The argument is supported by occurrence in the Smoky Hill of abundant inoceramid bivalves having morphological characters that are adaptations to life on soft substrates (see section on paleoecology). Near absence of infaunal body fossils among Smoky Hill benthic forms is further evidence of substrates too soft to support any but specially adapted, epifaunal skeletonized organisms. Animals that attached themselves to or bored into hard substrates occur almost exclusively on shells of inoceramids, rudists, and cephalopods. Further evidence for soft substrates is manifest in the broad, short growth form of many small rudists, evidence from distribution of rudist epizoans for toppled life attitude in some large adult forms, and changes of rudist growth direction in some specimens in response to toppling.

Bioturbated and granular chalk beds have higher carbonate content than stratified chalks, and represent relatively brief depositional intervals during which influx of terrigenous detritus was less than normal. Preservation of burrow structures in these beds apparently reflects either (1) firmer substrates, which fostered inhabitation by the trace-making organisms (worms), or (2) early inception of lithification, which prevented burrow structures from being obliterated by compaction. If the substrates were indeed firmer than those represented by the laminated chalk, then one would expect that such beds may also have supported other infaunal organisms. The only Smoky Hill bed in which I recorded infaunal bivalves (*Lucina* sp. A) is in fact a bioturbated unit. On the other hand, if preservation of burrow structures resulted from early lithification of these carbonate-rich beds, the implication is clear that the laminated chalks were also bioturbated but lack burrow structures because of subsequent compaction. Actually, the laminated chalks do contain sparse, scattered burrow structures, but the beds could not have undergone much bioturbation because the process would have destroyed much or all of the lamination and stratified grain fabric, as well as the very thin, widely traceable bentonite seams that occur in most well-stratified units. Therefore, the first explanation seems more plausible and the paucity of infaunal body fossils, even in bioturbated beds, is owing less to preservational factors than to poor benthic environmental conditions generally. After all, diversity of the epifaunal benthos was always very low, with inoceramids and their epizoic oysters being the only abundant and ubiquitous forms.

During deposition of Smoky Hill muds current action at the sea floor was minimal. Well-washed calcarenites and calcirudites, which characterize substantial portions of the older Greenhorn Limestone (Hattin, 1975c) and Fairport Member of the Carlile Shale (Hattin, 1962), are lacking in chalk of the composite section. Local lenses of fragmented inoceramid debris have a micritic matrix and resulted from *in situ* disintegration of valves, as noted above. Scour structures, such as noted in the Fort Hays member by Frey (1972, p. 23), and in the Hartland Member of the Greenhorn by Hattin (1975c, p. 27), are lacking in the composite section, although the skeletal calcarenite lens recorded in SE¼ Sec. 1, T.14S, R.31W, Gove County, apparently resulted from a minor and local episode of sea-floor scour. Thus, current action strong enough to concentrate skeletal debris or create scours is known to have affected beds of the Smoky Hill in only one place. The general absence of strong bottom currents during Smoky Hill deposition was noted also by Beecher (1900, p. 268) and Pinkley and Roth (1928, p. 1021). For the most part, bottom waters apparently were poorly circulated, which accounts for the preservation of so much organic matter in nonbioturbated beds of the member, and accounts also for the *in situ* preservation of most benthic macroinvertebrates as well as articulated skeletons of vertebrates. Even so, the levels of bottom-water oxygenation were not uniform. The normal condition seems to have involved low levels of dissolved oxygen, which supported modest numbers of inoceramids and their epizoic oysters. At times, circulation improved considerably, and fostered proliferation of inoceramids and oysters, and addition to the benthic community of cirripeds and rudists. Evidence for such episodes consists of the shelly zones mentioned above wherein enormous numbers of invertebrate skeletons are preserved *in situ* in small thicknesses of strata (Fig. 20). At times of lower-than-normal circulation, benthic organisms became very scarce. This condition is represented in the composite section by very poorly laminated to nonlaminated, nonbioturbated chalk beds such as those dominating the section at Locality 24 and comprising the lower part of the section at Locality 21. Reduced availability of oxygen as a major factor in producing low-diversity Smoky Hill benthic assemblages has been suggested also by Miller (1968, p. 19) and Frerichs and Dring (1981, p. 47).

Among nonbioturbated chalk beds, those containing moderate to large numbers of inoceramids and oysters are usually more or less laminated, whereas the fossil-poor beds (e.g., Locs. 24 and 21) are poorly laminated or lack laminations. Smoky Hill laminations are owing largely to vertical variations in fecal-pellet abundance. This variation may be related to activity of weak bottom currents. When current energy was sufficiently high, gentle winnowing of bottom muds concentrated pellets in thin laminae, which alternate with laminae containing fewer pellets. Thick intervals of nonlaminated, fossil-poor chalk resulted from prolonged periods when current strength was insufficient to winnow bottom muds or bring in enough dissolved oxygen to support an extensive macroinvertebrate benthos. Strata of this kind are common to predominant in measured sections lying stratigraphically above Marker Unit 11. The possibility that vertical variations in fecal-pellet abundance relate to productivity in the pelagic realm is negated by irregular thickness and distribution of laminae and by the distribution of foraminiferal tests in laminated units. These tests lack any systematic pattern with respect to vertical variation of abundance. Rare, discontinuous laminae composed mainly of foraminifer tests resulted also from winnowing of bottom muds. Levels of current energy at the sea floor were largely insufficient to produce the kinds of foraminifer-rich laminae and lenses that abound in some parts of the older Greenhorn Limestone (see Hattin, 1975c, pl. 8B, pl. 16E). In the scheme of sea-floor energy levels proposed (Hattin, 1975c, p. 97) for Greenhorn carbonates, the Smoky Hill was deposited almost entirely under conditions of level number one. Energy level 2 is represented by the poorly washed skeletal calcarenite that occurs in SE¼ Sec. 1, T.14S, R.31W, Gove County.

The preservation of laminae in Smoky Hill beds that contain common to abundant benthic fossils is contrary to the model of biofacies change in a stagnant basin proposed by Byers (1977, p. 9). In his model the aerobic zone is represented by a calcareous epifauna and extensive bioturbation of the substrate, the dysaerobic zone is marked by absence of a calcareous epifauna but continued presence of bioturbate textures, and the anaerobic zone is characterized by absence of evidence for benthic organisms and preservation of laminae in the fine muds. Clearly, the deposition of Smoky Hill muds in the type area occurred where bottom waters were rarely, if ever, truly anoxic. Low levels of oxygenation probably contributed to low diversity in the macroinvertebrate benthos, but only near the top of the Smoky Hill are macroinvertebrates sufficiently sparse to suggest intermittent stagnation or near stagnation in lower levels of the water column (for contrasting opinion, see Arthur and others, 1981). Byers (1979b, p. 22, 23) notes a condition of stagnation during deposition of the lower part of the overlying Pierre Shale, which suggests that poorly fossiliferous beds situated near the top of the Smoky Hill were the precursor of the Pierre anoxic environments.

The seemingly anomalous association of calcareous epifaunal organisms and laminated substrates is unrelated to the model proposed by Byers. The laminations are indeed preserved because bioturbation was at a minimum, but not because of anoxic conditions in the water column. That the interstitial environment may have been largely anoxic is suggested by preservation of organic matter and presence of abundant framboidal pyrite, but this alone cannot account for the absence of infaunal organisms. Infaunal suspension feeders have been observed in modern muds in which reducing conditions are so prevalent that valves of the living animals are partially replaced by pyrite (Robert Frey, oral communication, 1980). These animals survive because they maintain siphonal contact with oxygenated water above the sea floor. The absence of infaunal suspension feeders in most Smoky Hill strata is thus owing to a different factor, namely substrate fluidity, rather than to paucity of dissolved oxygen in the interstitial environment.

Hardgrounds, which are common features of European chalk deposits (e.g., Bromley, 1967b, 1968; Kennedy and Garrison, 1975; Hancock, 1975), are complex associations of hard, nodular chalks, burrows, discontinuity surfaces, omission-suite structures, and organisms that attached to or bored into hard substrates at the sea floor. Although bioturbated beds were apparently somewhat firmer substrates than the nonbioturbated muds, hardgrounds are developed nowhere in the Smoky Hill composite section. All of the bioturbated beds are gradational with overlying strata, thus manifesting continuous deposition. The bioturbated and granular chalk beds, as well as certain chalky limestone beds near the top of the member, have higher carbonate content than the laminated chalk beds. These purer carbonate units were developed during times of reduced terrigenous detrital influx but contain no evidence of nondeposition, sea-floor scour, or lithification at the mud-water interface.

Lateral persistence of bioturbated beds, shelly zones, organic-rich beds, and even the thinnest bentonite seams comprise evidence for extreme flatness of the sea floor during Smoky Hill deposition. Lack of organically constructed banks or mounds, scour channels, and wedge-shaped units are further evidence that the sea floor was devoid of local depositional topography.

Salinity. Paleobiotic elements furnish the principal evidence for water salinity during Smoky Hill deposition. I have documented above the strong control on distribution of benthic macroinvertebrates by substrate conditions and bottom-water circulation. For interpretation of salinity we must rely mainly on pelagic fossil remains and on geochemistry.

Most abundant of pelagic fossils are coccoliths, remains of which are a major element in all chalks of the composite section. Most extant species of coccolithophores cannot tolerate seawater that departs greatly from that of the open ocean (Black, 1965, p. 136), and few species can flourish at salinities less than 25 ‰ or greater than 38 ‰. The long-ranging extant species *Braarudosphaera bigelowi* (Gran & Braarud), which is known to tolerate salinity as low as 17 ‰ (Bukry, 1974, p. 358), and is uncommon in waters of normal salinity, has not been recorded from the Niobrara, but was recorded sparingly in the Smoky Hill equivalent of the Mancos Shale in northwestern Colorado (Trexler, 1967, p. 1359). Trexler (1967) reported a maximum of 35 coccolith species in Smoky Hill strata at Cañon City, Colorado. In contrast, the Austin Chalk of Texas (Bukry, 1969) contains more than 100 coccolith species in strata of Santonian age alone. From any one stratigraphic interval the number of species is smaller, but even so the numbers of Austin species greatly exceed those of the Smoky Hill. This evidence suggests that some parameter, here interpreted as depressed salinity, served to restrict the diversity of Smoky Hill species. Climatic differences between central Texas and the southern Western Interior were too small to effect such a major difference.

According to Bé (1977), living planktonic foraminifers comprise 37 species, which are distributed through five oceanic provinces. Maximum diversity occurs in the Tropical Province (20 species), but only slightly fewer species occur in the Subtropical Province (19 species) and Transition Zones (18 species). With few exceptions, living planktonic foraminifers inhabit waters of normal salinity. Boltovsky and Wright (1976, p. 172) list five species capable of living in waters having salinity as low as 30.5 ‰, but this is the lower limit for the group. In a paper on the southeastern Wyoming Niobrara, Frerichs and others (1975, p. 298) reported a total of 22 planktonic foraminiferal species, which are distributed as follows: lower chalk member, 17 species; upper shale member, 17 species; upper chalk member, 7 species. Only one sampling interval contained as many as 13 species, one contained 10 species, and the remainder contained 8 species or fewer. The section of this report dealing with temperature indicates that the central part of the U.S. Western Interior was in a temperate climatic belt (≅Transition Zones of Bé, 1977), implying that perhaps 18 species of planktonic foraminifers could be expected under normal marine conditions. The significantly smaller numbers reported by Frerichs and others (1975) suggest that some factor other than temperature caused restriction of the Wyoming foraminiferal assemblages. I suggest that this factor was below-normal salinity, but not as low as 30.5 ‰. In contrast, the Smoky Hill chalk of Kansas contains approximately 36 species of planktonic foraminifers (Frerichs and Dring, 1981), but only one sample produced as many as 18 species, and most contained fewer than 16 species. Also in Kansas, the foraminiferal data suggest below-normal salinity for all but a very limited part of the Smoky Hill section. Although many authors (e.g., Loetterle, 1937; Bolin, 1952; Kent, 1967a) have described foraminiferal faunas of the Niobrara, the Frerichs and others (1975) and Frerichs and Dring (1981) data were used for the foregoing analysis because the taxonomy is current and the planktonic species lists are the largest available.

Living crinoids apparently can withstand temporary salinity changes (Breimer, 1978, p. 326) but are otherwise stenohaline organisms (N.G. Lane, oral communication, 1981). Whereas crinoidal remains are common to abundant in some parts of the European Chalk, the only Smoky Hill crinoid has an extremely limited stratigraphic range. Exclusion of pelagic crinoids from most parts of the Smoky Hill is possible evidence of abnormal, probably depressed, salinity.

Modern cephalopods are essentially stenohaline, although a few forms have been recorded from seawater having salinity as low as 30 ‰ (Kennedy and Cobban, 1976, p. 2). Cephalopods are distributed irregularly through most of the Smoky Hill section, and in many intervals none was recorded during the course of this study. Scaphites and baculites are very common in beds of the *Clioscaphites choteauensis* Range Zone, which is apparently the same part of the section containing *Uintacrinus*. Although in smaller number, scaphites and baculites also occur together in the zone of *C. vermiformis*. A single scaphite mold fragment and a single collignoniceratid mold fragment were recorded with *Baculites* in the upper part of the *Inoceramus (Cladoceramus) undulatoplicatus* Range Zone. Otherwise Smoky Hill cephalopod occurrences are limited to a scattering of baculites, aptychi, and rare belemnites. The restricted nature of cephalopod diversity and numbers in most of the composite section suggests water of less-than-normal salinity. Perhaps only in the zone of *Clioscaphites choteauensis* did salinity reach nearly normal marine levels.

The biotic data suggest collectively that salinity was probably less than normal during Smoky Hill deposition, but probably did not descend below 30 to 31 ‰. Limited data (Scholle, 1977, p. 988) indicate negative δO^{18} values, suggesting deposition of the Niobrara at below-normal salinity or at elevated temperatures. The relatively shallow burial depths of Smoky Hill chalk seemingly rule out much increase in temperature values because of burial diagenetic effects. Scholle and Kauffman (1977, p. 24) stated that large shifts in Niobrara oxygen-isotopic values cannot be explained by temperature fluctuations alone, and concluded that the large negative δO^{18} values represent times when low-salinity water occupied the Western Interior seaway. Of course, the considerable amount of secondary calcite in foraminifer chambers, as syntaxial overgrowths on coccoliths and other skeletal remains and as interstitial cement, implies that negative δO^{18} values are to be expected in whole-rock analyses, which were the principal basis for conclusions drawn by Scholle and Kauffman (1977). However, the case for below-normal salinity during Smoky Hill deposition has been substantiated further by Arthur and others (1981) whose isotopic analyses of whole-rock and inoceramid samples suggest at least intermittent low salinity conditions, thus confirming general conclusions based on composition of the pelagic paleobiota. It is worth noting here that Tourtelot and Rye (1969) interpreted the isotopically light oxygen-isotopic composition of Pierre Shale belemnites as owing partly to below-normal salinity of water in the seaway.

PALEOECOLOGY OF MACROINVERTEBRATE FOSSILS

Preservation

Most Smoky Hill macroinvertebrate fossils are preserved as (1) calcareous skeletal material, (2) molds, (3) borings, (4) combinations of calcareous and organic matter, and (5) chitin.

In the first category are:
- Bivalves
  - Inoceramidae (abundant)
  - Ostreidae (abundant)
  - Radiolitidae (common)
  - Bakevelliidae (sparse)
  - Pectinidae (sparse)
- Cirripeds
  - Scalpellidae (common)
  - Stramentidae (common)
- Cephalopods
  - Belemnitellidae (sparse)
  - Collignoniceratidae (aptychi, rare)
- Crinoids
  - Uintacrinidae (sparse)
- Annelids
  - Serpulidae (rare)

In the second category are:
- Bivalves
  - Lucinidae (rare)
  - Inoceramidae (common)
- Cephalopods
  - Scaphitidae (common)
  - Baculitidae (common)
  - Collignoniceratidae? (rare)
  - Nautilidae (rare)

The third category includes:
- Sponges
  - Clionidae? (sparse)
- Cirripeds
  - Acrothoracica (common)

The fourth category includes:
- Cephalopods
  - Teuthida (sparse)

The final category includes:
- Crustacea
  - Malacostraca (rare)

Among the above-listed fossil groups, inoceramids and oysters are by far the most abundant forms, and both are nearly ubiquitous in measured chalk units of the composite section. Inoceramids are preserved mostly as calcitic valves in which only the prismatic layer remains. In these specimens the inner, nacreous layer is invariably absent, owing to early diagenetic dissolution. Large, platter-shaped inoceramids such as *Inoceramus (Platyceramus) platinus* are generally preserved intact, with paired valves pressed tightly together and usually with no sediment between the valves. Many valves encrusted by the oyster *Pseudoperna congesta* are so much compacted that the valve has been deformed around the encrusters and oyster outlines are clearly visible on the inoceramid valve interior. Some of these large inoceramids have suffered breakage during compaction, and valve fragments may be imbricated. Locally, *in situ* disintegration of these inoceramids has produced lenses of calcirudite, but presence in such lenses of chalk matrix demonstrates that such lenses were not produced by mechanical transport.

Large bowl-shaped inoceramids assigned to *Inoceramus (Volviceramus) grandis* are almost everywhere deformed and broken by compaction. Many collected specimens remain articulated (Pl. 3, 1) but most of the lower valve occurs as small fragments.

Small, thin-shelled inoceramids such as *I. cycloides* and *I. balticus* are invariably much compacted. Collected specimens are mostly molds, although in most parts of the thin prismatic shell layer are preserved.

Smoky Hill oysters, nearly all of which are referred here to *Pseudoperna congesta,* are represented almost entirely by well-preserved calcitic valves in which original lamellar structure remains intact. Most of these oysters are cemented firmly to exterior surfaces of inoceramid bivalves, but oysters occur also on rudists and on molds of scaphites and baculites. In some beds oysters appear to be isolated within chalk, but upon close inspection of left valves, even these are seen to have attachment scars that testify to the epizoic character of all such oysters. The oysters occur as spat, juveniles, and adults, the latter commonly with thick shells and high side walls where crowded. Valves are commonly articulated, and compaction has pressed the right valves tightly against left ones.

The rudist *Durania* has a calcitic skeleton in which structural detail is well preserved. Original void spaces within the shell wall have been filled with sparry calcite. Most specimens have suffered compaction, and some were broken apart before burial as attested by attachment of epizoic oysters even to broken surfaces.

Other Smoky Hill bivalves are of more restricted stratigraphic occurrence than the above-described groups. *Phelopteria,* recorded from just beneath Marker Unit 7 and from the zone of *Clioscaphites choteauensis,* has calcitic valves that were flattened by compaction. Pectinids occur as very thin, flattened, calcitic valves.

Smoky Hill lepadomorph cirripeds occur as articulated specimens or isolated valves that are invariably calcitic. Most of the specimens are minute and were recorded only by microscopic scanning of inoceramids, oysters, and ammonite molds.

The few known Smoky Hill belemnitellids are all calcitic and are preserved in the round. The recorded specimens of aptychi (Fischer and Fay, 1953) are apparently all calcitic. The single, possible sepioid reported by Miller (1968, p. 56) is calcitic, but is of vertebrate origin (J. D. Stewart, written communication, 1982).

All specimens of *Uintacrinus socialis* are calcitic and most, if not all, have suffered from effects of compaction and dissolution (Neugebauer, 1978a; Hattin, 1981). The specimens occur mostly in thin lenses of hard, brittle limestone in which some coccolith-rich matrix occurs.

Data on Smoky Hill serpulids are suspect. Of the three species occurring presumably in the Smoky Hill (Miller, 1968), only *Serpula intrica* White has locality data that strongly suggest a Smoky Hill occurrence but the record is based on a single specimen, which has been lost. The other two species, *S. tenuicarinata* and *S. semicoalita*, are abundant in the Fairport Member of the Carlile Shale. Despite many months of field work and extensive microscopic examination of substrates (inoceramids, oysters) on which serpulids are found commonly, I have not recorded specimens in the Smoky Hill Member. In other chalk units of Kansas serpulids are invariably calcitic and are preserved in the round.

Fossils preserved as molds are more difficult to detect in the field, and with few exceptions are discovered by extensive splitting of the chalk. All molds, whether of cephalopods or bivalves, have been flattened by compaction, although most specimens retain at least a small thickness.

Sparse circular pits in inoceramid bivalves are attributed tentatively to the boring sponge, *Cliona*. Extensive systems of excavated galleries within valves are very rare. In contrast, acrothoracican borings are common in the Smoky Hill, and are abundant in the shelly zones. Inoceramids were the usual substrates for these cirripeds, but such borings occur also on some *Durania* specimens. Most are assignable to the genus *Rogerella*.

Teuthid coleoids are sparse in most Smoky Hill rocks. Well-preserved specimens comprise a broad, flattened gladius and long, cylindrical guard. The skeleton of these cephalopods is more or less calcified, but retains much of the original conchiolin of which Recent teuthids are largely composed.

Except for cirripeds the Crustacea are poorly represented in Smoky Hill rocks. Malacostracans, which preserve the original chitinous exoskeleton, are known from very rare, imperfectly preserved specimens.

Inoceramids

Smoky Hill strata contain few species of benthonic macroinvertebrates, and those represented by body fossils were epifaunal suspension feeders. Inoceramids and ostreids were the principal macroinvertebrates that inhabited the sea floor during deposition of the member. Principal growth forms of inoceramids include large, highly inequivalved, bowl-shaped, thick-shelled forms, represented by *Inoceramus (Volviceramus) grandis*; giant-sized, equivalved, slightly biconvex forms, represented by *Inoceramus (Platyceramus) platinus* and *Inoceramus (Cladoceramus) undulatoplicatus*; and small- to medium-sized, thin-shelled, elongate, biconvex forms with prominent growth ridges, represented by *Inoceramus stantoni*, *I. balticus*, and *I.* sp.

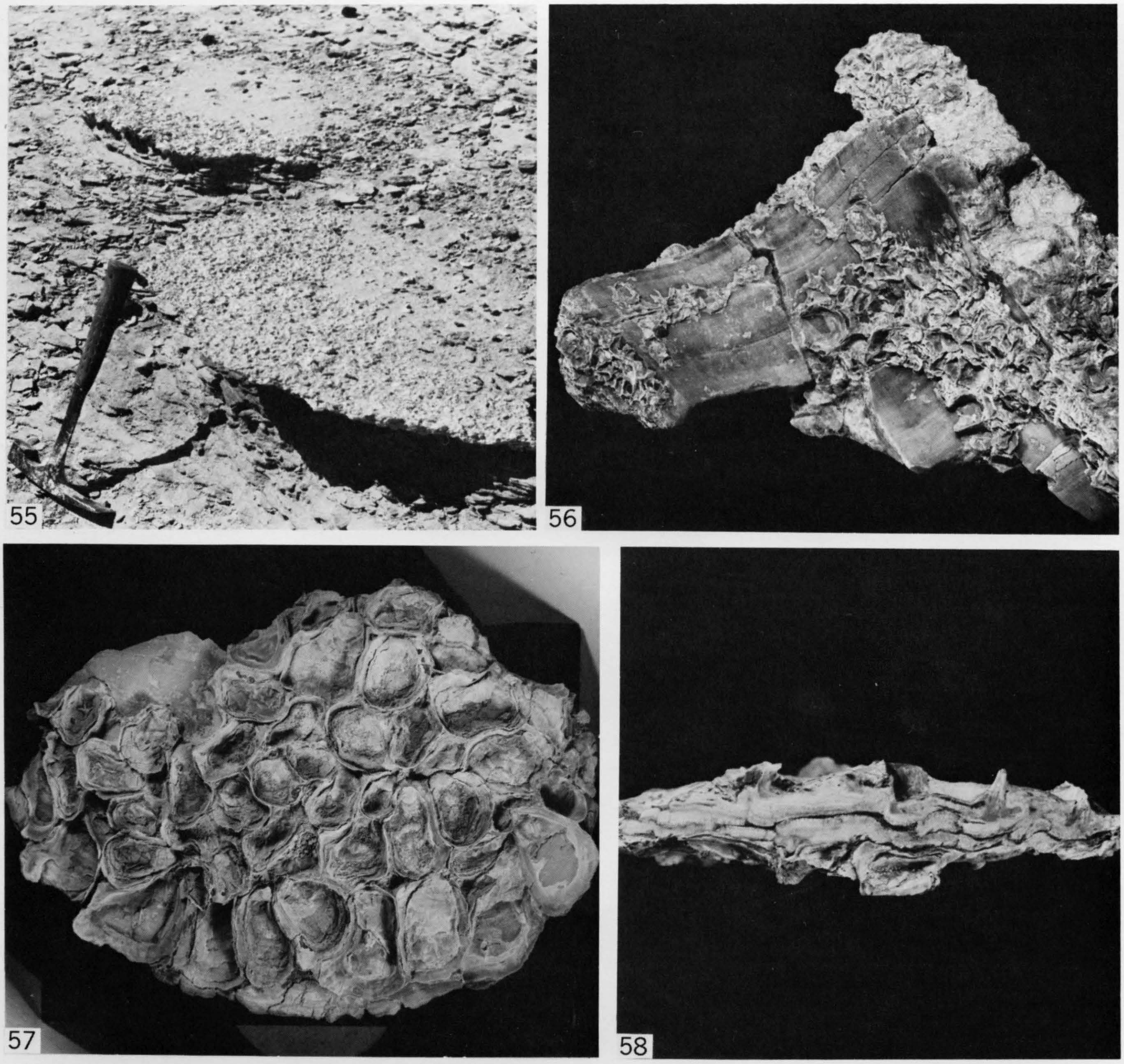
The bowl-like lower valve of *Inoceramus (Volviceramus) grandis* reflects an iceberg-like (Thayer, 1975) adaptation to life on a soft substrate, wherein the growing specimen sank progressively lower into the substrate, apparently displacing sufficient carbonate mud to maintain freeboard for the lower valve. Mostly random orientation of epizoic oysters on the upper valve suggests that the plane of commissure was oriented parallel to the mud-water interface and throughout life remained above that surface. The lower valve is thick, smooth, and coiled in the grypheate manner so common in bivalves that lived on soft substrates (e.g., Carter, 1972, p. 333). The upper valve is thinner and coarsely wrinkled in the central area, the rugosity apparently functioning to strengthen the valve much as in corrugated steel roofing.

The platter-like inoceramids, which reached maximum diameters approaching 2 m in *Inoceramus (Platyceramus) platinus*, reflect a snowshoe-like adaptation (Thayer, 1975) to life on soft carbonate mud. The large bivalves lay flat on the sea floor, with commissural plane oriented horizontally. None of the thousands of specimens I examined shows indication of vertical posture or partial burial. Together with *I. (Volviceramus) grandis* these bivalves were the principal "islands" for colonization by epizoans during much of Smoky Hill deposition (Fig. 55).

Thin-shelled, biconvex, apparently equivalved inoceramids such as *Inoceramus balticus* were neither heavy enough to sink deeply into the sediment, nor broad enough to rest wholly upon the carbonate-mud surface. Instead, these bivalves lay partially buried in the soft mud and their life attitude was stabilized by concentric growth ridges that characterized both valves. No evidence suggests that these forms were byssate or that they were burrowers. All specimens lie in the chalk with plane of commissure oriented parallel to the substrate surface. I conclude that such inoceramids were free-living, epifaunal nestlers that in essence "floated" like coracles on the soft carbonate mud in the manner reported for unionids by Eager (1974). All of these inoceramids were apparently true filter feeders whose gills strained food from water passing through a slightly gaping commissure.

Radiolitids

The rudist *Durania maxima* was also a sessile, free-lying (West, 1977) epifaunal bivalve. Specimens occur as iso-



FIGURES 55-58. **55,** Exposure of middle part of Smoky Hill Member at Locality 23, showing large, articulated specimen of *Inoceramus (Platyceramus) platinus* encrusted by crowded specimens of *Pseudoperna congesta.* Hammer is 28 cm long. **56,** Specimen of *Durania maxima* from lower part of Smoky Hill Member in SW¼ Sec. 21, T.15S, R.26W, Gove County, Kansas, showing encrustation by *Pseudoperna congesta* on exterior and interior surfaces, as well as on a broken surface (far left). KU108439, × ½. **57,** Fragment of *I. (Platyceramus) platinus* encrusted by crowded specimens of *Pseudoperna congesta,* which show radial orientation and commissureward elongation of specimens closest to inoceramid valve margin. Lower part of Smoky Hill Member in SW¼ Sec. 21, T.15S, R.26W, Gove County, Kansas. KU108432, × ½. **58,** Vertical section through paired valves of articulated *I. (Platyceramus) platinus,* showing encrustation by *Pseudoperna* on exterior surfaces of both valves. Middle part of Smoky Hill Member in SW¼ Sec. 1, T.14S, R.26W, Gove County, Kansas. KU108433, ×1.

lated valves, or in clusters of a few individuals, in at least four stratigraphic intervals of the member. The right valve is inversely conical, and stood erect when young, but was usually recumbent in the large, adult stage. Specimens reached heights as great as a meter (3-4 ft) according to Logan (1898, p. 494), although those examined by Miller (1968) and in my collection are much smaller. According to Miller (1968, p. 38) no left valves have been recorded. This suggests that the upper valves were very thin and have been destroyed by diagenetic dissolution. It has been suggested that in such forms the mantle extended across the broad rim of the valve and contained intracellular zooxanthellae (Kauffman and Sohl, 1974), as in the modern bivalve *Tridacna.* Absence of endolithic algae in all Smoky Hill skeletal remains examined in thin sections suggests deposition below the photic zone, and casts doubt on this interpretation. The conical shape of *D. maxima* indicates that specimens lay partly buried in the bottom, propped in the upright or recumbent position by surrounding mud. The Sternberg Memorial Museum contains a large specimen (13820-2) that clearly lay oblique to bedding, about half buried in the mud. This position is demonstrated by the occurrence of encrusting oysters, the distribution of which marks a clearly defined mud-water interface, with oysters occurring only above that plane. Another specimen in that collection (4093) shows evidence of initial growth, rotation in the mud, and final upward growth at an angle to the initial growth stage. Many collected specimens of *Durania* have been flattened laterally by compaction, which shows that they had been toppled to a prone position before burial, and one specimen in my collection was broken and encrusted by oysters before burial (Fig. 56). *Durania,* like the inoceramids, served as substrate for at least three kinds of epizoans. Logan (1898, p. 495) stated that the "type specimens are adult forms united by their entire lengths, one of the specimens having three young ones attached to it near its upper extremity by their lower valves."

My field data suggest that environmental conditions suitable for growth occurred mainly during episodes that fostered development of shelly beds, described above, which represent times of better-circulated bottom waters. Coates and others (in press) have suggested that occurrences of *Durania* mark marginal Tethyan transgressive pulses, and that one such pulse is represented by the *Clioscaphites choteauensis* Zone; however, to date I have not recorded a single rudist from that zone in Kansas. Furthermore, the richest accumulations in Kansas occur in the lower part of the Smoky Hill Member, which Coates and others (in press) relate to an episode of regression. The generalization that *Durania* occurrences reflect transgressive pulses from the Tethyan belt is therefore unsubstantiated.

Ostreids

Ostreid bivalves, mostly assignable to *Pseudoperna congesta,* are the principal epizoans on Smoky Hill inoceramids and rudists. In my collection scarcely any specimen of *Inoceramus (Volviceramus) grandis, I. (Platyceramus) platinus,* or *I. (Cladoceramus) undulatoplicatus* lacks at least partial encrustation by these small oysters. In fact, many articulated inoceramids are encrusted almost completely on the exterior surfaces of both valves. On *I. (Platyceramus) platinus* the oysters may be largely spat, juveniles, or adults, or may represent as many as four generations of oysters including spat through large adult forms. Oysters of second and third generations may be stacked on first-generation oysters. Where incompletely encrusted, these inoceramids may host uncrowded specimens of nearly circular or oval outline; but where the valves are heavily encrusted the oysters are crowded together, have irregular outlines that reflect competition for space, and may have high marginal walls formed by upward growth when lateral growth was impeded by impingement against neighboring oysters. On many large specimens of *I. (P.) platinus* the marginal oysters manifest strongly preferred orientation, with longest beak-to-commissure axes arranged perpendicular to inoceramid valve margins (Fig. 57), and with general parallelism to their immediate neighbors. Such oyster arrangement apparently resulted from marginal oysters elongating their shells so as to take advantage of newly created substrate. On other *I. (P.) platinus* a majority of encrusting oysters may show preferred orientation, not just those at the inoceramid valve margin, a condition suggesting rheotropism, i.e., growth in the direction of approaching currents so as to maximize feeding efficiency (Bottjer and others, 1978). Oyster clusters with radial orientation at inoceramid valve margins, as well as those displaying two or more generations, apparently signify growth on a living substrate. Inoceramids encrusted only by spat or small juveniles were probably moribund or dead at the time of oyster colonization, and were buried before the colonizing oysters could mature. Oyster spat are arranged commonly along depressions between inoceramid growth ridges, as if the oyster larvae selected sheltered places for settlement, but occurrence of spat also on crests of growth ridges or extensively across flat inoceramid valves demonstrates that shelter was not a major requirement for the larvae.

Most perplexing is occurrence of thick encrustations of crowded oyster specimens on external surfaces of both valves in articulated *Inoceramus (Platyceramus) platinus* (Fig. 58). Possible explanations include (1) the host was oriented vertically, either partly buried in the sea floor or suspended byssally from floating objects such as logs; (2) the host lay flat on the sea floor, oysters colonized the upper valve, and the inoceramid was then overturned by large predatory organisms in search of food (Hattin, 1965, p. 21); (3) same as (2) but inoceramids were overturned by waves or currents; or (4) the host lay flat on the sea floor and was colonized simultaneously on both upper and lower valves. The first hypothesis is rejected because (a) not a single specimen of *I. (P.) platinus* is preserved in the erect position, (b) the valves preserve no evidence of byssal attachment (Erle Kauffman, oral communication, 1977), and (c) logs, which are common in Greenhorn and Fairport strata of Kansas, and were thus readily preservable in chalky beds, are exceedingly rare in Smoky Hill strata. The second hypothesis is rejected because (a) evidence of predation (e.g., bite marks, extensive shell breakage, debris in coprolites) is sparse, (b) in some beds all articulated *I. (P.) platinus* are encrusted on both valves and the likelihood that all of these were overturned by predators is highly improbable, (c) chalk laminae show no sign of deformation such as would occur if the inoceramids had been overturned. The third hypothesis is also rejected because evidence for sufficiently strong waves or currents (e.g., skeletal lag concentrates, scour-and-fill structure) is lacking in Smoky Hill strata. The fourth hypothesis is therefore accepted as most plausible. Despite possible problems attending this hypothesis, one must remember that when deposited the chalk-forming mud initially consisted mostly of water, so that oysters facing downward into the mud actually lived in a predominantly aqueous environment. The hypothesis gains strength from observation of the same phenomenon in specimens of the highly inequivalved *Inoceramus (Volviceramus) grandis,* the large, bowl-shaped, downward-facing lower valve of which is usually preserved *in situ* and which in many large specimens collected is encrusted completely by crowded specimens of *Pseudoperna congesta.* My collection also contains a short, but broadly expanded specimen of *Durania maxima* the *underside* of which was colonized by numerous specimens of *P. congesta* (Pl. 7, 2-3). The encrusted part of this rudist can in no way be interpreted as having stood above the bottom muds.

Specimens of *Inoceramus (Volviceramus) grandis* also were host to large numbers of *Pseudoperna congesta.* The upper valve, or "lid," is invariably encrusted externally by oysters, and these epizoans commonly cover the surface completely. In some *I. (V.) grandis,* adult oysters cover the entire upper valve, with juveniles and spat stacked, in succession, on the larger specimens. In other *I. (V.) grandis,* large oysters are confined to the central area, and only juveniles or spat occupy marginal areas of the valve. Lower valves were crushed during compaction, so that collected materials are fragmented. Some thin lower-valve fragments from smaller specimens may have large areas that bear few epizoans, but the largest lower-valve fragments in my collection, representing thick-shelled, fully mature individuals, are entirely encrusted by *P. congesta* that are mostly adults. Because of the large size and thick, heavy shell the lower valves of adult *I. (V.) grandis* apparently lay deeply buried in the soft carbonate mud and many of the associated oysters apparently lived facing into this mud. I have not recorded large specimens that have a substantial part of the lower valve free of these epizoans, nor have I recorded a large lower valve that had been overturned.

Epizoans are rare on *Inoceramus balticus.* Specimens of small oysters are associated with a few *I. balticus,* but confirmation that these were actually attached to the inoceramid is lacking.

Pectinids

Specimens of the Pectinidae named *Pecten bonneri* by Miller (1968) are of uncertain stratigraphic position, and he made no mention of faunal associates or epizoans. Small pectinids that I collected from the top of Marker Unit 21 at Locality 21 lie free in the chalk and lack epizoans. It is likely that all of these pectinids were pelagic forms, which were uncommon in Kansas during deposition of the Smoky Hill Member.

Bakevelliids

A species of *Phelopteria,* referred to as *Pteria* cf. *P. petrosa* (Conrad) by Miller (1968, p. 35) and here called *Phelopteria* sp. A, occurs as free-lying specimens in chalky strata of the *Clioscaphites choteauensis* Zone, to which it is apparently restricted. A second form, here called *Phelopteria* sp. B, was recorded in the upper part of the *Inoceramus (Cladoceramus) undulatoplicatus* Zone at Locality 13. According to Kauffman and Powell (1977, p. 51) *Phelopteria* is a "byssate, commonly pendant, epifaunal bivalve," which probably was attached to inoceramids or erect algae, or may even have been epiplanktonic. Because the genus occurs in beds that are notably rich in cephalopods, and because specimens are very rare, the possibility of an epiplanktonic habit is attractive, but cannot be proved on the basis of available evidence.

Cirripeds

Smoky Hill cirripeds recorded to date include the borings of acrothoracicans and stalked forms with armored peduncles that belong to the two lepadomorph families Scalpellidae and Stramentidae. The stramentids are attached to valves of *Inoceramus (Volviceramus) grandis, I. (Platyceramus) platinus,* cephalopods or, rarely, oysters and rudists. *Stramentum haworthi* and *Zeugmatolepas* sp. are the most common species. The former occurs mostly as juveniles on inoceramid valves, as juveniles on living chambers and septate portions of *Clioscaphites choteauensis,* and as an adult (holotype specimen only) on *Pseudoperna congesta.* Adult specimens of *S. haworthi* have been recorded mostly on molds of a large, smooth species of *Baculites* from several places, including the middle and upper parts of the Smoky Hill Member of Kansas, the upper chalk member of the Smoky Hill at Pueblo, Colorado (Scott and Cobban, 1964), and from near Irene, South Dakota (W.A. Hasenmueller, oral communication, 1973). Miller (1968, p. 61) states that *S. haworthi* was "pseudoplanktonic," not benthic, but the presence of this and other lepadomorphs on inoceramid valves, a rudist, and an oyster demonstrates benthic existence and suggests that specimens on cephalopod molds may have settled on empty conchs that lay on the sea floor. I regard

S. haworthi as a benthic organism. *Zeugmatolepas* sp. and other scalpellids, represented by articulated and disarticulated skeletons, are associated almost exclusively with inoceramids and oysters and are also interpreted as benthic forms. Numerous articulated specimens of *Zeugmatolepas* sp. are preserved on the right valves of oysters attached to the upper valve of an *Inoceramus (Volviceramus) grandis* specimen that was collected from just below Marker Unit 5 at Locality 12. In addition, J. D. Stewart (written communication, 1982) has recorded the occurrence, in large numbers, of *Zeugmatolepas* on downfacing valves of some *I. (P.) platinus.* These are clearly benthic forms. The acrothoracican borings, assignable to the genus *Rogerella,* are common throughout the lower half of the Smoky Hill Member, and occur locally in great profusion (Fig. 59). The borings are preserved on inner and outer surfaces of inoceramid and rudist valves as well as on valves of *Pseudoperna congesta.* In some inoceramid valves rough alignment of borings in rows parallel to growth lines of the host suggest that the larvae settled in grooves for reasons of protection. However, many borings are on growth ridges (Fig. 59), thus dispelling the notion that sheltered settlement sites were a requirement for these boring cirripeds. Common occurrence of acrothoracican borings in oysters suggests that oyster colonization of inoceramid hosts occurred before acrothoracicans established themselves, but in a few inoceramids the acrothoracican borings were vacated, then occupied by oyster spat.

All of the cirripeds were suspension feeders, which strained food from the water column by means of appendages that projected from the capitulum.

Uintacrinids

The nature of *Uintacrinus* occurrences has been described in elaborate detail by Springer (1901). Specimens occur in very thin lenses of well-cemented limestone, with the most perfect specimens preserved only on the undersides. In each lens, overlying specimens are crushed, disarticulated, and cemented together in jumbled fashion. Springer (1901) described one slab 12 mm thick and 15.2 m wide that contained 1200 mostly adult specimens on the underside (Pl. 9, 2). All known Kansas specimens occur in aggregations of many individuals, and must, according to Springer (1901, p. 12), have lived in free-swimming swarms like the living stalkless crinoids. Springer's description of occurrences suggests that the species is restricted to a small stratigraphic interval that is within the zone of *Clioscaphites choteauensis.* The occurrence of such large numbers of individuals in solitary lenses suggests that the crinoids lived in separate schools and were killed during one or more mass-mortality events. Beecher (1900, p. 268) notes the preferred orientation of crinoid arms and an associated *Baculites* mold, which suggests that a gentle current prevailed at the time of

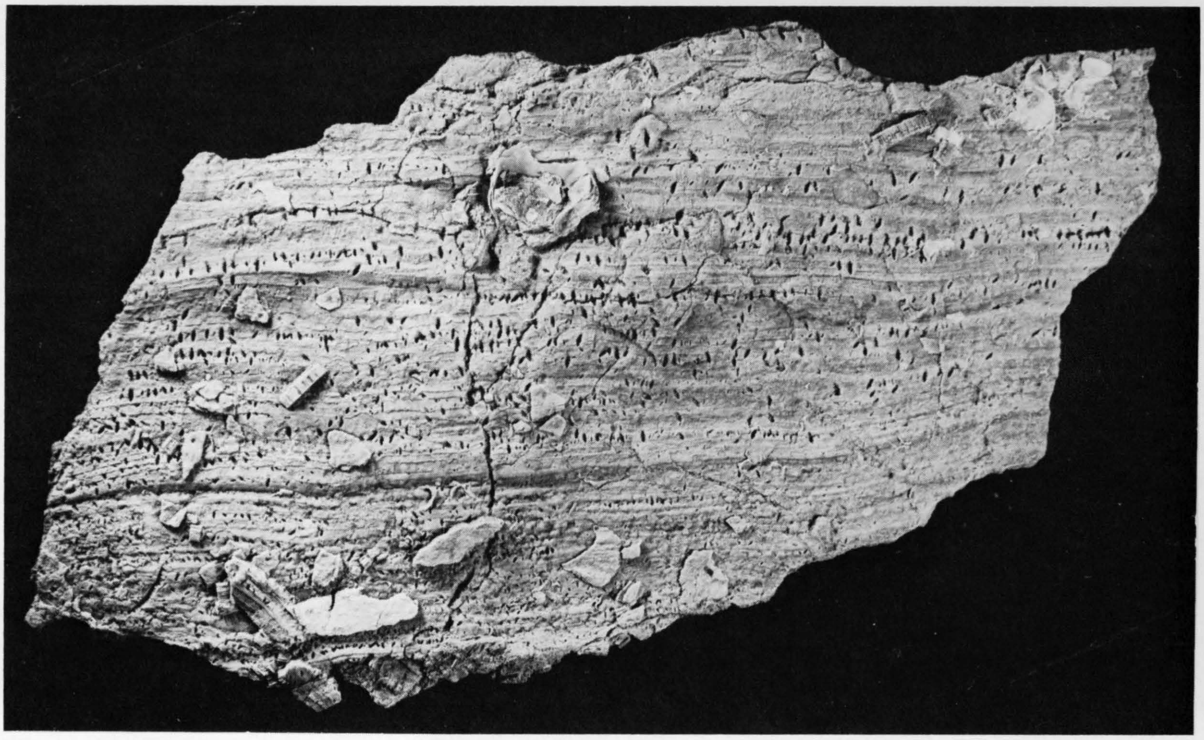


FIGURE 59. Valve fragment of *Inoceramus ?(Platyceramus) platinus,* showing profusion of acrothoracican cirriped borings *(Rogerella).* From lower part of Smoky Hill Member in SW¼ Sec. 16, T.14S, R.26W, Gove County, Kansas. KU108434, ×1.

settlement on the sea floor. The contrast in preservation of specimens on undersides of limestone lenses versus those above suggests further that the lowermost, buried specimens were better protected from decay, probably in an anaerobic situation, whereas those higher in the lenses decayed and fell apart before burial (cf. Kauffman, 1978, p. 35).

Cephalopods

The sparse examples of teuthids and belemnoids in Smoky Hill strata may be evidence of their general scarcity in the Western Interior Sea. It is possible that these forms were preyed upon heavily by large pelagic organisms, such as mosasaurs, turtles, sharks, or teleosts. Indeed, remains of teuthids have been recorded in several vertebrate coprolites (J. D. Stewart, written communication, 1982). Because living coleoids are all nektonic forms we have little reason to believe that those preserved in the chalk beds were not also swimmers in the open sea.

The sparse examples of large, spirally coiled ammonites belonging to the Collignoniceratidae may also have been rare in the Western Interior Sea. If they were a food source for large predators such fate is unsubstantiated by Smoky Hill specimens that preserve bite marks. At least occasional vertebrate predation on ammonoids is suggested by scaphite remains in a coprolite from the *Clioscaphites choteauensis* Zone (Stewart and Carpenter, in prep.).

In the absence of clear evidence for widespread shell destruction by predators, and because other cephalopods *(Baculites, Clioscaphites)* are common in some stratigraphic intervals and thus prove the ready preservability of ammonoids in the chalk, I conclude that the scarcity of non-heteromorph ammonoids is owing to environmental conditions. The few collignoniceratids that have been reported to date are probably strays from farther south, having drifted in small numbers into the Kansas area before death, or even after death. Belemnoids, which are characteristic of the so-called "Boreal realm," are rare not only in Kansas but also are very localized and mostly rare even in deposits of the Western Interior Sea in western Canada (Jeletzky, 1971, p. 1653). These belemnoids apparently are strays from the most northerly regions of North America.

The life habits of the scaphites and baculites are mostly speculative because comparable forms are not alive today. Regarding scaphitoids, a wide range of views is manifest in such works as those by Diener (1912, p. 78), who believed that *Scaphites* was perhaps a crawling form; by Scott (1940, p. 307), who suggested "a nectobenthonic crawling or swimming habit of limited extent"; and by Trueman (1941), whose studies of buoyancy centers suggested for scaphitoids a floating habit, with aperture facing upward, at least at rest, and possible life as plankton feeders at the surface. Similar diversity of opinion has been expressed with regard to the life habits of *Baculites*. The controversy has been summarized by Klinger (1981), who suggests that "a horizontal swimming position for orthoconic ammonites must be viewed with extreme caution." *Clioscaphites* and *Baculites* were probably poor swimmers, like most other ammonoids (Lehman, 1975; Mutvei, 1975; Kennedy and Cobban, 1976, p. 81). Heptonstall (1970) has implied that most ammonoids were able to control buoyancy by addition or removal of water from the living chamber, although this may have resulted only in slow vertical movements in the water column. He postulated that forms with a small siphuncle, which would include the scaphites, may have been restricted to narrow depth range and many, perhaps all, such forms were probably benthic (Heptonstall, 1970, p. 324). Indeed, Lehmann (1975) suggested that all ammonites were benthic forms. In marked contrast is the opinion of Mutvei (1975) that ammonoids were pelagic organisms that occupied the upper 1000 m of oceans and were probably capable of large diurnal migrations in the water column. Westermann (1975) believes that this figure is too large by a factor of five, which implies maximum depth range of only about 200 m. The contradictory opinions regarding ammonoid paleoecology thus continue to modern times and make impossible any realistic assessment of position in the water column or depth relations of Smoky Hill heteromorphs.

Kennedy and Cobban (1976, p. 46, 47) state that *Clioscaphites choteauensis* has a wide geographic distribution in the Western Interior and occurs in lithology of wide variety, from chalk to sandstone. This distribution does not indicate strong facies control or intimate association with the bottom. Abundance of *C. choteauensis* in Smoky Hill strata at several localities shows that this species, at least, was well adapted to environmental conditions that prevailed during deposition of that zone.

The large, smooth species of *Baculites* recorded in Plate 8 is abundant only in certain stratigraphic intervals of the Smoky Hill chalk, including *Inoceramus (Cladoceramus) undulatoplicatus, Clioscaphites vermiformis,* and *C. choteauensis* Zones. This distribution implies that conditions were favorable for baculite proliferation only sporadically. From the *C. vermiformis* Zone upward beds containing few benthic macroinvertebrates are also deficient in *Baculites*. Apparently conditions favorable to benthic macroinvertebrates were favorable also to *Baculites,* which implies that *Baculites* distribution was controlled more by benthic environment than by that of superjacent parts of the water column. I regard *Baculites* sp. (smooth) as a nektobenthic form.

Little is known about the feeding habits of ammonoids, but recent studies by Lehmann and Weitschat (1973) show that in genera studied the crop contains foraminifers, ostracodes, crinoid remains, and small ammonites.

Trace Fossils

The only common evidence of infaunal macroinvertebrates in Smoky Hill strata is burrow structures produced by deposit-feeding, worm-like organisms (Fig. 40, 41). Most such structures are compressed-ellipsoidal in vertical section and the larger ones, up to 1.3 cm in maximum dimension, are probably referable to *Planolites*. Slender burrows, possibly referable to *Chondrites,* were recorded sparingly only at Locality 13. Forms such as *Trichichnus, Zoophycos,* and *Teichichnus,* which are abundant in underlying Fort Hays beds, were not recorded in the Smoky Hill. In the lower half of the Smoky Hill, beneath the top of Marker Unit 11, bioturbated intervals are common, usually standing out as light-colored bands in fresh exposures or as resistant ledges in weathered exposures. Average insoluble residue content of these beds is 24 percent as compared to 34.3 percent for nonbioturbated, nongranular chalks from the same interval. The more pure beds of carbonate mud may represent slightly firmer substrates than normal, which were at least marginally suitable for inhabitation by the burrowers. Above Marker Unit 11, evidence of bioturbation is rare and consists mostly of sparse, minute structures that occur in beds of granular chalk. An exception is the thoroughly bioturbated calcarenite lens recorded between Marker Units 21 and 22 in SE¼ Sec. 1, T.14S, R.31W, Gove County. It is probably no coincidence that the part of the section in which benthic macroinvertebrates are sparse to rare also lacks the obvious kinds of bioturbated intervals that are so common in the more fossiliferous part of the member. The two lines of evidence suggest that during much of upper Smoky Hill chalk deposition the bottom was oxygenated marginally, and in fact may have approached an anaerobic condition.

Infaunal Body Fossils

Except for rare molds of *Lucina* sp. A (Miller, 1968; this paper), reported from the zones of *Inoceramus (Cladoceramus) undulatoplicatus* and *Clioscaphites choteauensis,* Smoky Hill strata lack preserved remains of infaunal body fossils. This fact might reflect diagenetic removal of originally aragonitic shells, such as characterize most infaunal bivalves, or may indicate that infaunal organisms, other than trace-making worms(?), were excluded from these deposits for environmental reasons. The first possibility is rejected because the Smoky Hill contains numerous baculitid and scaphitid fossils, the aragonitic skeletons of which were removed during early diagenesis, but are nevertheless very well preserved as molds. The second possibility is supported strongly by the absence also of body fossils from calcitic, infaunal forms such as echinoids. Furthermore, burrow traces attributable to infaunal bivalves or echinoids have not been recorded in Smoky Hill strata. Possibly the carbonate ooze was generally too fluid to support infaunal, skeleton-secreting organisms. I disbelieve that anoxic interstitial conditions were a principal factor, because many infaunal organisms maintain siphonal contact with the benthic waters, which were sufficiently well oxygenated to support an abundance of epifaunal life such as inoceramids and oysters during much of Smoky Hill deposition. The lucinids reported by Miller (1968, p. 37) occur in strata that are rich in other benthic and nektobenthic forms, and that probably represent an episode of exceptionally favorable benthic environments.

Community Structure and Habitat

Smoky Hill macroinvertebrates comprise low-diversity communities, the basic elements of which were large inoceramids and vast numbers of small ostreids that encrusted them. These organisms made up the minimal preservable assemblage and are virtually the only forms present in many parts of the composite section. In an environmental setting involving soft, oozy substrates and poorly circulated bottom waters, the inoceramids established themselves by virtue of growth forms that prevented sinking beneath the mud-water interface, and served as "islands" upon which oyster spat settled and commonly thrived. At times, bottom circulation improved sufficiently to foster proliferation of inoceramids and their epizoic oysters, and addition to the limited benthos of rudists, acrothoracic and lepadomorph cirripeds, and occasionally sponges?, lucinids, and serpulids. Conversely, when circulation decreased below the norm, the Smoky Hill macroinvertebrate benthos diminished nearly to zero. That improved circulation of bottom waters was a major factor controlling diversity increase is manifest in the lithologically similar Fairport Chalk Member, Carlile Shale (Hattin, 1962), in which strata containing well-washed calcarenites include not only large inoceramids and abundant ostreids, but abundance also of cirripeds, serpulids, and bryozoans.

In Smoky Hill assemblages a high proportion of oysters and inoceramids have articulated valves, and the rudists and especially the larger inoceramids are preserved apparently in life positions, the inoceramid-ostreid or inoceramid-ostreid-cirriped association was recorded repeatedly throughout the composite section, pre-burial shell fragmentation was minimal, and along individual horizons wide size range is evident among individuals of a given species. These features suggest that Smoky Hill assemblages represent fossil communities in the sense of Fagerstrom (1964). The only common modification of original hard-part distribution is the separation, probably by weak bottom currents, of some small, thin right oyster valves from the larger, attached left valves. This accounts for scattered occurrence of isolated right valves of ostreids throughout the member, but does not necessitate classifying the assemblages as residual communities (Fagerstrom, 1964, p. 1202).

Except for burrows of deposit-feeding worms(?), Smoky Hill benthic macroinvertebrates were exclusively suspension feeders. Among paleoecologists there is widespread belief that muddy biotopes are (were) generally unsuited for inhabitation by suspension feeders (e.g., Purdy, 1964; Levinton and Bambach, 1970, p. 97; Carter, 1972, p. 329; Thayer, 1974, p. 135), and that faunas associated with fine-grained deposits are (were) mostly infaunal deposit feeders. Evidence from macroinvertebrate body-fossil assemblages of the Greenhorn, Fairport, and Niobrara chalks demonstrates need for revision of this concept, and exceptions to the generality stated above have been noted by Walker (1974). Paucity of suspension feeders in muddy environments has been attributed to such factors as clogging of filtration systems and sinking into soft substrates (Thayer, 1974, p. 135). Morphologic adaptation of Smoky Hill inoceramids and rudists to soft substrates has been noted above, and the occurrence of vast numbers of suspension feeders, to the complete exclusion of deposit feeders (other than worms(?)), shows that the water was rarely, if ever, sufficiently turbid to be a controlling factor in trophic composition. The constant rain of food supplies, especially including plant debris, fecal pellets, and plankton, perhaps distributed by gentle bottom currents, was more than adequate to sustain communities of suspension-feeding organisms. Absence of deposit-feeder body fossils in Smoky Hill strata poses problems with respect to currently accepted concepts. Fine-grained deposits normally contain more organic matter than those that are coarse grained (Trask, 1939, p. 433; Purdy, 1964, p. 243; Levinton and Bambach, 1975, p. 98; Stanton and Dodd, 1976, p. 328). The abundance of fecal pellets and particulate organic matter in Smoky Hill rocks indicates that absence of deposit-feeding bivalves was not owing to food shortage, which has been suggested as a controlling factor by Wright (1974, p. 432). Furthermore, the preservation as molds of lucinids, scaphites, baculites, and collignoniceratids in the composite section makes unlikely the possibility that diagenetic removal of aragonitic skeletons accounts for absence of deposit-feeder skeletons in the Smoky Hill. As noted by Hallam (1976, p. 251), infaunal or semi-infaunal bivalves required a moderately firm muddy substrate. Exceedingly soft substrates, possibly combined with marginally oxygenated bottom waters, seems to account for absence in Smoky Hill deposits of infaunal deposit feeders other than worms(?).

Despite the presence in Smoky Hill strata of shell-crushing shark remains, such organisms were apparently nowhere abundant. During my study numerous remains of bony fish and aquatic reptiles were noted, but teeth of shell-crushing sharks are scarce, indeed. Evidence of predation, such as bite marks on bivalve shells, coprolites filled with shell debris, and scatterings of broken shells, are sparse in the Smoky Hill. Predation on bottom dwellers thus does not appear to have been a major element of community life in the Smoky Hill environment. Greatly elongated, almost funnel-shaped ostreids occur locally in the section. These apparently attached themselves to small shell fragments that sank gradually under the increasing weight of the rapidly upward-growing oysters. Such shell fragments may be the result of predation, but oysters having small attachment surfaces and elongate growth forms are common only in a few parts of the Smoky Hill. Growth to giant size of so many inoceramids and rudists indicates slow depositional rates. This conclusion is supported by development on these organisms of as many as four generations of epizoic oysters. Obviously, the inoceramids and rudists were able to maintain an exposed position for many years. Heavily encrusted hosts may eventually have sunk beneath the mud surface, as suggested by the fact that the youngest oyster generation consists usually of spat or juvenile forms. More rapid rates of deposition may be indicated by large inoceramids on which only oyster spat are preserved, but such occurrences could be explained also as evidence of dead or dying individuals that could no longer remain "afloat" on the mud surface.

The duration of Smoky Hill deposition was approximately five million years (Obradovich and Cobban, 1975, p. 50), and total thickness of my composite section is approximately 180 m. This equates to an average depositional rate of approximately 0.036 mm/yr for Smoky Hill deposition, which is very close to the figure (0.038 mm/yr) calculated by Fischer (1980, p. 100) for the same unit at Pueblo, Colorado. These figures confirm that rates of Smoky Hill deposition were slow, and help to account for the multiple generations of small oysters that encrust large inoceramids through most of the member.

GAS PRODUCTION FROM THE SMOKY HILL MEMBER

At the present time, the Niobrara Chalk is the basis for a major gas play in northwestern Kansas, northeastern Colorado, and southwestern Nebraska. The occurrence of natural gas in Niobrara rocks has been known since 1912, with the first significant production in 1918 from the Beecher Island field, Yuma County, Colorado (Lockridge, 1977, p. 271). Following several decades of relative inactivity, interest in the Niobrara was renewed in the 1970s and more than 30 fields are actively under production. Most commercial production is from reservoirs less than 854 m (2800 ft) below the surface. Lockridge and Scholle (1978) reported that the pay zone is a primary reservoir, with high porosity and low permeability, and that gas accumulation is nearly all controlled by structural closure. Those authors, together with Rountree (1979) and Rice and Shurr (1980), noted the regional potential of the Niobrara as a gas reservoir outside the area of present drilling activity.

Energy resources in the play area consist largely of biogenic gas (Rice and Claypool, 1981, p. 14) that resulted from bacterial decomposition of organic matter. The productive interval, approximately 6 to 15 m thick, is near the top of the Smoky Hill Member and apparently corresponds to the upper chalk unit (Scott and Cobban, 1964) of the Smoky Hill Member at Pueblo, Colorado, and to a 6-m-thick interval of granular chalk 8.5 m below the top of the Smoky Hill at Locality 21, Logan County, Kansas. According to Hann (1981, p. 148), hydraulic fracture stimulation is required for economic production in the target interval, which is known as the Beecher Island zone. Shallow drilling depths and favorable gas prices combine to make the production of Niobrara gas feasible economically.

SUMMARY AND CONCLUSIONS

1. The Smoky Hill Chalk Member crops out extensively in bluffs and badlands of the Smoky Hill River drainage basin of Trego, Gove, and Logan counties, Kansas. A composite section, based on detailed measurements of strata in 12 key exposures and several supplementary sections, is 182 m (596 ft) thick. The member lies conformably and gradationally on the Fort Hays Limestone Member, and is overlain conformably and gradationally by the Sharon Springs Member of the Pierre Shale.

2. The Smoky Hill consists mainly of obscurely to well laminated, fissile, fecal-pellet-speckled, shaly weathering chalk that is mostly olive gray to dark olive gray or olive black and weathers to various, mostly pale shades of yellow, orange, or brown. Laminations are owing mainly to vertical variations in fecal-pellet abundance. In the upper part of the section crinkly structure is common, and many nonbioturbated chalk beds lack laminations. All beds of chalk have relatively high content of organic carbon, and a few organic-rich beds form prominent dark-colored bands on little-weathered exposures. Beds of light olive gray bioturbated chalk are scattered irregularly through the lower half of the member. These beds are also fecal-pellet speckled but lack the laminae seen in many nonbioturbated chalk beds. In the upper half of the member, beds of chalk having somewhat granular appearance are the apparent equivalent of bioturbated beds, but contain only sparse evidence of a burrowing infauna. Both bioturbated and granular chalk beds are more resistant to erosion than nonbioturbated beds, and form caprocks in chalk badlands. Well-preserved macroinvertebrate skeletal remains are common through much of the composite section, and where most abundant form conspicuous shelly zones. Near the middle of the member concentrations of the pelagic crinoid *Uintacrinus socialis* occur in thin lenses of hard, brittle limestone that are limited apparently to the zone of *Clioscaphites choteauensis.* The Smoky Hill contains more than 100 bentonite seams, many of which are now represented only by concentrations of iron oxide and gypsum. In little-weathered exposures, the bentonites are mostly pale shades of gray or bluish gray, whereas in weathered exposures various shades of orange, gray, brown, olive, pink, or white prevail. Iron disulphide, commonly weathered to iron oxide and jarosite, occurs as oblate spheroidal bodies developed around large inoceramid valves or along bentonite seams. Several intervals of stratified chalk are characterized by nodules of crystalline, polycuboidal pyrite. Nodular chert is a common epigenetic feature of highly weathered chalk beds that lie directly beneath the Ogallala Formation (Miocene and Pliocene).

3. Compilation of the composite section was facilitated through use of 23 marker units, which are defined on the basis of bioturbated chalk beds, bentonite seams, and organic-rich chalk beds, either singly or in combination. These marker units are spaced sufficiently close together to permit precise determination of stratigraphic position of all but some of the most stratigraphically limited exposures. The marker units have wide geographic extent, and several are recognizable as far to the west as the Pueblo, Colorado, section.

4. Macroinvertebrate fossils serve to delineate a se-

quence of biostratigraphic zones, including (ascending): *Inoceramus (Volviceramus) grandis* Range Zone (Upper Coniacian), *Inoceramus (Cladoceramus) undulatoplicatus* Range Zone (Lower to Middle Santonian), *Clioscaphites vermiformis* Range Zone (Middle Santonian), *Clioscaphites choteauensis* Range Zone (Middle Santonian), and *Inoceramus balticus* s.l. Range Zone (Upper Santonian-Lower Campanian). Several species of ammonites used in the standard Western Interior zonal scheme have not been recorded in the Kansas section, so the Kansas zonation is less refined than in Colorado.

5. Stratified chalks of the Smoky Hill are mostly foraminiferal pelmicrite with packstone or wackestone texture. Fecal pellets, consisting almost entirely of little-altered coccoliths, have been flattened by compaction into oblate spheroids having average maximum diameter of 0.12 mm. Tests of planktonic foraminifers are preserved mostly with walls intact or only slightly altered, and the chambers are usually filled with one to a few crystals of sparry calcite. Accessory carbonate grains include prisms and fragments of inoceramid bivalves and oysters. The matrix is micritic, and comprises a heterogeneous mixture of coccoliths, crystals of secondary calcite, and noncarbonate (detrital) particles. The chalks also contain fish scales and bones; wisps or flakes and angular, silt-sized grains of black carbonaceous matter; minute framboids of pyrite or their oxidized equivalent both in the matrix and inside foraminifer chambers; and rare calcispheres. Principal detrital grains are quartz and clay materials. The stratified chalks have strongly preferred, bed-parallel orientation of elongate and tabular grains.

In the upper part of the composite section many chalk beds lack laminae, are not bioturbated, and contain few skeletal remains of macroinvertebrates. These rocks are related genetically to laminated chalk, and are similar petrographically. Insoluble residue content of laminated and nonlaminated chalk ranges from 5.8 to 52.5 percent, averaging 31.4 percent. Most of the rocks are best termed impure chalk; a few beds are better termed chalky marl.

6. Bioturbated chalks are mainly foraminiferal and pelletal micritic wackestones or packstones. The most highly bioturbated beds lack laminations, but all gradations were recorded between bioturbated chalk and laminated chalk. Bioturbated chalk contrasts with nonbioturbated chalk in having less well compacted fecal pellets, generally smaller number of crushed foraminifers, greater abundance of foraminiferal fragments, more common alteration of foraminiferal test walls, smaller amount of black organic carbon, lack or near lack of stratified grain fabric, and fewer pyrite framboids in the matrix. In bioturbated chalk both fecal pellets and matrix contain more secondary calcite than the nonbioturbated chalks. Granular chalk beds have microscopic features intermediate between those of bioturbated and nonbioturbated chalk, but are apparently related genetically to the bioturbated chalk. Granular and bioturbated chalks contain minor amounts of detrital mineral grains and have lower average insoluble residue content than the nonbioturbated chalks.

7. The most obvious diagenetic feature in Smoky Hill chalks is compaction of allochems and horizontal, sediment-filled burrows. Neomorphic calcite and interstitial cement occur in all samples although the amounts vary according to the degree of bioturbation. Foraminifer chambers are filled mostly with sparry calcite, although crushed specimens are usually filled with microspar or (rarely) micrite. Diagenetic dissolution of aragonitic skeletal remains was a major source of carbonate for secondary calcite. Some secondary calcite was derived from pressure solution, which is manifest in incipient microstylolites in many samples and in well-developed microstylolites in the *Uintacrinus* limestone, but this was not a major source of carbonate for cementation and void-filling. Dissolution of coccoliths was an insignificant source of secondary calcite, but many foraminifer tests are partly corroded and probably furnished a substantial amount of carbonate for secondary mineralization. Cement and neomorphic overgrowths on coccoliths are best developed in bioturbated rocks, suggesting that bioturbation enhanced the lithification process. Overall, Smoky Hill chalk beds are *not* well cemented, and large volumes of carbonate were not required to produce the observed diagenetic effects. Although the bioturbated beds may reflect slower deposition than the nonbioturbated beds, the Smoky Hill composite section lacks hardgrounds.

8. Smoky Hill muds were deposited on the stable eastern shelf region of the Western Interior foreland basin during the regressional part of the Niobrara cycle. In Kansas the depositional cycle began after a prolonged episode of nondeposition, during which Carlile strata were truncated by submarine erosion, which lasted longest along the more easterly portions of the basin. In Kansas, initial deposits of the Niobrara cycle comprise the Fort Hays Limestone Member, which rests sharply on the Carlile, and incorporate at the base material reworked from the Carlile. The transgressive maximum occurred during deposition of the Fort Hays, which contains little detritus derived directly from terrigenous source areas. In the Smoky Hill, larger quantities of detritus reflect increased influence of terrigenous source areas during a protracted regressional event. The Niobrara chalks become generally less pure upward stratigraphically as well as westward toward the principal source area of land-derived detritus.

9. Principal components of the Smoky Hill chalk beds are pelagic elements, especially including coccoliths, fecal pellets, and tests of planktonic foraminifers. Chief among benthic constituents are remains of inoceramids and

oysters, with only minor amounts of skeletal remains derived from other macroinvertebrate groups. Secondary carbonate material consists primarily of neomorphic calcite overgrowths on coccoliths and foraminifer tests, crystals of calcite cement occurring mostly in the chalk matrix, and sparry calcite fillings of foraminifer tests. Black organic matter, as angular silt-sized grains or as wisps and flakes, occurs in all little-weathered chalk samples, and is interpreted as plant debris. Much of the organic carbon is apparently of marine origin. Interstitial reducing conditions, especially in the nonbioturbated chalks, were responsible for relatively high organic carbon content and abundance of pyrite framboids in the chalk.

10. Smoky Hill muds accumulated in waters having a probable depth range of 150 to 300 m. In western Kansas, water depth apparently was greatest during the latter half of Smoky Hill deposition, although regional stratigraphic relationships suggest general regression at this time. In addition to eustatic sea-level rise and subsidence caused by isostatic adjustment for water and stratigraphic loads, tectonic subsidence may have been a factor in producing this greater depth. Alternatively, a minor transgressive pulse during the overall regression could have produced the same result.

11. Regional patterns of biotic distribution suggest a climatic gradient from south to north across the Western Interior region. For the most part Kansas lay in a mild-temperate belt, which was influenced by occasional incursions of subtropical waters from Tethys.

12. Biotic data suggest that Smoky Hill deposition took place in marine water of less-than-normal salinity, but probably not less than 30 to 31 ‰.

13. During Smoky Hill deposition the sea floor consisted mostly of watery oozes that excluded most infaunal organisms and supported a primary benthos (inoceramids, rudists) comprising forms adapted to life on soft substrates. Purer oozes accumulated at times of minimum terrigenous detrital influx and supported a limited, mostly soft-bodied infauna. Bottom currents were weak, and bottom waters were usually poorly oxygenated. At times of better circulation, increased oxygen levels fostered increase in diversity and numbers of benthic organisms, which are now preserved in shelly zones. In the upper part of the member, nonlaminated (and nonbioturbated) chalks, which contain few macroinvertebrate fossils, represent a nearly anoxic (perhaps intermittently anoxic) benthic environment. Smoky Hill laminae do not appear to be of seasonal origin. Winnowing of bottom muds by weak currents explains the unequal thickness and erratic distribution of laminae.

14. Smoky Hill fossils are preserved as calcareous skeletal remains (most abundant), molds, borings, combinations of calcareous and organic matter (rare), and chitin (rare). The most abundant fossils are inoceramids and oysters. Inoceramids, rudists, and conchs of dead cephalopods were hosts for a limited variety of attached and boring forms, including oysters, cirripeds, serpulids (rare), and sponges (rare). The inoceramids and rudists manifest growth forms signifying adaptation to life on soft substrates, and commonly grew to extraordinarily large size. Oysters commonly encrusted both exposed and buried sides of their hosts, and commonly have preferred orientation related to current direction or possibly to growth in the direction of newly created substrate. Hosts encrusted only by oysters in the spat stage of growth indicate burial before oysters could mature. Pectinids and bakevelliids are very sparse, and may be epiplanktonic forms. Pelagic crinoids occur as articulated specimens only on undersides of *Uintacrinus* limestone lenses, where disintegration was prevented because of reducing conditions. Restricted stratigraphic occurrence and enormous numbers of individuals suggest crinoid death by mass mortality. Cephalopods were all nektonic forms, some perhaps nektobenthonic, and present no evidence of death by predation. Concentration of scaphites in only a few, limited stratigraphic intervals suggests strong control by water chemistry, and is probably related to peak salinity. Trace fossils are less diverse than in the Fort Hays and are rare in the upper part of the Smoky Hill. Poor circulation of bottom waters and paucity of suitable substrates were the major factors that restricted development of the macroinvertebrate infauna.

15. Smoky Hill benthic communities were characterized by low diversity assemblages, the basic elements of which were inoceramids and epizoic oysters. Inoceramids and sparse rudists were "islands" on the soft sea floor, and served as the principal substrates for all other epifaunal species. At times, improved circulation of bottom waters fostered increase in numbers and diversity of benthic macroinvertebrates. Decreased circulation resulted in reduction of diversity and numbers of individuals nearly to zero. High proportions of bivalves with articulated valves, consistency of the basic assemblages, minimum of shell fragmentation, and wide size range of individuals at a given horizon indicate that Smoky Hill assemblages represent fossil communities. Except for vagile infaunal burrowers (worms?), all benthic macroinvertebrates were suspension feeders. Smoky Hill muds contained a plentiful food supply, which was not utilized extensively by infaunal deposit feeders because of unsuitable substrates and marginally oxygenated bottom waters. Teeth of shell-crushing sharks are rare and bite marks on shells were not observed, suggesting that predation was not a major factor in benthic community life.

16. During Smoky Hill deposition the seawater was relatively deep, slightly below normal salinity, and had a temperature characteristic of mild-temperate to subtropi-

cal climates. The sea floor was almost perfectly flat, the surficial deposits were soft and watery, and the depositional rate approximated 0.036 mm/year. Bottom currents were weak and bottom waters were mostly oxygenated poorly. The benthic scene was also dark, monotonous, and hostile to many groups of marine organisms.

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APPENDIX

General Statement

The appended descriptions are for sections that comprise the composite section of the Smoky Hill Member in the type area. Descriptive details are based largely on field notes, supplemented by species identifications made in the laboratory. All sections were measured by steel tape, stadia rod, and hand-level techniques. Colors (wetted rock) are based on the well-known Rock Color Chart (Goddard and others, 1948), and color-code numbers are used only to distinguish between color chips that have the same name or for colors that are not represented by a color chip. Ferruginous or ferruginous-gypsiferous seams are probably very thin, weathered bentonite seams. The speckled appearance accorded most chalk units is owing to presence of flattened, coccolith-rich fecal pellets. Unit numbers are the same as those shown on Plate 1. The sections are described in overlapping order, from the top of the member downward. Correlation of equivalent beds is shown on Plate 1.

Descriptions of Sections

LOCALITY 21—Section exposed along cut banks of intermittent tributary to Ladder Creek, NE¼ Sec. 20 and NW¼ Sec. 21, T.15S, R.32W, Logan County, Kansas.

	Thickness m	cm
PIERRE SHALE		
63. Bentonite, nearly white, with medium bluish gray band near base; very brittle, very silty, has bitter taste, makes conspicuous streak on gray shale slope; overlain by gray, noncalcareous shale		0.5
62. Shale, olive black to dark olive gray (5Y3/1), dries medium light gray; noncalcareous, silty, fissile, weathers flaky, stained by iron oxide, some jarosite stains on joints and bedding surfaces; contains abundant small crystals and rosettes of selenite; overall slope color is conspicuously greenish gray		32.0
Measured thickness of Pierre Shale		32.5
SMOKY HILL CHALK MEMBER		
61. Calcareous shale, olive gray (5Y4/1), dries very light gray to light gray; pronounced color change on slope above top of unit; very calcareous at base, nearly noncalcareous at top; silty, not speckled, weathers flaky		20.5
60. Bentonite, pale orange (10YR7/2), silty, stained by iron oxide and jarosite along fractures; made conspicuous by thickness and position close to color change at base of Pierre Shale		5.0
59. Calcareous shale and noncalcareous shale, alternating; calcareous shale dark olive gray, dries very light gray; noncalcareous shale olive black, dries near olive gray (5Y4/1), weathers thinly flaky		73.2
58. Bentonite, very pale orange, partly stained dark yellowish orange by limonite, slightly silty, soft, and mushy		2.5
57. Chalky shale, calcareous shale, and noncalcareous shale, represents initial upward transition to Pierre Shale; basal 9 cm shaly chalk, olive gray (5Y4/1), very tough, moderately speckled, grades upward into dark gray, nearly noncalcareous shale 27.5 cm above base, then grades upward into olive gray calcareous shale; uppermost 3.0 cm are dark gray noncalcareous shale; entire unit weathers soft and flaky, contains finely granular gypsum; least calcareous units contain jarosite; persistent ferruginous-gypsiferous seam lies 40 cm above base		76.0
56. Bentonite, pale orange (10YR7/2), stained dark yellowish orange by iron oxide, silty, feels waxy		2.7
55. Chalky shale, dark olive gray (5Y3/1), dries light gray, very silty, moderately speckled, breaks blocky, weathers flaky on slope; more argillaceous and silty than typical Smoky Hill units below; ferruginous-gypsiferous seam, limonitic and jarositic, 0.5 cm thick, lies 27.5 cm above base		79.3
54. Bentonite, yellowish gray (5Y7/2), mostly stained dark yellowish orange, almost nonsilty, feels waxy		1.3
53. Chalk, olive gray (5Y4/1), calcareous silty, speckled throughout, weathers soft and crumbly, crinkly structure throughout; contains prominent ferruginous-gypsiferous seam about 1 mm thick that marks a very thin seam of slightly silty, pale grayish orange bentonite. FOSSILS: teleost scales		79.3
52. Bentonite, mostly stained dark yellowish orange by iron oxide, contains large crystals of selenite, seam conspicuous because of heavy limonitization that locally expands unit to 6-cm thickness		1.0
51. Chalk, olive gray (5Y4/1), calcareous silty, speckled throughout, weathers soft and finely flaky, crinkly seams of gypsum abundant. FOSSILS: teleost scales, plesiosaur remains		47.3
50. Bentonite, medium light gray, very silty, feels very waxy		2.8
49. Chalk, olive gray (5Y4/1), calcareous silty, speckled throughout, weathers soft and finely flaky, crinkly structure throughout. FOSSILS: teleost scales		44.2
48. Bentonite, apparently dark olive gray, nearly nonsilty, 2 mm thick; seam heavily mineralized by limonite and jarosite; unit marked by projecting ledges of limonite above and below seam; mineralization causes unit to expand locally to thickness of 7.5 cm		1.2
47. Chalk, olive gray (5Y4/1), dries medium light to very light gray, calcareous silty, moderately speckled, weathers soft and finely flaky, crinkly structure throughout. FOSSILS: teleost scales, teleost jawbone, *Inoceramus* fragments, isolated small ostreid		49.0
46. Bentonite, light bluish gray, mostly weathered dark yellowish orange, silty, feels waxy, some limonite and gypsum		2.8
45. Chalk, olive gray (5Y4/1), dries medium light to very light gray, calcareous silty, moderately speckled; upper and lower parts weather soft and flaky, with crinkly structure; central 30 cm more massive, less crinkly, forms minor ledge		76.2
44. Bentonite, olive gray (5Y4/1), mostly white and much weathered, limonitic and jarositic, approximately 6 mm thick; seam marked by projecting ledges of limonitic chalk at top and base		1.3
43. Chalk, olive gray (5Y4/1), dries medium light to very light gray, calcareous silty, moderately speckled, weathers minutely flaky, all but basal 3.0 cm with crinkly structure; basal 30 cm slightly more massive and tougher; lowest 20 cm tends to weather very pale orange to grayish orange pink locally; unit contains local small limonite nodules. FOSSILS: *Pseudoperna congesta* (float), teleost bones and scales		67.1
42. Bentonite, near yellowish gray (5Y8/1); in part stained dark yellowish orange by limonite, slightly silty, feels waxy		4.0
41. Chalk, olive gray (5Y4/1), weathers near pale yellowish brown, calcareous silty, moderately to much speckled throughout, relatively soft, mostly weathers to minute flakes; much crinkly structure above basal 9 cm, less crinkled in upper 9 cm; basal 9 cm light-colored, near pale grayish orange (10YR8/4), weathers shaly. FOSSILS: *Pseudoperna congesta* (float), teleost scales		58.0
40. Bentonite, medium dark gray, bleaches medium light gray to very light gray, stained dark yellowish		

orange where weathered, very silty 11.5

39. Chalk, medium to dark yellowish brown, dries very light to light gray, calcareous silty, speckled throughout, weathers soft and finely flaky, crinkly structure throughout 64.0

38. Bentonite, weathered, dark yellowish brown, highly limonitic, slightly silty, feels waxy, marked by conspicuous row of small (15 cm × 5 cm) limonite-pyrite nodules; locally contains large selenite crystals . . . 0.6

37. Chalk, olive gray (5Y4/1), tough; weathers medium yellowish brown, soft; calcareous silty, speckled throughout, not obviously laminated but has good fissility, apparently with crinkly structure throughout, weathers finely flaky, most of unit forms spally, smoothly curved face; upper half with minor, ledge-forming interval; seam of ferruginous matter lies 7.5 cm above base. FOSSILS: teleost bones and scales, *Inoceramus balticus, Pseudoperna congesta* 90.0

36. Chalk or chalky limestone, olive gray (5Y4/1) to dark yellowish brown, massive, tough, calcareous silty, speckled, weathered surface roughened by projecting edges of horizontal, wafer-like gypsum bodies; crinkly structure especially prominent in upper half; unit forms vertical, spally face where fresh, pronounced overhanging ledge where weathered; one inoceramid valve partially pyritized. FOSSILS: *Inoceramus balticus,* sparse inoceramid fragments, teleost bones and scales 61.0

35. Bentonite and chalk; lower of two bentonite seams is 1.5 cm thick, dark yellowish orange, slightly silty, brittle, feels waxy; upper seam is 0.6 cm thick (less than 0.3 cm where not weathered), olive gray to light olive gray, silty, waxy, consists mostly of selenite crystals; bentonite seams are separated by shaly weathering chalk, olive gray (5Y4/1), speckled, in part weathered dark grayish orange. FOSSILS: in chalk, *Inoceramus balticus,* teleost scales 5.5

34. Chalk, olive gray (5Y4/1), dries light gray, calcareous silty, speckled, crinkly structure throughout, very tough where fresh, forms vertical spally face, weathered very finely flaky 24.5

33. Chalky limestone, partly weathered, medium yellowish brown (10YR5/2), dries very pale orange; forms steep spally face where fresh, conspicuously ledge-forming where weathered; forms smoothly rounded shoulder on slopes; weathered surface rough textured; horizontal, wafer-like gypsum bodies project from surface in lower 9 cm; limonite-pyrite nodules as much as 21 cm by 2 cm thick occur locally near center of unit; limonitic and jarositic seam, possibly weathered bentonite, lies 2 cm below top and hosts numerous small pyrite and limonite nodules. FOSSILS: *Inoceramus balticus,* teleost bones and scales 35.0

32. Chalk, olive gray (5Y4/1) to medium olive gray (5Y5/1), locally weathering to vivid yellowish orange, calcareous silty, more or less speckled throughout; unit comprises alternating thin to medium thicknesses of very tough chalk that forms smoothly rounded ledges and softer, shaly weathering chalk that is filled with crinkly structures that lie parallel to bedding; main tough beds lie (ascending) 0.0 to 3.0 cm, 40 to 55 cm, 58 to 63 cm, and 98 to 110 cm above base; unit contains scattered small limonite nodules. FOSSILS: teleost? skeleton, teleost scales, *Pseudoperna congesta* attached to inoceramid fragments, coprolite 1 33.0

31. Bentonite, medium yellowish brown (10YR5/2); contains much finely crystalline selenite 0.6

30. Chalk, olive gray (5Y4/1), dries light gray, speckled throughout, very tough; basal 15 cm forms light-colored shoulder on slope; remainder of unit weathers flaky, forms slope. FOSSILS: *Pseudoperna congesta,* possibly float from unit 32. . . . . 20.0

29. Bentonite, mostly dark yellowish orange with minor yellowish gray coloration; seam composed mostly of limonitic bentonite, with thin seams of prismatic selenite above and below. 2.8

28. Chalk, all partly weathered to medium olive gray (5Y5/1), light olive gray (5Y5/2), medium yellowish brown (10YR5/2), and dark yellowish brown; slope dries mostly light gray to very light gray, locally very pale orange; speckled throughout; intervals of softer, flaky weathering rock predominate, alternate with beds of tough, more resistant rock that forms rounded shoulders on slope and forms white bands when viewed from a distance; most prominent resistant layers have upper limits 98 cm and 1.58 m above base of unit. Laterally unit passes into medium light gray to medium gray, less-weathered chalk, which forms vertical spally face. From a distance, unit appears distinctly laminated, unlike most of underlying unit. In a local area of adjacent badlands, unit weathered to vivid yellowish orange color. Thin zone, 7.5 cm thick, comprising soft, crinkly bedded, shaly weathering chalk, marked by thin wafers of gypsum, lies 1.31 m above base of unit. Zone of widely spaced limonitic pyrite nodules lies 85 cm above base of unit. FOSSILS: sparse *Inoceramus balticus, Pseudoperna congesta,* teleost bones 2 1.5

27. Chalk and chalky limestone, medium olive gray in basal part grading to pale yellowish brown or medium yellowish brown (10YR5/2) in upper part; lower part and uppermost 37 cm weather very pale orange, remainder dries light gray; in nearby badlands, entire unit weathers moderate reddish orange; unit forms steep, spally face where little weathered, forms two or three rounded shoulders where weathered. Lowest 76 cm forms overhanging ledge where weathered; uppermost 37 cm is major, light-colored bench former and caps low pinnacles in nearby reddish-colored badlands; part of unit has tendency to weather shaly; contact with unit 28 somewhat arbitrary. All of rock is tough, speckled throughout, and from distance appears thinly stratified, but is not well laminated. Exposed faces exhibit prominent bed-parallel lines, not associated with bentonite, at 76 cm, 1.42 m, 1.62 m, and 1.89 m above base; line at 1.62 m has sparse associated iron oxide. Very thin, small wafers of selenite project conspicuously from weathered face in zone 7.5 cm thick, which lies 33 cm above base of unit. FOSSILS: *Inoceramus* fragment, *Pseudoperna congesta,* pectinids, teleost bones and scales, coprolite. 2 20.0

26. Bentonite, light brown (5YR5/6), as scattered flakes in seam consisting of mostly dark yellowish orange, finely granular gypsum, limonite, and jarosite . . . 1.0

25. Chalky limestone, all partly weathered, mostly dark yellowish brown to medium yellowish brown (10YR5/2) or grayish orange, relatively hard, punky where moist, speckled throughout; forms smoothly curved, spally surface where least weathered; forms resistant, cavernous, overhanging ledge where most weathered. Spally surfaces are olive gray (5Y4/1) to medium light gray where least weathered. Prominent line, not associated with bentonite, lies 27 cm above base, and forms minute reentrant locally. Very thin wafers of gypsum abundant in first 12 cm above line and also 35 cm below top. Unit forms resistant caprocks in nearby badlands, where unit weathers to conspicuous moderate reddish orange color. FOSSILS: *Inoceramus (Platyceramus) platinus?, Pseudoperna congesta,* teleost bones and scales 94.5

24. Bentonite. Seam consists mostly of powdery gyp-

sum, which contains local clayey lenticles. Bentonite represented only by 0.03 cm of waxy chalk at base of unit . . . 1.2

23. Chalky limestone, olive gray (5Y4/1) to medium dark gray, mostly weathered pale to very pale yellowish brown (10YR7/2), relatively hard, resistant, forms vertical faces to rounded, overhanging ledges that locally display cavernous weathering. Vertical and steep faces weather spally. Unit not obviously burrowed or laminated; some exposed surfaces manifest obscure laminae; rock has moderately developed fissility. Crinkly structure abundant in thin zones 23 cm below top of unit and 40 cm above base. Prominent line, forming reentrant, not associated with bentonite, lies 1.05 m above base. FOSSILS: teleost bones . . . 1 77.0
22. Bentonite, olive gray (5Y4/1), as chips in seam consisting mostly of finely granular gypsum. . . . 1.0
21. Chalky limestone, all partly weathered, pale yellowish brown to dark yellowish brown, tough, upper part generally punky, speckled throughout, neither burrowed nor laminated. Unit weathers cavernous locally, forms overhanging ledge locally. FOSSILS: inoceramid fragments, teleost scales . . . 24.5
20. Bentonite, yellowish gray (5Y7/2), stained dark yellowish orange, silty, with associated finely crystalline selenite and some limonite . . . 1.0
19. Chalky limestone, light olive gray (5Y5/2), medium olive gray (5Y4/2) on fresh vertical face, top of bed grayish orange with liesegang banding, homogeneous, neither laminated nor obviously burrowed, rather punky, passes laterally into orange-weathering limestone that forms overhanging ledge. FOSSILS: teleost scales . . . 41.0
18. Bentonite, marked by nearly white seam of powdery gypsum, locally contains small flakes of grayish orange bentonite . . . 0.6
17. Chalky limestone, light olive gray (5Y5/2), slightly darker in lower part, weathers pale grayish orange (10YR8/4), liesegang-banded in upper part, neither laminated nor burrowed, speckled throughout, tough to somewhat punky, relatively brittle where weathered. Unit forms vertical face where fresh, overhanging ledge where weathered . . . 9.2
16. Bentonite, two seams, separated by chalk. Lower bentonite seam 0.6 cm thick, dark yellowish orange, brittle, slightly silty. Upper seam 1.9 cm thick, grayish orange, silty, waxy. Chalk medium olive gray (5Y4/2), calcareous silty, much speckled, weathers flaky . . . 4.3
15. Chalky limestone, medium gray, weathers grayish orange to medium yellowish brown (10YR5/2), tough, speckled throughout, appears faintly laminated on least-weathered faces. Steep faces smoothly curved, sloping faces weather spally. Where weathered, unit forms overhanging ledge. FOSSILS: small teleost bones . . . 79.3
14. Bentonite, olive gray (5Y4/2), as waxy clay at top of seam consisting mostly of light-colored, finely crystalline, slightly clayey selenite . . . 0.6
13. Chalky limestone, medium gray, weathers grayish orange to medium yellowish brown (10YR5/2, tough, somewhat punky on exposed surfaces, speckled throughout, appears indistinctly laminated on fresh surfaces. Unit forms smoothly curved, nearly vertical face where fresh, prominent overhanging ledge where weathered. Prominent line, not associated with bentonite, lies 23.5 cm above base and forms reentrant on overhanging ledge. FOSSILS: teleost bones, scales, and teeth . . . 61.0
12. Bentonite, two(?) seams, separated by chalk. Lower seam is 0.3 cm thick, consists of vertical crystals of selenite, with no evidence of bentonite; upper seam 0.6 cm thick, grayish orange, bentonite occurs as scattered flakes in medium crystalline granular selenite. Chalk is 1.5 cm thick, dark yellowish brown, dries grayish orange pink, soft . . . 2.4
11. Chalk, dark olive gray (5Y3/1) to olive gray (5Y4/1), in part weathered very pale yellowish brown (10YR7/2), relatively hard, brittle, calcareous silty, speckled throughout, faintly laminated, with good fissility. Two prominent lines, without associated bentonite, lie 9.2 and 45.7 cm above base. FOSSILS: inoceramid fragments, ostreid bivalves. . . . 70.1
10. Bentonite, two seams, separated by chalk. Lower bentonite 0.3 cm thick, upper seam 0.9 cm thick. Chalk 3.3 cm thick, olive gray (5Y4/1), relatively hard, brittle, speckled throughout, not obviously laminated . . . 4.5
9. Chalk, olive gray (5Y4/1), relatively hard, brittle, calcareous silty, speckled throughout, not obviously laminated, has good fissility, weathers spally. FOSSILS: teleost bones and scales . . . 19.8
8. Bentonite, light brown (5YR5/6) to dark yellowish orange, moderately silty, with soft, plastic consistency, associated with minor amount of granular selenite . . . 0.3
7. Chalk, olive gray, as in unit 9. Prominent line lies 48.8 cm above base. FOSSILS: teleost scales. . . . 80.8
6. Bentonite, two seams, separated by chalk. Lower seam 0.3 cm thick; upper seam 0.6 cm thick, moderately silty; both consist mainly of granular gypsum, which contains flakes of light brown (5YR5/6) to dark yellowish orange flakes of bentonite. Chalk is 2.2 cm thick, weathers shaly . . . 3.1
5. Chalk, as in unit 9. FOSSILS: *I. (Platyceramus) platinus*, ostreids, teleost bones and scales . . . 74.8
4. Bentonite, light gray, weathers dark yellowish orange, brittle, very silty, bounded by seams of granular selenite . . . 0.9
3. Chalk, as in unit 9. FOSSILS: teleost bones and scales . . . 47.2
2. Bentonite, mostly yellowish gray (5Y7/2); seam consists mostly of granular selenite, with minor iron oxide . . . 0.3
1. Chalk, as in unit 9. FOSSILS: ostreid bivalves . . 1 28.0

Measured thickness of Smoky Hill Member . . . 24 93.1
Total thickness of measured section . . . 25 25.6

LOCALITY 25—Section exposed in small butte in SE¼ Sec. 30, T.15S, R.32W, Logan County, Kansas.

Thickness m cm

SMOKY HILL CHALK MEMBER

32. Bentonite, weathered, dark yellowish orange, waxy 0.9
31. Chalk, highly weathered to dark yellowish orange to grayish orange . . . 3.9
30. Bentonite, weathered, dark yellowish orange, waxy 0.6
29. Chalk, highly weathered . . . 18.3
28. Bentonite, weathered, dark yellowish orange, waxy 0.6
27. Chalk, highly weathered, rather massive, cliff-forming bed . . . 71.5
26. Bentonite, mostly dark yellowish orange, silty, waxy, limonitic, with some crystalline selenite . . . 0.3
25. Chalk, weathered, dark yellowish orange to grayish orange, punky, calcareous silty, speckled throughout 2.2
24. Bentonite, weathered, moderate yellowish brown, contains much limonite . . . 0.3
23. Chalk, weathered, pale yellowish orange to very light brown (5YR6/6), calcareous silty, speckled throughout, in part well laminated; where nonlaminated splits roughly parallel to bedding, where laminated splits evenly along bedding; prominent lines, not associated with bentonite, lie 31.5 cm above base and 15.2 cm below top. Unit forms part of nearly

vertical cliff. FOSSILS: teleost bones and scales . .	68.6
22. Bentonite, moderate yellowish brown, silty, appears earthy, waxy, contains minor amount of limonite .	0.6
21. Chalk, weathered, dark yellowish orange to pale grayish orange (10YR8/4), soft, punky, apparently well laminated, splits evenly parallel to bedding, calcareous silty, speckled throughout, with banded appearance owing to weathering. Unit forms rounded ledge. FOSSILS: *Pseudoperna congesta,* teleost bones and scales	42.2
20. Bentonite, light brown (5YR5/6), silty, occurs as flakes in seam consisting mostly of limonite	0.3
19. Chalk, weathered, dark yellowish orange to dark grayish orange (10YR6/4), apparently well laminated except for central part, splits evenly along laminae. Central 16.8 cm tough, granular, splits crudely along bedding, with faintly crinkled appearance. All rock calcareous silty, speckled, locally weathers shaly. Unit contains ferruginous streak 38.1 cm above base. Unit forms part of vertical cliff. FOSSILS: *Pseudoperna congesta, Inoceramus balticus?,* teleost bones and scales.	58.0
18. Ferruginous streak, easily traceable, possibly marks position of weathered bentonite seam	0.0
17. Chalk, weathered, dark grayish orange (10YR6/4) to moderate yellowish brown, streaked with yellowish gray to pinkish gray, relatively soft, apparently well laminated throughout, splits easily parallel to bedding, weathers somewhat shaly, passes laterally to somewhat more brittle rock, calcareous silty, speckled throughout, forms vertical face locally. FOSSILS: *Inoceramus balticus, Pseudoperna congesta,* teleost scales	74.7
16. Bentonite, dark yellowish brown, waxy, limonite stained	0.1
15. Chalk, weathered, very pale yellowish brown (10YR7/2) to dark yellowish orange, mostly well laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, locally quite brittle and forms part of vertical cliff. FOSSILS: inoceramid fragments, teleost bones and scales. . .	67.0
14. Bentonite, dark yellowish brown, silty, with local concentrations of limonite	0.02
13. Chalk, weathered, very pale yellowish brown (10YR7/2), surface dries very light gray, mostly well laminated; upper 6 cm tough and nonlaminated, weathers shalier than laminated part; speckled throughout, calcareous silty. Unit forms slope where least weathered and is part of steep cliff where much weathered. FOSSILS: *Pseudoperna congesta,* teleost scales	27.5
12. Bentonite, moderate olive brown, nonsilty, waxy, forms prominent reentrant in cliff sections.	0.03
11. Chalk, weathered, very pale yellowish brown (10YR7/2) with streaks of dark yellowish orange, calcareous silty, speckled throughout; lowest 26 cm and uppermost 10.5 cm thinly laminated; interval from 26 to 38.3 cm above base is not obviously laminated, weathers out as massive, smooth-surfaced shoulder on slope. Band of ferruginous matter lies within uppermost 3 cm. Unit has sharp upper and lower contacts and is conspicuous on face of exposure. FOSSILS: *Inoceramus balticus, Pseudoperna congesta,* teleost bones and scales	48.8
10. Chalk, weathered, grayish orange to pale grayish orange (10YR8/4), massive, very calcareous gritty, speckled throughout, tough, granular, forms smoothly rounded ledge, rock splits roughly parallel to bedding. Faint line, not associated with bedding, lies 62.6 cm above base. FOSSILS: *Inoceramus balticus, Pseudoperna congesta,* teleost bones and scales .	94.7
9. Bentonite, moderate yellowish brown, nonsilty, waxy, 1.2 cm thick, bordered by seams of coarsely crystalline selenite	2.8
8. Chalk, weathered, pale grayish orange (10YR8/4), soft, calcareous silty, speckled throughout, nonlaminated, with units 7 and 9 forms prominent reentrant beneath unit 10	5.2
7. Bentonite, light brown (5YR5/6), as small flakes scattered through seam consisting almost entirely of very coarsely crystalline selenite	1.2
6. Chalk, weathered, medium yellowish orange (10YR7/6), nonlaminated, speckled throughout; basal 6.2 cm and upper 12.2 cm soft, weather shaly; middle part tough, granular, forms smooth slope and locally projecting ledge. Shaly part splits evenly parallel to bedding. FOSSILS: teleost bones and scales	44.2
5. Ferruginous seam, dark yellowish orange, not associated with bentonite	0.1
4. Chalk, weathered, dark yellowish orange to very light brown (5YR6/6), rather punky, calcareous silty, speckled throughout, not obviously laminated, splits unevenly along bedding, forms minor ledge. FOSSILS: teleost bones and scales	25.9
3. Bentonite, yellowish gray (5Y7/2) to dusky yellow, slightly silty, waxy, with limonite along joints and fractures	11.6
2. Chalk, weathered, dark yellowish orange to light brown (10YR5/6), rather punky, not obviously laminated, calcareous silty, speckled throughout, forms smoothly convex slope, weathers shaly. FOSSILS: *Pseudoperna congesta,* teleost bones and scales	48.8
1. Bentonite, light olive gray (5Y7/2), almost nonsilty, waxy, limonite stained, with a little associated gypsum	6.0
Total thickness of measured section	7 27.0

LOCALITY 24—Section exposed along cliffs and gullies in bluff on east side of Ladder Creek, in SW¼ Sec. 30, T.15S, R.32W, Logan County, Kansas.

	Thickness m	Thickness cm
SMOKY HILL CHALK MEMBER		
61. Chalk, much weathered; contains large, oblate spheroidal nodules of chert (formed by secondary processes) adjacent to contact with overlying Ogallala Formation. Unit forms part of vertical cliff. Thickness approximately.	1	63.0
60. Bentonite, light greenish gray, almost nonsilty, earthy to waxy, limonite-stained on fractures, forms deep reentrant on cliff face		0.3
59. Chalk, weathered medium yellowish orange (10YR7/6) to moderate reddish orange, relatively soft, not obviously laminated, splits generally parallel to bedding, calcareous silty, speckled throughout. Unit contains large masses of liesegang-banded chert. Unit forms part of vertical cliff. FOSSILS: teleost scales.	1	46.3
58. Bentonite, yellowish gray (5Y8/1), nonsilty, waxy, forms prominent reentrant on slope		1.3
57. Chalk, weathered pale brown (5YR7/6) to dark yellowish orange, soft, not obviously laminated, streaked locally by horizontal white bands, breaks blocky. FOSSILS: teleost bones and scales		5.5
56. Bentonite, light brown (5YR5/6), mostly limonite, forms conspicuous reentrant on cliff face.		0.1
55. Chalk, weathered grayish orange, soft, not obviously laminated, splits evenly parallel to bedding, calcareous silty, speckled throughout, forms part of vertical cliff. Streaked with horizontal white bands near top. FOSSILS: teleost bones and scales		33.6
54. Ferruginous seam, dark yellowish orange, forms prominent reentrant of cliff face; unit climbs laterally to position 48.7 cm above top of unit 53, so is		

probably not a stratigraphic feature 0.1

53. Chalk, like unit 55, forms part of vertical cliff, locally iron-oxide-banded in upper part; unit contains prominent line, marked by minor seam of iron oxide, 10.7 cm above base. FOSSILS: teleost bones and scales 25.9
52. Bentonite, pale olive, dries light greenish gray (5GY8/1), earthy to waxy, very silty, forms prominent reentrant on cliff face 9.7
51. Chalk, weathered dark yellowish orange, soft, punky, not obviously laminated, splits evenly parallel to bedding, calcareous silty, speckled throughout, forms rounded ledge to somewhat shaly weathering slope. FOSSILS: *Pseudoperna congesta,* teleost scales. 33.5
50. Bentonite, dark yellowish orange, slightly silty, waxy, forms prominent reentrant on cliff face . . . 5.2
49. Chalk, mostly weathered dark yellowish orange with color banding owing to weathering; not obviously laminated, splits evenly parallel to bedding, relatively soft, somewhat punky, calcareous silty, speckled throughout, with color banding owing to weathering. Unit forms part of cliff at top of section. FOSSILS: *Pseudoperna congesta,* teleost bones and scales 97.5
48. Bentonite, very pale yellowish brown (10YR7/2), almost nonsilty, waxy, iron-stained 1.5
47. Chalk, mostly weathered very pale orange, not obviously laminated but parts of unit are color banded owing to weathering, relatively brittle, calcareous silty, speckled throughout, forms nearly vertical face, weathers to thin, flat slabs. Unit contains prominent lines, possibly marking very thin weathered bentonite seams, 13.0 cm and 16.4 cm above base; prominent reentrant marks a third line lying 53.3 cm above base. FOSSILS: *Pseudoperna congesta,* teleost bones and scales 1 12.8
46. Bentonite, light brown (5YR5/6), earthy to waxy, limonitic, silty 0.6
45. Chalk, weathered pale yellowish orange, has granular texture, apparently massive, splits roughly parallel to bedding, soft, calcareous silty, speckled throughout, forms vertical face. Laterally, unit passes into soft, shaly weathering chalk. FOSSILS: *Inoceramus (Platyceramus) platinus?, Pseudoperna congesta,* teleost scales. 21.4
44. Bentonite, light brown (5YR5/6) to dark yellowish brown, limonite-stained, slightly silty, waxy 3.1
43. Chalk, weathered dark yellowish orange to medium yellowish orange (10YR7/6), with band of moderate reddish orange coloration, 7.6 to 13.7 cm thick, along center of unit. Faintly liesegang(?)-banded, but not obviously laminated; rock splits roughly parallel to bedding. Unit marked by three prominent lines, each marked by small concentration of limonite, which lie 9.7, 17.3, and 30.7 cm above base. FOSSILS: *Pseudoperna congesta,* teleost scales and bones 73.1
42. Bentonite, grayish yellow (5Y8/4) to yellowish gray (5Y7/2), slightly silty, waxy, limonite-stained. . . . 2.1
41. Chalk, weathered dark yellowish orange, granular, not obviously laminated, splits evenly parallel to bedding, calcareous silty, speckled, forms part of steep cliff face, weathers shaly and forms slope where most intensively weathered. Unit divided into three beds of subequal thickness by two 3-cm-thick darker-colored zones with crinkly structure. Possible weathered bentonite seam lies 9.1 cm below top. FOSSILS: *Pseudoperna congesta,* teleost bones. 41.2
40. Bentonite, light olive gray (5Y6/1) to greenish gray, very silty, earthy to waxy 0.3
39. Chalk, weathered dark yellowish orange, granular, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled, liesegang-banded in lower half. FOSSILS: *Pseudoperna congesta,* teleost bones and scales. 9.1
38. Bentonite, yellowish gray (5Y7/2), slightly silty, waxy, with some limonite staining. 4.6
37. Chalk, weathered dark yellowish orange to grayish orange, granular, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout. FOSSILS: *Pseudoperna congesta,* teleost bones and scales 12.2
36. Bentonite, light gray to light brown (5YR5/6); seam composed mostly of limonite 0.02
35. Chalk, as in unit 37, tough, granular, weathers shaly, with liesegang banding in lower part. FOSSILS: *Pseudoperna congesta,* teleost bones and scales. 27.4
34. Bentonite, light olive brown, with pale olive brown (5Y6/6) stains, almost nonsilty, waxy. 2.1
33. Chalk, weathered grayish orange, tough, granular, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, forms rounded ledge. Upper part of unit softer, weathers shaly, dark yellowish orange to very pale orange, streaked with pale bluish gray (5B8/1), calcareous silty, speckled, splits easily along bedding. FOSSILS: teleost scales and bones. 33.5
32. Bentonite, light brown (5YR5/6), as a few flakes scattered in a seam consisting mostly of limonite . 0.3
31. Chalk, partly weathered to moderate yellowish brown to medium yellowish brown with streaks of light olive gray (5Y5/2), tough, faintly laminated, splits easily along bedding, calcareous silty, weathers shaly. FOSSILS: *Pseudoperna congesta,* teleost bones and scales 42.7
30. Chalk and five weathered bentonite seams. Chalk partly weathered to medium olive gray (5Y4/2) to yellowish gray (5Y7/2), mostly with crinkly structure. Uppermost chalk bed dries to conspicuous pale bluish gray (5B8/1), laminated, forms distinctive marker. Other chalk beds in part laminated. All chalk calcareous silty, speckled, splits easily parallel to bedding. Bentonite? seams represented mostly by iron oxide; lowest seam consists largely of powdery gypsum; uppermost seam locally 0.6 cm thick, light olive brown, bentonitic. 35.0
29. Chalk, dark olive gray to olive gray (5Y4/1), weathers medium yellowish brown (10YR5/2). Lower 1.62 cm comprises tough, granular chalk with some crinkly structure; forms steep, spally weathering face, with uppermost portion forming smoothly rounded, lighter-colored shoulder; not obviously laminated, but has stratified appearance; calcareous silty, speckled throughout. Uppermost 54.9 cm is olive gray (5Y4/1), calcareous silty, speckled, with crinkly structure, less resistant than lower part. Entire unit weathers shaly. Prominent line, parallel to bedding, lies 7.6 cm below top. FOSSILS: *I. ?(Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales 2 16.7
28. Bentonite, moderate yellowish brown, silty, as flakes scattered in seam consisting mostly of coarsely crystalline selenite and powdery gypsum. Seam expands locally to 1.8 cm where much weathered . . 0.6
27. Chalk, olive gray (5Y4/1), weathering medium yellowish brown (10YR5/2), tough, granular, calcareous silty, speckled, with central zone of crinkly structure, forms gently shouldered slope; where highly weathered forms shaly slope with two lighter-colored, more resistant zones at top and base. FOSSILS: *I. ?(Platyceramus) platinus, Pseudoperna congesta,* teleost scales and bones. 45.7
26. Ferruginous seam, moderate yellowish brown, limonitic, expands locally to 1.3 cm where mineralized

with gypsum 0.3

25. Chalk, olive gray (5Y4/1) to medium olive gray (5Y4/2), very tough, granular, nonlaminated, splits unevenly parallel to bedding, calcareous silty, speckled throughout; uppermost 9.1 cm with crinkly structure, remainder with sparse crinkly structure; weathers shaly. FOSSILS: *I. ?(Platyceramus) platinus,* coprolite, teleost bones and scales 18.3

24. Bentonite, mostly grayish orange medium-crystalline selenite, with scattered flakes of silty bentonite, which are dark yellowish brown. Where weathered, seam expands to 1.5 cm and is heavily mineralized by selenite 0.6

23. Chalk, olive gray (5Y4/1), forms darker-colored band on slope, calcareous silty, speckled, with crinkly structure; weathers shaly. FOSSILS: *Pseudoperna congesta,* coprolite 6.1

22. Bentonite, pale grayish orange (10YR8/4), with seam of limonite forming top of unit, expands laterally to 3 cm owing to secondary mineralization; actual bentonite seam 1.2 cm thick 1.8

21. Chalk, olive gray (5Y4/1), weathers dark yellowish orange, mostly tough, granular, nonlaminated, in part solution-crinkled, forms gently rounded shoulders on slope, with thin, softer interval of darker chalk with crinkly structure near center. Upper 9.2 cm olive gray (5Y4/1) to medium olive gray (5Y4/2), highly solution-crinkled, forms distinctly darker band on weathered face. All rock calcareous silty, speckled throughout, splits parallel to bedding. FOSSILS: inoceramid valves, *Pseudoperna congesta,* teleost scales and bones 76.3

20. Bentonite, dark yellowish orange, silty; seam consists mostly of crystalline selenite, with local concentrations of powdery gypsum. 0.6

19. Chalk, dark olive gray (5Y3/1), or partly weathered to medium olive gray (5Y4/2); mostly tough, granular chalk, which is hard and brittle where least weathered, lighter colored where partially weathered; calcareous silty, speckled throughout, nonlaminated, splits parallel to bedding; locally forms steep, spally face; elsewhere weathers shaly. Unit contains scattered crinkly structure. FOSSILS: *Pseudoperna congesta,* teleost bones and scales 64.0

18. Bentonite, grayish orange, slightly silty; actual bentonite seam 0.9 cm thick, bordered by projecting ledges of hard limonite of subequal thickness. Seam hosts local nodules of limonite that contain gypsum and jarosite 3.4

17. Chalk, moderate yellowish brown (10YR5/2), not obviously laminated, splits easily along bedding, calcareous silty, speckled throughout, weathers spally in steep faces, weathers shaly elsewhere. FOSSILS: teleost bones and scales 29.0

16. Bentonite, light brown (5YR5/6), associated with underlying seam of crystalline gypsum; actual bentonite seam 0.1 cm thick. 0.9

15. Chalk, olive gray (5Y4/1) to dark olive gray (5Y3/1), relatively hard, brittle, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers spally in steep faces, weathers soft and shaly elsewhere. Unit contains scattered zones of crinkly structure. FOSSILS: inoceramid fragments: *Pseudoperna congesta,* teleost bones and scales 1 44.3

14. Ferruginous seam, mostly light brown (10YR5/6), hosts isolated nodules of limonite. (In fresh, unweathered exposures this seam is not detectable.) . 0.2

13. Chalk, olive gray (5Y4/1), or partly weathered light olive gray (5Y5/2), relatively hard, brittle, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled, locally forms steep, spally face, weathers soft and shaly. Unit has sparse crinkly structure. FOSSILS: coprolite, teleost scales and bones 1 13.0

12. Ferruginous seam, moderate yellowish brown (10YR5/2), hosts numerous limonite nodules 0.3

11. Chalk, medium gray to olive gray (5Y4/1) or medium olive gray (5Y5/1), relatively hard, brittle, not obviously laminated, splits easily along bedding, calcareous silty, speckled throughout, forms steep spally face, in part with crinkly structure, weathers soft and shaly. FOSSILS: *Pseudoperna congesta* 61.0

10. Bentonite, very pale orange, slightly silty, partly stained dark yellowish orange by limonite, bordered by subequal seams of limonite that form projecting ledges. Actual bentonite seam 4.0 cm thick 6.1

9. Chalk, as alternating beds of lighter-colored granular and darker-colored chalk with crinkly structure. Granular chalk very tough, medium olive gray (5Y5/1), nonlaminated, calcareous silty, speckled throughout, in beds as much as 18 cm in thickness. Crinkly chalk olive gray (5Y4/1) to medium olive gray (5Y4/2), calcareous silty, speckled throughout, not obviously laminated, splits parallel to bedding, locally forms spally faces, weathers shaly. Ferruginous seams, less than 0.1 cm thick and marked by rows of oblate spheroidal limonite nodules, lie 94.6 cm and 1.16 m below top of unit. Granular and shaly weathering chalk beds gradational. FOSSILS: *Pseudoperna congesta* 1 86.0

8. Bentonite, grayish orange, much stained by limonite, gritty (disseminated gypsum crystals), passes laterally into seam heavily mineralized by limonite 0.2

7. Chalk, as alternating beds of lighter-colored granular and darker-colored chalk, both with crinkly structure. Granular chalk olive gray (5Y5/2) to dark olive gray (5Y3/1), tough, calcareous silty, speckled throughout, medium yellowish brown (10YR5/2) where partly weathered, forms four distinct bands on slope, maximum thickness 15.2 cm, with some crinkly structure. Darker chalk olive gray (5Y5/2) to dark olive gray (5Y3/1), relatively hard, calcareous silty, speckled throughout, not obviously laminated, splits easily parallel to bedding, much crinkly structure in upper 39.5 cm, forms steep spally faces, weathers shaly. Conspicuously darker, organic-rich bed, 10.5 cm thick, lies 35 cm below top. Granular and shaly weathering chalk beds gradational. Ferruginous-gypsiferous seam, 0.1 cm thick, locally hosts small limonite nodules, lies 70.2 cm below top of unit. FOSSILS: teleost bones 2 32.0

6. Bentonite; seam consists mostly of moderate yellowish brown (10YR5/2) granular gypsum, locally hosts oblate spheroidal masses of dark yellowish orange to light brown (5Y5/6) limonite/jarosite/gypsum as much as 33.5 cm wide and 6 cm thick 0.3

5. Chalk, medium olive gray (5Y4/2), slightly calcareous silty, speckled throughout, weathers shaly, with crinkly structure 12.2

4. Bentonite, yellowish gray (5Y7/2), in part limonite-stained, bordered by equal thicknesses of dark yellowish brown limonite. Actual bentonite seam is 0.5 cm thick 3.0

3. Chalk, medium light gray to light olive gray (5Y5/2), not obviously laminated, splits easily parallel to bedding, with crinkly structure, forms spally faces, weathers shaly. Unit contains two beds of lighter-colored granular chalk, 27.5 cm and 12.2 cm thick, lying 24.4 cm and 1 m above base of unit, respectively, very tough, calcareous silty, speckled throughout, appears crudely stratified, forms gently convex shoulders on moderate slopes, gradational with darker-colored chalk. FOSSILS: teleost scales 1 61.8

	m	cm
2. Bentonite, very pale orange, very silty, with sour taste, mineralized along contacts by limonite/jarosite/selenite, locally hosts oblate spheroidal limonitic nodules that have rotten marcasite in center. Actual bentonite seam is 0.9 cm thick		1.2
1. Chalk, olive gray (5Y4/1), hard, brittle, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, forms steep spally face, weathers shaly, contains widely scattered, weathered pyrite nodules 70 cm below top. Unit contains two beds of lighter-colored, tough granular chalk, 3.1 cm and 30.5 cm thick, lying 93.1 cm and 1.7 m above base; both beds form gently convex shoulders on slope	1	46.5
Total thickness of measured section	24	77.4

LOCALITY 20—Cliffs along bluff on south side of Twin Butte Creek, in SW¼ Sec. 16, T.15S, R.34W, Logan County, Kansas.

SMOKY HILL CHALK MEMBER	Thickness m	cm
25. Highly weathered chalk extending to top of bluff		
24. Bentonite, very pale orange, silty; seam hosts hollow, gypsiferous geode-like structures. Seam heavily mineralized by selenite and limonite, which form hard, projecting ledges above and below bentonite, and with bentonite forming unit as much as 13.5 cm thick		3.7
23. Chalk, as alternation of tough, lighter-colored granular chalk and darker-colored chalk with crinkly structure. Granular chalk is partly weathered, pale yellowish brown, calcareous silty, speckled throughout. Darker-colored chalk is partly weathered, dark yellowish brown, calcareous silty, speckled, with crinkly structure, weathers to fine flakes. Entire unit has horizontally banded appearance. Layer of small limonite/marcasite nodules centers 55 cm below top of unit. FOSSILS: *Pseudoperna congesta,* teleost scales and bones	1	11.4
22. Gypsum, mostly granular selenite, characterized by oblate spheroidal limonite/marcasite nodules as much as 24.5 cm in diameter		0.6
21. Chalk, olive gray (5Y4/1), somewhat laminated in appearance, calcareous silty, much speckled, fissile, weathers shaly, with some crinkly structure. Contains several beds, as much as 0.9 cm thick, of harder chalk. Unit mostly soft and crumbly. FOSSILS: *Pseudoperna congesta,* coprolite		32.1
20. Bentonite, light brown (10YR5/6); seam consists mostly of limonite, with some jarosite, and small limonitic nodules. Mineralized part of seam projects as ledge locally. Actual bentonite seam 0.01 cm thick		0.6
19. Chalk, all partly weathered, comprises alternation of lighter- and darker-colored beds that impart banded appearance to exposure. Darker beds medium yellowish brown (10YR5/2) to very dark yellowish brown (10YR3/2), calcareous silty, much speckled, with crinkly structure, fissile, weathers minutely flaky. Lighter-colored unit, light olive gray (5Y5/2) to pale yellowish brown, tough, calcareous silty, much speckled, with sparse crinkly structure. Seam of secondary selenite, 0.6 cm thick, lying 1.9 m above base, hosts small limonite nodules. Second selenite seam, 0.6 cm thick, lying 1.76 m above base, with associated limonitic nodules, contains film of bentonite at top. Limonitic seam, 0.3 cm thick, lying 1.61 m above base, associated with jarosite and granular gypsum, hosts oblate spheroidal limonite/marcasite nodules as much as 39.6 cm in diameter and 9.1 cm thick. FOSSILS: *Pseudoperna congesta,* teleost bones	4	0.0
18. Ferruginous/gypsiferous seam, dark yellowish orange		0.6
17. Chalk, all partly weathered, light olive gray (5Y6/1) to pale yellowish brown, not obviously laminated, breaks blocky, calcareous silty, speckled throughout, forms gently sloped, curved face, weathers shaly. FOSSILS: *Inoceramus* fragments, *Pseudoperna congesta,* teleost bones and scales		64.4
16. Bentonite, grayish orange, silty; unit consists mostly of iron oxide and granular selenite; actual bentonite seam approximately 0.5 cm thick		2.9
15. Chalk, all partly weathered, olive gray (5Y5/2), pale yellowish brown and grayish orange, not obviously laminated, fissile, breaks blocky, calcareous silty, speckled throughout, soft and punky where moist, forms gently shouldered slopes on part of steep cliff face. Unit appears well stratified. FOSSILS: *Inoceramus* sp., *Baculites?,* teleost scales and bones	1	83.0
14. Bentonite, white, brittle; lower part of unit consists mostly of dark yellowish orange limonite and gypsum; upper part mostly medium to coarse crystals of selenite		2.5
13. Chalk, partly weathered, medium olive gray (5Y4/2) to light olive gray (5Y5/2), obscurely to well laminated, fissile, calcareous silty, speckled throughout, tough, softer where weathered, forms smoothly shouldered slope, weathers flaky. Unit well laminated in interval 49 cm thick that lies 1.7 m below top, and within uppermost 52 cm. Granular chalk, light olive gray (5Y5/2), much tougher than flaky weathering chalk, faintly stratified, as three conspicuous beds 21.2 cm, 8.2 cm, and 4.5 cm thick and lying 96 cm, 3.1 m, and 6.7 m above base, respectively, forms more resistant, convex shoulders on slope; imparts widely banded appearance to unit. Bed of conspicuously darker chalk, 48.8 cm thick, dark yellowish brown, lies directly beneath uppermost bed of light-colored chalk. FOSSILS: *Inoceramus (Platyceramus) platinus, Pseudoperna congesta,* acrothoracican borings, teleost bones and scales; many inoceramids pyritized extensively	7	22.5
12. Bentonite?, dark yellowish orange; seam consists mostly of selenite and limonite; mineralization thickens unit locally to 7.6 cm. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta* in limonite mass associated with seam		0.6
11. Chalk, medium olive gray (5Y5/1) to olive gray (5Y4/1), in part weathered light olive gray (5Y5/2), obscurely laminated, in part well laminated where exposed in vertical faces, calcareous silty, speckled throughout, forms vertical spally faces, weathers flaky. Granular chalk, very tough, nonlaminated, in bed 36.6 cm thick, lies 73.2 cm below the top. Very faint ferruginous seam lies 76.2 cm above base; second faint ferruginous seam lies 1.1 m below top of unit. Lower 1.5 m contains scattered polycuboidal pyrite nodules, some of which are much limonitized. Some large inoceramids are pyritized, now altered to limonite, and host nodules of rotten marcasite. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones	4	14.6
10. Bentonite, pale grayish orange (10YR8/4), with light brown (5YR5/6) iron oxide stains, brittle, very silty. Iron oxide and finely granular gypsum comprise about half of unit		1.2
9. Chalk, most partly weathered, medium olive gray (5Y4/2), yellowish gray (5Y7/2), and light olive gray (5Y5/2), obscurely to well laminated, mostly fissile, brittle or tough, calcareous silty, speckled throughout. Organic-rich chalk, dark yellowish brown, 27.4 cm thick, lies 30.5 cm above base, forms conspicuous marker on little-weathered surfaces. Ferruginous/gypsiferous seam, 0.1 cm thick, lies 12 cm below top. Unit contains scattered polycuboidal nodules of		

pyrite and widely scattered limonitized marcasite nodules as much as 1.07 m wide and 10.5 cm thick, many of which are localized around inoceramid valves. Inoceramids mostly limonitized. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, Baculites* sp. (smooth molds), teleost scales and bones 3 47.5

8. Bentonite, dark yellowish orange, as a very thin film at top of unit, which consists mostly of powdery and finely granular gypsum, with minor iron oxide. . . 0.6
7. Chalk, partly weathered, medium yellowish brown (10YR5/2) to grayish orange, tough, brittle, not obviously laminated, fissile, weathers flaky. FOSSILS: *Inoceramus* sp. (mold), *Pseudoperna congesta* . . 21.3
6. Bentonite, dark yellowish orange, very silty, as flakes scattered throughout seam consisting mostly of limonite and finely granular gypsum. Unit expands locally to 1.5 cm; locally hosts limonite/jarosite/marcasite nodules 0.6
5. Chalk, partly weathered, medium olive gray (5Y5/1) to light olive gray (5Y6/1), tough, not obviously laminated, fissile, calcareous silty, speckled throughout, weathers flaky. Unit contains widely scattered limonite/marcasite nodules as much as 15.2 cm in diameter, and much platy selenite. FOSSILS: *Inoceramus balticus?, I. (Platyceramus) platinus, Pseudoperna congesta,* large vertebrate tooth 1 9.0
4. Bentonite, dark yellowish orange, silty, as very thin films at top and base of unit. Unit consists mostly of powdery and crystalline gypsum, hosts abundant oblate spheroidal limonite/marcasite nodules 0.9
3. Chalk, partly weathered, medium olive gray (5Y5/1), light olive gray (5Y6/1), and moderate yellowish brown (10YR5/2), tough, brittle, obscurely laminated, fissile, calcareous silty, speckled throughout, weathers flaky, much powdery gypsum throughout. Unit contains scattered marcasite limonite/jarosite nodules. FOSSILS: *Inoceramus balticus?, Inoceramus* sp., *Pseudoperna congesta, Baculites* sp. (smooth mold) 1 92.2
2. Bentonite, light brown (5YR5/6), silty, in seam consisting mostly of powdery to medium crystalline selenite in lower part, and limonite in upper part. Thickness locally to 1.5 cm 0.6
1. Chalk, partly weathered, very pale yellowish brown (10YR7/2), to light olive gray (5Y6/1), laminated, fissile, calcareous silty, speckled throughout. 33.5

Total thickness of measured section 26 46.9

LOCALITY 23—Bluffs along small southern tributary to Smoky Hill River, in SW¼ Sec. 7, T.15S, R.31W, Gove County, Kansas, and SE¼ Sec. 12, T.15S, R.32W, Logan County, Kansas.

SMOKY HILL CHALK MEMBER — Thickness m cm

32. Chalk, much weathered, pale orange (10YR7/2) to very pale orange, soft and punky to relatively brittle, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, harder part lichen-splotched. Unit forms caprock at top of bluff. FOSSILS: *Inoceramus* sp. (mold), *Pseudoperna congesta,* teleost bones and scales 97.5
31. Bentonite, nearly white to very pale orange, slightly silty, waxy, comprises about half of unit thickness, remainder of which is limonite and jarosite. Unit forms prominent reentrant on cliff face. 0.6
30. Chalk, partly weathered, light olive gray (5Y6/1), grading upward to medium yellowish brown (10YR5/2) and finally to grayish orange, all relatively tough and brittle, most is not obviously laminated but unit has generally well-stratified appearance overall, breaks parallel to bedding, calcareous silty, speckled, weathers shaly. Unit contains three beds of granular chalk, 18.3, 15.2, and 33.6 cm thick lying 1.37 m, 2.35 m, and 3.87 m above base, respectively, medium yellowish brown (10YR5/2) to yellowish gray (5Y7/2), tough, nonlaminated, breaks crudely parallel to bedding, calcareous silty, speckled throughout, forms distinctive light-colored bands on slope. Many large inoceramids host limonite/jarosite nodules with rotten marcasite centers, as much as 24.5 cm in diameter, throughout unit. Prominent zone of large inoceramids 6 cm thick lies 1.32 m above base. Faint streaks marked by thin crusts of limonite lie in zone 3.0 cm thick and 33.5 cm below top; zone hosts widely spaced crumbly marcasite nodules. FOSSILS: *Inoceramus (Platyceramus) platinus, Pseudoperna congesta, Baculites* sp. (smooth molds) 4 90.8
29. Bentonite, light brown (5YR5/6), silty, in seam consisting mostly of limonite and finely granular gypsum, which are concentrated at top and base of unit. Unit hosts limonitic masses, as much as 45.7 cm wide and 9.1 cm thick, which have rotten marcasite cores 0.9
28. Chalk, partly weathered, light olive gray (5Y5/2) to yellowish gray (5Y7/2), not obviously laminated but appears bedded, most splits easily along bedding, calcareous silty, speckled. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost scales and bones 12.2
27. Ferruginous seam, mostly limonite and jarosite, with some granular gypsum. Seam expands locally to 2.5 cm. 0.2
26. Chalk, mostly partly weathered, dark yellowish brown to pale yellowish brown or light olive gray (5Y6/1) above, tough, obscurely to nonlaminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers shaly. Bed of organic-rich chalk, olive gray (5Y4/1), 18.3 cm thick, lies 41.2 cm above base, forms conspicuous dark-colored band on slope. Granular chalk, medium yellowish brown (10YR5/2), tough, nonlaminated, speckled throughout; in three beds 49.0, 6.1, and 15.2 cm thick; lying 1.0 m above base, 76.2 cm below top, and at top of unit, respectively. Granular chalk dries to lighter color than remainder of unit and forms conspicuous bands on slope. Large inoceramids in unit commonly host masses of limonite/jarosite, which have rotten marcasite cores. Upper 1.22 m contains scattered nodules of pyrite. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales 2 89.6
25. Bentonite, light brown (5Y5/6), silty, as scattered flakes in seam consisting mostly of limonite and finely granular gypsum. Unit expands in thickness where more heavily mineralized 0.2
24. Chalk, partly weathered, very pale yellowish brown (10YR7/2) to pale yellowish brown, tough, obscurely laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers shaly, contains small limonite nodules with rotten marcasite cores. FOSSILS: *I. ?(Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales 18.3
23. Bentonite, pale yellowish brown, in seam consisting mostly of limonite, jarosite, and selenite. Actual bentonite seam about 0.1 cm thick. Unit thickens to 3.4 cm where most heavily mineralized 1.5
22. Chalk, partly weathered, medium olive gray (5Y4/2) to light olive gray (5Y5/2), relatively tough, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout. Unit contains scattered limonite nodules, with rotten marcasite cores, some of which are localized around valves of large inoceramids. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta* 1 13.6
21. Ferruginous/gypsiferous seam, dark yellowish or-

ange, locally jarositic. Unit hosts limonite/jarosite/gypsum nodules as much as 24.4 cm in diameter and 4.6 cm thick — 1.2

20. Chalk, partly weathered, medium olive gray (5Y4/1) to yellowish gray (5Y7/2), tough, in part obscurely laminated, calcareous silty, speckled throughout, weathers flaky. Lower 30 cm contains abundant invertebrate shells. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* sponge borings, *Stramentum haworthi,* teleost bones and scales — 1 61.8
19. Ferruginous gypsum seam, dark yellowish orange, hosts limonite/jarosite/gypsum masses as much as 38 cm wide and 9.2 cm thick. Unit greatly thickened locally by addition of secondary mineral matter — 0.3
18. Chalk, partly weathered, medium yellowish brown (10YR5/2) to light olive gray (5Y5/2), more weathered rock grayish orange to very pale orange, tough, obscurely laminated to not obviously laminated, calcareous silty, speckled throughout, weathers flaky. Unit contains scattered limonite/jarosite nodules, with rotten marcasite cores, in zone 76.3 to 91.5 cm above base, and commonly localized around large inoceramid valves. Many inoceramid valves limonitized. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales — 1 16.9
17. Bentonite, dark yellowish orange, in seam consisting mostly of limonite and gypsum. Unit hosts limonite/jarosite/gypsum nodules. Bentonite is thin film at top of unit — 1.2
16. Chalk, weathered, grayish orange, soft, calcareous silty, speckled throughout, laminated, splits easily along bedding, weathers flaky. FOSSILS: tail of *Xiphactinus* at base — 3.7
15. Ferruginous gypsum seam, light brown (5YR5/6), comprises two layers of limonitic gypsum that embrace a central layer of limonite. Unit hosts abundant limonite/jarosite/gypsum nodules as much as 24.4 cm in diameter and 6.1 cm thick. Unit forms minor ledge, held up by platy masses of selenite — 1.2
14. Chalk, partly weathered, light olive gray (5Y5/2) to medium yellowish brown (10YR5/2) to yellowish gray (5Y7/2), relatively tough, in part well laminated, in part obscurely laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Unit contains widely scattered limonite nodules, with rotten marcasite cores, as much as 8.3 cm in diameter and 3.1 cm thick. FOSSILS: *I. (Platyceramus) platinus, Inoceramus* sp., *Pseudoperna congesta,* acrothoracican borings, *Baculites* sp. (smooth mold), *Squalicorax* tooth — 2 25.6
13. Bentonite, light brown (5YR5/6), gritty, waxy, underlain by powdery to finely crystalline gypsum; actual bentonite is less than 0.1 cm thick. Unit hosts small nodules of limonite — 0.6
12. Chalk, partly weathered, medium yellowish brown to light olive gray (5Y5/2) to grayish orange, tough, poorly to well laminated, splits easily along bedding, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, Inoceramus* sp. (mold), teleost scales — 1 16.0
11. Bentonite, grayish yellow, gritty, waxy, with strong taste of melanterite, bordered by seams of jarosite- and limonite-stained selenite. Actual bentonite seam 1.2 cm thick. Unit hosts limonite nodules that have rotten marcasite centers. Unit forms projecting ledge where heavily mineralized; otherwise forms prominent band on slope — 2.5
10. Chalk, olive gray (5Y4/1), most partly weathered dark yellowish brown to grayish orange, tough, more or less well laminated, splits easily parallel to bedding, weathers flaky, contains scattered small limonite nodules. Zone of granular gypsum seams, 10 cm thick, lies 45.7 cm below top. Ferruginous/gypsiferous seam, 0.6 cm thick, lies 30.5 cm below top. Unit contains scattered oblate spheroidal nodules of limonite/jarosite/selenite, commonly with rotten marcasite cores which are especially common 1.07 m and 2.13 m above base. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales — 3 65.8
9. Ferruginous/gypsiferous seam, light brown (5YR5/6), locally hosts limonite/jarosite masses as much as 1.8 cm thick — 0.3
8. Chalk, olive gray (5Y4/1), weathers light olive gray (5Y5/2, 5Y6/1), tough, in part well laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* inoceramid fragments, phosphatic coprolite, teleost bones and scales — 96.1
7. Bentonite, yellowish gray (5Y7/2), slightly stained by light brown (5YR5/6) limonite, contains much jarosite, bordered above and below by limonite/gypsum seams that form projecting ledges. Actual bentonite is 2.1 cm thick. Unit hosts limonite nodules, with rotten marcasite centers, which are as much as 24.5 cm in diameter and 6.1 cm thick — 3.7
6. Chalk, partly weathered, light olive gray (5Y5/2, 5Y6/1) to pale grayish orange, soft at surface, harder below, more or less laminated, contains sparse faint burrow structures but splits easily along bedding, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost scales and bones — 1 22.5
5. Ferruginous seam, moderate reddish brown — 0.1
4. Chalk, partly weathered, very pale yellowish brown (10YR7/2) to grayish orange, relatively soft, moderately well laminated, splits easily parallel to bedding, slightly calcareous silty, speckled throughout. FOSSILS: *Pseudoperna congesta,* teleost scales — 14.5
3. Bentonite, very pale orange, in part stained dark yellowish orange by iron oxide; top and base of unit consist of limonite-stained gypsum. Actual bentonite seam is 3.3 cm thick — 6.4
2. Chalk, olive gray (5Y4/1), weathers light gray to medium yellowish brown (10YR5/2), relatively soft, in part laminated, splits easily along bedding, slightly calcareous silty, speckled throughout, weathers flaky. Bed of granular chalk, 3.7 cm thick, relatively hard, pale yellowish brown to very pale orange, speckled throughout, faintly burrow-mottled, lies 61 cm below top of unit. FOSSILS: limonitized inoceramid valves, *Pseudoperna congesta,* teleost bones and scales — 2 62.1
1. Ferruginous seam, dark yellowish orange, jarositic — 0.3

Total thickness of measured section — 25 28.2

LOCALITY 22—Gully in area of small badlands in SW¼ Sec. 18, T.15S, R.31W, Gove County, Kansas.

Thickness (m, cm)

SMOKY HILL CHALK MEMBER

16. Bentonite, light olive gray (5Y6/1), silty, with jarosite and much soft limonite in upper part of unit. — 2.1
15. Chalk, weathered, very pale orange to dark yellowish orange, mostly soft, apparently laminated, splits easily along bedding, slightly calcareous silty, speckled throughout. Where most weathered unit forms brittle, lichen-splotched, resistant caprock; where least weathered forms shaly weathering slope. FOSSILS: *Inoceramus (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales — 2 31.7
14. Ferruginous gypsum seam, dark yellowish orange, probably a weathered bentonite seam — 0.6
13. Chalk, weathered, yellowish orange (10YR7/6) soft,

apparently laminated throughout, splits easily along bedding, slightly calcareous silty, speckled throughout, weathers flaky. FOSSILS: teleost bones and scales 15.8

12. Bentonite, very pale orange, lower part waxy and brittle, upper part consists of jarosite, coarsely crystalline selenite and chips of bentonite, actual bentonite seam 3.4 cm thick. Unit heavily mineralized, expands locally to 6.7 cm in thickness, forms resistant ledge on slopes and prominent reentrant on vertical faces 4.9
11. Chalk, weathered, yellowish orange (10YR7/6) with very light gray streaks, soft to very soft, apparently more or less laminated throughout, calcareous silty, speckled throughout, weathers shaly, forms small pinnacles or gently rounded low slopes. Unit contains sparse limonite nodules that have rotten marcasite cores, in zone 1.28 m below top. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales 2 74.4
10. Ferruginous seam, very dark yellowish orange (10YR5/6), hard, platy, with very thin seam of coarsely crystalline selenite along center. Unit forms prominent bench, thickens locally to 4.6 cm. 3.1
9. Chalk, partly weathered, light olive gray (5Y5/2) to yellowish gray (5Y7/2), tough, well laminated near top, not obviously laminated through much of interval, slightly calcareous silty, speckled throughout, weathers flaky, forms smoothly rounded slopes. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost scales 1 46.5
8. Chalk, medium olive gray (5Y5/1) to light olive gray (5Y5/2), very tough, mostly with somewhat granular appearance, not obviously laminated, splits rather unevenly along widely spaced planes, slightly calcareous silty, speckled throughout, possibly bioturbated in part. Steep faces spally, slopes weather flaky. Unit contains sparse limonite nodules with rotten marcasite cores in lower 1.52 m, common limonitized marcasite nodules in upper 1.68 m, and local polycuboidal pyrite nodules in upper 1.52 m. Uppermost 42.7 cm is conspicuous medium yellowish brown (10YR5/2) to pale yellowish brown, organic-rich bed, which is gradational with underlying chalk, slightly calcareous silty, not obviously laminated, much speckled, softer than underlying chalk, and weathers shaly. Unit contains shell-rich zone 67.0 cm thick, 1.71 m above base. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, Baculites* sp. (smooth molds), teleost bones, coprolite 5 97.5
7. Bentonite, grayish yellow (5Y8/4), much limonite-stained locally, with seams of ferruginous gypsum at top and base. Actual bentonite seam 2.8 cm thick. Unit forms prominent bench. FOSSILS: *Pseudoperna congesta* 6.1
6. Chalk, partly weathered, very pale yellowish brown (10YR7/2), silty, speckled with black grains (organic matter?). FOSSILS: *Pseudoperna congesta* 12.2
5. Bentonite, light brown (5YR5/6). Unit consists mostly of coarsely crystalline selenite 0.6
4. Chalk, partly weathered, light olive gray (5Y5/2), bioturbated, slightly calcareous silty, much speckled throughout. FOSSILS: *I. (Platyceramus) platinus,* burrow structures, teleost bones 13.1
3. Bentonite, light brown (5YR5/6), silty. Unit consists mostly of coarsely crystalline selenite, with powdery gypsum at base. 0.9
2. Chalk, olive gray (5Y4/1), tough, bioturbated, slightly calcareous silty, speckled throughout, weathers shaly. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones 42.7
1. Bentonite, light brown (5YR5/6), silty. Unit composed mostly of limonite and gypsum. 0.3

Total thickness of measured section 13 52.5

LOCALITY 18—Bluff and adjacent erosional pinnacle directly south of Castle Rock, in SW¼ Sec. 1, T.14S, R.26W, Gove County, Kansas.

SMOKY HILL CHALK MEMBER	Thickness m	cm
38. Chalk, highly weathered, pale yellowish orange, soft, weathers shaly, gradational with overlying soil		21.4
37. Bentonite, very dark yellowish orange (10YR5/6), somewhat silty, waxy		0.3
36. Chalk, highly weathered, very pale orange to dark yellowish orange, fissile, apparently laminated, calcareous silty, much speckled throughout, weathers shaly		39.6
35. Chalk, much weathered, grayish orange, apparently laminated, with poor to fair fissility, erodes to form smoothly curved cavernous surfaces, forms slopes, lichen-splotched. Rock contains numerous small solution vugs. Prominent gray line, parallel to bedding, 45.8 cm above base of unit. Limonite nodules occur in zone 9 cm thick, centered 45.8 cm above base. FOSSILS: *Pseudoperna congesta,* teleost scales and bones		91.4
34. Bentonite, yellowish gray (5Y7/2), as thin film underlain by dark yellowish orange limonite		0.2
33. Chalk, much weathered, pale yellowish orange, with traces of lamination, and fair fissility, calcareous silty, speckled throughout. Forms rounded, lichen-splotched ledge. Paper-thin ferruginous seam lies 6.7 cm above base. FOSSILS: *Inoceramus (Platyceramus) platinus, Pseudoperna congesta,* teleost scales and bones		35.0
32. Bentonite, dark yellowish orange, silty, marked by small limonite nodules		0.3
31. Chalk, weathered, very pale yellowish brown (10YR7/2) to pale orange pink (5YR8/2), tough, resistant, cliff-forming, with traces of stratification, breaks with fair degree of fissility, lichen-splotched, calcareous silty, speckled, with sparse solution vugs. Very thin seam of limonite, less than 0.1 cm thick, lies 6.2 cm above base. Unit contains smooth, vertical joints, forms caprock. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales	1	2.3
30. Bentonite, moderate yellowish brown, hard, brittle, very silty, waxy. Upper 0.6 cm of unit consists of limonitic bentonite. Unit hosts small limonite nodules, forms part of reentrant at base of unit 31		2.1
29. Chalk, weathered, lower 1.56 m medium yellowish brown (10YR5/2) with local pale grayish orange (10YR8/4) horizontal banding, tough; upper 39.2 cm medium grayish orange (10YR6/4) and pale grayish orange (10YR8/4), lichen-splotched. Lower part apparently well laminated, with good fissility, weathers flaky. Upper part lacks obvious laminations, with good fissility, soft and punky, with unit 31 forms part of small vertical cliff. All rock calcareous silty, much speckled. Bed of limonite nodules, as much as 20 cm in diameter and 2.5 cm thick, lies 73 cm above base, marks very thin ferruginous seam. Second bed of limonite nodules, small, lies 52 cm below top of unit. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost scales and bones	1	95.2
28. Chalk, partly weathered, light olive gray (5Y5/2), pale yellowish brown and very pale yellowish brown (10YR7/2), forms steep, cavernous slope. Unit not laminated in lowest 2.13 m, moderately well laminated in upper 34.2 cm. All rock is calcareous silty, speckled, has fair degree of fissility, weathers flaky. Middle part of unit weathers to lighter colors locally, and forms irregular, projecting ledges of hard, brittle yellow-colored chalk. Uppermost 27.5 m is distinctly		

darker colored than rest of unit, dark yellowish brown, probably organic rich, weathers distinctly shalier than rest of unit. Beds of small limonite nodules lie 48.8 cm and 80.5 cm below top, respectively. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones and scales 3 47.6

27. Bentonite, yellowish gray, slightly silty, flaky, enclosed within lensing layers of limonite that include some jarosite and coarsely crystalline selenite. Where thickest, seam is bordered by crusts of crystalline selenite. Mineralized parts of unit form ledges on eroded slope. Where most mineralized the unit thickens to 6.1 cm. 4.6
26. Chalk, weathered, grayish orange to pale grayish orange (10YR8/4), soft, breaks blocky, burrow-mottled, not conspicuously speckled. FOSSILS: *Pseudoperna congesta,* teleost bones and scales 9.2
25. Bentonite, dark yellowish orange, as very thin film at top of unit consisting mostly of crystalline selenite. 0.9
24. Chalk, weathered, pale grayish orange to very pale yellowish brown, breaks blocky, burrow-mottled, not conspicuously speckled. FOSSILS: *Pseudoperna congesta* 10.7
23. Bentonite, dark yellowish orange, slightly silty, brittle, in unit consisting predominantly of granular calcite. 0.9
22. Chalk, weathered, pale yellowish brown to grayish orange, tough, faintly bioturbated, calcareous silty, speckled throughout, forms pronounced, rounded shoulder on slope, weathers flaky, uppermost part weathers slabby. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta* 29.0
21. Bentonite, light brown (5YR5/6), silty, brittle, as minor component in seam consisting mainly of limonite and gypsum. Unit hosts sparse limonite nodules. 0.6
20. Chalk, partly weathered, medium olive gray (5Y5/1) to dark yellowish brown, surface dries to conspicuous light gray or very light gray. Rock very tough, somewhat granular, poorly stratified, more or less bioturbated, calcareous silty, speckled throughout. Unit forms smoothly convex, spally, buttressed slope where least weathered, lichen-coated caprock where highly weathered. Where most weathered, unit has fair fissility. Conspicuous shelly zone, 1.7 m thick, with abundant *I. (Platyceramus),* lies 3.8 m above base of unit. Inoceramids and oysters common throughout unit. Dark line, 4 m above base of unit, marks position of small oblate spheroidal pyrite nodules. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, ?Baculites* sp. (smooth mold frags?), *Stramentum haworthi, Zeugmatolepas* sp., coprolite, teleost scales . 6 69.2
19. Chalk and bentonite. Chalk medium olive gray (5Y5/1), very tough, not obviously laminated, bioturbated, shows some stratification, splits crudely parallel to bedding, calcareous silty, speckled throughout. Unit contains five subequally spaced bentonite seams occurring at base, 22.2 cm above base, 39.6 cm above base, 59.4 cm above base, and at top. Basal seam 0.6 cm thick, dark yellowish orange, consists solely of limonite and white, powdery gypsum; probably a weathered bentonite. Second seam is 0.6 cm thick, dark yellowish orange, brittle, silty, waxy, with associated powdery gypsum. Third seam is 0.3 cm thick, consists mostly of limonite and granular calcite. Fourth seam 1.5 cm thick, dark yellowish orange, brittle, silty, consists mostly of limonite and gypsum, hosts limonite nodules. Uppermost seam is 0.6 cm thick, medium olive gray (5Y5/1) to dark yellowish orange, brittle, silty, as very thin film in seam consisting mostly of limonite and some powdery gypsum. Uppermost seam hosts limonite nodules, thicker where most extensively mineralized. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, Inoceramus balticus?, Clioscaphites choteauensis, Baculites* sp. (smooth molds) 82.3
18. Chalk, medium olive gray (5Y5/1), very tough, not laminated, poorly fissile, weathers shaly, calcareous silty, speckled throughout, upper part bioturbated. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta* 35.1
17. Ferruginous/gypsiferous seam, light brown (5YR5/6). 0.2
16. Chalk, olive gray (5Y4/1), dark yellowish brown to medium olive gray (5Y5/1) where partly weathered, very tough, lower 30 cm with poor fissility, upper part with fair fissility, no obvious laminations, calcareous silty, speckled throughout, weathers shaly, upper 9.2 cm bioturbated. Lower part of unit with abundant fossils, litters slope with shelly debris. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, Clioscaphites choteauensis, Inoceramus balticus, Baculites* sp. (smooth molds) 76.2
15. Bentonite, yellowish gray (5Y7/2), soft, waxy, slightly silty, 0.2 cm thick, in unit consisting mostly of limonite and gypsum, which overlie the bentonite seam 1.8
14. Chalk, olive gray (5Y4/1), tough, not laminated, poorly fissile, in part bioturbated, calcareous silty, speckled throughout. Lighter-colored bed, 9.2 cm thick, bioturbated, lies 33.5 cm above base of unit, forms conspicuous band on eroded slope. Unit abundantly fossiliferous, slope littered with shelly debris. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta* 77.7
13. Bentonite, moderate yellowish brown (10YR5/2), silty, waxy, soft. Unit hosts sparse limonitized marcasite nodules as much as 70 cm in diameter and 9 cm thick 0.7
12. Chalk, light olive gray (5Y6/1) to olive gray (5Y4/1), tough, not obviously laminated, fissile, calcareous silty, speckled throughout, in part stained by iron oxide, weathers shaly. Bed of limonite nodules lies 54.8 cm below top. Upper 30 cm richly fossiliferous, litters slope with shelly debris. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta* 1 17.5
11. Bentonite, very dark yellowish orange. Unit consists mostly of white, powdery gypsum, which encloses a central seam composed mainly of limonite. 1.2
10. Chalk, light olive gray (5Y6/1) to medium olive gray (5Y5/1), tough, not obviously laminated, fissile, calcareous silty, much speckled throughout, weathers shaly. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost vertebrae 36.6
9. Bentonite, light brown (5YR5/6). Unit dominated by granular gypsum in fresh exposure, limonite in weathered exposure, thickens locally to 1.2 cm, locally hosts large limonite nodules 0.3
8. Chalk, olive gray (5Y4/1) to medium olive gray (5Y5/1), very tough, obscurely laminated, poorly fissile, calcareous silty, much speckled throughout, weathers shaly. Prominent dark bed, 6 cm thick, probably organic rich, lies 1.7 m above base of unit. Some large inoceramids are partially surrounded by limonitized marcasite nodules. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* coprolite 1 77.0
7. Bentonite, dark yellowish orange, silty, brittle. Actual bentonite is 0.3 cm thick, lies in center of seam dominated by limonite and gypsum 0.9
6. Chalk, olive gray (5Y4/1), tough, not obviously laminated, moderately fissile, calcareous silty, much speckled throughout, weathers shaly. Some large inoceramids are partially surrounded by limonitized marcasite nodules. FOSSILS: *I. (Platyceramus) plati-*

	m	cm
nus, Pseudoperna congesta, coprolite, teleost scales. . .	1	86.1
5. Bentonite, pale grayish orange pink (5YR8/2), brittle, 0.6 cm thick, between seams of ferruginous gypsum		1.2
4. Chalk, olive gray (5Y4/1) to light olive gray (5Y6/1), tough, poorly laminated, fissile, calcareous silty, much speckled throughout, weathers shaly. Seam of iron oxide, 0.2 cm thick, lies 56.4 cm below top of unit. Some inoceramid valves limonitized. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* coprolite, teleost bones	2	1.2
3. Bentonite, grayish orange, underlain by crystalline selenite. Large inoceramid valve partially surrounded by limonitized marcasite nodule. FOSSILS: *I. (Platyceramus) platinus*		0.3
2. Chalk, dark olive gray (5Y3/1) to medium olive gray (5Y5/1), tough, obscurely laminated, fissile, calcareous silty, much speckled throughout, weathers shaly. Some inoceramid valves partially surrounded by large, limonitized marcasite nodules. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* coprolite, teleost bones	1	28.2
1. Bentonite, very light olive gray (5Y7/1), mostly stained dark yellowish orange, very silty, as seam approximately 0.1 cm thick, in unit consisting mostly of limonite and granular gypsum		1.2
Total thickness of measured section	26	86.2

LOCALITY 19—Small badlands along southern tributary to Smoky Hill River, in NE¼ Sec. 2, T.14S, R.26W, Gove County, Kansas.

SMOKY HILL CHALK MEMBER	Thickness m	cm
28. Bentonite, pale grayish orange pink (5YR8/2) or pinkish gray, bordered above and below by seams of limonite and gypsum, dark yellowish orange to moderate reddish brown		1.2
27. Chalk, weathered, grayish orange, dark yellowish orange or very light gray, mostly soft, not obviously laminated to faintly laminated, good fissility, calcareous silty, speckled throughout. Paper-thin ferruginous seam lies 61.0 cm below top of unit. Bed 12.2 cm thick, tough, apparently burrow-mottled, lies 39.6 cm above base. Large inoceramids commonly surrounded in part by limonitized marcasite nodules. FOSSILS: *Inoceramus (Platyceramus) platinus, Pseudoperna congesta, Clioscaphites vermiformis,* acrothoracican borings, teleost bones and scales	1	95.2
26. Bentonite, dark yellowish orange to medium gray, very silty, somewhat brittle		0.3
25. Chalk, medium olive gray (5Y5/1), mostly weathered light olive gray (5Y6/1) to pale grayish orange (10YR8/4) and dark yellowish orange, tough, weathers soft, not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Limonite nodules with rotten marcasite cores scattered throughout, concentrated in two zones 76.2 cm and 94.5 cm above base. Thin bed of brownish-colored chalk centers 10.7 cm below top of unit. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta, Clioscaphites vermiformis,* acrothoracican borings, *Baculites* sp. (smooth molds), teleost bones and scales, lignitized log	1	30.0
24. Bentonite, light olive gray (5Y6/1), very silty, soft, with associated limonite and medium crystalline selenite. Unit thickens locally to 1.5 cm where heavily mineralized		0.9
23. Chalk, olive gray (5Y4/1) at base grading up to partly weathered chalk, dark yellowish brown to very pale yellowish brown (10YR7/2), not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Unit bioturbated in bed 12.2 cm thick that lies 67.2 cm above base. Tough chalk, non-fissile, occurs in two beds, 6.1 cm and 12.2 cm thick, which lie 51.8 cm and 73.1 cm above base, respectively. Two very thin seams of iron oxide lie 30.5 cm and 49.8 cm below top. Large limonite nodules with rotten marcasite cores are scattered throughout unit, partially surround some large inoceramid valves. FOSSILS: *I. (Platyceramus) platinus, Stramentum haworthi, Zeugmatolepas* sp., *Pseudoperna congesta,* acrothoracican borings, teleost bones and scales	1	49.6
22. Bentonite?, grayish orange, in unit consisting mostly of powdery gypsum and minor amounts of light brown (10YR5/6) limonite. Unit hosts a few limonite nodules, as much as 61.0 cm in diameter and 6.1 cm thick, that have rotten marcasite cores. FOSSILS: *Pseudoperna congesta*		0.3
21. Chalk, olive gray (5Y4/1), partly weathered to medium olive gray (5Y5/1) in upper 30 cm, tough, obscurely laminated, moderately fissile, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta*	2	7.3
20. Bentonite, dark yellowish orange, in seam consisting mostly of powdery gypsum with some limonite. Unit thickens to 3.1 cm where heavily mineralized. Unit hosts limonite nodules with rotten marcasite cores, and hard, smooth oblate spheroidal pyrite nodules		0.3
19. Chalk, olive gray (5Y4/1) in lower part, grading upward to medium gray (5Y5/1) in uppermost part, tough where fresh, mostly obscurely laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, less calcareous and less speckled in lowest 1.52 m, weathers flaky. Bioturbated chalk, in bed 7.7 cm thick, lies 64.0 cm above base, forms weak bench covered with brittle chips of lighter-colored chalk. Lower 2.86 m characterized by small spheroidal pyrite nodules. Similar nodules scattered sparingly through remainder of unit. Limonitized marcasite nodules, partially enclosing valves of large inoceramids, scattered throughout unit. Some inoceramids partially to entirely limonitized. More prominent zones of nodules lie 91.3 cm, 1.74 m, 3.63 m, and 5.21 m above base unit. Limonite nodules are oblate spheroids, reach maximum dimensions of 67.0 cm in diameter and 9.2 cm thick. Paper-thin ferruginous seam lies 1.15 m above base. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* acrothoracican borings, teleost scales and bones	7	50.0
18. Bentonite, dark yellowish orange, in unit consisting mostly of limonite and gypsum. Unit hosts abundant marcasite nodules, most of which have been altered to limonite		0.6
17. Chalk, olive gray (5Y4/1), tough where fresh, brittle where dry, laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Paper-thin ferruginous seam lies 1.38 m below top. Unit contains widely spaced limonite nodules. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* teleost scales	2	86.5
16. Bentonite, greenish gray, moderately silty, with numerous veinlets of jarosite		1.5
15. Chalk, medium olive gray (5Y5/1) to olive gray (5Y4/1), tough, brittle where dry, well laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, spally on steep faces, weathers flaky. Paper-thin ferruginous seam, 22.9 cm above base, hosts small, flat limonite nodules. Unit bioturbated locally. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta*	1	25.5
14. Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2), soft		0.3
13. Chalk, medium olive gray (5Y5/1), relatively soft,		

Unit	m	cm
moderately well laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky, basal part waxy (bentonitic?)		12.5
12. Bentonite, moderate yellowish brown (10YR5/2) to dark yellowish orange, extremely silty, in seam consisting mostly of gypsum and limonite. Actual bentonite approximately 0.2 cm thick		0.6
11. Chalk, olive gray (5Y4/1), partly weathered to medium olive gray (5Y5/1), very tough where fresh, more brittle where partly weathered, obscurely laminated to not obviously laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Bioturbated chalk interval, 21 cm thick, forms light-colored weak bench on slopes, weathers to brittle chips, lies 42.8 cm above base of unit. Nodules of soft limonite partially enclose some large inoceramid valves in upper 30 cm of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Cladoceramus) undulatoplicatus, Pseudoperna congesta,* teleost bones	1	20.5
10. Bentonite, moderate yellowish orange (10YR7/6), moderately silty, soft, waxy, with granular gypsum at base		0.9
9. Chalk, olive gray (5Y4/1), tough, obscurely laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Basal few cm bioturbated. FOSSILS: *I. (Cladoceramus) undulatoplicatus, Pseudoperna congesta,* teleost bones and scales		83.9
8. Ferruginous seam, dark yellowish orange and light brown (10YR5/6), consisting mostly of powdery limonite		0.1
7. Chalk, olive gray (5Y4/1) to medium olive gray (5Y5/1), tough, very brittle where dry, laminated to poorly laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, spally in steep faces, weathers flaky. Upper 21 cm with very thin bioturbated zones. Small polycuboidal pyrite nodules, subspherical, some partly limonitized, scattered through unit. FOSSILS: *Pseudoperna congesta,* teleost bones and scales	1	34.2
6. Bentonite, light olive gray (5Y6/1), very silty, with much coarsely crystalline selenite. Unit stained dark yellowish orange by iron oxide. Seam hosts abundant limonite nodules		0.6
5. Chalk, medium olive gray (5Y5/1) to olive gray (5Y4/1), mostly laminated, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Bioturbated chalk, as very thin zone, lies 42.7 cm below top of unit, weathers to small brittle chips. Small, smooth to polycuboidal nodules of pyrite scattered throughout unit. FOSSILS: *I. (Platyceramus) platinus,* coprolite, teleost scales	1	49.5
4. Bentonite, light olive gray (5Y6/1), very silty, in seam consisting mostly of dark yellowish orange, limonitic, coarsely crystalline selenite. Unit hosts scattered limonite nodules		0.6
3. Chalk, olive gray (5Y4/1), tough to brittle, obscurely to very well laminated, calcareous silty, speckled throughout, weathers soft and flaky. Bioturbated intervals very thin, lighter gray than rest of unit. weather to brittle chips, lie 39.6 cm and 1.1 m above base of unit. Polycuboidal nodules of pyrite occur in zones lying 61.0 cm and 1.25 m below top of unit. Some invertebrate shells partially limonitized. Unit contains scattered, oblate spheroidal limonite nodules. FOSSILS: *I. (Platyceramus) platinus, Pseudoperna congesta,* lignitized log, teleost bones	2	28.6
2. Bentonite, grayish orange to very pale orange, very silty, brittle, bordered above and below by soft seams of limonite/jarosite. Actual bentonite seam 0.6 to 0.9 cm thick		2.5
1. Chalk, olive gray (5Y4/1) in lower 1.83 m, medium olive gray in upper part, very pale orange where weathered, tough, very well laminated throughout, splits easily parallel to bedding, calcareous silty, speckled throughout, weathers soft and flaky. Upper third of unit contains polycuboidal pyrite nodules and spherical limonite nodules with rotten marcasite cores. Paper-thin ferruginous seam lies 70 cm above base of unit. FOSSILS: *I. (Cladoceramus) undulatoplicatus, Pseudoperna congesta*	3	30.8
Total thickness of measured section	29	14.8

LOCALITY 13—Extensively eroded bluff and badlands on west side of small southern tributary to Smoky Hill River, in SE¼ Sec. 29, T.15S, R.26W, Gove County, Kansas.

SMOKY HILL CHALK MEMBER	Thickness m	cm
27. Chalk, partly weathered, light olive gray (5Y6/1) to grayish orange and pale grayish orange (10YR8/4), soft, poorly laminated, splits easily along bedding, calcareous silty, speckled throughout, with oblate spheroidal, oxidized pyrite nodules, as much as 12 cm in diameter and 4.5 cm thick, in zone 39.6 cm above base. FOSSILS: *Pseudoperna congesta, Baculites* sp. (smooth molds), teleost bones and scales	1	78.5
26. Bentonite, olive gray (5Y4/1), brittle, waxy, silty		1.2
25. Chalk, lower 48.8 cm olive gray (5Y4/1), grading upward to weathered rock, grayish orange tinged with light olive gray (5Y6/1). Lower part of unit relatively soft, weathered part relatively harder; all rock poorly laminated, splits easily along bedding, calcareous silty, speckled throughout. Lower, darker chalk contains bed of lighter-colored chalk, 4.5 cm thick, weathers into brittle chips, forms minor ledge, 39.6 cm above base. Zone of small, oblate spheroidal pyrite nodules lies 91.5 cm above base. FOSSILS: *Inoceramus (Platyceramus) platinus, I. ?(Cladoceramus) undulatoplicatus, Pseudoperna congesta,* teleost scales	1	37.3
24. Ferruginous seam, light brown (5YR5/6)		0.1
23. Chalk, medium olive gray (5Y5/1), soft, poorly laminated, calcareous silty, speckled throughout, weathers flaky		13.7
22. Bentonite, light brown (5YR5/6), silty, with much associated iron oxide		0.3
21. Chalk, weathered, grayish orange to moderate yellowish brown (10YR5/2), soft, poorly laminated, calcareous silty, speckled throughout. Bed of tough chalk, 51.8 cm thick, pale yellowish brown, 9.1 cm above base of unit, forms prominent bench, weathers into brittle chips. FOSSILS: *I. (Cladoceramus) undulatoplicatus, Pteria* sp. B, *Lucina* sp. A, *Baculites* sp. (smooth molds), *I. (Platyceramus) platinus, Pseudoperna congesta, Clioscaphites* sp. (mold fragment), teleost scales	1	8.3
20. Bentonite, medium gray, mostly weathered light brown (5YR5/6), with much associated limonite		0.6
19. Chalk, weathered, dark grayish orange (10YR6/4), with iron oxide stains, relatively hard, poorly laminated, splits easily along bedding, calcareous silty, much speckled throughout, weathers flaky. FOSSILS: juvenile *I. (Platyceramus) platinus*	1	17.5
18. Chalk, partly weathered, light gray to grayish orange, tough, nonlaminated, bioturbated, calcareous silty, speckled throughout, forms prominent bench, weathers into brittle chips. Layer of small spheroidal pyrite nodules lies at center of unit. Lower half with scattered nodules of limonite/jarosite/marcasite. FOSSILS: *I. (Cladoceramus) undulatoplicatus, Baculites* sp. (smooth molds)		36.6
17. Chalk, olive gray (5Y4/1) to medium yellowish brown (10YR5/2), relatively soft, nonlaminated, calcareous silty, faintly speckled, weathers flaky. Ferruginous seam, 0.2 cm thick, lies 1.46 m above base.		

		m	cm
	FOSSILS: *Inoceramus* fragments, *Pseudoperna congesta, Baculites* sp. (smooth mold)	2	68.3
16.	Bentonite, medium light gray, stained dark yellowish orange by iron oxide, with associated selenite crystals		0.6
15.	Chalk, olive gray (5Y4/1) in lower part, grading upward to partly weathered rock, dark yellowish brown and light olive gray (5Y5/2), soft, not obviously laminated, splits parallel to bedding, calcareous silty, speckled throughout, weathers flaky, with small nodules of oxidized pyrite scattered on slope and sparse oblate spheroidal limonite nodules with marcasite cores in zone at middle of unit. FOSSILS: *I. (Platyceramus) platinus, Inoceramus stantoni?, Pseudoperna congesta,* ammonite mold fragment, *Baculites* sp. (smooth molds), teleost remains	3	4.5
14.	Bentonite, pale yellowish brown, stained dark yellowish orange by iron oxide, underlain locally by gypsum. Unit hosts scattered oblate spheroidal limonite nodules with marcasite cores, as much as 18.3 cm in diameter and 6.1 cm thick		1.2
13.	Chalk, partly weathered, light olive gray (5Y5/2) to moderate yellowish brown (10YR5/2), in part very well laminated, splits parallel to bedding, calcareous silty, speckled throughout, weathers flaky. Zone 45.8 cm thick, lying 45.8 cm below top of unit, is olive gray (5Y3/2). Uppermost 45.8 cm is weathered, grayish orange. Zone 12 cm thick, lying 1.28 m below top of unit, is olive gray (5Y4/1), more clayey and less well speckled than remainder of unit. Ferruginous seam, 0.2 cm thick, lies 36.6 cm above base. Spheroidal pyrite nodules, as much as 3 cm in diameter, are scattered through unit and are especially common in zone 61 cm thick and lying 61 cm below top of unit. Oblate spheroidal limonite nodules partially enclose large inoceramid valves near base of unit. FOSSILS: *I. (Cladoceramus) undulatoplicatus, Pseudoperna congesta, Baculites* sp. (smooth mold), *I. (Volviceramus) grandis* (highest level for species), *Durania maxima*	2	95.7
12.	Ferruginous seam, moderate yellowish brown (10YR5/2)		0.2
11.	Chalk, medium olive gray (5Y4/2), relatively soft, moderately well laminated, splits along bedding, calcareous silty, speckled throughout, weathers flaky. Harder chalk, weathers light gray, bioturbated, weathers into small brittle chips, in two very thin zones lying 53.4 cm and 76.1 cm above base. Small pyrite nodules, polycuboidal type, widely scattered in unit. FOSSILS: *I. (Volviceramus) grandis, I. (Platyceramus) cycloides, I. (Platyceramus) platinus, Pseudoperna congesta,* teleost bones, flattened carbonized log	2	68.3
10.	Ferruginous/gypsiferous seam, moderate yellowish brown, hosts nodules of limonite/jarosite/marcasite, as much as 30.5 cm in diameter and 10.7 cm thick, partially enclose large inoceramid valves. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta*		0.3
9.	Chalk, medium olive gray (5Y5/1), relatively soft, poorly laminated, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* teleost bones	2	22.5
8.	Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2)		0.2
7.	Chalk, partly weathered, moderate yellowish brown (10YR5/2), relatively soft, laminated, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta*		22.9
6.	Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2), hosts large limonite/jarosite/marcasite nodules		0.3
5.	Chalk, olive gray (5Y4/1), relatively tough, upper portion partly weathered, light olive gray (5Y5/2), softer. Unit well laminated, splits easily along bedding, spalls in large blocks on steep faces, weathers flaky, calcareous silty, speckled throughout. Ferruginous/gypsiferous seam, 0.3 cm thick, dark yellowish orange, lies 1.51 m below top. Unit contains scattered hemispherical to spheroidal pyrite nodules. Some inoceramid valves pyritized or limonitized. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta, Durania maxima,* teleost bones	4	42.1
4.	Bentonite, medium gray, mostly weathered dark yellowish orange		0.6
3.	Chalk, dark olive gray (5Y3/1), very tough, very well laminated, splits easily along bedding, calcareous silty, much speckled throughout, spally on steep faces, weathers flaky. Bioturbated chalk, in zone 13.7 cm thick, lies 41.2 cm above base. Ferruginous seams, dark yellowish orange, 0.3 cm or less in thickness, lie 53.4 cm and 1.51 m below top of unit. Some inoceramid valves are limonitized. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta*	2	95.7
2.	Bentonite, light brown (5YR5/6) to moderate yellowish brown (10YR5/2), associated with small selenite crystals and local, very small nodules of limonite/gypsum		0.6
1.	Chalk, dark olive gray (5Y3/1), relatively soft, mostly very well laminated, splits easily along bedding, calcareous silty, much speckled throughout, spally on steep faces, weathers flaky. Uppermost 30.5 cm pale yellowish brown, bioturbated, tough, speckled, forms small bench, weathers into brittle chips. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta*	1	83.3
	Total thickness of measured section	29	1.4

LOCALITY 12—Extensively eroded bluff on west side of small southern tributary to Smoky Hill River, in SW¼ Sec. 16, T.15S, R.26W, Gove County, Kansas.

SMOKY HILL CHALK MEMBER		Thickness m	cm
24.	Ferruginous seam, moderate yellowish brown		0.2
23.	Chalk, partly weathered at base, light olive gray (5Y5/2, 5Y6/1), grading upward to weathered chalk, grayish orange, relatively soft, laminated, fissile, calcareous silty, speckled throughout, weathers shaly. Paper-thin ferruginous seam lies 36.6 cm below top of unit. FOSSILS: *Inoceramus (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta, Squalicorax falcatus*	2	83.5
22.	Bentonite, dark yellowish orange, associated with granular gypsum, hosts limonite/jarosite nodules		1.2
21.	Chalk, partly weathered, light olive gray (5Y5/2, 5Y6/1), relatively soft, laminated, splits easily along bedding, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta*		51.8
20.	Ferruginous seam, limonitic and jarositic		0.2
19.	Chalk, partly weathered, light olive gray (5Y5/2, 5Y6/1), relatively soft, laminated, splits easily along bedding, calcareous silty, speckled throughout, weathers flaky. Layer of small polycuboidal pyrite nodules lies 99.0 cm above base. Limonite/marcasite nodules, some partially enclosing inoceramid valves, common in zone near middle of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta, Durania maxima* (float)	1	57.2
18.	Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2)		0.3
17.	Chalk, partly weathered, light olive gray (5Y5/2), tough, more or less well laminated, splits easily along		

bedding, calcareous silty, speckled throughout, weathers flaky. Basal 6.1 to 7.7 cm yellowish gray (5Y7/2), thinly laminated, with unit 15 forms conspicuous light-colored band on eroded slope. Zone of bioturbated chalk, light gray, 12.2 cm thick, calcareous silty, almost nonspeckled, lies 30.5 cm above base. Limonite nodules common in lower 46 cm of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta, Stramentum haworthi,* teleost bones 1 25.5

16. Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2) 0.3
15. Chalk, light gray, tough, laminated, with discrete burrow structures, calcareous silty, faintly speckled, with unit 17 forms conspicuous light-colored band on eroded slope. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta* 27.5
14. Chalk, partly weathered, moderate yellowish brown (10YR5/2) to dark yellowish brown, partly light olive gray (5Y6/1) in lower portion of unit, relatively hard, in part well laminated, calcareous silty, more or less highly speckled throughout, weathers flaky. Ferruginous/gypsiferous seam, moderate yellowish brown, 0.3 cm thick, with associated spheroidal limonitic pyrite nodules as much as 12.2 cm in diameter, lies 41.2 cm above base of unit. Zone of hard chalk, probably bioturbated, dark yellowish brown, 9.1 cm thick, lies 1.27 m above base of unit. Layer of limonitic marcasite concretions lies 77.5 cm below top of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Durania maxima* (float), *Pseudoperna congesta, Zeugmatolepas* sp. 2 34.7
13. Chalk, light gray, relatively hard, bioturbated, forms conspicuous white band on slope 12.2
12. Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2) 0.3
11. Chalk, partly weathered, moderate yellowish brown (10YR5/2) to dark yellowish brown, relatively soft, not obviously laminated, less speckled than subjacent chalk, forms distinctive brown band on eroded slope. Sparse oblate spheroidal limonite concretions occur in upper part of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta* 1 19.4
10. Ferruginous/gypsiferous seam, light brown (5YR5/6). Hosts oblate spheroidal limonite/jarosite nodules as much as 20 cm in diameter and 9.2 cm thick 0.3
9. Chalk, partly weathered, medium olive gray (5Y5/1) to light olive gray (5Y5/2, 5Y6/1), soft, more or less laminated, splits easily along bedding, calcareous silty, speckled throughout, weathers flaky. Layer of limonite nodules lies 79.3 cm above base of unit. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta,* teleost remains, *Squalicorax falcatus* 1 25.1
8. Ferruginous/gypsiferous seam, dark yellowish orange. 0.2
7. Chalk, partly weathered, medium olive gray (5Y5/1) to moderate yellowish brown (10YR5/2), moderately hard, more or less laminated throughout, calcareous silty, speckled throughout, weathers flaky. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta, Durania maxima* (1.6 km to east) 1 37.3
6. Ferruginous/gypsiferous seam, moderate yellowish brown (10YR5/2) 0.3
5. Chalk, partly weathered, light gray to grayish brown and light olive gray, tough, more or less burrow-mottled throughout, calcareous silty, speckled throughout. Basal 12.2 cm harder, much bioturbated, forms light gray band on slope. Uppermost 15.3 cm nonbioturbated, laminated. Unit weathers flaky. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta*. 61.0
4. Ferruginous/gypsiferous seam, dark yellowish orange, hosts oblate spheroidal limonite/jarosite nodules as much as 30.5 cm in diameter and 7.3 cm thick 0.3
3. Chalk, partly weathered, medium olive gray (5Y5/1) to light olive gray (5Y6/1), relatively soft, mostly obscurely laminated, calcareous silty, speckled throughout, weathers flaky. Unit contains scattered pods of bioturbated chalk, light olive gray (5Y6/1), weathers to form large, brittle chips. Basal 15.3 cm is tough, bioturbated chalk, light olive gray (5Y6/1), weathers into small brittle chips, conspicuous on eroded slope. Paper-thin ferruginous seam lies 45.7 cm above base of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta* 2 43.9
2. Bentonite, dark yellowish orange, associated with gypsum, hosts limonite/jarosite/marcasite nodules as much as 30.5 cm in diameter and 9.2 cm thick . . 0.6
1. Chalk, olive gray (5Y4/1), tough, laminated, calcareous silty, speckled throughout, weathers flaky. Unit contains several thin zones of harder, bioturbated chalk, light olive gray (5Y6/1), weathers to form small brittle chips, form light-colored bands on eroded slope. Paper-thin ferruginous seam lies 82.3 cm above base. Limonitized marcasite nodule, oblate spheroidal, 42.7 cm in diameter and 9.1 cm thick, lies 1.6 m above base of unit. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta* 3 11.0

Total thickness of measured section 18 94.3

LOCALITY 17—Badlands and bluffs on west side of Hackberry Creek, in SW¼ Sec. 16, T.14S, R.25W, Trego County, Kansas.

Thickness m cm

SMOKY HILL CHALK MEMBER

12. Chalky limestone, weathered, grayish orange, relatively hard, brittle, bioturbated, forms conspicuous, flat-topped bench. FOSSILS: *Inoceramus (Platyceramus) platinus, Pseudoperna congesta* 9.1
11. Bentonite, light brown (5YR5/6), ferruginous . . . 0.3
10. Chalk, weathered, grayish orange with streaks of yellowish gray (5Y7/2), soft, laminated, very well laminated in uppermost 15.3 cm, splits easily along bedding, calcareous silty, speckled throughout. Limonite nodules, widely spaced, occur in zones lying 61.0 cm, 76.3 cm, and 1.28 m below top of unit. Unit eroded locally so as to form steep face with three prominent ledges. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta* 2 16.5
9. Chalk, weathered, grayish orange, relatively soft, more or less well laminated throughout, calcareous silty, much speckled throughout, weathers shaly. Chalky limestone bed, grayish orange, relatively hard, brittle, 10.5 cm thick, bioturbated, ledge-forming, lies 42.7 cm above base of unit. Uppermost 18 cm of unit also harder than main body of unit, laminated, forms minor bench. Ferruginous seams, central one bentonite?, each less than 0.4 cm thick, lie 42.7 cm, 97.5 cm, and 1.83 m above base of unit. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta* 2 22.6
8. Chalk, weathered, grayish orange, relatively soft, well laminated, splits easily along bedding, calcareous silty, speckled throughout, weathers shaly, forms cavernous slope. Unit contains two prominent beds of chalky limestone, pale grayish orange (10YR8/4), bioturbated, ledge-forming. Lower bed is 18.3 cm thick and lies 1.30 cm above base of unit; upper bed is 15.2 cm thick, lies at top of unit, weathers into irregular slabs, forms prominent, flat-topped bench. Chalky limestones locally coated with lichens. Paper-thin ferruginous seams, light brown

(5YR5/6), each less than 0.1 cm thick, lie 61.0 cm and 97.5 cm above base. Upper seam hosts small limonitized marcasite nodules. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta*. 2 28.7

7. Chalk and chalky limestone, weathered. Chalk is grayish orange to dusky yellow, relatively soft, more or less laminated, calcareous silty, speckled throughout, forms reentrants on steep faces, gradational with harder beds, weathers shaly. Chalky limestone is grayish orange to very pale orange, relatively hard, brittle, bioturbated, with sparse speckling. Uppermost hard bed lichen-splotched locally. Unit rich in inoceramid debris. Limonitized marcasite nodules, as large as 61.0 cm in diameter and 6.2 cm thick, lie in layers 73 cm and 1.19 m above base. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta, I. (Platyceramus) platinus, Durania maxima,* isolated lepadomorph cirriped plates, acrothoracican borings, *Portheus, Ptychodus* 2 89.6
6. Chalk, partly weathered, olive gray (5Y3/2) to light olive gray (5Y5/2), relatively soft, obscurely laminated, uppermost part bioturbated, calcareous silty, speckled throughout, weathers flaky. Layers of limonitized marcasite nodules lie at base and 58.0 cm above base of unit. Unit rich in inoceramid debris. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta, Stramentum haworthi, Zeugmatolepas* sp., acrothoracican borings, *Durania maxima,* teleost bones, lignitized log with *Teredolithus*. . 1 61.7
5. Chalk, olive gray (5Y4/1), in part weathered light olive gray (5Y5/2), tough, brittle, mostly well laminated, calcareous silty, speckled throughout, weathers flaky. Bioturbated chalk, in thin zones, especially 1.8 m above base, form light-colored bands on eroded slope, weather into small brittle chips. Ferruginous/gypsiferous seams, light brown (5YR5/6), each less than 0.2 cm thick, lie 6.88, 7.48, and 8.1 m above base. First and third seams host limonitized marcasite nodules as much as 45.7 cm thick and 9.1 cm thick. Granular gypsum seams, each less than 0.2 cm thick, lie 1.75 m above base and 88.5 cm below top of unit. Lower of these seams hosts limonitized marcasite nodules. Unit contains scattered limonitized marcasite nodules not associated with mineralized weathered bentonite? seams. Unit contains interval rich in inoceramid debris, approximately 60 cm thick, lying 6.08 m above base. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* acrothoracican borings 8 88.7
4. Bentonite, moderate yellowish brown (10YR5/2), very silty 0.3
3. Chalk, olive gray (5Y4/1), light olive gray (5Y6/1), and medium light gray, relatively hard, softer where weathered, well laminated, splits evenly along bedding, slightly calcareous silty, speckled throughout, with conspicuous smooth vertical joints, weathers flaky. Bed of harder chalk, light gray, 21.4 cm thick, lies 24.4 cm above base, forms smoothly rounded shoulder on weathered surfaces. Ferruginous/gypsiferous seam, less than 0.2 cm thick, lies on top of harder bed. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* teleost scales 1 0.8
2. Bentonite, very pale orange to dark yellowish orange. Unit thickens locally to 4.9 cm by addition of ferruginous/gypsiferous seams at top and base. Unit locally hosts limonite nodules with rotten marcasite cores. Unit forms conspicuous reentrant on steep faces 2.5
1. Chalk, medium olive gray (5Y5/1) to olive gray (5Y4/1), grades upward to light olive gray (5Y6/1), tough, obscurely laminated, splits irregularly along bedding, slightly calcareous silty, speckled throughout, weathers flaky. Bed of bioturbated chalk, 20 cm thick, lying 21.3 cm below top of unit, granular, contains very small limonite nodules near base, forms light-colored band on weathered exposure, forms minor shoulder on eroded slope. Ferruginous/gypsiferous seam, less than 0.2 cm thick, lies on top of bioturbated chalk. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* teleost bones and scales. 1 98.3

Total thickness of measured section 23 19.1

LOCALITY 1—Bluffs and badlands along western side of Hackberry Creek, in west half Sec. 24 and NW¼ Sec. 25, T.14S, R.25W, Trego County, Kansas.

Thickness m cm

SMOKY HILL CHALK MEMBER

61. Chalk, weathered, very pale orange to yellowish gray (5Y8/1) to nearly white, mostly brittle and relatively resistant. Bed of softer chalk, 13.8 cm thick, splits easily along bedding, 58 cm above base. Unit in part well laminated, with thin bioturbated zone shortly above middle. Limonite nodules occur sparingly in zone 46 cm below top. Basal 49 cm forms resistant ledge. Bentonite seam, 0.6 cm thick, light brown (5YR5/6), lies in center of soft chalk bed, 97.5 cm below top of unit. Ferruginous seam, 0.3 cm thick, lies 26 cm above base of unit. FOSSILS: *Inoceramus (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* acrothoracican borings, teleost scales 1 80.0
60. Chalk, weathered, grayish orange, soft, forms conspicuous reentrant on steep faces, weathers shaly, with bentonite seam, 2.1 cm thick, pale yellowish green, limonitic, 18.3 cm above base. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* teleost scales 48.8
59. Chalk, weathered, very pale orange, grayish orange or dark yellowish orange, in part relatively hard and moderately resistant, in part softer and weathering shaly. Central bed of more resistant chalk, 30 cm thick, well laminated. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* teleost scales. 1 6.9
58. Chalk, olive gray (5Y4/1), partially weathered to light olive gray (5Y5/2), grading upward to weathered chalk, dark yellowish brown, grayish orange and dark yellowish orange (at top); relatively soft, splits easily along bedding, slightly calcareous silty, speckled throughout, weathers shaly. Bentonite seam, 1.5 mm thick, dark yellowish orange, at base of highly gypsiferous interval 4.6 cm thick, lies 1.71 m above base. Second bentonite seam, 1.5 mm thick, dark yellowish orange, selenitic, lies 2.68 m above base of unit. Unit contains a few limonitic nodules lying about 2.44 m below top. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* acrothoracican borings, sponge? borings, teleost bones 5 82.3
57. Chalk, pale yellowish gray (5Y8/2), pale yellowish orange, and grayish orange, relatively soft, splits easily along bedding, calcareous silty, speckled throughout, weathers shaly. Lowermost and uppermost few cm are slightly harder, sparsely bioturbated, form slightly projecting ledges on weathered slope. FOSSILS: *I. (Volviceramus) grandis, I. (Platyceramus) platinus, Pseudoperna congesta* 70.1
56. Chalk, weathered, pale grayish orange to grayish orange, relatively hard, gradational with adjacent units, bioturbated, calcareous silty, forms projecting ledge on eroded slope. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta* 18.3

	m	cm
55. Chalk, olive gray (5Y4/1), in part weathered to grayish yellow or pale yellowish orange, relatively soft, splits easily along bedding, calcareous silty, speckled throughout, weathers crumbly. Three intervals of chalk, weathered, pale grayish to grayish orange, 9.2, 30.5, and 45.5 cm thick, lying 27.4 cm, 1.22 m, and 2.35 m above base, respectively, are harder, more massive in appearance, laminated, form conspicuous ledges on eroded slope. Large oblate spheroidal nodules of limonite, with rotten marcasite cores, scattered through unit, some partially enclosing large inoceramid valves, are especially common just above middle of unit. Both hard and soft chalks contain burrow structures locally. Eroded slope of unit is littered with skeletal debris, much of which is derived from upper half of interval. FOSSILS: *I. (Platyceramus) platinus, I. (Volviceramus) grandis, Pseudoperna congesta,* acrothoracican borings, *Durania maxima* (float)	3	90.2
54. Chalky limestone, weathered, medium light gray near base, yellowish gray (5Y7/2) to pale yellowish gray (5Y8/2) above, relatively hard, brittle, resistant, forms conspicuous low bench. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta, I. (Platyceramus) platinus?*		58.0
53. Bentonite, dark yellowish orange, paper-thin, in seam consisting mostly of powdery gypsum		0.6
52. Chalk, partly weathered, dark yellowish brown to light olive gray (5Y6/1), relatively soft, obscurely laminated, splits easily along bedding, slightly calcareous silty, sparingly speckled. FOSSILS: *I. (Volviceramus) grandis, Pseudoperna congesta, I. (Platyceramus) platinus?*		12.6
51. Bentonite, dark yellowish orange, slightly silty. Upper part of unit is selenitic		1.8
50. Chalk, weathered, grayish orange, relatively soft		5.2
49. Bentonite, dark yellowish orange, as paper-thin seam at top of unit consisting mostly of powdery gypsum		1.5
48. Chalk, weathered, olive gray (5Y4/1), in part weathered grayish yellow to grayish orange, relatively soft, bioturbated, weathers shaly. Bed of harder chalk, 9.1 cm thick, brittle, lies 45.7 cm above base, forms projecting ledge on eroded slope. Unit contains partially limonitized, nearly spherical pyrite nodules near top. FOSSILS: *I. (Volviceramus) grandis, I. (Platyceramus) platinus?, Pseudoperna congesta*		73.1
47. Chalk, partly weathered, pale olive gray (5Y7/1) to yellowish gray (5Y7/2, 5Y8/1), nonresistant, splits easily along bedding, slightly calcareous silty, speckled throughout, weathers shaly. Basal 39.6 cm is more massive, bioturbated. Zone 12.2 cm thick, bioturbated, lies 39.6 cm above base of unit. Uppermost 9.0 cm also bioturbated. FOSSILS: *Inoceramus* sp. (fragments)		88.3
Measured thickness of Smoky Hill Chalk Member	16	37.7
FORT HAYS LIMESTONE MEMBER		
46. Chalky limestone, weathered, pale yellowish gray (5Y8/2) to light olive gray (5Y6/1), dries nearly white, relatively hard, brittle, resistant, thoroughly bioturbated, forms conspicuous platform across sizeable area of exposure. FOSSILS: *Inoceramus (Volviceramus) koeneni, Pseudoperna congesta, Bullopora* sp.		79.2
45. Bentonite, olive gray (5Y4/1), selenitic, with abundant black specks (biotite?), forms prominent reentrant		0.9
44. Chalky limestone, weathered, yellowish gray (5Y7/2) to pale yellowish gray (5Y8/2), dries nearly white, relatively hard, brittle, bioturbated throughout, forms part of vertical cliff		30.5
43. Chalk, olive gray (5Y4/1), weathered partly to light olive gray (5Y6/1), relatively soft, thoroughly bioturbated, forms small reentrant on cliff face. FOSSILS: *Inoceramus* sp. (fragments)		15.3
42. Bentonite, light olive gray, stained grayish orange by limonite		2.2
41. Chalky limestone, partly weathered, light gray to light olive gray (5Y5/2, 5Y5/1), weathers pale yellowish gray (5Y8/2) to nearly white or pale grayish orange (10YR7/4), relatively hard, brittle, bioturbated throughout, forms major ledge in face of cliff exposure. Shaly weathering interval, medium olive gray (5Y5/1) where least weathered, at center of bed, forms small reentrant on cliff face. FOSSILS: *Inoceramus* sp. (fragments), *Pseudoperna congesta*	1	31.2
40. Bentonite?, light olive gray (5Y5/2), shaly, streaked with chalk, speckled by black grains (biotite?)		1.5
39. Chalky limestone, weathered, yellowish gray (5Y8/1), pale grayish orange (10YR8/4) to nearly white, locally stained dark yellowish orange, nearly all bioturbated, lichen-splotched, relatively hard, brittle, forms part of cliff face. Unit is divided into three parts by subequally spaced bedding planes. Faint laminations occur adjacent to lower bedding plane. FOSSILS: *Inoceramus* sp. (fragments), *Pseudoperna congesta*	1	46.4
38. Chalk, partly weathered, pale yellowish brown to light olive gray (5Y6/1), in part weathered to grayish orange, relatively soft, in part bioturbated, forms prominent reentrant on cliff face, weathers shaly. Bentonite seam, light olive gray (5Y5/2), lies 1.5 cm above base. Unit contains sparse, small limonite nodules		13.8
37. Chalky limestone, weathered, pale yellowish gray (5Y8/2), pale grayish orange (10YR8/4) to nearly white, relatively hard, brittle, bioturbated especially in lower half and near top, forms part of steep cliff face. FOSSILS: *Inoceramus* sp. (bowl-shaped lower valve), *Pseudoperna congesta*		89.9
36. Shale, light olive gray (5Y5/2) bentonitic?, with sparse black specks (biotite?), forms prominent reentrant on cliff face		4.0
35. Chalky limestone, weathered, pale yellowish gray (5Y8/2) to pale grayish orange (10YR8/4), relatively hard, brittle, bioturbated throughout, locally lichen-splotched, forms ledge of cliff face. Unit contains sparse, small pyrite nodules. Soft chalk, argillaceous, shaly, in very thin unit lying 9.2 cm above base, forms minor reentrant on vertical face. FOSSILS: *Inoceramus* sp. (coarsely ribbed fragments)		45.7
34. Chalk, light olive gray (5Y5/2), argillaceous, bentonitic?, bioturbated, with lenticular chalk-filled burrows. Unit forms reentrant on cliff face		2.5
33. Chalky limestone, weathered, pale yellowish gray (5Y8/2) to pale grayish orange (10YR8/4), relatively hard, brittle, bioturbated throughout, lichen-splotched, forms part of steep cliff face. FOSSILS: *Inoceramus* sp. (bowl-shaped lower valve)		30.5
32. Chalk, light olive gray (5Y5/2), argillaceous, bentonitic?, highly bioturbated, with chalk-filled burrows, weathers shaly. Unit forms reentrant on cliff face		3.1
31. Chalky limestone, weathered, pale yellowish gray (5Y8/2) mottled with light gray, relatively hard, brittle, bioturbated throughout, lichen splotched, forms part of steep cliff face. Prominent bedding plane lies 15.3 cm below top		73.0
30. Chalk, weathered, yellowish gray (5Y7/2), dries yellowish gray (5Y8/1) to nearly white, top and base slightly darker and shalier than rest of unit, bioturbated, uppermost part with nearly white chalk-filled burrows, forms reentrant on cliff face, weathers shaly. FOSSILS: *Inoceramus* sp. (bowl-shaped lower		

valve), *Pseudoperna congesta* 13.8

29. Chalky limestone, weathered, pale yellowish gray (5Y8/2), dries nearly white, relatively hard, brittle, bioturbated, forms small projecting ledge in midst of shalier interval. Unit contains scattered small limonite nodules. FOSSILS: *Inoceramus* cf. *I. (Cremnoceramus) browni, Pseudoperna congesta* 15.3
28. Chalk, partly weathered, light olive gray (5Y5/2), bentonitic?, relatively soft, in part laminated, in part bioturbated, with nearly white chalk-filled burrows in upper part. Unit forms reentrant on cliff face, weathers shaly 6.1
27. Bentonite, light olive gray (5Y6/1), biotitic 1.5
26. Chalky limestone, weathered, pale yellowish gray (5Y8/2) to yellowish gray (5Y8/1), dries nearly white, relatively hard, brittle, bioturbated throughout, lichen-splotched, forms part of steep cliff face. Basal part weathers shaly, produces undercut part of ledge. Very thin shaly weathering interval, 70 cm above base, forms reentrant on cliff face. Unit contains sparse limonitized pyrite nodules 24.5 cm above base. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans?, Pseudoperna congesta* 1 16.0
25. Bentonite, light olive gray (5Y5/2), forms deep reentrant on cliff face 1.5
24. Chalky limestone, weathered, yellowish gray (5Y8/1), dries nearly white, relatively hard, brittle, bioturbated throughout, lichen-splotched, forms projecting, rounded ledge on cliff face. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans, Pseudoperna congesta* 61.0
23. Chalk, partly weathered, light olive gray (5Y5/2), with dark yellowish orange iron oxide staining locally, soft, weathers shaly, forms prominent reentrant on cliff face. FOSSILS: *Inoceramus* sp. (crushed, bowl-like valve), *Pseudoperna congesta* . . . 3.1
22. Chalky limestone, weathered, yellowish gray (5Y8/1) to pale grayish orange (10YR8/4), dries nearly white, relatively hard, brittle, sparsely bioturbated, lichen-splotched, forms projecting, rounded ledge on cliff face. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans, Pseudoperna congesta* 51.9
21. Bentonite, light olive gray (5Y5/2), biotitic, stained dark yellowish orange by iron oxide, forms deep reentrant on cliff face 3.1
20. Chalky limestone, weathered, yellowish gray (5Y8/1) to grayish orange, dries nearly white, relatively hard, brittle, bioturbated, lichen-splotched, forms prominently projecting ledge on cliff face. FOSSILS: *I. (Cremnoceramus) browni, Pseudoperna congesta* 67.1
19. Bentonite, light olive gray (5Y5/2), stained dark yellowish orange by iron oxide, speckled with biotite, with small selenite crystals, forms reentrant beneath overhang of unit 20 . . . . 1.5
18. Chalk, partly weathered, light olive gray (5Y6/1), dries yellowish gray, relatively soft, weathers shaly, forms major reentrant on cliff face. Uppermost 6 cm harder, bioturbated, forms rounded, projecting ledge. Unit contains selenite seam, 3.1 cm thick, 7.6 cm below top. Unit contains sparse small limonite nodules. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans, Pseudoperna congesta,* acrothoracican borings 47.2
17. Chalky limestone, weathered, pale yellowish gray (5Y8/2) to pale grayish orange (10YR8/4), relatively hard, brittle, mostly bioturbated, lichen-splotched, forms projecting ledge on cliff face. Zone of softer chalk, 3.1 cm thick, 24.4 cm above base, weathers shaly, forms conspicuous reentrant just above middle of unit. Basal part of unit contains limonite nodules as much as 3 cm in diameter. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans, Pseudoperna congesta,* sponge? borings 48.8
16. Chalky limestone, weathered, yellowish gray (5Y7/2) to pale grayish orange (10YR8/4), relatively hard, brittle, bioturbated, lichen-splotched, forms overhanging ledge above unit 15. Uppermost 6.0 cm and 3.0-cm-thick interval lying 18.3 cm below top of unit are softer, shaly weathering, form reentrants on cliff face. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans, Pseudoperna congesta,* acrothoracican borings, *Serpula?* sp. 88.4
15. Chalk, partly weathered, yellowish gray (5Y7/2) to moderate yellowish brown (10YR5/2), soft, bioturbated, forms major reentrant on cliff face. Middle part of unit highly bioturbated, weathers shaly, contains many limonitized burrow structures. FOSSILS: *I. (Cremnoceramus) browni, I. (Cremnoceramus) inconstans, Pseudoperna congesta* 42.7
14. Chalky limestone, weathered, pale yellowish gray (5Y8/2), dries yellowish gray (5Y8/1) to nearly white, mottled in lower 30 cm with medium gray, relatively hard, brittle, bioturbated throughout, forms part of cliff face. Unit contains numerous blebs of pyrite, most of which is limonitized. FOSSILS: *I. (Cremnoceramus) inconstans, I. (Cremnoceramus) browni, Pseudoperna congesta,* acrothoracican borings. 88.3
13. Chalk, olive gray (5Y4/1) below, light olive gray (5Y7/2) above, relatively soft, speckled sparingly, calcareous silty, bioturbated, weathers shaly, forms reentrant on steep cliff face. Unit contains sparse flakes of biotite. FOSSILS: *I. (Cremnoceramus) inconstans, Pseudoperna congesta* 9.2
12. Chalky limestone, partly weathered, light olive gray (5Y6/1), dries yellowish gray (5Y8/1), relatively hard, brittle, bioturbated throughout, forms part of cliff face. Unit weathers shaly at top and in very thin zone lying 15.3 cm below top; latter shaly interval marked by reentrant. FOSSILS: *I. (Cremnoceramus) inconstans, I. deformis, Pseudoperna congesta* 70.0
11. Chalk, olive gray (5Y4/1), calcareous silty, speckled sparingly, argillaceous, weathers shaly, forms small reentrant on cliff face 3.1
10. Chalky limestone, weathered, pale yellowish gray (5Y8/2) to grayish yellow, dark yellowish orange where stained by iron oxide, relatively hard, brittle, bioturbated throughout, lichen-splotched, forms part of cliff face, weathers shaly in uppermost 15 cm. FOSSILS: *Inoceramus deformis, Pseudoperna congesta* . 1 13.0
9. Chalk, olive gray (5Y4/1), calcareous silty, argillaceous, speckled sparingly, also speckled by black biotite grains, weathers shaly, forms reentrant on cliff face, may be bentonitic 3.1
8. Chalky limestone, weathered, yellowish gray (5Y7/2), pale yellowish gray (5Y8/2) and pale grayish orange (10YR8/4), relatively hard, brittle, bioturbated throughout, forms part of cliff; very thin shaly weathering interval at base forms part of prominent reentrant on cliff face. FOSSILS: *Inoceramus deformis, Pseudoperna congesta, Pycnodonte aucella* . 1 31.2
7. Chalky limestone, weathered, yellowish gray (5Y7/2), dries pale yellowish gray (5Y8/2), light olive gray (5Y6/1) in thin interval near middle, relatively hard, brittle, bioturbated throughout, forms part of cliff face. Unit weathers shaly at top and base; shaly weathering interval at top forms part of reentrant on cliff face. Unit contains irregular lenses of calcarenite, pale yellowish brown, hard, brittle, in lower 30 cm. FOSSILS: *Inoceramus deformis, Pseudoperna congesta* 1 68.1
6. Chalky limestone, partly weathered, light olive gray (5Y7/2), to weathered, grayish orange, relatively

hard, brittle, bioturbated throughout, forms part of cliff face. Uppermost 3.1 to 6.2 cm weathers shaly, forms reentrant on cliff face. Basal part of unit weathers cavernous. Limonite nodules up to 3 cm in diameter, occur sparingly in zone lying 6.2 cm above base. Unit contains scattered thin lenses of calcirudite. Thin interval near center of bed is thinly cross laminated. FOSSILS: *Inoceramus deformis, Pseudoperna congesta, Pycnodonte aucella*	1	37.3
5. Chalky limestone, weathered, yellowish gray (5Y7/2) to pale grayish orange (10YR8/4), relatively hard, brittle, bioturbated throughout, forms part of cliff face. Uppermost 18.3 cm light olive gray (5Y6/1), bioturbated, weathers shaly, forms reentrant beneath unit 6. Limonitized pyrite nodules, less than 3 cm thick, occur in layer 18.3 cm below top of unit. FOSSILS: *Inoceramus deformis, Pseudoperna congesta*	1	22.0
4. Chalk, dark gray, in part weathered to light olive gray (5Y6/1), relatively hard, slightly calcareous silty, weathers shaly, contains sparse flakes of biotite, forms prominent reentrant on cliff face		3.1
3. Chalky limestone, weathered, pale grayish orange (10YR8/4), grayish orange, and medium yellowish orange (10YR6/4), relatively hard, brittle, bioturbated throughout, forms part of cliff face. Limonite nodules, as much as 7.7 cm in diameter, occur in thin zone lying 24.5 cm above base of unit. FOSSILS: *Inoceramus* sp. (fragments), *Pseudoperna congesta?, Pycnodonte aucella*		48.8
2. Chalky limestone, weathered, yellowish gray (5Y8/1), relatively hard, brittle, bioturbated throughout, slightly silty, especially at base. Uppermost 3 cm is olive gray (5Y4/1), finely sandy, weathers shaly, forms small reentrant beneath unit 3. Unit contains small, scattered, cylindrical pyrite bodies. Lies with sharp contact on unit 1. FOSSILS: *Pycnodonte aucella*	—	57.9
Total thickness of Fort Hays Limestone Member	21	93.8
CARLILE SHALE		
1. Shale, dark gray to olive gray (5Y4/1), sandy, with irregular very thin beds and laminae of light olive gray (5Y5/2), very fine grained sandstone	—	30.1
Measured thickness of Carlile Shale		30.1
Total thickness of measured section	38	61.6

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LAWRENCE, KANSAS 66044