Stratigraphy and Composition of the Sharon Springs Member of the Pierre Shale in Western Kansas

GEOLOGICAL SURVEY PROFESSIONAL PAPER 728

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By JAMES R. GILL, WILLIAM A. COBBAN, *and* LEONARD G. SCHULTZ

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Stratigraphic and mineralogic study of one of the more distinctive and widespread shale units of Late Cretaceous age in the western interior of the United States

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By JAMES R. GILL, WILLIAM A. COBBAN, and LEONARD G. SCHULTZ

ABSTRACT

The Sharon Springs Member of the Pierre Shale is a widespread unit that can be recognized readily in outcrops by its distinctive lithologic character and in the subsurface by electric and gamma-ray well-log characteristics. The Sharon Springs Member is in Kansas, Nebraska, North and South Dakota, and parts of Colorado, Wyoming, Montana, and eastern Utah. Its type locality is in Wallace County, Kans., where the member is about 215 feet thick and consists of three units: a lower dark soft shale unit 115 feet thick, a middle hard organic-rich shale unit 90 feet thick, and an upper hard slightly phosphatic shale unit about 10 feet thick. The Sharon Springs contains abundant vertebrate remains but few mollusks.

Minerals in the Sharon Springs Member, as determined from well cuttings, are predominantly clay minerals but include about 25 percent quartz and several percent each of pyrite, dolomite, organic matter, and, in the lower part where the member grades into the Niobrara Formation, calcite. The most abundant clay mineral is mixed-layered montmorillonite-illite; there are lesser amounts of illite, kaolinite, and chlorite. Pyrite, dolomite, and chlorite are leached from outcrops. Bentonite beds in the Sharon Springs contain unusually large amounts of kaolinite and beidellite with interlayered hydrated aluminum complexes in comparison with the usual montmorillonitic bentonites in other parts of the Pierre Shale. The rare mineral basaluminite occurs as white earthy lumps at the top of the Sharon Springs Member.

Semiquantitative spectrographic data indicate that most trace elements occur in the clay component of the shale or in closely associated heavy clastic grains. Iron, nickel, cobalt, and molybdenum are concentrated in pyrite. Molybdenum and probably uranium and silver seem strongly concentrated in organic matter. Strontium is concentrated in calcite.

INTRODUCTION

The Pierre Shale, which includes the Sharon Springs Member at its base, is chiefly a marine medium- to dark-gray noncalcareous shale of Late Cretaceous age that overlies the calcareous Niobrara Formation and underlies the Fox Hills Sandstone. The maximum thickness in Kansas is about 1,600 feet in extreme northwestern Cheyenne County (Merriam, 1963, p. 42). Elias (1931, p. 56–57) divided the Pierre into the following members, from oldest to youngest: Sharon Springs, Weskan, Lake Creek, Salt Grass, an unnamed member, and Beecher Island.

The Sharon Springs Member of the Pierre Shale is stratigraphically unique. It differs from the rest of the Pierre Shale because of its dark color, resistance to erosion, richness in organic material, and high radioactivity. At most localities, many bentonite beds are in the lower part of the member, and gray septarian limestone concretions are conspicuous in many places. The member derives its name from the town of Sharon Springs in Wallace County near the west boundary of Kansas (fig. 1).

From 1956 to 1968, a detailed regional study of the stratigraphy, paleontology, mineralogy, and geochemistry of the Pierre Shale and equivalent rocks in the northern part of the western interior was undertaken by various members of the U.S. Geological Survey (Tourtelot, 1956, 1962; Tourtelot and others, 1960; Schultz, 1964, 1965; Scott and Cobban, 1963, 1965; Barnett, 1961; Rader and Grimaldi, 1961; Kepferle, 1959; Landis, 1959; Gill and Cobban, 1961, 1962, 1965, 1966a, b; Robinson and others, 1959). During this investigation, they studied type sections of members of the Pierre Shale along the Missouri River and in the Black Hills region in South Dakota as well as the equivalent rocks in North Dakota, Montana, Wyoming, and Colorado. That the Pierre Shale is a diverse lithologic sequence marked by east-west facies changes which are subtle in some places and conspicuous in others soon became apparent and made correlation of individual units difficult. However, the Sharon Springs Member was found to be so nearly uniform in lithology over long distances that it could be easily identified on the surface and in the subsurface throughout much of the western interior of the United States and the adjacent region in southern Canada.

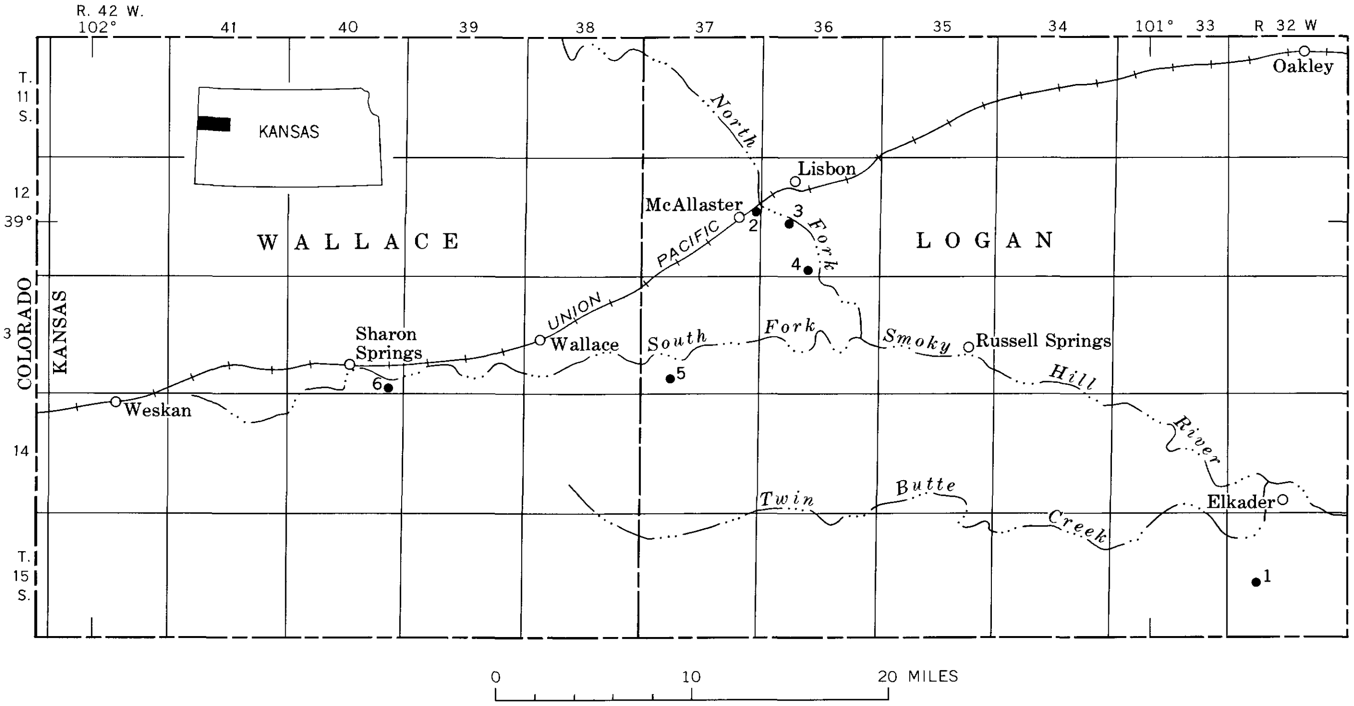

Figure 1. — Location of six measured sections of the Sharon Springs Member of the Pierre Shale. (Town of Lisbon is abandoned.)

Throughout most of the western interior, the Sharon Springs Member is characterized by shale that is rich in organic material as well as by persistent bentonite beds in the lower unit. Distinctive electric and gamma-ray log characteristics permit delineation of the western edge of shale that is rich in organic material and subsurface tracing of the bentonite beds westward from this area into areas of nearshore deposition.

A brief reconnaissance of exposures of the Sharon Springs Member in Wallace and Logan Counties was made in the fall of 1959 and in the spring of 1960 to determine the thickness, lithology, and fossil content of the unit. Only part of the thickness of the member could be measured at any one locality; therefore, to determine total thickness, the State Geological Survey of Kansas drilled two test holes in the fall of 1962, one near McAllaster and the other near Sharon Springs. The test hole near McAllaster penetrated 50 feet of the Sharon Springs Member and 115 feet of the underlying Smoky Hill Member of the Niobrara Formation. The test hole near Sharon Springs penetrated the entire Sharon Springs Member (222 feet) and 78 feet of the Smoky Hill Member.

Outcrops of the Pierre Shale, including those of the Sharon Springs Member, are generally poor in western Kansas. In Wallace and Logan Counties, most exposures of the Sharon Springs Member are restricted to the main and tributary valleys of Twin Butte Creek and the North and South Forks of the Smoky Hill River. (See maps by Hodson, 1963, pl. 1, and Johnson, 1958, pl. 1.) Owing to the fact that the Sharon Springs Member is unconformably overlain by deposits of Tertiary and Quaternary age in much of these areas, a complete section of the member cannot be obtained at any single locality. Six partial sections (fig. 1, loc. 1–6), the location of which follows immediately, were measured and are included in this report.

Loc.	*Location*
1	NE¼NE¼ sec. 20, T. 15 S., R. 32 W., Logan County.
2	SE¼ sec. 13, T. 12 S., R. 37 W., Logan County.
	SW¼NE¼ sec. 13, T. 12 S., R. 37 W., Logan County (McAllaster Buttes test hole).
3	SE¼ sec. 20, T. 12 S., R. 36 W., Logan County.
4	SW¼SE¼ sec. 33, T. 12 S., R. 36 W., Logan County.
5	SE¼NE¼ sec. 32, T. 13 S., R. 37 W., Logan County.
6	SW¼SE¼NW¼ sec. 36, T. 13 S., R. 40 W., Wallace County.
	SE¼SE¼NW¼ sec. 36, T. 13 S., R. 40 W., Wallace County (Guy Holland test hole, Devils Halfacre).

In Phillips County, a remnant of the lower unit of the Sharon Springs is preserved in a fault block exposed along Prairie Dog Creek (Frye and Leonard, 1949, p. 31, pl. 5); this exposure was also measured.

ACKNOWLEDGMENTS

We acknowledge the assistance of D. F. Merriam, formerly with the State Geological Survey of Kansas, in arranging for the drilling of the two holes in the study area and for encouragement in preparing the report. Our colleagues in the U.S. Geological Survey, I. C. Frost, J. C. Hamilton, Lorraine Lee, H. H. Lipp, Wayne Mountjoy, and G. D. Shipley, provided analyses. Robert E. Burkholder, also of the U.S. Geological Survey, photographed the fossils and phosphatic nodules.

HISTORICAL BACKGROUND

Many of the early observations of the rocks now assigned to the Sharon Springs Member of the Pierre Shale were incidental to the descriptions of fossils, chiefly vertebrates, from western Kansas. Cretaceous strata of the Great Plains were first divided into the following formations (Meek and Hayden, 1861, p. 419):

	Formation
Fox Hill beds	5
Fort Pierre Group	4
Niobrara Division	3
Fort Benton Group	2
Dakota Group	1

The Fort Pierre Group [Pierre Shale] was not subdivided.

In 1867, Dr. Theophilus H. Turner, physician at Fort Wallace, Kans., collected parts of three large vertebrae which he presented to John L. LeConte, who was engaged in a geological survey to determine the route for the Union Pacific Railway. LeConte passed these on to Prof. E. D. Cope, who indicated that they belonged to a large marine reptile (plesiosaur). Shortly thereafter Dr. Turner collected the remaining bones and sent them to Cope, who briefly described them as the new species *Elasmosaurus platyurus* Cope (1868a, b). Cope (1868b) noted that more than 100 vertebrae were present and that the original length of the vertebral column must have been 38 feet. This huge plesiosaur became the subject of many papers, mainly as a result of Joseph Leidy's conclusion that Cope had misidentified the order of the vertebrae from head to tail (Leidy, 1870a, b; Cope, 1870, 1875). Regarding the rock which yielded the specimen, Cope (1868b, p. 93) stated, "The beds were argillaceous, with much gypsum [selenite]; the latter mineral coating the bones." It is now known that Cope's specimen came from the Sharon Springs Member, the outcrops of which ordinarily have numerous crystals and joint fillings of selenite. The outcrops are characterized also by many septarian limestone concretions that contain thick veins of pale-yellow calcite and scattered barite crystals. Cope's paper (1868b) is an appendix to a much larger report by LeConte, who examined some of the barite and made the following statement (LeConte, 1868, p. 11): "I received from Dr. Turner, U.S.A., the medical officer of the post [Fort Wallace], several fine crystals of sulphate of baryta, found in geodes, with calcite and selenite, about seven miles west of the fort. * * * Dr. Turner had found in the same ravine with the geodes some irrecognizable fragments of fossil bone." This statement and that of Cope (1868b) may be the first description of rocks now assigned to the Sharon Springs Member.

Cope (1871) spent part of the fall of 1871 in the Fort Wallace area. He (1872a, p. 325) noted that in the Fort Hays–Fort Wallace area the "Niobrara division" consisted of two parts—"a lower of dark bluish calcareo-argillaceous character, often thin-bedded; and a superior, of yellow and whitish chalk, much more heavily bedded." He apparently mistook the dark shale in the Fort Wallace area, now assigned to the Sharon Springs Member, for the lower part of the "Niobrara division." Cope (1872a, p. 326) described the beds as follows:

> The blue shale * * * frequently contains numerous concretions, and great abundance of thin layers of gypsum and crystals of the same. Near Sheridan [a former town a few miles east of what is now McAllaster[1]], concretions and septaria are abundant. In some places the latter are of great size, and being imbedded in the stratum have suffered denudation of their contents, and the septa standing out form a huge honey-comb.

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[1] Mohler (1889, map on page 278) showed McAllaster to be along the Union Pacific Railroad, just north of the center of sec. 23, T. 12 S., R. 37 W., and Sheridan to be along this railroad east of the North Fork of Smoky Hill River in about the W½ sec. 8, T. 12 S., R. 36 W.

Cope described the beauty of the gypsum [selenite] crystals:

> These are hexagonal-radiate, each division being a pinnate or feather-shaped lamina of twin rows of crystals. The clearness of the mineral and the regular leaf and feather forms of the crystals give them much beauty. The bones of vertebrate fossils preserved in this bed are often much injured by the gypsum formation which covers their surface, and often penetrates them in every direction.

At that time Cope (1872b) also briefly described another plesiosaur (*Plesiosaurus gulo* Cope, n. sp.) and the mosasaur *Clidastes*, collected "in close proximity near Sheridan, Kansas, by Joseph Savage of Leavenworth." Cope believed the plesiosaur had devoured the smaller mosasaur and mentioned that the bones were associated with a few fragments of a large turtle. The collection was not referred to any one formation, but later Cope (1875, p. 256) assigned the plesiosaur to the Niobrara. At that time, Cope (1875, p. 79–88) more thoroughly described his *Elasmosaurus platyurus* and remarked that it came from an "escarpment of a bluff of clay-shale rock, with seams and crystals of gypsum." Regarding the presence of fossil fish beneath the plesiosaur skeleton, Cope (1875, p. 79–80) stated that they consisted of "scales and teeth of some six species of *Physoelyst* and *Physostomus* fishes * * * including an *Enchodus* and a *Phasganodus;* the latter indicating a new species * * * called *P. carinatus.* These animals had doubtless been the food of the *Elasmosaurus.*"

Although Cope mistook the Sharon Springs Member for the lower part of the "Niobrara division," Hayden apparently mistook the same beds for the Benton Group that underlies the Niobrara. In mentioning the occurrence of vertebrates, Hayden (1872, p. 68) remarked that "In [Formation] No. 2 [Benton], not far from Fort Wallace, have been found, the remains of gigantic reptiles 40 or 50 feet in length."

That the beds near Fort Wallace actually represented part of the Pierre was suggested by F. B. Meek in a letter to B. F. Mudge (1877, p. 284). Mudge had collected from "a bed of *Baculites*" near Sheridan some well-preserved ammonites which he sent to Meek, who identified them as *Baculites anceps* Lamarck. Meek pointed out that this species was known only from rocks of post-Niobrara age and that, unlike the internal molds collected from the Niobrara, Mudge's specimens had the shell material preserved. Williston (1893, p. 110) later visited Mudge's locality and found "one or two other mollusks" that seemed to be Pierre types. The association of these and other invertebrates with a new species of vertebrate, the mosasaur *Clidastes westii* Williston, that had been collected by C. H. Sternberg near Sheridan, had been documented previously in a paper by Williston and Case (1892, p. 29). Sternberg said the mosasaur came from the uppermost Niobrara beds, but Williston and Case (1892, p. 29) stated, "The character of the associated invertebrate fossils seems to indicate a different geological horizon, either the Fox Hills group, or transition beds to that group." In 1897, Williston, in discussing the Niobrara, pointed out that the Fort Pierre [Pierre Shale] had been "confounded with the Niobrara" by earlier collectors and that *Clidastes westii* and the baculites from Sheridan came from the Pierre.

Sheridan was a terminus of the Kansas Pacific Railroad (now Union Pacific) in the early 1870's (Bardack, 1965, p. 10). Apparently, it was abandoned about 20 years later, as indicated by reference to it as "the old town of Sheridan" (Williston and Case, 1892, p. 29). Sometime in the 1890's the new town of Lisbon was approximately at the site of Sheridan (Bardack, 1965, p. 6). Cragin (1896, p. 52) gave the name "Lisbon shales" to the beds now assigned to the Sharon Springs Member and the overlying Weskan Member. Cragin's description is brief:

> Named from Lisbon, Kansas, near which they outcrop. Dark-bluish and brownish shales. Seen above the Smoky Hill chalk in Logan and Wallace Counties, Kansas and Elbert County, Colorado. Contains concretions of yellow phosphate of iron. * * * Supposed to be lower Ft. Pierre. Fossils: *Inoceramus barabini, Baculites,* limpets, etc.

Cragin's stratigraphic name seems to have been adopted only by Stewart (1899, p. 110; 1900, p. 337), who described the new series of fish *Empo lisbonensis,* or *Cimolichthys nepaholica* (Cope) according to Goody (1970, p. 3), *Protosphyraena gigas,* and *Pachyrhizodus* as coming from the Lisbon shales near Lisbon. About that time, Wagner (1898) described a turtle (*Toxochelys latiremis* Cope) collected by S. W. Williston at Eagle Tail Creek near Sharon Springs and another specimen (*Toxochelys* aff. *T. latiremis*) from the Lisbon area. These specimens, which were said to have come from the "Fort Pierre," are from beds now assigned to the Sharon Springs Member. At that time, Adams (1898) presented a geologic map of Logan County in which the "Fort Pierre Shales" were mapped with the Niobrara, but he noted that they "* * * may be recognized by the blue shales and the concretions or septaria which they contained. It is typically exposed at McAlister [sic]." Darton (1905, p. 320) applied the name Pierre Shale to strata in Wallace County and estimated that about 300 feet was present in the Smoky Hill River valley east of Wallace.

During the interval 1906–27, nothing seems to have been published about the lower part of the Pierre Shale of western Kansas. In the period 1928–30, interest in volcanic ash, cave-ins, and oil and gas possibilities in western Kansas created renewed interest in the Pierre. Pinkley and Roth (1928) mentioned bentonite beds in the lower part of the Pierre Shale and presented a photograph of one. Russell (1929, p. 599) observed that the basal 400 feet of the Pierre Shale was divisible into five lithologic members, the contacts of which were reliable marker horizons. He reported the lowest member to be a soft shale and the overlying member to be a hard fissile shale that weathered light brownish gray and contained septarian concretions. He gave no thicknesses, but these two units make up the present Sharon Springs Member. Elias (1930), in describing a cave-in along the Smoky Hill River near Sharon Springs, estimated that as much as 350 feet of Pierre Shale was in the area and that the lowest part consisted of clayey shale intercalated with dark-gray calcareous shale.

Elias published his classic study of the Pierre Shale of Wallace County and adjacent areas in 1931. He divided the Pierre Shale into the following members, from oldest to youngest: Sharon Springs, Weskan, Lake Creek, Salt Grass, an unnamed member, and Beecher Island. He reported on cephalopods of the Pierre Shale in 1933.

Since Elias's work, few papers have been published about the Sharon Springs Member of western Kansas. Frye and Leonard (1949, p. 32–33) drew attention to outcrops of the lower part of the Pierre Shale northeast of the Wallace-Logan County area and near the Kansas-Nebraska boundary. Bradley and Johnson (1957, p. 20–22), Johnson (1958, p. 41–43), and Hodson (1963, p. 16–18, 46–48) briefly described parts of the Sharon Springs Member in Wallace and Logan Counties in connection with studies of ground-water resources. Landis (1959) investigated the Sharon Springs in these counties for radioactivity and uranium content and measured several sections of parts of the unit.

Two large collections of *Baculites asperiformis* Meek from the McAllaster area were reported by Cobban (1962, p. 708–709, pl. 106). Each collection came from a separate limestone concretion in the upper part of the Sharon Springs Member. Specimens from one of the concretions, showing various growth stages, are shown on plate 2. A fragment of another ammonite, *Trachyscaphites spiniger* (Schlüter) subsp. *porchi* Adkins (pl. 2, fig. 12), was reported by Cobban and Scott (1964, p. E2, E3, E5, E11) from one of the concretions.

David Bardack (written commun., 1965) of the University of Illinois recently collected an almost complete fish skeleton from the Sharon Springs Member of Kansas. This specimen, *Pachyrhizodus minimus*, was found at the type locality of the Sharon Springs Member in sec. 8, T. 12 S., R. 36 W.

GEOLOGIC SETTING

During Late Cretaceous time (Cenomanian-Maestrichtian), a broad epicontinental sea which extended from Mexico to the Arctic covered much of the western interior of the United States and Canada. The position of the western border of the sea fluctuated, apparently chiefly in response to tectonic and volcanic activity in the elevated land areas to the west. Most of the sediment delivered to the sea seems to have been derived from western source areas; the low-lying landmass that formed the eastern shore supplied but little detritus. Clastic materials in the form of sand, mud, and volcanic ash, represented by the Graneros, Carlile, and Pierre Shales and equivalent rocks, form most of the Upper Cretaceous rocks. Biogenic sediments of shallow-water origin, such as marlstone, chalk, and limestone, which make up the Niobrara and Greenhorn Formations as well as parts of the Pierre Shale in the Dakotas and Nebraska, constitute only a minor part of the total rock volume.

That numerous fluctuations of the western border of the sea occurred during the Cretaceous is evidenced by complex interfingering of marine and nonmarine deposits. Evidence of similar interfingering along the eastern margin of the sea has been largely obliterated by post-Cretaceous erosion. During three long periods of carbonate deposition in Late Cretaceous time, the Greenhorn Limestone, the Fairport Chalk Member of the Carlile Shale, and the Niobrara Formation were formed. These three deposits are westward-pointing wedges of calcareous sediments enclosed by eastward-pointing wedges of noncalcareous shales and sandy sediments.

During early Niobrara time (late Turonian and Coniacian), when the Cretaceous interior sea was at least 900 miles wide, conditions were favorable to the deposition and preservation of carbonates over an area from the eastern shoreline westward to eastern Utah, central Wyoming, and central Montana (fig. 2). The area of carbonate accumulation is thought to have been a shallow-water shelf that extended westward from the eastern shoreline for 400–800 miles. By latest Niobrara time (early

Campanian), the western edge of the area of carbonate deposition had retreated 200 miles eastward to central Colorado and, farther north, 500 miles eastward into the eastern Dakotas (fig. 2). The eastward shift in the position of the western edge of the shallow-water carbonate accumulation was accompanied by an eastward migration of the deeper water depositional environment in which the organic-rich shales of the Sharon Springs Member are assumed to have accumulated. That the organic-rich shales become progressively younger from west to east is shown by stratigraphic and paleontologic data from several widely separated areas.

The Niobrara Formation seems to reflect a broad-scale westward expansion of the Cretaceous sea during the early part of its depositional history and a recession of the sea during the later part of its depositional history (fig. 2). Hattin (1966, p. 217) recognized the overall transgressive nature of the Niobrara but regarded the overlying Pierre Shale strata as the succeeding regressive depositional sequence. The upper part of the Niobrara Formation is equivalent to the Telegraph Creek Formation and to the Eagle Sandstone and equivalent beds in Montana, Wyoming, and Colorado; these rocks represent a widespread regression of the Cretaceous sea. The base of the Pierre Shale in Kansas, the Sharon Springs Member, is equivalent to the Claggett Shale of Montana. Their distribution demonstrates that the Claggett Shale and the Sharon Springs were deposited during the time of an expanding sea and should therefore be regarded as transgressive, rather than regressive, deposits.

STRATIGRAPHIC RÉSUMÉ

NIOBRARA FORMATION

The name Niobrara Formation, of Late Cretaceous age (late Turonian-early Campanian), was given by Meek and Hayden (1861, p. 419, 422) to a 200-foot-thick sequence of yellowish-weathering marlstone and white limestone exposed along the Missouri River near the mouth of the Niobrara River in Knox County, Nebr. In western Kansas the formation is as much as 750 feet thick (Merriam, 1963, p. 45). It was divided by Mudge (1876, p. 214–219) into a lower member, the Fort Hays Limestone, and an unnamed upper member which was later called the Smoky Hill Chalk Member by Cragin (1896, p. 51).

Logs from oil and gas test wells in Wallace County indicate that the Fort Hays Limestone Member is about 60 feet thick and that the Smoky Hill Chalk Member is about 660 feet thick. According to Elias (1931, p. 29), no more than the upper 100 feet of the Smoky Hill Chalk Member is exposed in Wallace County. Hattin (1965, p. 62–64) described in detail an 85-foot-thick sequence in the upper part of the Smoky Hill Member in the southern part of Logan County. This section did not extend as high as the Pierre-Niobrara contact, but it is thought to represent most of the upper part of the Niobrara Formation exposed in that area.

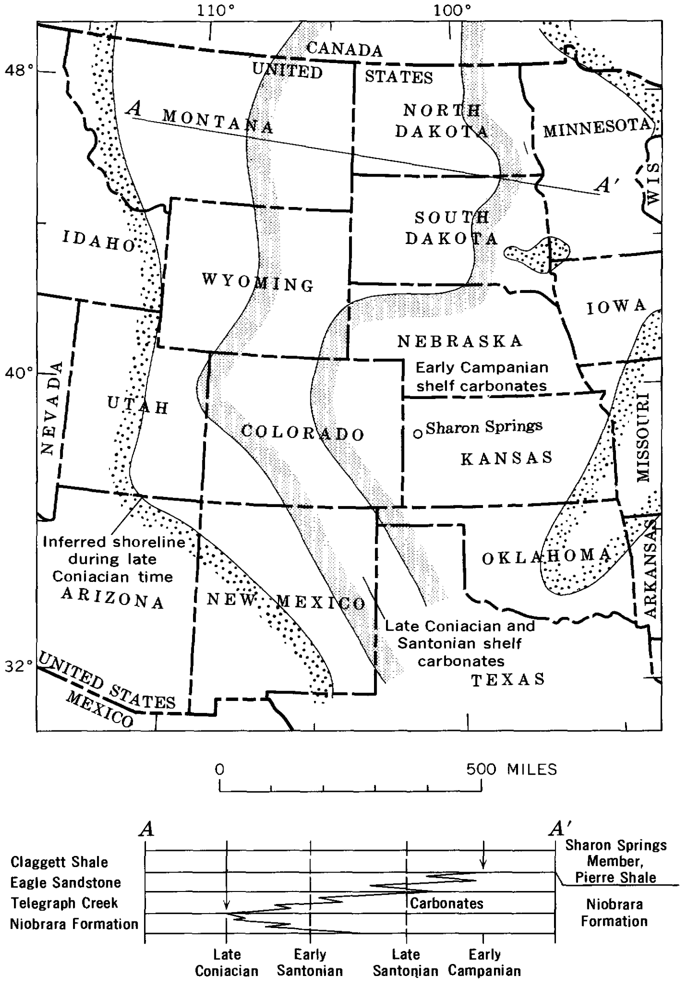


FIGURE 2. — Paleogeographic map showing the eastward migration of areas of shallow-water carbonate accumulation during latter part of Niobrara time (late Coniacian to early Campanian).

The upper part of the Niobrara Formation is composed of thin to thick beds of marlstone, shaly chalk, and chalk which is bluish gray to lead gray in fresh exposures but which weathers white or to shades of yellowish gray and orange. The contact between the Niobrara and the overlying Pierre is ordinarily difficult to determine in fresh exposures, inasmuch as the two formations are similar in color and beds characteristic of each formation appear to alternate with each other. Locally, the basal part of the Pierre contains a transitional unit in which dark beds of calcareous shale are interbedded with dark beds of noncalcareous shale. We placed the contact at the horizon dividing the dominantly calcareous rocks below from those that are dominantly noncalcareous above. The use of acid is helpful as a test in locating the contact, although calcareous shales in the lower part of the Pierre can also be recognized by the minute white or light-gray calcareous specks they contain. The precise contact between the two formations is also difficult to determine from test-hole cuttings (locs. 2, 6), but electric and gamma-ray logs are of considerable assistance. The contact between the Pierre and Niobrara Formations is pinpointed on the electric log at the sharp downward increase in resistivity and decrease in the self potential (fig. 17) changes which apparently reflect the transition from the noncalcareous rocks of the Pierre to the dominantly calcareous rocks of the Niobrara.

PIERRE SHALE

SHARON SPRINGS MEMBER

The name Sharon Springs Member of the Pierre Shale was applied by Elias (1931, p. 58–65) to exposures in Logan and Wallace Counties that consist of an upper hard buttress-weathering black shale containing abundant fish scales and bones and a lower softer dark-gray flaky shale. A complete section of the member is not known to be exposed in western Kansas, but fieldwork, supplemented by drilling, indicates that the member is about 225 feet thick. The Sharon Springs Member conformably and transitionally overlies the Niobrara Formation. The Weskan Member of the Pierre conformably overlies the Sharon Springs, the contact being marked by an abrupt change upward from hard slightly phosphatic shale which contains abundant organic material and numerous layers of phosphate nodules to a soft shale which contains many thin bentonite beds. Elias (p. 62) originally included a bed of "large lenslike bodies of light-gray to yellowish-white laminated limestone" at the top of the Sharon Springs. This concretionary limestone is unlike septarian limestone concretions in the underlying part of the Sharon Springs Member; it is more like limestone concretions in the Weskan Member. Furthermore, the concretionary limestone bed contains the kind of fossils that is in the lower part of the Weskan Member. For these reasons, we exclude this bed from the Sharon Springs and make it part of the Weskan Member.

The type locality for the Sharon Springs Member designated by Elias (1931, p. 63–64) is about 2 miles east of McAllaster Buttes near the abandoned town of Lisbon (fig. 1), apparently in about the center of sec. 8, T. 12 S., R. 36 W., Logan County, Kans. The name was derived from the town of Sharon Springs, the Wallace County seat.

In areas outside Kansas, the name Sharon Springs has been used widely for rocks that are similar in stratigraphic position and lithology (fig. 3). In 1937, the Sharon Springs was recognized by Dane, Pierce, and Reeside (1937, p. 225) as a member of the Pierre Shale in eastern and southern Colorado, where the name was applied to rocks formerly called the Barren zone by Gilbert (1897). Griffitts (1949, p. 2012, 2015) applied the name Sharon Springs to dark-gray shales overlying the Niobrara Formation east of the Front Range in central and northern Colorado, and LeRoy and Schieltz (1958) described a number of sections of the Sharon Springs that extended along the Front Range from Canon City to near the Colorado-Wyoming boundary. The Sharon Springs equivalent extends into the Book Cliffs area of western Colorado and Utah where it is lithologically distinctive in the upper part of the Mancos Shale. Recently the Sharon Springs Member of the Pierre Shale was formally recognized in the Middle Park area near Kremmling, Colo. (Izett and others, 1971).

In 1938, Searight (p. 137) applied the name Sharon Springs to hard black shales at the base of the Pierre along the Missouri River in central South Dakota, and a year later he used the name for similar strata around the Black Hills in western South Dakota and southeastern Wyoming (Moxon and others, 1939, p. 20–21). It is interesting to note that in 1931 Elias had suggested a similar correlation of the Sharon Springs Member in Colorado and South Dakota. Condra and Reed (1943, p. 17) applied the name to the lowermost part of the Pierre in Nebraska.

WESKAN MEMBER

Elias (1931, p. 77–88) described the Weskan Member as a 170-foot-thick sequence of dark-gray unctuous shale that contains abundant thin bentonite beds and limestone and ironstone concretions. The type locality for the Weskan Member is along the bank of a small creek in the SE¼ sec. 2, T. 13 S., R. 42 W., Wallace County, Kans. The member, named for the town of Weskan in west-central Wallace County, can be divided into a lower unit about 90 feet thick and an upper unit about 80 feet thick.

			Western interior ammonite zones	Millions of years[1]		Kansas				Colorado				Nebraska	
				Estimated age	Potassium-argon date	Wallace County				Pueblo area		Fort Collins area		Chadron arch[2]	
Upper Cretaceous	Maastrichtian	Lower	*Baculites clinolobatus*			(Eroded)				Trinidad Sandstone		Pierre Shale	Transition member	Pierre Shale	Upper part
			Baculites grandis	70	70					Pierre Shale	Shale		Sandstone and shale		
			Baculites baculus			Unnamed member									
	Campanian	Upper	*Baculites eliasi*	71		Pierre Shale	Salt Grass Member								
			Baculites jenseni										Richard Sandstone Member Sandstone and shale		
			Baculites reesidei	72			Lake Creek Member						Larimer and Rocky Ridge Sandstone Members		
			Baculites cuneatus										Sandstone and shale		
			Baculites compressus	73	75±2										
			Didymoceras cheyennense				Weskan Member				Tepee zone of Gilbert, (1897)				
			Exiteloceras jenneyi	74									Terry Sandstone Member		Middle part
			Didymoceras stevensoni										Shale		
			Didymoceras nebrascense	75	75.5±2[3]										
			Baculites scotti								Rusty zone of Gilbert, (1897)		Hygiene Sandstone Member		
			Baculites gregoryensis	76											
			Baculites perplexus[4]	77			Sharon Springs Member	Upper unit			Sharon Springs Member		Sandstone and shale		
			Baculites sp. (smooth)	78											
			Baculites asperiformis					Middle unit							
			Baculites mclearni	79	79.5[3]								Sharon Springs Member		Sharon Springs Member
		Lower	*Baculites obtusus*					Lower unit			Apache Creek Sandstone Member				
			Baculites sp. (weakly ribbed)	80							Transition member		Transition member		
			Baculites sp. (smooth)			Niobrara Formation (part)				Niobrara Formation (part)		Niobrara Formation (part)			
			Scaphites hippocrepis	81	81±2									Niobrara Formation (part)	

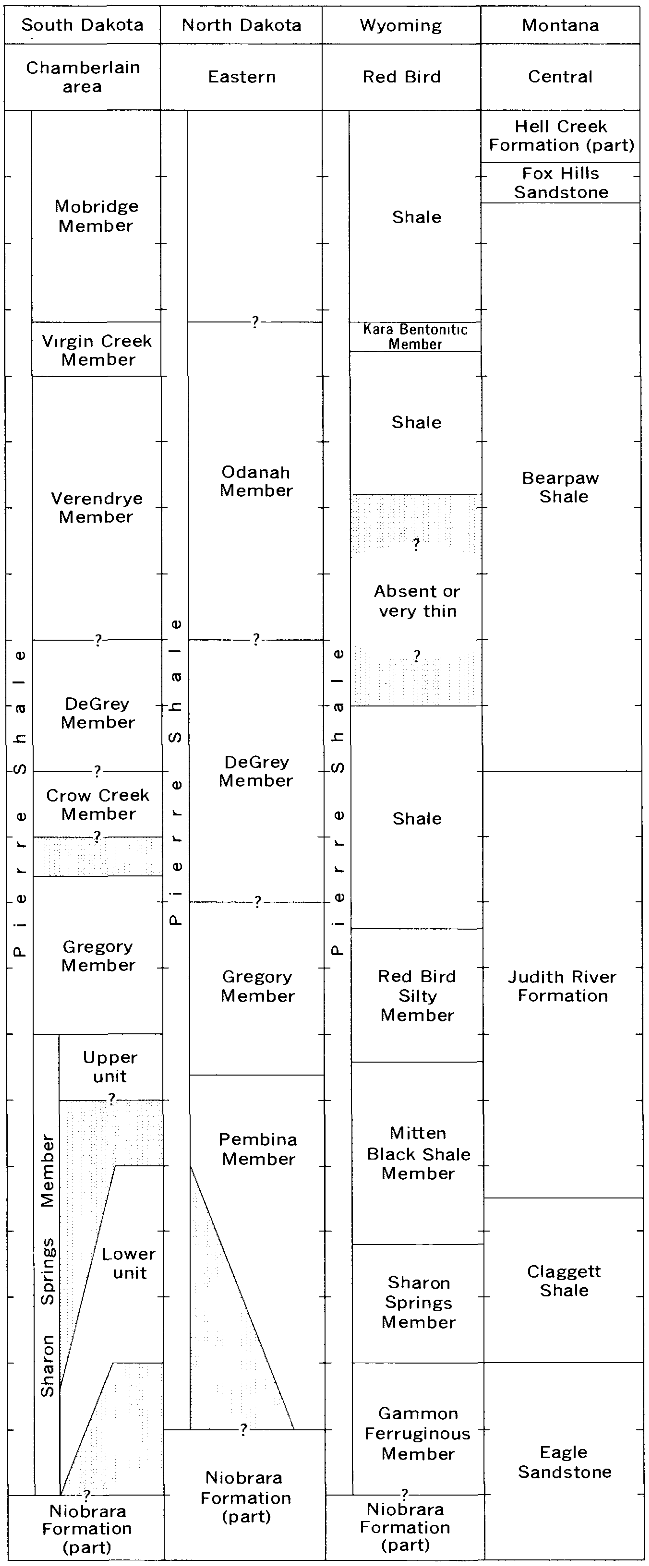
[1] Gill and Cobban (1966b).

[2] Dunham (1961).

[3] J. D. Obradovich (written commun., 1968).

[4] This zone, which includes 1,000 ft. of Pierre Shale in eastern Wyoming, is divisible into an early and late form of *Baculites perplexus*, separated by *B. gilberti*.

FIGURE 3. — Time span of the Pierre Shale in western Kansas and equivalent rocks in nearby States.



The lower unit contains numerous bentonite beds, one of which is at least 1 foot thick. Large fossiliferous gray- and brown-weathering limestone and purple-brown-weathering ironstone concretions, common in the lower unit of the Weskan, are not as abundant in the upper unit. The base of the Weskan is marked by long light-gray-weathering fossiliferous limestone lenses as much as 1 foot thick and 50 feet across. These were regarded by Elias (p. 62) as the top of the Sharon Springs Member.

The upper unit of the Weskan Member contains three conspicuous zones of large gray limestone concretions and two zones of purple-brown-weathering ironstone concretions. Locally, there are irregular masses of cavernous "tepee butte" limestone, which contains many pelecypods. Limestone concretions in the upper unit have a fairly large and diverse marine fauna. The shale in this part of the member contains many thin bentonite layers, none of which is more than 1 inch thick. The Weskan Member is conformably overlain by the Lake Creek Member and, in the Weskan, the contact is marked by one or more layers of closely spaced dark-gray compact limestone concretions that locally form ledges.

To date (1971) the name Weskan has been applied only to rocks in western Kansas, but the member can be recognized in the Pierre Shale of eastern Colorado where the name could appropriately be used. The Weskan is equivalent to most of the Tepee zone of Gilbert (1897, p. 3) in the Pueblo area of Colorado and to the Terry Sandstone Member of the Pierre Shale and part of the underlying and overlying unnamed shale members near Fort Collins, Colo. In the area of the type Pierre Shale along the Missouri River in central South Dakota, the Weskan is equivalent to the upper part of the Gregory Member, the Crow Creek Member, and the lower two-thirds of the DeGrey Member. The limestone concretion layer that forms the base of the Weskan contains poorly preserved inocerams and ammonites that suggest the zone of *Baculites gregoryensis* Cobban. The upper unit of the Weskan contains *Inoceramus vanuxemi* Meek and Hayden, *Placenticeras meeki* Boehm, and other fossils. (For a more complete list of fossils, see Elias, 1931, p. 62, 78, 93.) Near Wild Horse, Colo., gray limestone concretions, believed to be in the upper unit of the Weskan Member, contain a baculite that has the conspicuous ventral ribbing associated with *Inoceramus vanuxemi*. This association suggests the zone of *Didymoceras cheyennense* (Meek and Hayden) for that part of the member.

LAKE CREEK MEMBER

The name Lake Creek Member of the Pierre Shale was applied by Elias (1931, p. 93) to a 200-foot-thick sequence of dark-gray and black flaky shale containing ironstone concretions that is exposed along Lake Creek in northwestern Wallace County. The name Lake Creek has been used only in Wallace County, but it could be used equally well elsewhere in western Kansas and eastern Colorado. The sparseness of large limestone concretions distinguishes the Lake Creek Member from the overlying Salt Grass and underlying Weskan Members.

In addition to numerous small ironstone concretions, the Lake Creek Member contains many thin layers of concretionary limonite associated with small yellowish-white or light-gray limestone or marl concretions. The soft limy concretions are less than 0.1 foot thick and are unlike the large hard limestone concretions of the contiguous members. Lower and middle parts of the member contain numerous *Baculites reesidei* Elias. The upper part of the member has yielded *B. reesidei* at some localities and *B. jenseni* Cobban at others. (For a more complete list of invertebrate fossils, see Elias, 1931, p. 95.)

In east-central Colorado, the Lake Creek Member equivalent is the Larimer and Rocky Ridge Sandstone Members of the Pierre Shale (fig. 3) and the upper two-thirds of the unnamed sandstone and shale member that underlies them. The Lake Creek is also equivalent to about the lower three-fourths of the Verendrye Member of the type Pierre Shale in central South Dakota. Beds equivalent to the lower two-thirds of the Lake Creek are missing in the Black Hills area and in eastern Wyoming (Gill and Cobban, 1966a).

SALT GRASS MEMBER

The name Salt Grass Member of the Pierre Shale was given by Elias (1931, p. 101) to exposures of gray clayey shale in Salt Grass Canyon, the southern tributary to Goose Creek in secs. 1 and 12, T. 12 S., R. 42 W., Wallace County, Kans. The shale of this member is lighter than the dark-gray to black shale of the conformably underlying Lake Creek Member. The Salt Grass Member, about 60 feet thick, is divisible into three units, the lowest of which contains large fossiliferous limestone concretions and masses of tepee-butte limestone. The middle unit contains many layers of concretionary limonite, and the upper unit contains well-developed ledge-forming concretions with cone-in-cone structure. *Baculites reesidei* and *B. jenseni* are in the basal beds, and abundant *B. eliasi* Cobban are in the middle unit. Numerous other marine invertebrates found in the member have been listed by Elias (p. 102–104).

UNNAMED MEMBER

Overlying the Salt Grass Member of the Pierre Shale is a 500- to 600-foot-thick unit of gray and black shale that is only partly exposed in Wallace County and poorly exposed elsewhere in western Kansas. Elias (1931, table opposite p. 58) studied only the lower 30 feet and the uppermost exposed 90 feet of the member. The distribution, lithology, and fossil content of this member are largely unknown in western Kansas and eastern Colorado.

BEECHER ISLAND MEMBER

The Beecher Island Member, designated the uppermost unit of the Pierre Shale in western Kansas and eastern Colorado by Elias (1931, p. 123–124), consists of about 100 feet of light-gray shale that, being transitional between the clay shale of the Pierre and the sandy beds of the overlying Fox Hills Sandstone, is somewhat silty or sandy. It is exposed along the Arikaree River near the town of Beecher Island in southeastern Yuma County, Colo. The member is also exposed along the Arikaree River in Cheyenne County, Kans., where Cragin (1896, p. 52) long ago applied the name "Arickaree shales" to it. The member conformably overlies the unnamed shale member and is conformably overlain by the Fox Hills Sandstone.

The lower part of the member contains gray fossiliferous silty limestone concretions that weather yellowish gray, and the upper part of the member contains thin layers of limonite, rusty-weathering limestone, and concretions having cone-in-cone structure. The Beecher Island contains *Baculites grandis* Hall and Meek in the lower part and *B. clinolobatus* Elias in the upper part, in addition to *Tenuipteria fibrosa* (Meek and Hayden) and species of *Discoscaphites* and *Hoploscaphites*. A complete list of fossils in the Beecher Island Member is in Elias (1931, p. 130).

SHARON SPRINGS MEMBER

The type locality for the Sharon Springs Member is in western Logan County. Regarding this locality, Elias (1931, p. 63–64) stated: "The section of the Sharon Springs member that was originally studied by the writer and set apart from the rest of the Pierre shale lies east of McAllaster station in Logan County. On a left tributary to Smoky Hill river, about 2 miles east of McAllaster buttes * * *." The name of the member was taken from the town of Sharon Springs, in the center of Wallace County, about 25 miles southwest of the type locality.

The lithology of the Sharon Springs is different from that of the rest of the Pierre Shale, a fact which led Elias to give the Sharon Springs formal member status. He (1931, p. 58–59) described it as follows:

> The member consists of black, slightly bituminous shale, with which is interbedded dark-gray shale in the lower portion and about in the middle of the member. The shale is full of the remains of small fishes, which were probably the source of the bituminous matter in it. The small scales and bones of fishes can be detected in nearly every piece of the black shale. The Sharon Springs member can be conveniently subdivided into Upper and Lower Sharon Springs. The Upper Sharon Springs, which is about 65 feet thick, can be recognized by the abundance of concretions, many very large (pl. V), whereas in the Lower Sharon Springs the concretions, none of which are large, are very scarce and in many places practically absent. The shale of the Upper Sharon Springs is also somewhat different from that of the Lower Sharon Springs. Some beds of the former resist weathering more than the ordinary shale of the formation and appear as slightly prominent bands in the outcrops.

For the present investigation a threefold division of the Sharon Springs is recognized (fig. 4). In this report, the lower unit, about 115 feet of dominantly dark-gray soft flaky shale having a few concretions of yellow chalky limestone, is referred to as the "dark soft shale unit." The middle unit, called the "organic-rich shale unit," consists of about 90 feet of hard buttress-weathering shale, is rich in organic material and in varied limestone concretions, and has yielded abundant vertebrate and a few invertebrate fossils. The upper unit, about 10 feet of hard-platy-weathering slightly phosphatic shale that contains numerous layers of soft highly weathered phosphate nodules, is referred to as the "phosphatic shale unit."

DARK SOFT SHALE UNIT

The most complete exposure of the lower unit of the Sharon Springs Member is along the west valley wall of Burris Draw (loc. 1) about 4 miles southwest of Elkader. At this locality, the contact between the Sharon Springs and the Smoky Hill Chalk Member of the Niobrara Formation is well exposed (fig. 5), and approximately 90 feet of the lower unit of the Sharon Springs Member can be measured (fig. 6). The lower unit consists largely of light- to medium-gray, light-olive-gray, and black shale and, near the top, contains a thin dark-yellowish-orange chalky concretionary layer. As a result of pre-Tertiary(?) oxidation and weathering, certain layers in the shale were altered from various shades of gray to dark yellowish orange, causing the upper part of the exposure to appear banded. The shale is soft and weathers readily to a deep soil which obscures the bedrock.

At localities 1, 4, and 5 the lower unit of the Sharon Springs Member contains some thin beds of hard buttress-weathering organic-rich shale (measured sections, and figs. 4, 5, and 7) that is quite similar to the overlying organic-rich shale unit. It is quite possible that, if these hard shales could be traced westward, they would be found to be tongues of the overlying unit. Thin persistent bentonite beds are also characteristic of the lower unit of the Sharon Springs in many areas outside western Kansas. At the Burris Draw section (loc. 1) there are only four thin bentonite beds, whereas 30 miles to the northwest at locality 5, there are nine beds, some as much as 1 foot thick, in the lower 20 feet of the unit. (See measured sections.) The lower unit of the Sharon Springs Member is in northern Phillips County, Kans., where about 55 feet of dark soft shale is interbedded with 14 thin nonswelling bentonite beds which appear as light bands on the outcrop (fig. 8) and range in thickness from an inch or two to about half a foot. The few fossils from concretions, which are sparse in the lower unit of the Sharon Springs, indicate that this unit was deposited during the range of the ammonites *Baculites* sp. (weakly ribbed) and *Baculites obtusus* (fig. 3 and pl. 1). *B. obtusus* is in the organic-rich shale unit at several localities along the Front Range in Colorado and around the Black Hills in eastern Wyoming and western South Dakota. Its presence in shales that are rich in organic matter in western areas and below shales that are rich in organic matter in eastern areas, such as western Kansas, clearly indicates that deposition of the organic-rich shale unit began earlier in the western areas and that the organic-rich shale unit decreases in age from west to east (fig. 9). Subsurface studies in the Great Plains permit delineation of the western edge of the organic-rich shale unit, which was deposited during the range of *B. obtusus*. Figure 10 shows the inferred position of the shoreline during the range of *B. obtusus* and the western edge of the organic-rich shale unit. At present, the eastern limit of this unit cannot be accurately determined, but stratigraphic and faunal data indicate that it was somewhere in eastern Colorado. The dark soft shale unit grades laterally into and intertongues with the organic-rich shale unit toward the west and northwest.

ORGANIC-RICH SHALE UNIT

Approximately 90 feet of dark-brownish-black organic-rich shale containing abundant layers of closely spaced limestone concretions of various shapes and sizes constitutes the middle unit of the Sharon

Springs Member in Wallace and Logan Counties. The organic material in the shale, which consists largely of macerated fish scales and bones, may also have been partly derived from marine and terrestrial plants. This unit of the Sharon Springs Member is best and most completely exposed on the north face of McAllaster Buttes. Other good exposures are about 1.5 miles north of McAllaster Buttes, about 2 miles northeast of McAllaster near the abandoned towns of Lisbon and Sheridan (fig. 1), and at Devils Halfacre (loc. 6) southeast of the town of Sharon Springs.

The organic-rich unit is harder and resists weathering to a greater degree than the upper or lower units. It contains on the average about 4.9 percent organic carbon, and some beds near the top contain as much as 9.6 percent (table 1). Though test-hole cuttings from the phosphatic shale unit contain less than 1 percent organic carbon, selected outcrop samples contain about 6 percent, and the organic-rich shale unit has an average organic-carbon content of 3.8 percent. Shales high in organic carbon are darker than those low in organic carbon and are more resistant to erosion, weathering to tough papery flakes. They contain large amounts of jarosite, limonite, and gypsum, minerals that coat joint surfaces and bedding planes and are thought to be the weathering products of pyrite. Some gypsum crystals in the upper part of the unit form interlocking rosettes as much as 1 foot in diameter (fig. 1). These rosettes were noted by Cope (1872a, p. 326), and those from the McAllaster area, by Elias (1931, pl. 13, figs. *B*, *C*) and Tolsted and Swineford (1957, p. 40).

The upper part of the organic-rich shale unit contains numerous layers of closely spaced limestone concretions. Some of the concretions are irregular in shape and are composed of dense dark-gray to black limestone (fig. 12). These concretions weather light gray to white, are nonfossiliferous, and are so hard that they can be broken only with great difficulty. They are characteristic of the organic-rich shale unit in Kansas, Colorado, southeastern Wyoming, and western South Dakota. Gigantic septarian concretions, also characteristic of the Sharon Springs at many localities, crop out about 20 feet below the top of the unit. These concretions, which are closely spaced and form ledges, are as much as 3 feet thick and at least 20 feet in diameter and have internal fractures that are almost completely filled with dark-brown fibrous calcite (fig. 13). Bluish-gray barite is in these and other septarian concretions near the top of the unit. Barite crystals from this area were first reported by LeConte (1868, p. 11). Mudge (1876, p. 215) mentioned a rich-amber-colored barite crystal weighing 8¼ pounds that had been collected from the unit near the old town of Sheridan. Elias (1931, p. 61) noted, "A rare transparent variety of the local barite is of beautiful wine-brown color." Ovate to spherical septarian concretions are found near the top of the organic-rich shale unit. Fractures in these concretions are not completely filled but generally contain a thin lining of fibrous calcite coated with pale-yellow to transparent calcite crystals and, rarely, bluish-gray barite crystals. Limestone with cone-in-cone structure is common in the unit and occurs as flat tabular masses (fig. 14) and as rinds or envelopes which enclose septarian limestone concretions.

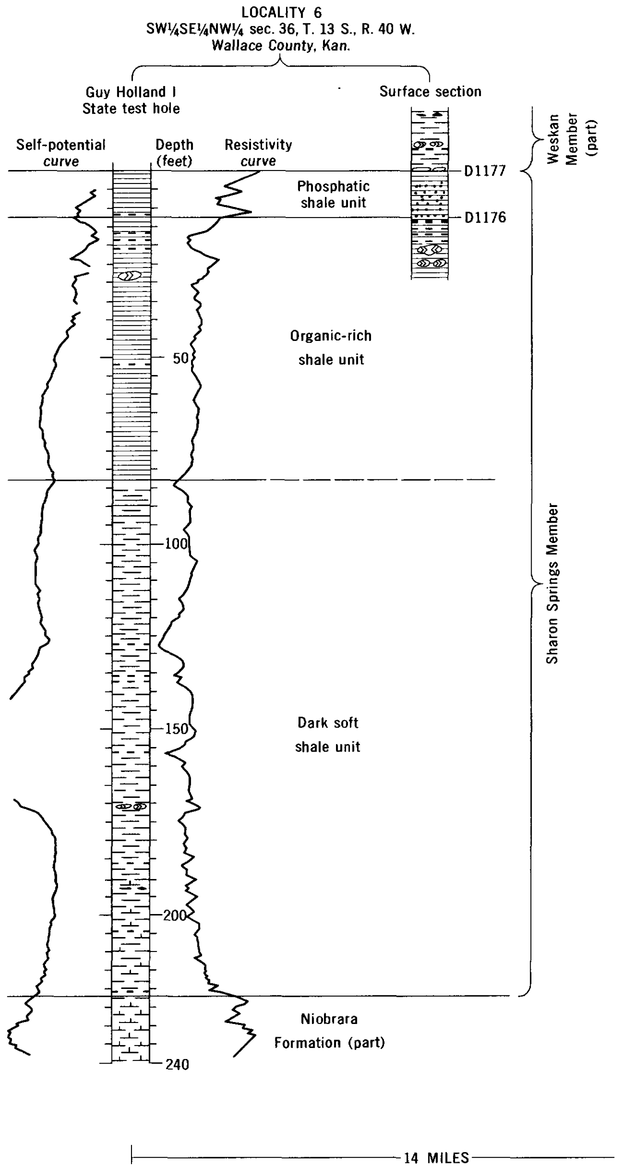


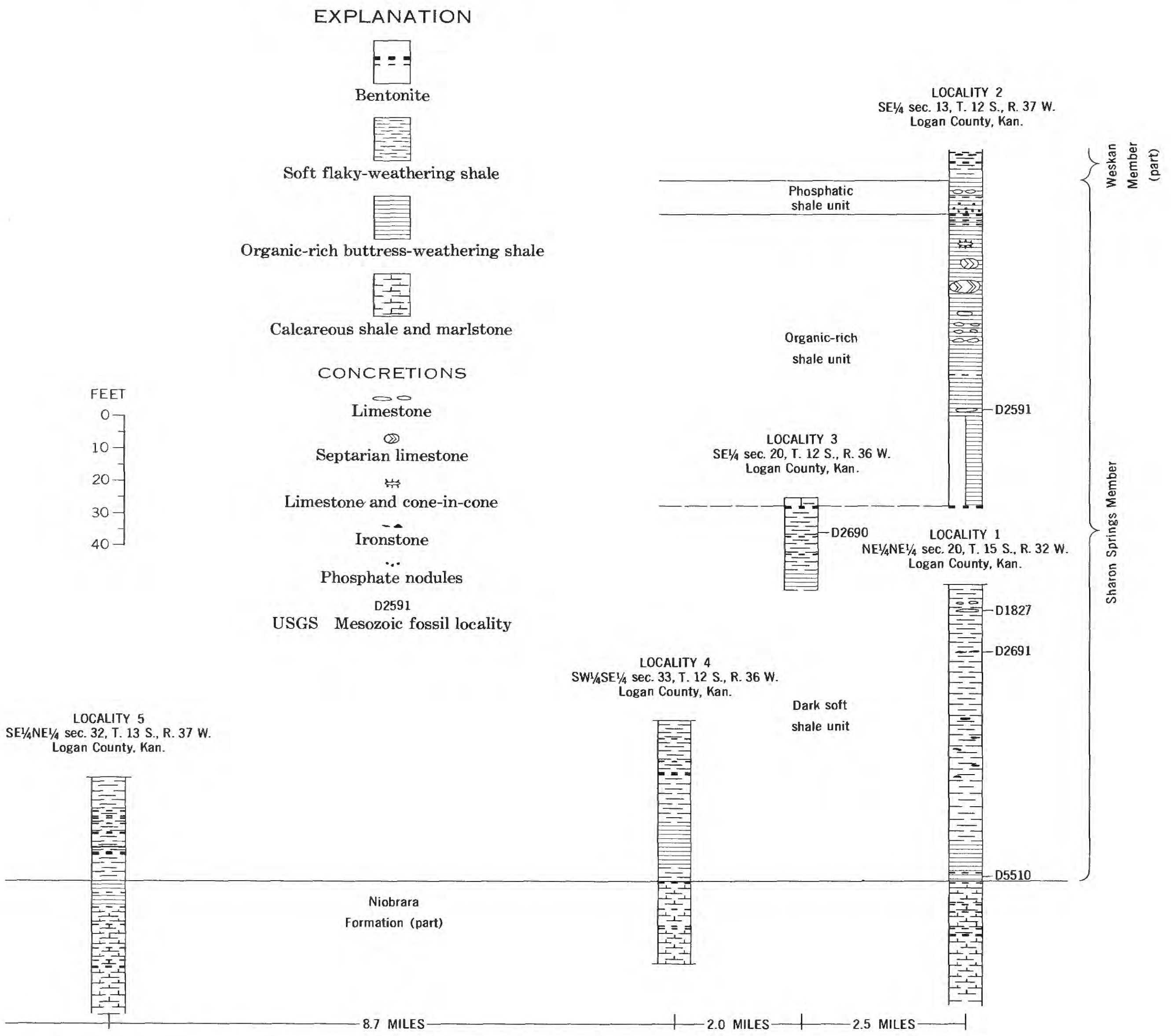
FIGURE 4. — Graphic sections and electric

Thin persistent pale-yellowish-gray nonswelling bentonite beds are in the upper part of the organic-rich shale unit. The nonresistant character of the bentonite, because it contrasts sharply with the resistance of the enclosing hard shale, gives the outcrop (fig. 15) a stairstep form.

The organic-rich shale unit contains fish bones and scales and the remains of large marine reptiles, but it does not contain many invertebrate fossils that are useful for correlation. Though megafossils are rare, two discoveries are spectacular. In the section at McAllaster Buttes, a gray limestone concretion (USGS Mesozoic loc. D2951) about 1 foot thick and 6 feet in diameter yielded 1,553 specimens of *Baculites asperiformis* Meek which are 2–37 mm (millimeters) in diameter. A limestone concretion of similar size 3 miles southwest of McAllaster yielded 1,597 specimens of *B. asperiformis* which are 0.9–33.5 mm in diameter.

The unit was probably deposited during the ranges of *Baculites mclearni* and *B. asperiformis;* only *B. asperiformis* is in collections from western Kansas (pl. 2). Figure 16 shows the inferred position of the shoreline and the inferred west edge of the organic-rich shale unit during the range of *B. asperiformis.*

On electric logs the organic-carbon content of the Sharon Springs is reflected by a marked increase in the electrical-resistivity and electrical-induction



log of Sharon Springs Member of Pierre Shale in Wallace and Logan Counties, Kans.

curves and by a similar but greater response on the gamma-ray curve. The electric and gamma-ray log cross section (fig. 17) shows the subsurface correlation of the Sharon Springs Member from Wallace County, Kans., to Fall River County, S. Dak. Fossils indicate that lines bounding units of high radioactivity and resistivity in the Sharon Springs Member are not time-stratigraphic markers. In western Kansas, for example, *Baculites obtusus* (pl. 1) is in the dark soft shale unit of the Sharon Springs, and *B. asperiformis* (pl. 2) is in the organic-rich shale unit of the member. Along the Front Range in central Colorado, and around the Black Hills in eastern Wyoming and western South Dakota, *B. obtusus* is restricted to the organic-rich shale unit of the Sharon Springs, and *B. asperiformis* occurs in younger beds which are not typical of Sharon Springs lithology (Gill and Cobban, 1966b, pl. 2). Because organic-rich shale typical of the Sharon Springs was deposited in the Colorado–Wyoming–South Dakota area earlier (Range Zone of *B. obtusus*) than in Kansas, the organic-rich shale unit must become younger in an easterly and southeasterly direction (fig. 9).

PHOSPHATIC SHALE UNIT

The phosphatic shale unit of the Sharon Springs Member, which conformably overlies the organic-rich shale unit, consists of 10–13 feet of dark-brownish-black to grayish-brown shale that contains as many as 10 thin layers of dark-bluish-gray- to yellowish-gray-weathering phosphate nodules. The shale is moderately hard, contains fish scales and bones, and weathers into irregular plates that, together with the phosphate nodules, litter the outcrop. It also contains several thin pale-yellow- to orange-weathering nonswelling bentonite beds (fig. 18). The unit is overlain by a 1-foot-thick bed of shaly to laminated concretionary limestone (fig. 19) which was regarded as the top of the Sharon Springs Member by Elias (1931, p. 62) but is placed in the overlying Weskan Member by us.

FIGURE 5. — Contact of Sharon Springs Member (above) of Pierre Shale and Smoky Hill Chalk Member (below) of Niobrara Formation exposed in Burris Draw (loc. 1).

The upper part of the phosphatic shale unit contains some thin brownish-gray shale beds that weather light gray to white and that are very porous and light in weight (specific gravity about 1.4). Elias (1931, p. 59), describing this peculiar shale at considerable length, remarked,

> Another kind of shale, which somewhat resembles the softer samples of Mowry shale of the Graneros and is remarkably light in weight, appears locally in slightly prominent bands near the top of the Upper Sharon Springs. This shale is light gray to nearly white when much weathered, and is porous and unpleasant to touch, not being "soapy" like the ordinary Pierre shale, but somewhat "chalky." However, no calcium carbonate or dolomite could be detected in this rock.

Samples of this shale contain slightly more than 1.5 percent P_2O_5, which apparently accounts for some of the peculiar properties of the shale.

Elias (1931, p. 61) described the phosphate nodules in the upper part of the unit as concentric concretions that are "* * * nearly spherical and are composed of calcite, rusty limonite, gypsum and soft, rotten shale. They are fragile and usually have the outer crust made up of gypsum and this crust filled with rotten shale * * *." The concretions are much as Elias described them (fig. 20) except that, instead of being cores of rotten shale, they are highly weathered phosphate nodules. Sawed surfaces (fig. 21) of the nodules show pronounced concentric bands of light and dark phosphatic material. The outside of the nodule consists of concentric layers of white gypsum and dark clay containing about 0.15 percent P_2O_5, as determined volumetrically by G. D. Shipley of the U.S. Geological Survey. The inner light-brown bands contain about 0.9 percent P_2O_5, and the dark-brown core, about 2.6 percent. Fresh phosphate nodules are dark brown to brownish black, weather bluish gray, and contain as much as 16 percent P_2O_5.

The phosphate nodules generally occur in thin layers separated by a few inches of shale; this bedding suggests slow uniform deposition. Locally, as in the SW¼ sec. 1, T. 12 S., R. 37 W., Logan County, bottom currents have eroded preexisting layers of phosphate nodules and concentrated them as lenslike masses of phosphate pebble conglomerate. The

FIGURE 6. — Outcrop of dark soft shale unit of Sharon Springs Member of Pierre Shale exposed along west side of Burris Draw (loc. 1).

origin of the phosphate nodules and phosphatic shale is unknown; however, the shale seems to have accumulated very slowly, in contrast with the rest of the Sharon Springs Member and the Pierre Shale as a whole. This interpretation is in general agreement with that of Goldman (1922) on the significance of phosphate-rich beds.

The phosphatic shale unit is conformably overlain by soft bentonitic shale of the Weskan Member of the Pierre Shale (figs. 19, 22). At most localities the contact is marked by a layer of shaly to laminated light-gray-weathering limestone concretions. At Devils Halfacre, locality 6 (see measured section), a 0.2-foot-thick bed of gypsum and soft white basaluminite ($2Al_2O_3 \cdot SO_3 \cdot 10H_2O$) marks the contact between the two members.

RATE OF SEDIMENTATION

Fossils from the Sharon Springs Member in western Kansas and elsewhere in the western interior indicate that the member was deposited during the range of eight ammonite zones. In western Kansas the dark soft shale unit of the Sharon Springs Member is about 115 feet thick and contains the Range Zones of *Baculites* sp. (weakly ribbed) and *B. obtusus*. The organic-rich shale unit is about 90 feet thick and contains the Range Zones of *Baculites mclearni* and *B. asperiformis*. The phosphatic shale unit, which is approximately 10 feet thick, is represented by the range zones of the following fossils: A smooth unnamed baculite, an early form of *B. perplexus*, *B. gilberti*, and a late form of *B. per-*

FIGURE 7. — Hard buttress-weathering shale rich in organic material, fish scales, and bones in lower unit of Sharon Springs Member of Pierre Shale at locality 1. Hammer marks position of a 0.2-foot-thick yellowish-gray nonswelling bentonite bed.

FIGURE 8. — Northeasternmost outcrop of Sharon Springs Member of Pierre Shale in Kansas. Exposed along east bank of Prairie Dog Creek about 1 mile east of town of Long Island in the E½SE¼ sec. 24, T. 1 S., R. 20 W., Phillips County, Kans. Contact with Niobrara Formation is near water level. Light bands on outcrop are bentonite beds.

plexus. In a previous investigation, we concluded that each of the above ammonite zones represents about 500,000 years (Gill and Cobban, 1966b, p. A36). If a similar relationship of ammonite zones to time is applicable to this area, about 4 million years was required to deposit the type Sharon Springs Member. On the basis of the number of ammonite zones, this figure can be broken down to 1 million years for the deposition of the dark soft shale unit, 1 million years for the organic-rich shale unit, and 2 million years for the phosphatic shale unit. Depositional rates would then be 115 feet per million years (35 mm per 1,000 yr) for the lower unit of the Sharon Springs Member, 90 feet per million years (27 mm per 1,000 yr) for the middle unit, and 5 feet per million years (about 1.5 mm per 1,000 yr) for the upper unit.

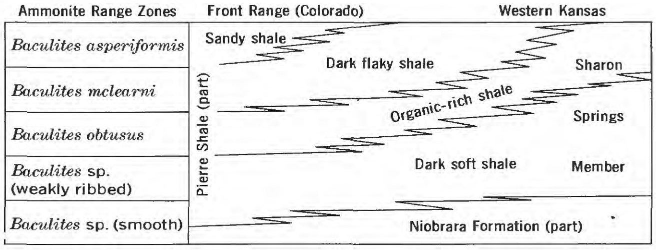


FIGURE 9. — Diagram showing eastward and upward migration of organic-rich shale unit of Sharon Springs Member of Pierre Shale.

Figure 10. — Paleogeographic map of early stage of deposition of Sharon Springs Member of Pierre Shale (range of *Baculites obtusus*, late early Campanian), showing western edge of organic-rich shale unit.

Figure 12. — Irregularly shaped light-gray-weathering concretions of dense dark-gray limestone from upper part of organic-rich shale unit at McAllaster Buttes (loc. 2).

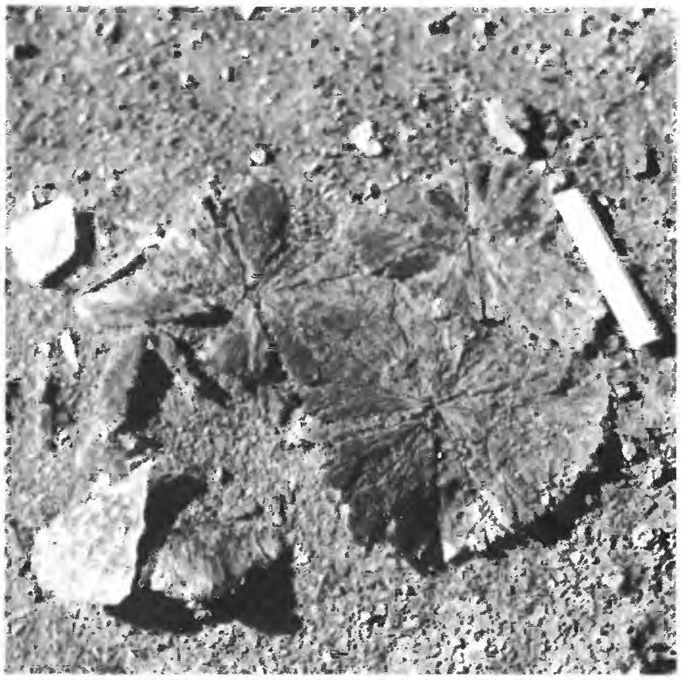


Figure 11. — Gypsum rosettes from upper part of organic-rich shale unit of Sharon Springs Member of Pierre Shale at McAllaster Buttes. Rule is 7 inches in length.

Figure 13. — Large ledge-forming septarian limestone concretions about 20 feet below the top of the organic-rich shale unit of Sharon Springs Member in vicinity of McAllaster Buttes. These concretions contain thick septa of light-brown fibrous calcite and have a botryoidal lower surface and a flat or concave upper surface. Locally they are more than 3 feet thick and 20 feet in diameter.

FIGURE 14. — Tabular bed of cone-in-cone limestone in upper part of organic-rich shale unit of Sharon Springs Member of Pierre Shale at McAllaster Buttes.

FIGURE 15. — Contact of phosphatic shale unit with organic-rich shale unit of Sharon Springs Member of Pierre Shale at Devils Halfacre (loc. 6). Contact is at the top of a 0.4-foot-thick bentonite bed which is second from the top of six bentonite beds visible in the center of the photograph. Upper slope of outcrop is littered with plates of hard phosphatic shale and nodules of phosphate.

FIGURE 16. — Paleogeographic map of late stage of deposition of Sharon Springs Member of Pierre Shale (early late Campanian) showing eastward shift of west edge of the organic-rich shale unit.

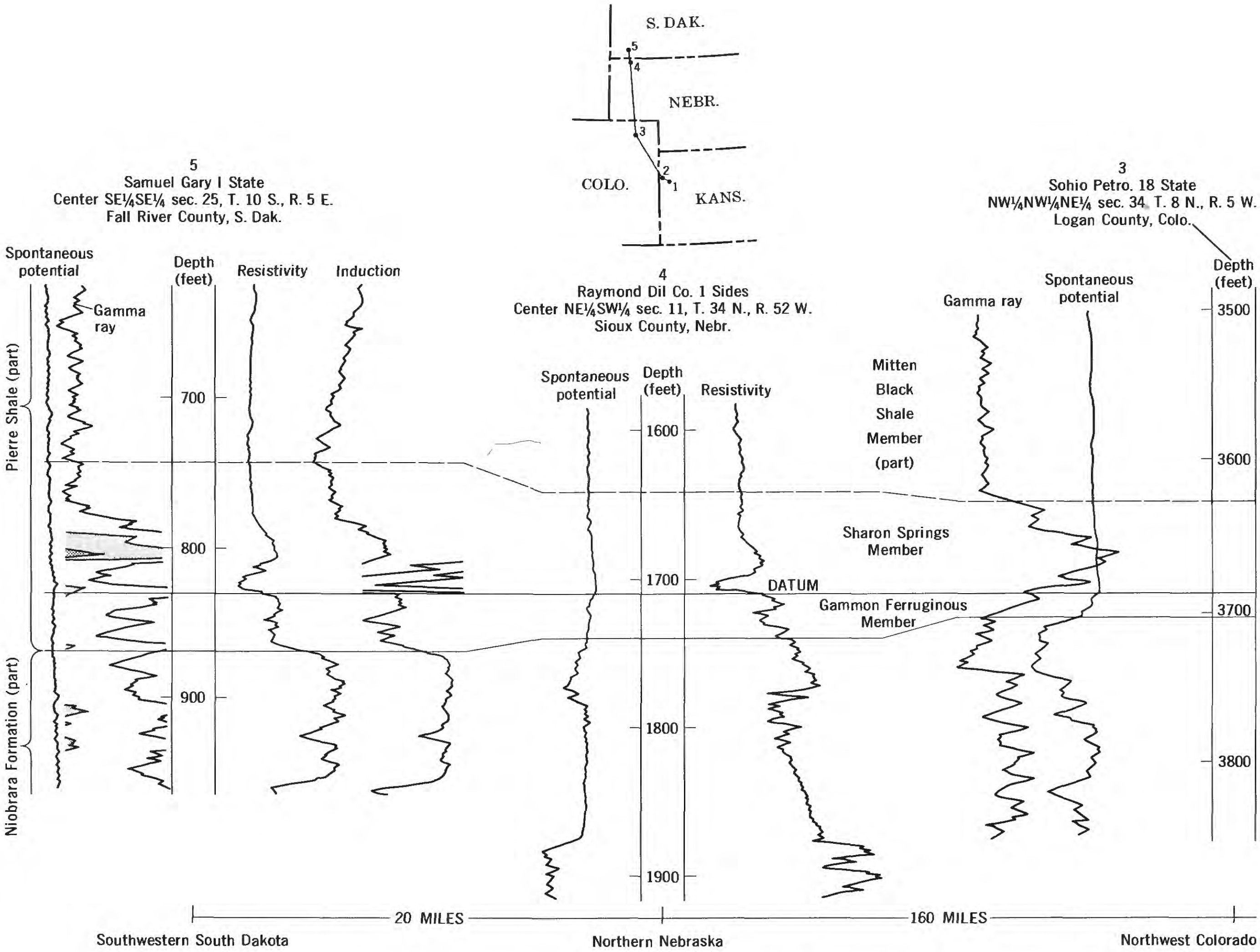


FIGURE 17. — Electric and gamma-ray log correlation of Sharon Springs

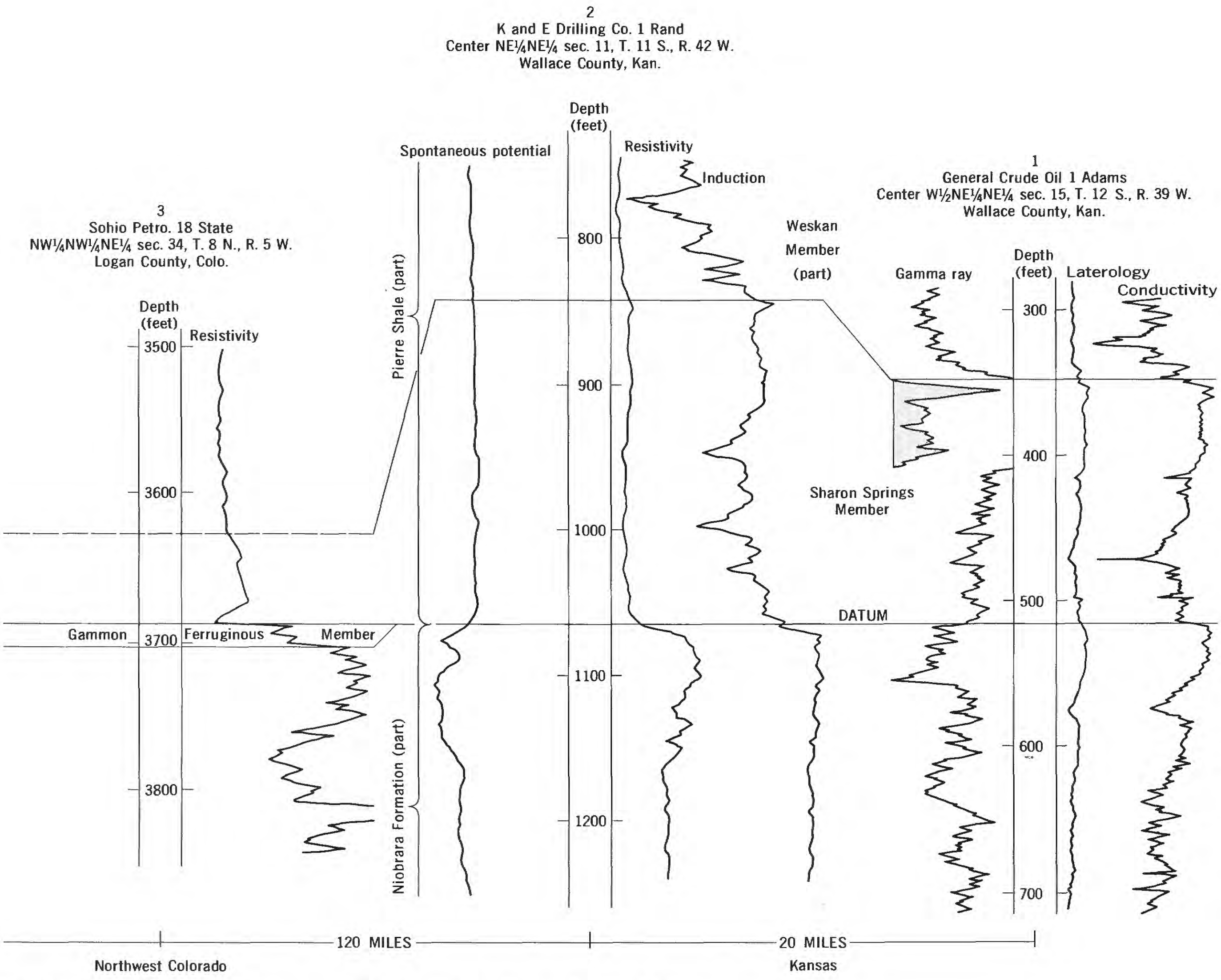
Figure 23 shows diagrammatically the thickness and time relationship between the Sharon Springs of western Kansas and time-equivalent rocks in Colorado and Wyoming. If the upper unit of the type Sharon Springs Member was deposited at a rate of 5 feet per million years, time-equivalent strata at Pueblo, Colo., and at Red Bird, Wyo., were deposited, respectively, 20 and 100 times as rapidly.

The lower and middle units of the Sharon Springs are estimated to have accumulated at a rate of about 115 and 90 feet per million years, respectively. Time-equivalent rocks at Red Bird accumulated at a rate of about 75 feet per million years, whereas those at Round Butte in northern Colorado (fig. 23) were deposited at a rate of about 400 feet per million years. At Red Bird, on the southwestern flank of the Black Hills uplift, the average rate of sedimentation for the entire Pierre Shale is calculated to have been about 340 feet per million years (Gill and Cobban, 1966b, p. A42), which is considerably more rapid than the deposition of the Sharon Springs Member in western Kansas.

COMPOSITION

PREVIOUS STUDIES

Investigations of the chemical composition of Cretaceous rocks in western Kansas have been restricted



Member of Pierre Shale in Kansas, Colorado, Nebraska, and South Dakota.

largely to the selenium and uranium content of the lower part of the Pierre Shale and the Niobrara Formation, as well as the soils derived from them. Byers (1935, p. 34; 1936, p. 24–50) showed that samples of the Sharon Springs Member of the Pierre Shale collected at McAllaster Buttes and elsewhere in western Kansas contained 6–23 ppm (parts per million) selenium and that vegetation growing on these rocks contained as much as 3,700 ppm selenium. Landis (1959, p. 304, pl. 35) showed that the organic-rich shale unit of the Sharon Springs contained 10–40 ppm uranium. The Sharon Springs Member and its lateral equivalents are abnormally radioactive over large areas in the Great Plains. Radioactivity and uranium content have been reported by Tourtelot (1956) for parts of northeastern Colorado, Nebraska, and South Dakota; by Kepferle (1959) for South Dakota and northeastern Nebraska; and by Landis (1959) for eastern Colorado and western Kansas. After a study of surface and subsurface data, the above workers concluded that, on the average, the Sharon Springs Member contains between 10 and 15 ppm uranium and has some thin beds containing as much as 250 ppm uranium. Landis (p. 304, pl. 35) collected four channel samples from the upper 11 feet of the organic-rich shale unit of the Sharon Springs at McAllaster Buttes (loc. 2, this rept.) that contained about 0.004 percent uranium.

FIGURE 18. — Phosphatic shale unit of Sharon Springs Member of Pierre Shale showing buttress-weathering character of shale and numerous thin layers of phosphate nodules, locality 6. Light bands to left of pick handle are thin nonswelling bentonite beds.

FIGURE 19. — Contact of phosphatic shale unit of Sharon Springs Member with overlying Weskan Member of Pierre Shale, SE¼ sec. 1, T. 12 S., R. 37 W., Logan County, Kans., about 2 miles north of McAllaster Buttes. Contact is at base of yellowish-gray laminated tabular limestone concretion.

MINERALOGY

Compositional data from this study are reported in tables 1–5. X-ray, six-step spectrographic analyses, and partial chemical analyses in table 1 are for samples of cuttings from the Guy Holland test hole, and data in table 2 are for samples from outcrops within a few hundred feet of the test hole. Table 3 gives X-ray analyses for samples of the Pierre Shale at other localities, and table 4 gives X-ray analyses for bentonite beds from both the test hole and the outcrops in western Kansas. Localities and stratigraphic relations of most of the samples are in the measured sections or at the bottom of table 3.

The Guy Holland test hole (loc. 6) started at the Weskan–Sharon Springs contact, penetrated approximately 220 feet of Sharon Springs and about 80 feet of the Niobrara Formation, and bottomed at a total depth of 300 feet. Samples of cuttings were collected by W. A. Cobban for each 5 feet of drill-hole depth, except near the bottom where a 10-foot sampling interval was used. Mineralogical analyses were only made of every other 5-foot sample from the middle depths of the test hole because of the apparent homogeneity of the material. For the mineralogical analyses, particles of bentonite were separated from the shale and analyzed separately (table 4).

Mineralogical composition was determined mostly by the X-ray diffraction methods described by Schultz (1964). Amounts of carbonate minerals were calculated from amounts of mineral carbon, and amounts of organic matter (tables 1 and 2) were calculated by multiplying the determined organic-carbon values by 1.4, a factor derived from unpublished studies of organic matter from the Pierre Shale.

FIGURE 20. — Phosphate nodule enclosed in gypsum and clay rinds, typical of nodules described by Elias (1931, p. 61) as concentric concretions, from phosphatic shale unit of Sharon Springs Member of Pierre Shale, locality 6.

NIOBRARA FORMATION

Niobrara samples from the Guy Holland test hole contain much more calcite and therefore lesser amounts of most other minerals than samples from the Sharon Springs, but the amount of pyrite and organic matter is about the same. Mixed-layer clay in the Niobrara, like that in the calcareous beds at the base of the Sharon Springs, contains a large proportion of nonexpanding illitelike layers.

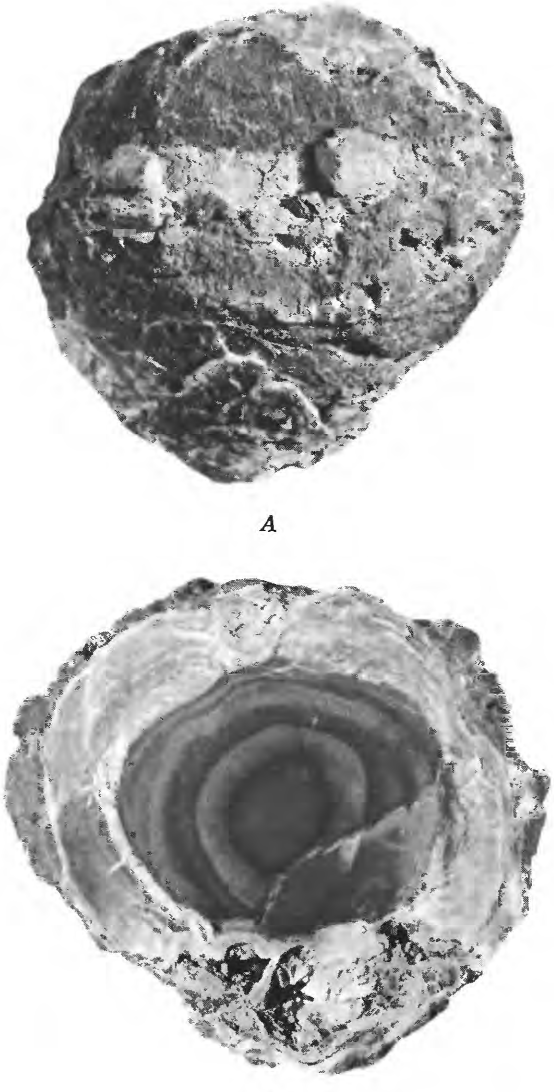


FIGURE 21. — Phosphate nodules from phosphatic shale unit of Sharon Springs Member of Pierre Shale. Natural size. *A*, Weathered phosphate nodule from phosphatic shale. *B*, Sawed surface of phosphate nodule. Outer rind of white gypsum and dark clay contains 0.16 percent P_2O_5, inner light-brown bands contain 0.93 percent, and dark-brown core contains 2.62 percent.

SHARON SPRINGS MEMBER OF THE PIERRE SHALE

Most samples of shale from the Sharon Springs of western Kansas (tables 1–3) contain 50–70 percent clay minerals. The clay-mineral fraction is composed mostly of montmorillonite and mixed-layer clay, plus about 20 percent illite, 10 percent kaolinite, and, in the fresh test-hole cuttings, a few percent chlorite. Montmorillonite and mixed-layer components probably represent a single mixed-layer clay with varying proportions of swelling montmorillonitelike layers and nonswelling illitelike layers. The low proportion of montmorillonite indicates that nonexpandable illitelike layers are abundant in the mixed-layer clay, especially in the calcareous samples in the lower part of the member (table 1). Lithium treatment of the shale samples (discussed in "Bentonites") indicates that most of the expandable layers of the mixed-layer clay are beidellitelike rather than truly montmorillonitic.

Nonclay minerals from the fresh test-hole cuttings of the Sharon Springs consist of quartz, a few percent feldspars, and about 5 percent each of dolomite, pyrite, and organic matter. Near its base, where the shale grades into the Niobrara Formation, the member contains several percent calcite.

Weathering effects are evident in most outcrop samples from the Sharon Springs Member. Each of the top two test-hole samples contains only about 1 percent organic matter and is conspicuously lighter in color than samples from below, owing to near-surface oxidation of organic matter (table 1). The top two samples also contain jarosite rather than pyrite, which is at greater depths. Nearby outcrop samples (table 2) contain jarosite and some gypsum but are not conspicuously bleached. The mineralogical data in tables 1 and 2 suggest other effects of near-surface weathering. Chlorite is not found above a depth of 20 feet, dolomite not above 25 feet, and pyrite not above 15 feet in the test hole, and none of the three minerals is found in nearby surface samples. In subunits 1 and 3 at locality 6, outcrop samples collected from a deep gully below the layer of large concretions (fig. 4) are stratigraphically equivalent to samples that are from beds below the same concretion layer in the test hole at a depth of 25–35 feet and that contain pyrite, chlorite, and dolomite.

Most other outcrop samples from the Sharon Springs in western Kansas (table 3) show similar effects of weathering. The two Sharon Springs samples that do contain chlorite or dolomite are from the light- to medium-gray beds in the dark soft shale unit of the member. Sulfuric acid from oxidized pyrite apparently leaches fairly soluble dolomite and

FIGURE 22. — Contact of phosphatic shale unit of Sharon Springs Member of Pierre Shale with overlying soft dark shale of Weskan Member. Large blocks littering outcrop are float from Ogallala Formation which caps McAllaster Buttes, locality 2.

chlorite only from the dark-gray fissile organic-rich pyritic Sharon Springs shales. Iron and sulfur reprecipitates as jarosite, limonite, and gypsum. The analyzed jarosite from the outcrop sample of stratigraphic subunit 15 near the test hole was a hydrogen variety [$HFe_3(SO_4)_2(OH)_6$] rather than the more common potassium variety [$KFe_3(SO_4)_2(OH)_6$].

UPPER MEMBERS OF THE PIERRE SHALE

The samples from the Weskan, Lake Creek, and Salt Grass Members of the Pierre Shale are more montmorillonitic than typical Sharon Springs shale (table 3). Several contain chlorite and dolomite, and thus they seem not so susceptible to weathering, probably because the shales are more montmorillonitic and are therefore less permeable to surface solutions and because they contain less acid-forming pyrite. These differences between the Sharon Springs and overlying members of the Pierre in western Kansas are generally comparable to those observed farther north, in Nebraska, South Dakota, Wyoming, and Montana (Tourtelot and others, 1960; Schultz, 1965).

BENTONITES

Bentonites in the Sharon Springs Member and the Niobrara Formation of western Kansas differ from those in the Weskan Member and from most other bentonites in that they contain significant amounts of kaolinite and in that the montmorillonite composing the remainder of the clay fraction tends to be an aluminum-interlayered beidellitic variety (table 4). These features, which seem to be most strongly developed in the thinner bentonites, are explained with reference to the diagram of the montmorillonite structure in figure 24.

The montmorillonite layer is composed of a layer of alumina octahedrons (an Al^{+3} ion surrounded by four O^{-2} ions and two $(OH)^{-1}$ ions) between sheets of silica tetrahedrons (a Si^{+4} ion surrounded by four O^{-2} ions). Each oxygen at the apex of the silica tetrahedron is shared with an alumina octahedron. As illustrated, the positive charge on the Si^{+4} and Al^{+3} cations is exactly balanced by the negative charge on the O^{-2} and $(OH)^{-1}$ anions. However, substitutions of cations of lower charge for the Si^{+4} and Al^{+3} (fig. 24) produce a net negative layer charge. In the octahedral layer, Mg^{+2} replaces Al^{+3}, and the resultant mineral is montmorillonite; in the tetrahedral layer, Al^{+3} replaces Si^{+4}, and the resultant mineral is beidellite. The net negative layer charge caused by substitutions within the layer must be balanced by cations, most commonly Na^{+1} or Ca^{+2}, in interlayer positions. The thickness of the montmorillonite layer (fig. 24) is about 9.6 *A* (angstroms), but this thickness applies only at extremely low humidity or when the clay is heated to a few hundred degrees centigrade. Under normal room conditions, water molecules from the air are absorbed between the layers and so the layers swell to 12–15 *A* in thickness.

Many Sharon Springs and Niobrara bentonites from western Kansas contain montmorillonitic clay in which Al^{+3}, rather than Na^{+1} or Ca^{+2}, is the principal interlayer cation. The Al^{+3} forms fairly stable Al-hydrate complexes that are not dehydrated at 300°C, or even at 550°C in some samples, and the basal spacing of the heated sample remains notably greater than 9.6 *A*. Such abnormally high basal spacings on X-ray diffraction patterns for heated clay are the basis for evaluations of the interlayer aluminum complexes reported in table 4.

Beidellite is distinguished from montmorillonite (table 4) on the basis of the lithium test of Greene-Kelly (1955). In the montmorillonite structure (fig. 24), all tetrahedral cation positions are occupied, but one of every three octahedral Al^{+3} positions is not. When a Li^{+1}-saturated sample of the mineral montmorillonite is heated, small Li^{+1} ions enter vacant cation sites in the octahedral layer and neutralize the negative layer charge, which causes the clay to become nonexpanding and to have a basal spacing of about 9.6 *A*. Beidellite, similarly treated, remains expanding because its layer charge is in the tetrahedral layer, which contains no vacant cation sites for the Li^{+1} ions. Effects of the lithium test on bentonites from western Kansas (table 4) show that the Weskan bentonites contain octahedrally charged montmorillonites and thus are similar to most Pierre bentonites. Those from the Sharon Springs Member and the Niobrara Formation are exceptionally beidellitic. It should be noted that the name montmorillonite is used both as a group name (tables 1–4) and as a specific mineral name (table 4).

The relationship between composition and thickness of Sharon Springs bentonites is illustrated by the six bentonites from near the Guy Holland test hole (table 4). The two thickest (loc. 6, subunits 12, 14) are the least kaolinitic, the two thinnest (subunits 8, 16) are predominantly kaolinite, and the two of intermediate thickness (subunits 6, 10) have intermediate amounts of kaolinite. The three thinnest bentonites contain the most interlayer aluminum. There is a smaller proportion of montmorillonite layers than beidellite layers in the thinner bentonites, though this relation is not as consistent as the others. Actually, even the thicker bentonites with a montmorillonite-beidellite ratio of 55:45 are still considerably more beidellitic than most Pierre bentonites.

The Sharon Springs and Niobrara bentonites just described are exceptionally aluminous owing to kaolinite content, beidellitic character, and interlayer aluminum complexes. Kaolinite differs from montmorillonite (fig. 24) in that kaolinite has only one silica layer combined with an alumina layer and has no cation substitutions, interlayer cations, or absorbed interlayer water. Thus, kaolinite contains 40 percent Al_2O_3, whereas the mineral montmorillonite contains about 20 percent. Beidellite, because Al^{+3} replaces Si^{+4}, contains about 25–30 percent Al_2O_3 and little MgO. Interlayer aluminum adds further to the Al_2O_3 content of these bentonites. An additional result of these unusual features is that the content of magnesium, calcium, sodium, and potassium is unusually small (tables 2 and 4; subunits 12, 14), totaling about 2 percent, less than half the normal content for the mineral montmorillonite (Grim, 1968, p. 578). Even lower amounts of these elements would be expected in other bentonites (table 4) in which all three of the aluminous characteristics are more highly developed than in the two bentonites shown in table 2.

The aluminous character of these clays implies acidic conditions either at the time of formation or during subsequent alteration or weathering. As previously mentioned, recent weathering of the shales has oxidized the pyrite, from which the iron and sulfur went into the jarosite, limonite, and gypsum. Sulfuric acid solutions have removed dolomite and chlorite from near-surface shales. Similar acid solutions could have formed the aluminous clays of the bentonites, except that such bentonites are at considerable depth in the test hole (table 4) interbedded with pyrite-, dolomite-, and chlorite-bearing shales (table 3). Therefore, the type of acidic conditions that produced the highly aluminous bentonites remains a problem.

TABLE 1. — *Analyses of sample cuttings from the Sharon Springs Member of the Pierre Shale*

[Analyses reported as percentages. Carbon analyses by I. C. Frost. Total carbon determined by induction-furnace analysis, mineral carbon determined by gasometric analysis, and organic carbon computed as difference between total and mineral carbons. Six-step spectrographic analyses by J. C. Hamilton, reported to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, and so on; values represent approximate midpoints of groups of data on a geometric scale. The assigned group for six-step results will include more accurately determined values about 30 percent of the time. Symbols used

Sample depth (ft)	Laboratory No.	Carbon analyses			Six-step spectrographic analyses															
		Total	Mineral	Organic	Si	Al	Fe	Mg	Ca	Na	K	Ti	Mn	Ag	B	Ba	Co	Cr	Cu	Ga
PIERRE SHALE, SHARON SPRINGS MEMBER																				
Phosphatic shale unit																				
0–5	D110–651	0.88	0.15	0.7	M	M	3	1	2	1	3	0.3	0.015	0	0.015	0.05	0.001	0.01	0.01	0.005
5–10	652	1.03	.15	.9	M	5	5	.5	7	1	2	.1	.07	0	.005	.05	.001	.007	.01	.002
Organic-rich shale unit																				
10–15	D110–653	4.75	0.03	4.7	M	7	7	0.5	1.5	1.5	2	0.2	0.015	0	0.015	0.05	0.001	0.015	0.02	0.005
15–20	654	9.81	.16	9.6	M	7	5	.7	1.5	.7	2	.2	.03	.00015	.01	.03	.002	.01	.02	.003
20–25	655	5.99	.19	5.8	M	M	3	1.5	1	.7	2	.2	.015	.0001	.015	.03	.0015	.007	.015	.005
25–30	656	8.53	5.42	3.1	M	7	2	1	M	.5	2	.1	.07	0	.003	.2	.001	.005	.007	.0015
30–35	657	5.69	.63	5.1	M	7	3	1.5	1.5	.7	2	.3	.02	0	.015	.03	.002	.007	.01	.003
35–40	658	5.28	.48	4.8	M	7	2	1.5	1	.7	2	.2	.02	0	.015	.05	.0015	.007	.01	.003
40–45	659	5.32	.33	5.0	M	M	5	1.5	1	1	3	.3	.02	0	.015	.03	.002	.01	.01	.005
45–50	660	4.53	.54	4.0	M	7	5	1.5	1.5	.7	2	.3	.02	0	.015	.03	.002	.007	.01	.003
50–55	661	5.47	.70	4.8	M	M	5	1.5	2	1	3	.2	.02	0	.02	.03	.002	.007	.007	.003
55–60	662	5.28	.54	4.7	M	7	5	1.5	1.5	.7	3	.2	.02	0	.015	.03	.002	.007	.007	.003
60–65	663	5.88	.67	5.2	M	7	5	1.5	1.5	1	3	.2	.02	0	.015	.03	.002	.007	.007	.003
65–70	664	5.28	.89	4.4	M	7	3	1.5	2	1	3	.2	.02	0	.015	.03	.002	.007	.007	.003
70–75	665	5.39	.91	4.5	M	7	3	1.5	1.5	1	2	.2	.02	0	.015	.03	.0015	.007	.007	.003
75–80	666	4.98	.88	4.1	M	7	3	1.5	1.5	1	2	.2	.02	0	.015	.03	.0015	.007	.007	.003
Dark soft shale unit																				
80–85	D110–667	4.91	0.89	4.0	M	7	3	2	2	1	3	0.3	0.02	0	0.015	0.03	0.0015	0.007	0.007	0.003
85–90	668	4.85	.80	4.0	M	7	3	1.5	1.5	1	2	.2	.02	0	.015	.03	.001	.01	.007	.003
90–95	669	4.91	.84	4.1	M	7	3	2	1.5	1	3	.2	.02	0	.015	.05	.0015	.007	.007	.003
95–100	670	5.03	.89	4.1	M	7	3	1.5	2	1	2	.2	.02	0	.015	.03	.001	.007	.007	.003
100–105	671	5.17	.87	4.3	M	7	3	1.5	2	1	2	.3	.02	0	.015	.03	.0015	.01	.007	.003
105–110	672	5.21	.97	4.2	M	7	3	1.5	2	1	3	.3	.02	0	.015	.03	.0015	.007	.007	.003
110–115	673	5.51	1.06	4.4	M	7	3	1.5	2	1	2	.2	.02	0	.015	.05	.001	.007	.007	.003
115–120	674	4.88	.90	4.0	M	7	3	1.5	2	1	2	.2	.02	0	.015	.05	.001	.007	.007	.003
120–125	675	5.86	.92	4.4	M	7	3	1.5	2	1	3	.2	.02	0	.015	.03	.0015	.007	.007	.003
125–130	676	5.37	.96	4.4	M	M	5	2	3	1	2	.3	.02	0	.015	.05	.0015	.01	.007	.003
130–135	677	6.10	1.11	5.0	M	7	3	1.5	2	1	2	.2	.02	0	.015	.03	.0015	.007	.007	.003
135–140	678	5.57	.95	4.6	M	M	5	2	2	1	2	.3	.02	0	.015	.03	.0015	.01	.01	.003
140–145	679	5.38	.89	4.5	M	7	3	1.5	2	1	3	.3	.02	0	.015	.05	.0015	.01	.01	.005
145–150	680	5.07	.98	4.1	M	7	3	1.5	2	1	3	.3	.02	0	.015	.07	.0015	.007	.01	.003
150–155	681	5.07	1.28	3.8	M	7	3	1.5	3	1	2	.2	.02	0	.015	.03	.0015	.007	.007	.003
155–160	682	4.43	.85	3.6	M	M	3	1.5	1.5	1	2	.3	.02	0	.015	.05	.0015	.01	.007	.003
160–165	683	4.81	.98	3.8	M	M	5	1.5	2	1	3	.3	.02	0	.015	.05	.0015	.01	.007	.003
165–170	684	5.29	.88	4.3	M	M	5	2	1.5	1	3	.3	.02	0	.02	.05	.0015	.01	.007	.003
170–175	685	5.94	2.45	3.5	M	M	3	1.5	7	1	2	.2	.02	0	.01	.05	.0015	.01	.007	.003
175–180	686	4.15	.78	3.4	M	M	3	2	1.5	1	3	.3	.02	0	.015	.05	.0015	.01	.01	.005
180–185	687	4.53	.99	3.5	M	M	3	1.5	1.5	1	3	.3	.015	0	.015	.05	.0015	.01	.005	.005
185–190	688	4.44	1.32	3.1	M	7	3	1	1.5	1	3	.2	.015	0	.015	.05	.0015	.01	.005	.005
190–195	689	4.74	1.48	3.3	M	M	3	1.5	3	1	3	.3	.015	0	.02	.05	.0015	.01	.005	.005
195–200	690	4.60	1.58	3.0	M	M	3	1.5	3	1	3	.3	.015	0	.015	.05	.0015	.01	.005	.003
200–205	691	4.64	1.85	2.8	M	M	3	1.5	3	1	3	.3	.015	0	.015	.05	.0015	.01	.005	.003
205–210	692	5.13	2.23	2.9	M	M	3	1.5	5	1	3	.2	.015	0	.015	.05	.0015	.01	.005	.003
210–215	693	4.90	1.88	3.0	M	M	3	1.5	5	1	3	.3	.015	0	.015	.05	.0015	.01	.005	.003
215–220	694	6.22	2.63	3.6	M	7	3	1.5	7	1	3	.2	.015	0	.015	.05	.0015	.007	.005	.003
NIOBRARA FORMATION, SMOKY HILL MEMBER (PART)																				
220–225	D110–695	8.57	4.62	4.0	M	7	3	1	M	1	3	0.2	0.015	0	0.01	0.03	0.0015	0.007	0.005	0.002
225–230	696	9.97	5.70	4.3	M	5	2	1	M	.7	3	.07	.01	0	.003	.05	.0015	.007	.005	.002
230–235	697	10.6	6.05	4.6	M	3	2	.7	M	.1	2	.07	.01	0	.003	.02	.0015	.007	.003	.0015
235–240	698	10.8	7.38	3.4	7	5	2	.7	M	.7	2	.05	.015	0	0	.02	.0015	.005	.003	.0015
240–245	699	11.7	7.67	4.0	7	5	3	.5	M	.7	2	.07	.015	0	0	.02	.0015	.005	.003	.001
245–250	700	11.5	8.56	2.9	7	5	2	.3	M	.7	2	.05	.01	0	0	.02	.0015	.005	.002	.001
250–255	701	11.1	7.93	3.2	7	3	2	.5	M	.7	2	.05	.01	0	0	.05	.001	.005	.002	.001
255–260	[3]702	......	......	....	....	....	..	....	....	..	..	....	....	....	....	....	....	....	....	....
260–265	703	(3)	(3)	(3)	7	3	2	0.5	M	0.7	2	0.07	0.01	0	0	0.02	0.001	0.005	0.002	0.0015
265–270	704	7.98	4.71	3.3	M	7	3	1.5	M	1	2	.2	.015	0	.007	.03	.0015	.007	.003	.002
270–280	705	7.67	6.04	1.6	7	5	1.5	1	M	1	2	.07	.015	0	.003	.02	.001	.005	.003	.0015
280–290	706	12.0	8.42	3.6	3	2	3	.3	M	.7	1.5	.05	.01	0	0	.05	.0015	.005	.003	.0007
290–300	707	12.0	8.32	3.7	3	2	2	.3	M	.7	1.5	.03	.01	0	0	.02	.0015	.005	.003	.0007

[1] 7 percent jarosite. [2] 4 percent jarosite. [3] Insufficient sample.

BASALUMINITE AND HYDROBASALUMINITE

Basaluminite ($2Al_2O_3{\cdot}SO_3{:}10H_2O$), accompanied by a trace of hydrobasaluminite ($2Al_2O_3\cdot SO_3\cdot 41H_2O$), occurs as white earthy lumps in association with gypsum and limonite in a 0.2-foot-thick zone at the top of the Sharon Springs Member near the Guy Holland test hole (loc. 6, subunit 22). The layer resembles the "trash" zones at disconformities in the Sharon Springs along the Missouri River in South Dakota (Schultz, 1965, p. B6). Basaluminite and hydrobasaluminite are rare minerals, first described from England by Hollingsworth and Bannister (1950). In the United States, these minerals have *and the Smoky Hill Member of the Niobrara Formation from the Guy Holland test hole*

are: M, major constituent, greater than 10 percent; 0, looked for but not detected. Elements looked for but not detected: P, As, Au, Be, Bi, Cd, Ce, Ge, Hf, In, Li, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Pr, Nd, Sm, Eu. Equivalent uranium analyses, by Wayne Mountjoy, Lorraine Lee, and H. H. Lipp, were by beta-gamma scaler. Mineralogical analyses by X-ray diffraction]

Six-step spectrographic analyses — Continued													Mineralogical analyses													
													Clay mineral, as percentage of total clay					Composition of sample, in percent								
La	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr	Equivalent uranium analyses	Montmorillonite	Mixed layer	Illite	Chlorite	Kaolinite	Total clay	Quartz	Plagioclase	K-feldspar	Calcite	Dolomite	Pyrite	Organic matter	Total
PIERRE SHALE, SHARON SPRINGS MEMBER — Continued																										
Phosphatic shale unit — Continued																										
0.003	0.0005	0	0.003	0.003	0.001	0.03	0.03	0.003	0.0003	0	0.01	0.003	18	40	30	0	12	65	22	4	0	0	0	(1)	1	99
0	.0015	0	.003	.002	.0007	.05	.02	.002	.0003	0	.005	.002	23	40	26	0	11	65	24	2	2	0	0	(2)	1	98
Organic-rich shale unit — Continued																										
0.003	0.003	0	0.005	0.002	0.001	0.05	0.03	0.003	0.0003	0	0.01	0.003	22	41	25	0	12	70	20	2	2	0	0	0	7	101
.003	.003	0	.01	.002	.001	.02	.03	.003	.0005	.05	.01	.004	20	48	19	0	13	50	15	2	1	0	0	16	13	97
0	.003	.001	.007	.003	.001	.015	.03	.003	.0003	.03	.007	.002	26	41	21	6	6	55	22	1	0	0	0	9	8	95
0	.002	0	.005	.0015	.001	.07	.02	.0015	.0002	0	.003	.001	12	51	20	6	11	35	12	1	1	42	2	7	3	103
.003	.005	0	.007	.003	.0015	.02	.03	.003	.0005	.07	.01	.002	10	46	24	4	16	55	24	1	2	0	4	9	7	102
0	.003	0	.007	.003	.001	.02	.03	.002	.0003	0	.007	.002	10	52	20	3	15	55	22	1	1	0	4	9	7	99
.003	.005	0	.007	.005	.001	.02	.03	.003	.0003	.07	.01	.003	10	53	20	4	13	55	23	1	0	0	2	8	7	96
.003	.005	0	.007	.003	.001	.015	.03	.002	.0003	.05	.01	.003	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.005	.001	.007	.005	.001	.02	.03	.002	.0003	.03	.01	.003	11	48	25	4	12	50	24	2	1	0	5	10	7	99
0	.005	.001	.007	.005	.001	.02	.03	.002	.0003	0	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.005	.001	.007	.005	.001	.02	.03	.003	.0003	0	.01	.005	13	47	24	3	13	50	25	1	0	0	4	10	7	97
0	.003	0	.007	.003	.001	.02	.03	.002	.0003	0	.01	.003	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.002	0	.005	.003	.001	.02	.02	.002	.0003	0	.01	.002	11	50	26	4	9	50	25	1	1	0	8	9	6	100
0	.003	0	.007	.003	.001	.02	.02	.002	.0003	0	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
Dark soft shale unit — Continued																										
0.003	0.002	0	0.007	0.007	0.001	0.02	0.03	0.003	0.0003	0	0.01	0.002	16	42	27	3	12	50	27	1	1	0	8	5	6	98
0	.002	0	.005	.005	.001	.02	.03	.002	.0003	0	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.002	.001	.007	.005	.001	.02	.03	.002	.0003	.03	.01	.002	19	46	23	3	9	50	28	2	0	0	7	7	6	100
0	.0015	.001	.005	.003	.001	.02	.03	.002	.0003	0	.01	.002	19	45	22	3	11	50	27	2	1	0	8	4	6	98
0	.002	.001	.007	.003	.001	.02	.03	.003	.0003	0	.01	.002	23	40	21	2	14	55	27	3	2	0	8	3	6	104
0	.003	0	.007	.005	.001	.02	.03	.003	.0003	.05	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.0015	.001	.007	.003	.001	.02	.03	.002	.0003	.03	.01	.001	18	47	20	3	12	55	22	3	0	0	8	6	6	100
0	.0015	.001	.005	.003	.001	.02	.02	.002	.0003	0	.007	.003	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.002	.001	.007	.005	.001	.02	.03	.003	.0005	.03	.01	.003	25	45	17	3	10	50	25	2	2	0	7	7	6	99
0	.002	.001	.007	.005	.001	.03	.03	.003	.0005	.03	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.003	.0015	.007	.005	.001	.03	.03	.002	.0003	.03	.01	.002	50	25	20	1	4	50	25	3	0	0	8	8	7	101
.003	.003	.0015	.007	.005	.001	.02	.03	.002	.0003	.05	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.0015	.0015	.005	.005	.001	.02	.03	.002	.0003	.05	.01	.002	23	42	22	2	11	55	26	2	0	0	6	4	6	99
.003	.0015	0	.005	.005	.001	.02	.03	.003	.0003	.03	.01	.003	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.002	.001	.005	.003	.001	.03	.03	.002	.0003	0	.01	.002	16	48	19	3	14	50	27	3	1	2	8	6	5	102
0	.0015	.001	.005	.005	.001	.02	.03	.002	.0003	.03	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.002	.001	.007	.007	.001	.03	.03	.003	.0003	0	.01	.001	17	46	20	1	16	55	27	1	0	0	7	4	5	99
.003	.002	.001	.007	.005	.0015	.03	.03	.003	.0003	0	.01	.003	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.0015	0	.005	.003	.001	.03	.03	.002	.0003	.05	.007	.001	9	48	24	3	16	45	15	1	0	17	4	3	5	90
0	.002	.001	.007	.005	.001	.03	.03	.002	.0003	.03	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.0015	.002	.005	.005	.001	.02	.05	.003	.0003	.03	.01	.003	7	48	27	3	15	55	20	2	1	2	7	4	5	96
0	.001	.0015	.005	.003	.001	.03	.03	.002	.0003	0	.007	.001	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.0015	.0015	.005	.005	.001	.03	.05	.003	.0005	.05	.01	.002	4	54	23	1	18	55	20	1	0	9	4	3	5	97
.003	.0015	.0015	.005	.003	.001	.05	.05	.002	.0003	0	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.001	.0015	.005	.005	.001	.03	.05	.002	.0003	0	.007	.002	0	58	22	3	17	55	20	1	0	10	5	4	4	99
.003	.0015	.0015	.005	.003	.001	.05	.05	.002	.0003	0	.007	.003	....	....	....	..	....	....	....	..	..	..	..	..	..	....
.003	.002	.0015	.005	.003	.001	.05	.05	.003	.0003	0	.007	.002	0	60	21	3	16	50	23	2	1	8	6	6	4	100
0	.002	.0015	.007	.003	.001	.05	.05	.002	.0003	0	.01	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
NIOBRARA FORMATION, SMOKY HILL MEMBER (PART) — Continued																										
0.003	0.002	0.0015	0.007	0.002	0.001	0.07	0.05	0.002	0.0003	0	0.007	0.002	0	56	23	2	19	40	15	1	0	29	5	5	6	101
0	.002	0	.007	.002	.0007	.1	.05	.002	.0003	0	.005	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.002	0	.007	.0015	.0007	.1	.05	.0015	.0003	0	.003	.002	6	52	20	0	22	20	7	0	0	50	1	8	7	93
0	.002	0	.007	.0015	.0007	.15	.05	.002	.0002	0	.003	.001	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.003	0	.007	.001	.0007	.15	.05	.0015	.0003	0	.003	.002	5	56	22	1	16	20	10	1	0	55	0	8	6	100
0	.003	0	.007	.001	.0007	.2	.05	.0015	.0002	0	.003	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.0015	0	.005	.0015	.0007	.15	.05	.0015	.0002	0	.003	.001	7	41	19	1	32	0	4	0	0	65	0	7	5	91
......	......	......	......	......	......	......	......	......	......	......	......	......	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	0.0015	0.0015	0.005	0.002	0.0007	0.15	0.05	0.0015	0.0002	0	0.003	0.002	4	55	22	4	15	30	12	1	0	40	2	5	..	90
.003	.003	0	.007	.003	.001	.1	.05	.002	.0003	0	.007	.002	....	....	....	..	....	....	....	..	..	..	..	..	..	....
0	.0015	0	.005	.002	.0007	.15	.03	.0015	.0002	0	.005	.001	7	54	22	1	16	15	5	0	0	60	0	10	2	92
0	.003	0	.007	0	.0005	.15	.05	.0015	.0002	0	.003	.002	7	54	18	1	20	15	6	1	0	70	0	6	5	103
0	.003	0	.007	.001	.0005	.2	.05	.0015	.0002	0	.003	.001	0	54	20	1	25	10	3	0	0	68	0	11	5	97

been found in Tennessee (Milton and others, 1955) in an altered residuum at the base of the Chattanooga Shale, in southwestern Indiana (Sunderman and Beck, 1965) in a weathered residuum at the unconformity between Mississippian and Pennsylvanian rocks, and in southeastern Kansas (Tien, 1968) in an altered shale above a Pennsylvanian coal. In most of these the basaluminite or hydrobasaluminite is attributed to leaching of silicate minerals at ancient or modern land surfaces by acid solutions derived from oxidizing pyrite. The presence of these minerals in the Pierre is probably similarly related to oxidation of pyrite.

TABLE 2. — *Analyses of samples from the Sharon Springs and Weskan*

[Subunit 24 is in Weskan Member; all others in Sharon Springs Member. All analyses, except atomic-absorption analyses, reported as percentages.
method, reported as parts per billion. Mineralogical

Sub-unit sampled	Rock type	Laboratory No.	Carbon analyses			Six-step spectrographic analyses															
			Total	Mineral	Organic	Si	Al	Fe	Mg	Ca	Na	K	Ti	Mn	Ag	B	Ba	Co	Cr	Cu	Ga
24	Shale	D128–364	0.45	<0.01	0.4	M	10	2	1.0	0.07	0.7	5	0.3	0.07	0	0.01	0.05	0.007	0.015	0.015	0.003
21	Carbonaceous shale	363	1.99	<.01	2.0	M	7	2	.5	.2	.7	5	.3	.003	0	.01	.07	.0003	.02	.02	.003
15 (upper)	....do	362	6.48	<.01	6.5	M	7	2	.5	.15	.7	3	.2	.003	.0003	.01	.07	.0003	.03	.05	.003
15 (lower)	....do	361	10.4	<.01	10.4	M	5	2	.5	.3	.7	3	.15	.007	.0001	.007	.05	.0005	.015	.03	.003
7	....do	360	6.04	.02	6.0	M	7	1.5	.7	.07	.7	5	.2	.007	0	.01	.05	.0005	.01	.015	.003
3	....do	359	6.54	<.01	6.5	M	7	1.5	.5	.15	.7	5	.2	.003	0	.01	.05	.0003	.01	.007	.003
1	....do	358	.80	.01	.8	M	7	1.5	.7	.15	.5	3	.2	.003	0	.01	.05	.0003	.01	.03	.003
14	Bentonite	366	.21	.01	.2	M	7	1.0	1.0	.1	.2	.7	.07	.01	0	.01	.015	.0003	.0005	.0015	.002
12	....do	365	.18	<.01	.2	M	M	1.5	1.5	.07	.05	0	.15	.015	0	.01	.007	.0007	.0007	.007	.002

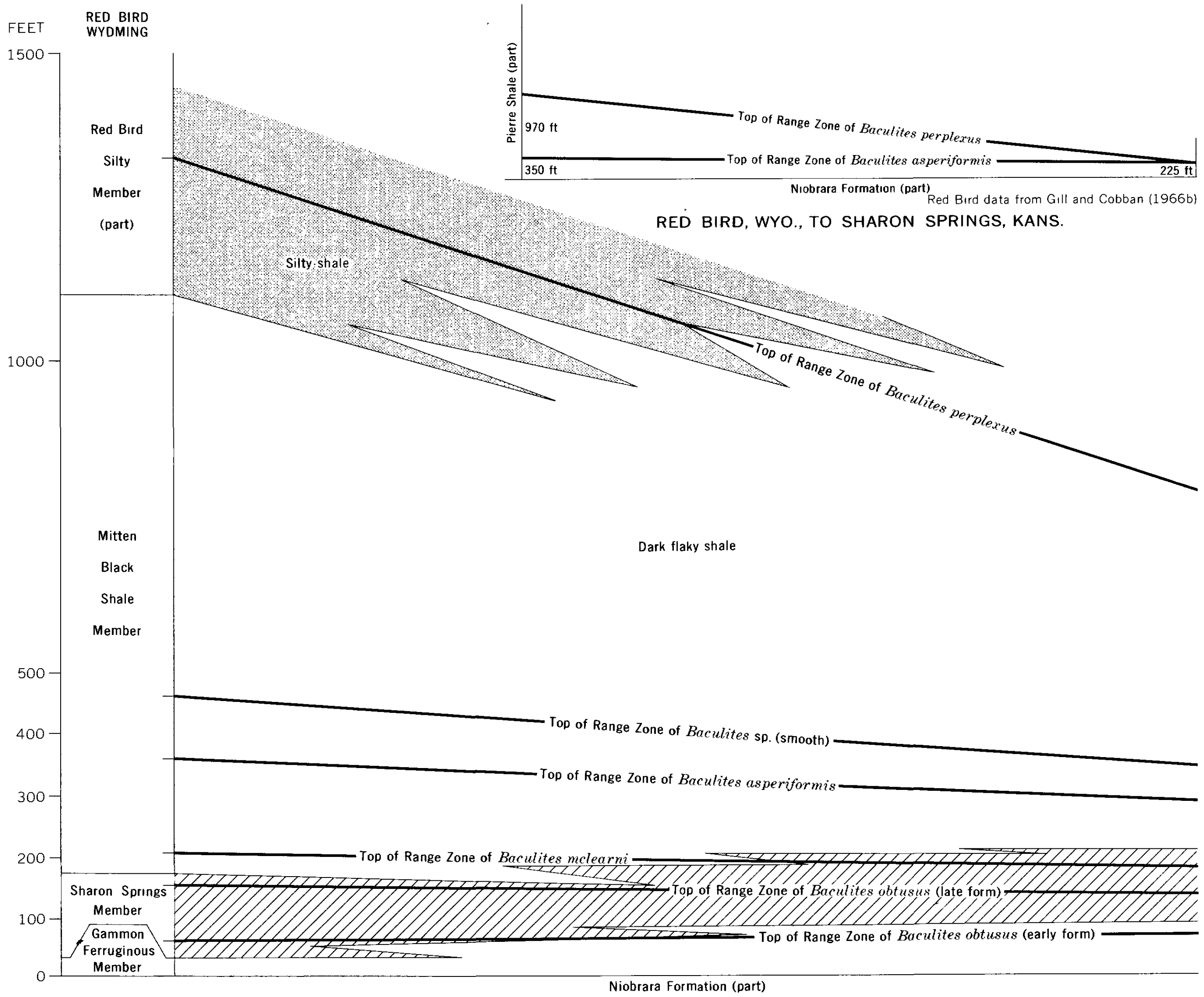
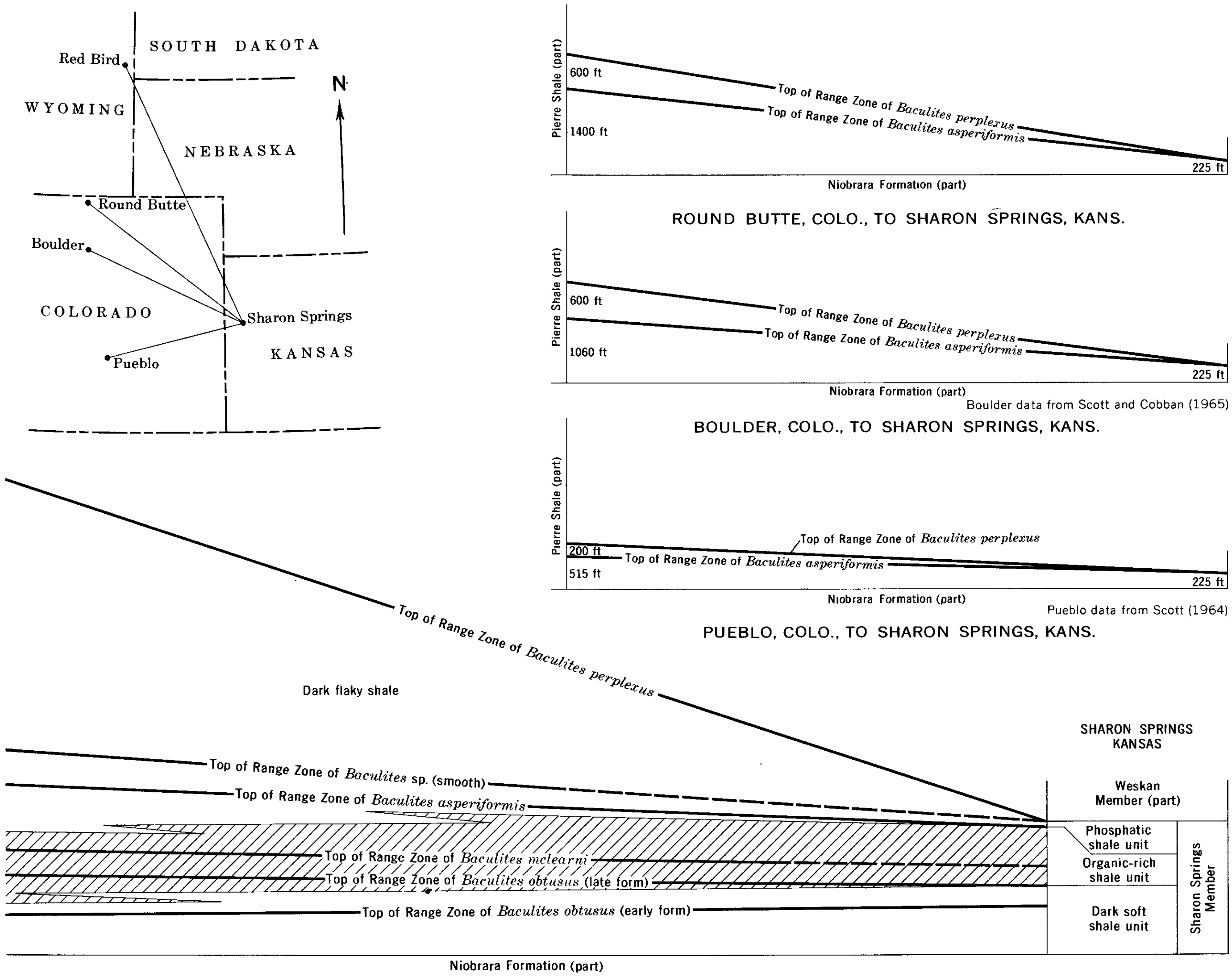


FIGURE 23. — Thickness and implied rates of sedimentation of the Pierre Shale in western Kansas compared with thickness

Members of the Pierre Shale from outcrops near the Guy Holland test hole

Carbon analyses, six-step spectrographic analyses, and mineralogical analyses, see table 1 headnote. Gold and silver contents, determined by atomic-absorption analyses by J. A. Thomas and J. D. Mensik, Tr., trace]

Six-step spectrographic analyses — Continued												Atomic-absorption analyses		Mineralogical analyses												
														Clay mineral, as percentage of total clay					Composition of sample, in percent							
La	Mo	Nb	Ni	Pb	Sc	Sr	V	Y	Yb	Zn	Zr	Au	Ag	Montmorillonite	Mixed layer	Illite	Chlorite	Kaolinite	Total clay	Quartz	Plagioclase	K-feldspar	Gypsum	Jarosite (H+)	Organic matter	Total
0.003	0.0007	0	0.002	0.003	0.0015	0.03	0.05	0.0015	0.0003	0	0.01	<0.02	0.4	11	59	17	0	13	70	20	1	2	1	2	1	97
.007	.0007	0	.0007	.003	.0015	.03	.07	.005	.0005	0	.015	<.02	.3	13	64	15	0	8	65	23	1	1	0	4	3	97
.003	.0015	0	.0007	.002	.0015	.015	.03	.007	.0007	0	.015	<.02	1.8	32	34	20	0	14	60	18	0	3	0	1	9	91
0	.0015	0	.003	.0015	.0007	.007	.03	.001	.0003	0	.007	<.02	1.1	14	50	24	0	12	50	18	1	1	3	10	13	96
0	.002	0	.002	.002	.0007	.005	.05	.001	.0002	0	.007	<.02	.8	21	46	20	0	13	60	25	0	1	2	2	8	98
0	.003	0	.0015	.0015	.0007	.007	.07	.001	.0002	0	.007	<.02	.6	13	53	20	0	14	65	28	0	1	1	1	9	105
0	.001	0	.0015	.0015	.0015	.007	.05	.0015	.0003	0	.007	<.02	.5	15	57	15	0	13	65	27	2	1	0	1	1	97
0	0	0	.0015	.001	0	.0015	.015	.001	.00015	0	.005	<.02	.3	95	0	0	0	5	95	1	0	3	0	Tr.	0	99
0	.0005	0	.005	.001	.0005	.001	.015	.0015	.0002	0	.007	<.02	.4	95	0	0	0	5	95	Tr.	0	0	0	1	0	96



and rates in other localities. Each ammonite zone represents approximately 500,000 years (Gill and Cobban, 1966b).

TABLE 3. — *Mineralogy of samples from the Pierre Shale*

[Tr., trace; ?, presence doubtful]

Locality	Sub-unit	Member	Clay mineral, as percentage of total clay					Composition of sample, in percent							
			Montmorillonite	Mixed layer	Illite	Chlorite	Kaolinite	Total clay	Quartz	Plagioclase	K-feldspar	Dolomite	Gypsum	Jarosite	Total
12[1]	1	Salt Grass......	35	41	17	0	7	70	19	3	0	0	0	0	92
11[2]	1	Lake Creek.....	28	52	13	1	7	60	19	2	0	3	0	0	84
14[3]	4	Weskan......	41	25	31	2	1	75	25	2	0	0	2	0	104
14	5	....do............	31	36	20	4	9	65	27	Tr.	0	9	0	0	101
13[4]	1	....do............	37	40	18	0	5	80	19	2	0	0	0	0	101
2	35	....do............	36	41	17	2	4	75	18	2	?	0	0	0	95
6	17	Sharon Springs..	8	52	20	0	20	30	10	0	50	0	0	0	90
3	3	....do............	15	53	17	3	12	55	27	1	1	0	Tr.	0	84
1	37	....do............	20	41	22	0	17	70	28	0	1	0	0	0	99
1	35	....do............	15	45	14	3	23	60	20	1	0	2	0	Tr.	85
2	8	....do............	0	69	19	0	12	60	21	0	1	0	2	0	84
2	6	....do............	16	52	19	0	13	65	20	1	Tr.	0	5	5	96
2	3	....do............	17	53	15	0	15	50	20	1	1	0	10	7	89
14	2	....do............	8	53	21	0	18	75	28	1	1	0	?	0	105

[1] SW¼ sec. 19, T. 12 S., R. 40 W., Wallace County.
[2] SE¼ sec. 29, T. 11 S., R. 39 W., Wallace County.
[3] W½ sec. 7, T. 14 S., R. 38 W., Wallace County.
[4] SW¼ sec. 31, T. 12 S., R. 38 W., Wallace County.

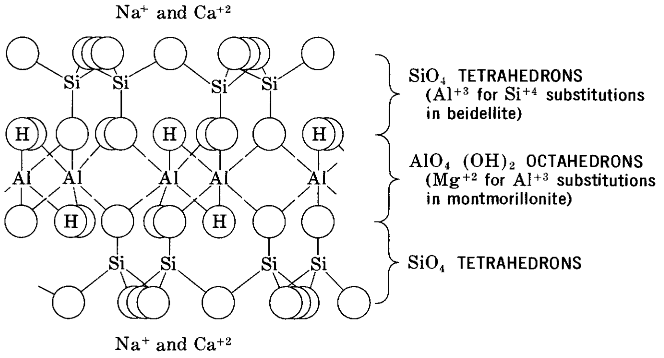


FIGURE 24. — Structure of a montmorillonite layer (Bragg, 1937, p. 206). Open circle is oxygen, O^{-2}; circled "H" is hydroxyl, $(OH)^{-1}$. Certain O^{-2} and $(OH)^{-1}$ that otherwise would be superimposed have been slightly displaced. Common cation substitutions within the layer are shown in parentheses.

POTASSIUM FELDSPAR

It seems unlikely that the large amount of potassium feldspar in the thin light-colored shale subunit (table 3, loc. 6, subunit 17) in the lower part of the phosphatic unit of the Sharon Springs Member, is a normal detrital accumulation. Instead it appears to be adularia, a pseudomonoclinic potassium feldspar of diagenetic origin.

BARITE AND APATITE

Other minerals in the Pierre samples which affect the chemical data given in tables 1 and 2 are barite, apatite, and possibly gypsum. The barite is in fillings

TABLE 4. — *Mineralogy of bentonites*

[All analyses by X-ray diffraction. A, abundant; Nd., not determined; 0, none; Tr., trace; S, some; Na., not applicable]

Locality	Subunit	Thickness or depth of sample (feet)	Member or formation	Interlayer aluminum complexes	Clay mineral, as percentage of total clay			Nonclay mineral, as percentage of sample		
					Proportion of layers in montmorillonite[1] after lithium test		Kaolinite	Quartz	Other	
					Nonexpanded montmorillonite[2]	Expanded beidellite			Mineral	Percent
					SURFACE SAMPLES Near Guy Holland test hole (fig. 15)					
		Thickness								
6	16	0.05	Sharon Springs.......	A	Nd.	Nd.	85	8	K-feldspar	2
6	14	.4	............do....................	O	55	45	5	1	....do............ Jarosite	3 Tr.
6	12	.25	............do....................	O	55	45	5	Tr.	....do............	1
6	10	.15	............do....................	O	30	70	13	Tr.	K-feldspar Jarosite	Tr. Tr.
6	8	.05	............do....................	A	40	60	55	Tr.	K-feldspar Jarosite	Tr. Tr.
6	6	.1	............do....................	A	50	50	50	Tr.	K-feldspar Jarosite	Tr. 7
					SURFACE SAMPLES Other localities					
14	3		Weskan......................	O	90	10	3	0		
13	2		......do..........................	O	95	5	0	0		
2	32		......do..........................	S	85	15	0	0	Plagioclase	2
2	34		......do..........................	O	100	0	0	0		
14	1		Sharon Springs.......	A	25	75	45	3		
4	1		Niobrara....................	A	50	50	45	3	K-feldspar	2
4	7		........do.........................	S	Nd.	Nd.	30	0		
					SAMPLE CUTTINGS Guy Holland test hole					
		Depth								
		20–25	Sharon Springs.......	A	50	50	10	0	Pyrite	3
		50–55	............do....................	A	Nd.	Nd.	90	0		
		135–140	............do....................	S	50	50	15	2	....do............	10
		155–160	............do....................	O	25	75	10	0		
		200–205	............do....................	Na.	0	0	100	0	....do............	15
		220–225	Niobrara....................	Nd.	Nd.	Nd.	75	0	....do............	80

[1] Montmorillonite as a group. [2] Montmorillonite as a specific mineral.

of septaria in limestone concretions, fragments of which are in cuttings from the 25- to 30-foot sample depth. Concretionary calcite material is also evident from the high calcium and mineral carbon contents in cuttings from the 170- to 175-foot interval. The high calcium determined for the 5- to 10-foot cuttings cannot represent a calcite source because of the small amount of mineral carbon reported; most likely, the calcium is from gypsum and apatite in phosphate nodules which are abundant in this unit.

CHEMICAL COMPOSITION

Cuttings from the Guy Holland test hole (table 1) and samples from nearby outcrops (table 2) were analyzed by the Denver laboratory of the U.S. Geological Survey for selected elements by the six-step spectrographic method. The approximate lower limits for visual detection of elements are shown in table 5. Total and mineral carbon were also determined; organic carbon is the difference between total and mineral carbon. Equivalent uranium was determined only for the test-hole samples.

TABLE 5.—*Approximate lower limits for visual detection of elements*

[Determined by the six-step spectrographic method at the Denver, Colo., laboratory, U.S. Geological Survey]

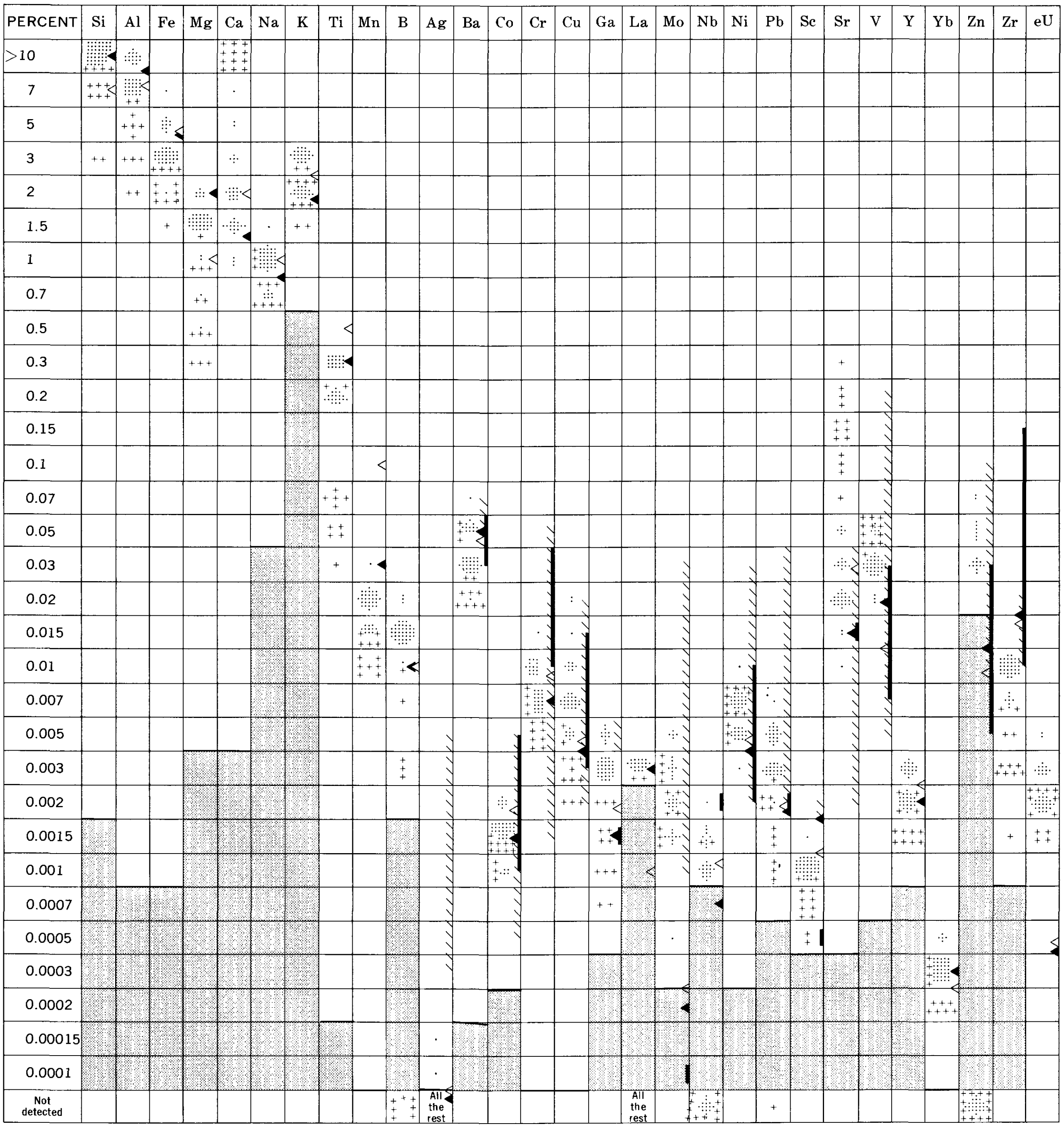
Element	Percent	Element	Percent	Element	Percent
Si	0.002	Dy	0.005	Rb	10
Al	.001	Er	.005	Re	.005
Fe	.001	Eu	.01	Rh	.0002
Mg	.005	Ga	.0005	Ru	.001
Ca	.005	Gd	.005	Sb	.02
Na	.05	Ge	.001	Sc	.0005
K	.7	Hf	.01	Sn	.001
Ti	.0002	Hg	1	Sr	.0005
P	.5	Ho	.002	Sm	.01
Mn	.0001	In	.001	Ta	.02
Ag	.0001	Ir	.005	Tb	.03
As	.2	La	.003	Te	.2
Au	.002	Li	.01	Th	.02
B	.002	Lu	.003	Tl	.005
Ba	.0002	Mo	.0003	Tm	.002
Be	.0001	Nb	.001	U	.05
Bi	.001	Nd	.007	V	.0007
Cd	.005	Ni	.0003	W	.01
Ce	.015	Os	.005	Y	.001
Co	.0003	Pb	.001	Yb	.0001
Cr	.0001	Pd	.0002	Zn	.02
Cs	2	Pr	.01	Zr	.001
Cu	.0001	Pt	.005		

Summaries of compositional features of the spectrographically analyzed samples in figure 25 and tables 6 and 7 are the basis for comparisons in subsequent parts of this report. Figure 25 illustrates the common range of composition for sample cuttings from the Sharon Springs Member and the Niobrara Formation and for samples of other groups of shales.

Geometric means of concentrations of chemical elements and of minerals are listed at the left side of table 6. Amounts of elements and minerals in the Niobrara are recalculated to a calcite-free figure to provide a better basis for comparison with the Sharon Springs samples, because, judged from the low content of most trace elements in Niobrara samples (fig. 25), the calcite they contain must contain few trace elements and, thus, it acts only to dilute the trace elements in the other minerals.

Occurrence of most elements detected in the Sharon Springs and Niobrara samples from western Kansas, as inferred from factors discussed in the following section, is listed on the right side of table 6. Under "Inferred occurrence," the percentages given are those estimated for each element in each mineral. For example, the clay minerals in these samples contain an estimated average of 2 percent Fe and make up 52 percent of an average unweathered noncalcareous sample of Sharon Springs shale, and so about 1 percent Fe is in the clay; pyrite contains 46 percent Fe, and so the 7 percent pyrite in an average unweathered noncalcareous sample contains 3.2 percent Fe. The 4.2-percent sum for iron in clay and pyrite is higher than the calculated 3.5 percent mean value under "Mean content," but the occurrence figures should be regarded only as gross estimates.

Correlation coefficients (table 7) also have been calculated between most of the elements and between elements and the major mineral components that most likely contain them. A strong positive correlation indicates that the two elements or the mineral and element tend to occur together, possibly in the same mineral, as is obvious for the +0.9 correlation between calcium and calcite. However, a positive correlation does not necessarily mean that the two occur in the same mineral. Possibly they occur in different minerals that are favored by similar geologic conditions; pyrite and organic matter, both of which require reducing conditions, are good examples. A strong negative correlation normally indicates that the two elements occur in different minerals; probably little or no titanium or zirconium occurs in calcite. Silicon and aluminum are not included in table 7 because they occur in amounts for which the ranges of the spectrographic groups are so large that they are not useful for the correlation statistics. At the other end of the scale, silver and lanthanum were detected in too few samples to be useful and thus are not shown in table 7. Coefficients less than 0.32 are not shown in table 7 because, if a log-normal distribution of values is assumed, they are not significant at the 99-percent level. Significant coefficients are rounded to the nearest single number and the decimal is dropped. In table 7, the order of constituents has been arranged to group constituents with similar correlation coefficients.



EXPLANATION

\+ Niobrara

· Sharon Springs

Samples from Guy Holland test hole

◀ Average for Pierre Shale

Ag, La, Nb, Y, *and* Yb *from Tourtelot (1962); other elements from Tourtelot and others (1960)*

▌ Common range for ordinary shale

From Krauskopf (1955)

⟍ Common range for black shale

From Krauskopf (1955)

◁ Average for shale

From Turekian and Wedepohl (1961)

▨ Below detection limit

NOTE.—No surface or nodule-bearing samples are included

FIGURE 25. — Distribution of elements in sample cuttings from the Guy Holland test hole compared with that in other shales. Data for Niobrara and Sharon Springs samples from table 1.

TABLE 6. — *Mean content and inferred occurrence, in percent, of chemical elements and minerals in samples from the Pierre Shale and Niobrara Formation*

[...., no appreciable amount; Na., not applicable; ?, doubtful; Nd., not determined]

Elements and minerals	Mean content							Inferred occurrence				
	Guy Holland test-hole samples (from data in table 1)					Outcrop samples (from data on table 2)		Pierre Shale and Niobrara Formation				
	Pierre Shale, Sharon Springs Member			Niobrara Formation		Pierre Shale, Sharon Springs Member						
	Weathered, depth 0–25 feet	Unweathered noncalcareous, depth 25–190 feet	Unweathered calcareous, depth 190–220 feet	Marlstone	Marlstone, calcite free	Shale	Bentonite	Clay minerals and associated clastics	Pyrite	Organic matter	Calcite	Other
Fe	4.2	3.5	3.0	2.2	5.1	1.7	1.2	2	46	....	....	Jarosite.
Mg	.9	1.6	1.4	.6	1.4	.6	1.2	1.5	....	....	....	Dolomite.
Ca	1.5	1.8	3.6	20	Na.	.2	.8	1	....	....	40	Do.
Na	.9	.9	1.0	.8	1.7	.7	.1	2	....	....	....	
K	2.2	2.4	3.0	2.0	4.7	3.9	.6	5	....	....	....	
Ti	.22	.25	.25	.07	.16	.20	.10	.05	....	....	....	Anatase?
Mn	.018	.020	.015	.012	.027	.004	.012	.03	?	....	?	Nodules.
B	.014	.015	.016	.0024	.006	.009	.010	.03	....	....	....	
Ba	.039	.037	.050	.027	.062	.056	.010	.05	....	....	?	Barite.
Co	.0013	.0015	.0015	.0014	.0031	.0004	.0005	.002	.01	?	....	
Cr	.010	.008	.009	.006	.013	.014	.0006	.015	....	....	....	
Cu	.016	.008	.005	.003	.007	.021	.004	.015	....	....	....	
Ga	.004	.003	.003	.0013	.003	.003	.002	.006	....	....	....	
Mo	.002	.002	.0014	.002	.005	.0015	.0003	.001	.01	.02	....	
Nb	.0008	.0009	.0015	.0008	(1)	(1)	(1)	.002?	....	....	....	Zircon
Ni	.006	.006	.005	.006	.015	.0014	.001	.005	.05	.01?	....	
Pb	.003	.004	.004	.0014	.003	.002	.001	.008	....	....	....	
Sc	.001	.001	.001	.0007	.0016	.001	.0004	.002	....	....	?	
Sr	.02	.02	.04	.13	.3	.001	.001	.04	....	....	.2	
V	.03	.03	.05	.05	.11	.05	.015	.05	....	?	?	
Y	.003	.002	.002	.002	.004	.002	.001	.004	....	....	?	Apatite?
Yb	.0003	.0003	.0003	.0002	.0005	.0003	.0002	.0005	....	....	....	Do.
Zn	.02	.03	.02	(1)	(1)	(1)	(1)	?	?	?	?	?
Zr	.009	.010	.008	.004	.009	.009	.006	.02	....	....	....	Zircon.
Equivalent uranium	.003	.002	.002	.002	.004	Nd.	Nd.	.002	....	.02	....	
Organic carbon	5.2	4.3	3.1	3.5	8.4	5.4	.02					
Calcite	0	.1	10	55	Na.	0	0					
Dolomite	0	6	5	1	2	0	0					
Pyrite	6	7	4	7	18	0	0					
Total clay	60	52	55	20	42	61	95					

[1] Mostly below visual-detection limits. See text and table 5.

In tables 6 and 7, elements reported as undetected in a sample were assigned values just below the limit of detection. This procedure probably is reasonable for elements like boron or lead which are below detection limits in only a few samples (fig. 25). However, for elements like niobium and zinc for which more than half the values were below the limit of detection, the mean values (table 6) are probably too high.

MODE OF OCCURRENCE OF ELEMENTS

The amount of each element in each mineral and in the organic constituent of the samples is deduced on the basis of several factors: (1) the common modes of occurrence in other rocks, such as have been summarized for sedimentary rocks by Tourtelot (1962, p. 46), (2) concentration of elements in individual samples with unique composition, such as the top two test-hole samples which contain little organic matter and no pyrite or the outcrop samples which contain variable amounts of organic matter but no pyrite, (3) concentration of an element in the calcite-rich Niobrara samples and the relative concentration when the element is recalculated calcite free, and (4) correlation coefficients. The few elements which are most abundant in the Niobrara probably are in

TABLE 7. — *Correlation coefficients, ×10⁻¹, between elements and minerals in sample cuttings from the Guy Holland test hole and nearby outcrops*

[Coefficients less than 0.32 not shown]

	Ti	Zr	B	Ga	Clay	Pb	Sc	Y	Yb	Cr	Cu	Fe	Mg	Dolomite	Na	K	Mn	Nb	Ba	eU	Zn	Co	Ni	Mo	Organic carbon	Pyrite	V	Sr	Ca
Zr	9																												
B	9	9																											
Ga	9	8	9																										
Clay	9	8	9	9																									
Pb	8	8	8	8	7																								
Sc	9	8	9	8	8	7																							
Y	7	7	7	7	8	6	6																						
Yb	7	7	7	6	6	6	6	7																					
Cr	7	7	7	8	7	6	6	6	6																				
Cu	7	7	7	7	8	5	6	6	6	6																			
Fe	6	6	6	5	6	4	5	5	5	6	6																		
Mg	8	8	8	7	6	9	8	6	5	5	5																		
Dolomite	7	7	7	5	4	7	6	3	4	3			7																
Na	6	7	6	6	6	6	4	4	3	6	3	4	4	5															
K	5	5	5	5	5	6	4	4	3	4			5	3	4														
Mn	4	3	3		4		4				6	4	3																
Nb	4		4	4		4				4			3	4	4	3													
Ba										3							4												
eU	4	4	4	4	5		3	5	4	3	4	5				3													
Zn	4	4	3	4	4	3	4		5		5		3																
Co								4				3								4									
Ni																			−4			6							
Mo												3							−4			6	7						
Organic carbon						−3			4		5	3								4	4	5	7	6					
Pyrite					−4					−4					−5				−4			5	7	6	6				
V	−4	−4	−5	−4	−5	−4	−4				−7	−3	−4	−4			−7												
Sr	−8	−9	−9	−8	−8	−8	−8	−6	−6	−5	−8	−5	−8	−7	−4	−3	−5			−4					−4		6		
Ca	−8	−8	−9	−8	−8	−7	−7	−6	−6	−6	−8	−6	−7	−6	−5	−3	−3			−4					−4		6	9	
Calcite	−9	−9	−9	−9	−9	−8	−8	−7	−7	−7	−8	−6	−8	−7	−6	−4	−5			−5							6	9	9

the calcite. When several other elements are recalculated calcite free, their means are notably higher in the Niobrara than in the noncalcareous Sharon Springs. This could mean either that the element is partly in calcite or that it is in pyrite or in organic matter, both of which are shown to be about as abundant in the Niobrara before the recalculation as they are in the Sharon Springs. If, for example, an element is only in organic matter, its mean concentration in the recalculated Niobrara would be twice that in the noncalcareous Sharon Springs because the Niobrara samples average about half calcite. Only large differences of a factor of about 2 are considered significant in comparing the calcite-free values.

The presence and amount of major elements obviously are determined by the mineralogy of the samples. Silicon is mainly in quartz and clay. Aluminum, potassium, and sodium are mostly in the clay minerals; only minor amounts are in feldspars. The exceptionally large amounts of potassium in the calcareous Sharon Springs and in the Niobrara that have been recalculated calcite free are due, in part at least, to the very illitic character of the mixed-layer clay in these samples (table 1). About three-fourths of the iron must be in pyrite and only about one-fourth in clay; some of the iron from the leached pyrite is retained in the weathered samples in jarosite. More than half the magnesium and calcium in the fresh Sharon Springs sample cuttings must be in dolomite, the remainder in clay. Though dolomite probably is not a clastic mineral, its abundance generally seems to parallel the abundance of clay, so dolomite and clay have similar correlation coefficients.

Four elements — titanium, boron, gallium, and zirconium — have very strong positive correlations with the total amount of clay (table 7) and are thought to occur almost exclusively in it or with other clastic grains that are associated with it (Tourtelot, 1962, p. 46). Gallium replaces aluminum in the clay structures, and boron is strongly absorbed on clays. Part of or all the titanium and zirconium can occur in the clay structures; titanium can also occur in separate titanium minerals such as ilmenite or anatase (Frederickson, 1948), and zirconium, in zircon. If these separate titanium and zirconium minerals occur, their abundance must so closely parallel the abundance of clay in these fine-grained rocks that titanium, zircon, boron, and gallium, as well as clay itself, can be equated with the "Clay minerals and associated clastics" boxhead in table 6. The strong positive correlation coefficients of these clay-associated elements with all the other elements listed in table 7 between clay and dolomite indicate that all are mainly in clay or in other clastic components of the sediment.

Lead probably replaces large K^+ ions, comparable in size to lead, in the interlayer positions of the illitic and mixed-layer clays. Scandium can also occur in interlayer positions of the clay but, because of its small size (0.81 A), is more likely to be in the structure of the clay minerals. The strong negative correlation between scandium and calcium (table 7) indicates that scandium does not substitute for calcium in calcite.

Yttrium and ytterbium normally tend to be concentrated with rare earths in monazite and other phosphate minerals, which accounts for the exceptionally high yttrium and ytterbium values and the highest reported lanthanum value in surface samples from subunits 15 (upper) and 21 of the apatite-rich carbonaceous shale (table 2). In most samples, however, these elements are in clays or associated heavy clastics that contain rare earths. Rankama and Sahama (1950, p. 528) reported that yttrium may replace calcium in calcite. If this substitution accounts for the slightly high yttrium mean for the recalculated Niobrara, the substitution is slight.

Chromium and copper contents are fairly uniform, showing little or no evidence of variation in those samples that contain small amounts of pyrite or organic matter. Their contents in the recalculated Niobrara are not notably high. If anything, the elements are concentrated in the near-surface pyrite-free samples. They show their highest positive correlations with clay and the four clay-associated elements, and are most likely substituting in the octahedral sheets of the layers in the clay.

Manganese shows all its positive correlations with clay and clay-associated elements, but yet the weakness of all its correlation factors indicates that manganese is also disseminated in small amounts in other components that are not easy to identify from the data. The slightly high mean value of manganese for the calcite-free Niobrara samples suggests that there is some manganese in calcite, where it commonly replaces calcium (Tourtelot, 1962, p. 46). However, the strong negative correlations of manganese with calcium and with strontium and vanadium which also are closely associated with calcite indicate that the amount is very small, except perhaps in the calcite from concretions (25- to 30-foot sample depth, table 1). The very small amounts of manganese in the outcrop samples suggest that some manganese has been leached from surface samples.

Barium occurs uniformly in most Sharon Springs samples, regardless of the presence of pyrite or organic matter; it occurs in slightly smaller amounts in the Niobrara marls. Thus, it must be in the one component common to all the samples — the clays — where it replaces potassium. Its exceptionally weak correlation coefficients indicate that it also occurs in other components. In sample cuttings from the 25- to 30-foot depth, it is in barite and may also be in other samples in smaller undetected amounts. The large amount of barium in the recalculated Niobrara suggests that small amounts of barium occur in calcite, although the barium ion is generally too large to replace calcium in calcite.

Equivalent uranium shows very weak correlation coefficients. Its strongest correlations are with clay-associated elements. The usual strong concentration of uranium in organic material in many rocks (Tourtelot, 1962, p. 46) is barely suggested by the weak positive correlation with organic carbon in the Guy Holland samples. The sample from the 15- to 20-foot depth with the highest measured organic-carbon content also has the highest reported equivalent uranium. The weak correlations of equivalent uranium probably indicate that it is not a very reliable measure of elemental uranium except in very large amounts.

Cobalt and nickel both seem to occur about half, or a little more, in the clays and half in pyrite. Concentrations in the three pyrite-free sample cuttings from the top of the test hole are one-half to two-thirds the Sharon Springs average, and sample cuttings from the pyrite-rich 15- to 20-foot depth contain a maximum reported amount of both nickel and cobalt. The mean amounts in recalculated Niobrara are more than double the Sharon Springs average. The strong positive correlations with both organic matter and pyrite would normally indicate that nickel and cobalt occur in both. The moderate abundance of nickel in the sample cutting from the 10- to 15-foot depth (table 1) which contains 7 percent organic matter but no pyrite also indicates nickel in organic matter. However, the very small amounts of nickel and cobalt in the organic-rich but pyrite-free outcrop samples (table 2) indicate that these elements actually are mostly in pyrite and that their strong positive correlations with organic matter are attributable to the fact that abundance of organic matter and that of pyrite commonly is parallel in the subsurface samples.

Molybdenum shows its strongest positive correlations with pyrite and organic matter and with the elements nickel and cobalt, both of which occur in pyrite. Like nickel and cobalt, molybdenum is more than twice as abundant in the calcite-free Niobrara as in the Sharon Springs. Yet, unlike nickel and cobalt, the amount of molybdenum in the pyrite-free surface samples is only slightly lower than in fresh Sharon Springs samples, a fact which indicates that molybdenum is concentrated more in the organic matter than in the pyrite. The distribution of molybdenum parallels fairly well the highly variable abundance of organic matter in the surface samples. Also, molybdenum is commonly interpreted to be concentrated in organic matter (Tourtelot, 1962, p. 46). The small amounts of molybdenum in samples nearly devoid of pyrite or organic matter must occur in clay.

Strontium shows very strong positive correlations with calcium and calcite. All other correlation coefficients except those with vanadium either are negative or are not significant. The association of strontium with calcite in the Niobrara samples seems obvious and, in general, it is a common one (Tourtelot, 1962, p. 46). However, the association may not be due to the substitution of strontium for calcium in calcite, but rather to the mixing of small amounts of strontianite ($SrCO_3$) with the calcite (Rankama and Sahama, 1950, p. 481). Small amounts also must occur in clays in interlayer positions to account for the strontium in calcite-free samples.

Vanadium correlation coefficients of +0.6 with calcite, calcium, and strontium are surprising. The coefficients, together with the large amounts of vanadium in Niobrara samples (table 6), indicate that vanadium occurs in calcite. Yet, limestones are normally poor in vanadium (Rankama and Sahama, 1950, p. 600). Theoretically the +3 charge of vanadium is too high and its size (0.66 A) is too small to replace Ca^{+2} (0.99 A). Vanadium is reported to be strongly concentrated in clay and organic matter (Krauskopf, 1955; Tourtelot, 1962, p. 46). Relations of vanadium in the Kansas samples seemed so anomalous that the calcite was leached from one sample with 0.1 *N* HCl; the insoluble residue and leachate were analyzed separately. The insoluble residue contained 0.07 percent vanadium and the leachate, 0.03 percent vanadium. The whole sample (table 1, 220- to 225-foot depth) contained 0.05 percent vanadium. Vanadium, thus, is not concentrated in the calcite but rather in one of the insoluble constituents. The normal amounts of vanadium in the top two sample cuttings (table 1) and in the three surface samples of shale with low organic-carbon content (table 2, subunits 1, 21, 24) indicate that most of the vanadium in the Kansas samples is in the clay. Conditions that have affected the Niobrara sediments have somehow favored concentration of vanadium in the clay structures. A possible partial explanation is suggested by Le Riche (1959), who determined that, although the amount of vanadium in certain English shales closely parallels the amount of organic matter, the vanadium actually occurs in the clay minerals. Le Riche believed that vanadium was adsorbed on organic matter when the sediment was deposited but that it subsequently migrated into the structures of the clay minerals. The Niobrara samples contain nearly as much organic matter as the Sharon Springs samples but much less clay. If vanadium in the Niobrara sediments behaves as Le Riche suggested, fairly large amounts of vanadium originally adsorbed on organic matter would be concentrated in small amounts of clay and would give the anomalous relations observed, although, in all probability, the amount of vanadium would not be in excess of that in the Sharon Springs samples.

Niobium, zinc, silver, and lanthanum were detected in less than half the samples. The correlation coefficients calculated for niobium and zinc are, therefore, all weak and of limited significance. Neither correlation coefficients nor mean values have been calculated for lanthanum and silver. Lanthanum, like geochemically similar yttrium and ytterbium, is most concentrated in the apatite-rich carbonaceous shale at the top of the Sharon Springs (table 2, subunit 21). Niobium's positive correlation coefficients are all with elements that occur in clays or associated clastics; like zirconium, which it resembles geochemically, niobium probably occurs in the clay minerals or zircon. Little can be inferred about the occurrence of zinc. Silver was detected spectrographically in only four samples, all of which contained exceptionally large amounts of organic matter where silver commonly is concentrated (Tourtelot, 1962, p. 61). The atomic-absorption values for silver (table 2) are considerably lower than those from the spectrographic method, but they also roughly parallel the reported amounts of organic matter.

In summary, the striking feature of the Kansas samples is the large number of elements associated primarily or almost exclusively with clay (table 6). Only iron, nickel, cobalt, and molybdenum occur in pyrite as well as clay. Only molybdenum definitely, probably uranium, and possibly also silver are strongly concentrated in organic matter. Only strontium is strongly concentrated in carbonates other than the concretions. That some elements inferred to occur predominantly in the clay minerals, such as manganese and barium, show relatively weak correlations with all elements suggests that small amounts may be disseminated in components other than clay. In the Kansas rocks, a concentration of elements such as copper, chromium, vanadium, cobalt, and possibly nickel is not evident in organic matter, although reported to be in other organic-rich shales (Krauskopf, 1955, 1956; Tourtelot, 1962; Vine, 1966).

LEACHING OF SURFACE SAMPLES

Compared with subsurface shale samples (table 6), surface Sharon Springs samples are systematically depleted in several elements. Depletion of magnesium and calcium is partly due to leaching of dolomite. In addition, some calcium must have been removed from the clays. The observed depletion of iron, nickel, and cobalt is due to oxidation of pyrite. Some of the iron from the pyrite is retained in the surface rocks in jarosite. Manganese and strontium and, to a lesser extent, boron and lead are partly leached from the clays. Tourtelot (1962, p. 29 and 45) showed similar though smaller decreases in iron, calcium, magnesium, boron, manganese, strontium, and lead, but not nickel and cobalt, in a weathered outcrop of Pierre Shale. Vine (1966) reported depletion of iron, manganese, and cobalt in outcrop samples of Pennsylvanian black shale from Kentucky.

BENTONITES

Compared with the fresh shales, the two bentonites (tables 2, 6) contain slightly less magnesium, manganese, gallium, boron, ytterbium, and zirconium and much less of all the other elements, except silicon and aluminum. This small content, typical for several trace elements in most Pierre bentonites (authors' unpub. data), probably reflects the same leaching by unknown processes that has produced the kaolinite and abundant interlayer hydrated aluminum complexes that distinguish the Kansas Sharon Springs bentonites from most other bentonites.

COMPARISON WITH OTHER SHALES

The elements in the Kansas samples of Pierre Shale are compared with those of four other groups of shale in figure 25.

Major Elements

Aluminum, iron, and sodium in all groups of shale are about the same. Turekian and Wedepohl's silicon value for shale seems abnormally low. Potassium in the Kansas Sharon Springs samples, which is higher than that in Tourtelot's Pierre samples, reflects the more illitic character of the mixed-layer clays typical of the Sharon Springs shales as compared with the more montmorillonitic shales of the Pierre as a whole.

Calcium in the Kansas samples, which is higher than in Tourtelot's samples, reflects the presence of several percent of dolomite in samples from the unweathered cuttings. The expected, but unobserved, difference in magnesium content that would be caused by the presence of dolomite must be offset by lesser amounts of magnesium in the clay components of the Kansas samples.

Minor and Trace Elements

Many of the differences in minor- and trace-element contents between the groups of samples reported in figure 25 seem to be controlled by two interrelated factors — content of organic matter and grain size. Krauskopf's black shale group is generally the most organic rich, having contents ranging from a few percent to over 50 percent. The Kansas Sharon Springs samples generally have contents of 5–10 percent. Most of Tourtelot's Pierre samples are from members of the Pierre that contain relatively little organic matter. The grain size of most Pierre rocks is exceptionally fine, and that of the organic-rich shales of Krauskopf, even finer. Thus, both the Pierre and Krauskopf's black shale are likely to be finer grained than the ordinary shales. The finer grained rocks and, indirectly, the more carbonaceous shales thus should be depleted in elements concentrated in coarser or heavier detrital mineral grains.

In figure 25, element content is related to organic content or to grain size in the following ways. The general ranges of contents given by Turekian and Wedepohl and by Krauskopf for many elements in common shales and by Krauskopf for black shales overlap, but for most elements the average contents in the black shale extend either below (indicating a grain-size control) or above (indicating organic-matter control) the range of contents for common shale. Trace-element content in most of the Kansas shales centers near the end of the range for common shale, beyond which the trace-element average content of black shale extends farthest. For elements whose ranges of contents in common shale and black shale do not overlap, the content of the Kansas shales commonly falls between those two ranges. Thus the contents of the Kansas samples are about what would be expected in moderately carbonaceous shales, which they are. Elements in Tourtelot's Pierre samples whose concentrations differ appreciably from those in the Kansas shales (manganese, gallium, molybdenum, nickel, lead, vanadium, zirconium) are more like those in the ordinary shales. Elements which show no strong affinities for organic matter, for pyrite, or for heavy minerals commonly are about equally abundant in all the categories of shale for which data are available.

Titanium, zirconium, and niobium contents in ordinary shale that are notably larger than in the other three categories reflect the larger average grain size of ordinary shale and thus of heavier clastics, such as zircon, anatase, and ilmenite, in which these elements should occur.

Manganese is conspicuously less abundant in the Pierre samples than in ordinary shale. Heavy manganese oxides in coarser rocks are exceptionally sparse in the finer grained Pierre samples. The small amounts of manganese in shales of the Pierre occur mainly in clay structures.

The slightly higher lead content in the Kansas Sharon Springs than in Tourtelot's Pierre samples probably follows from its substitution for K^+ in the more illitic Sharon Springs samples.

Molybdenum, uranium, silver, nickel, copper, vanadium, and gallium, as shown in figure 25, all appear to be concentrated in organic-rich shales. The reason for the higher contents of molybdenum, uranium, and silver in the more carbonaceous rocks seems obvious.

Nickel and copper are only slightly more abundant in the Kansas shales than in Tourtelot's Pierre samples or in most ordinary shales. The higher nickel content is due mainly to the relatively large amount of nickel-bearing pyrite. No similar explanation is evident for copper in the Kansas samples, although in other rocks copper commonly is concentrated in pyrite or organic matter (Tourtelot, 1962, p. 46). Although cobalt, like nickel, has been inferred to occur in pyrite in the Kansas samples, the expected high cobalt content relative to that in other shales is not evident.

Vanadium content of the four groups of shales is entirely consistent with the occurrence of the element in organic matter, where it is thought to be concentrated (Krauskopf, 1956, p. 29; Tourtelot, 1962, p. 46). As previously explained, the relation with organic matter may be indirect; the vanadium may actually be in the clay-mineral fraction of some sediments.

Gallium is generally most abundant in Krauskopf's black shale and least abundant in Tourtelot's Pierre samples and the ordinary shales. This relation indicates gallium concentration in organic matter. The correlation statistics for the Kansas samples, however, and the well-established fact that gallium replaces aluminum in clay (Goldschmidt, 1954, p. 319) strongly contradict this interpretation. A possible explanation might be a higher percentage of clay, and hence a greater amount of gallium substituted for aluminum, in finer grained shales rich in organic matter. Such an explanation, however, does not apply well to the Kansas samples, because they are only a little over 50 percent clay, which, if anything, is slightly less than average for the Pierre Shale in general. The large amount of gallium in the Kansas samples cannot be explained at this time.

Barium, cobalt, chromium, scandium, yttrium, and ytterbium occur in approximately equal concentrations in the Kansas and the other groups of samples, as expected from their inferred occurrence in the clays. Yttrium and ytterbium, being closely related to the rare earths, might be expected to occur in heavy clastic mineral grains like monazite and thus be depleted like titanium, zirconium, and niobium in the finer grained groups of rocks. No such depletion is evident, and the yttrium and ytterbium apparently occur in clays.

MEASURED SECTIONS

Seven partial surface sections and two well logs of the Sharon Springs Member of the Pierre Shale were measured in Wallace, Logan, and Phillips Counties, Kans. Five of the sections represent a part of the dark soft shale unit and two represent the upper part of the organic-rich shale unit and the phosphatic shale unit. Sample logs of two test holes, drilled by the State Geological Survey of Kansas to determine the thickness and character of the Sharon Springs, are included with the measured sections.

LOCALITY 1. — *Section of the lower unit of the Sharon Springs Member of the Pierre Shale and the upper part of the Smoky Hill Chalk Member of the Niobrara Formation*

[Exposure measured in the valley of Burris Draw in the NE¼NE¼ sec. 20, T. 15 S., R. 32 W., Lake McBride 7½-minute quadrangle, Logan County, Kans.]

		Feet
Pierre Shale (lower part) :		
Sharon Springs Member (lower unit) :		
42.	Shale, light-gray; oxidizes to dark yellowish orange. Tan-weathering gray irregularly shaped limestone concretions 0.3 ft thick by 0.8 ft wide 2 ft above base	8.0
41.	Limestone concretions, dark-yellow-orange; has white calcareous specks; marly, weathering in thin slabs; persistent; forms lenses as long as 6 ft. Fossiliferous, containing poorly preserved baculites and pelecypods (USGS Mesozoic loc. D1827). Fossils: *Inoceramus* cf. *I. subcompressus* Meek and Hayden, *Pteria* sp., *Ostrea* sp., *Baculites obtusus* Meek. (See pl. 1)	.4
40.	Shale, light- to medium-gray; soft, weathering to fine flaky crust; 0.2-ft-thick limonite-gypsum layer at base contains fragments of large thin-shelled inocerams (USGS Mesozoic loc. D2691). Fossils: *Inoceramus* aff. *I. cycloides* Wegner. (See pl. 2)	12.6
39.	Shale, like subunit 42	9.6
38.	Shale, like subunit 40	3.0
37.	Shale, like subunit 42	3.7
36.	Shale, light-olive-gray; weathers dusky yellow to gray; soft, weathering to fine flaky crust; a few thin ferruginous streaks; poorly exposed; slightly bentonitic except in heads of some gullies	24.9
Pierre Shale (lower part) — Continued		
Sharon Springs Member (lower unit) — Continued		
35.	Shale, light-olive-gray; hard in lower part; weathers to small chips and plates; becomes very soft in upper part; contains very sparse fish scales	17.4
34.	Bentonite parting, white	.02
33.	Shale, dusky-yellowish-brown; hard, fissile to papery weathering; abundant fish scales and bones; contains gypsum and jarosite on fracture surfaces and bedding planes; also contains selenite crystals	6.8
32.	Bentonite, white	.01
31.	Shale, like subunit 33	1.0
30.	Bentonite, light-gray to white	.02
29.	Shale, black; weathers platy and light olive gray to light gray, blocky; thin calcareous streaks	1.8
28.	Bentonite, yellowish-gray, nonswelling, granular, persistent; sharp lower contact and gradational upper contact	.2
27.	Shale, black to grayish-black; noncalcareous; brownish-gray clayey calcareous shale streaks; 0.2-ft-thick bed of gray clay 0.5 ft below top. Contains a few fragments of inoceramid shells (USGS Mesozoic loc. D5510). Fossils: *Inoceramus* sp	2.7
	Total lower unit of Sharon Springs Member measured	92.2
Niobrara Formation (part) :		
Smoky Hill Chalk Member (part) :		
26.	Bentonite, dark-yellowish-orange, nonswelling; color results from limonite that coats bedding and fracture surfaces; contains abundant selenite crystals and hairline black-shale streaks	.1
25.	Shale, dark-gray; weathers medium gray; calcareous, abundant white calcareous specks	2.5
24.	Bentonite, like subunit 26; contains black-shale streaks cemented in limonite	.05
23.	Marlstone, dark-gray; weathers medium gray; shaly, deeply weathered, soft	2.3
22.	Bentonite, like subunit 24	.03
21.	Marlstone, like subunit 23	2.3
20.	Bentonite, like subunit 26; contains black-shale streaks	.1
19.	Marlstone, medium-dark gray; weathers very pale orange; very shaly	1.2
18.	Bentonite parting, like subunit 26	.03
17.	Marlstone, like subunit 19	.8
16.	Bentonite, like subunit 26; contains limonite streaks	.1
15.	Marlstone, like subunit 19	1.4
14.	Bentonite parting, like subunit 26	.03
13.	Marlstone, like subunit 19	2.2
12.	Bentonite parting, like subunit 26	.05
11.	Marlstone, like subunit 19	1.9
10.	Bentonite, moderate-yellowish-brown, nonswelling; abundant pyrite nodules, limonite, and gypsum throughout; oxidized pyrite nodules enclose soft white kaolinlike nodules	.2

	Feet
Niobrara Formation (part) — Continued	
Smoky Hill Chalk Member (part) — Continued	
9. Marlstone, like subunit 19	2.1
8. Bentonite, moderate-yellowish-brown, nonswelling, granular, deeply weathered; persistent bed	.5
7. Marlstone, like subunit 19	2.7
6. Bentonite parting, calcareous, like subunit 8	.03
5. Chalk, medium-dark-gray; weathers very pale orange; hard-ledge former; clayey; abundant white calcareous specks and numerous fresh pyrite nodules	5.8
4. Bentonite, like subunit 8	.05
3. Chalk, light-olive-gray; weathers light gray; hard; clayey; slabby to chunky; abundant fresh and weathered pyrite nodules	7.0
2. Bentonite, like subunit 8	.05
1. Chalk, like subunit 3	15+
Total Smoky Hill Member measured	48.5

LOCALITY 2. — *Partial section of the Pierre Shale*

[Measured at McAllaster Buttes, in the SE¼ sec. 13, T. 12 S., R. 37 W., Logan County, Kans.]

	Feet
Pleistocene deposits, not measured.	
Pierre Shale (part):	
Weskan Member (part):	
38. Covered, in part greenish-brown shale that weathers black and contains sparse rusty-weathering siderite concretions	20.0
37. Shale, greenish-black, soft; limestone concretions in lower part of this subunit	25.0
36. Bentonite, white, nonswelling	1.0
35. Shale, grayish-green, soft	2.0
34. Bentonite, reddish-brown, nonswelling	.7
33. Shale, very dark gray; weathers light gray, having a fine-textured soft crust; soft	6.0
32. Bentonite, cream to light-tan, granular, nonswelling; limonite and jarosite stained. Contains abundant gypsum in form of selenite crystals	.1
31. Clay, olive-gray, plastic	.2
30. Bentonite, like subunit 32	.15
29. Clay, like subunit 31	.1
28. Siderite concretions, reddish-brown-weathering; 0.4 ft thick by 1.5 ft in diameter	.4
27. Shale, dark-gray; weathers light gray; soft; flaky	2.0
26. Bentonite, like subunit 32	.5
25. Shale, like subunit 27	1.2
24. Bentonite, like subunit 32	.05
23. Clay, like subunit 31	.25
22. Bentonite, white	.03
21. Clay, like subunit 31	.4
20. Shale, like subunit 27; has a few phosphate nodules at base	2.4
19. Limestone, concretionary, shaly to laminated; dark gray, weathering tan to rusty yellow; lenslike; 1.0 ft thick by 20 ft in diameter	1.0
Total Weskan Member measured (rounded)	63.5
Sharon Springs Member (upper unit):	
18. Bentonite, white, nonswelling	.02
17. Shale, black, hard, hackly; not buttress forming	3.0
16. Bentonite, like subunit 18; has horizon of gray limestone concretions 0.3 ft thick by 1.0 ft in diameter	.05
15. Shale, like subunit 17	1.3
14. Bentonite, like subunit 18	.1
13. Shale, like subunit 17	2.0
12. Bentonite, like subunit 18	.02
11. Shale, dark-brownish-black, hard, flaky to papery; abundant scales and other fish remains. Weathers grayish brown and in thicker units weathers to form vertical buttresses	.3
10. Shale, like subunit 11; has eight layers of dark-bluish-gray-weathering phosphate nodules. Some brown shale nodules having concentric bands or rinds of gypsum. Most nodules contain abundant fish scales and bones and possibly fecal pellets. Contains four thin bentonite streaks	3.5
Total upper unit of Sharon Springs Member measured (rounded)	10.3
Sharon Springs Member (middle unit):	
9. Bentonite, cream to light-tan, nonswelling, granular	.25
8. Shale, like subunit 11; has five light-gray bentonite streaks	3.7
7. Shale, like subunit 11; gray tan-weathering limestone concretion layer 0.8 ft thick by 3–5 ft in diameter 6 ft above base; dark-gray limestone concretion with tan cone-in-cone structure 12 ft above base	17.0
6. Limestone concretions, septarian, 3 ft thick by 9 ft in diameter; contains thick septa of light-brown fibrous calcite	3.0
5. Shale, like subunit 11; crisscrossed with veins of gypsum, jarosite, and limonite. Sparse dark-gray white-weathering dense limestone concretions 0.6 ft thick by 1.5 ft in diameter at 10, 13, and 15 ft above base. Concretions are of irregular shape and have 0.02-ft-thick gypsum crusts. At 18 ft above base is a layer of gray sparsely fossiliferous septarian limestone concretions 1 ft thick by 2 ft in diameter containing a few specimens of *Baculites asperiformis* Meek	25.0
4. Bentonite, cream-colored, nonswelling, granular; jarosite and limonite stained; containing abundant gypsum	.2
3. Shale, like subunit 11; contains a highly fossiliferous limestone concretion 1 ft	

	Feet
Pierre Shale (part) — Continued	
Sharon Springs Member (upper unit) — Continued	
thick by 6 ft in diameter (USGS Mesozoic loc. D2591). Fossils: *Inoceramus* sp., *Ostrea inornata* Meek and Hayden, *Baculites asperiformis* Meek, *Trachyscaphites spiniger* (Schlüter) subsp. *porchi* Adkins. (See pl. 2.)	13.0
2. Shale, like subunit 11; poorly exposed	28.5
1. Bentonite, poorly exposed	.4
Total middle unit of Sharon Springs Member measured (rounded)	91.0
Total Sharon Springs Member measured	101.3
Total Pierre Shale measured	164.8

LOCALITY 2.—*Sample log of test hole McAllaster Buttes 1 State*

[Drilled in the SW¼NE¼ sec. 13, T. 12 S., R. 37 W., Logan County, Kans. Hole collared at about 100 feet below the contact between the Weskan and Sharon Springs Members of the Pierre Shale. Sampled and described by W. A. Cobban]

	Thickness (feet)	Depth (feet)
Pierre Shale:		
Sharon Springs Member (samples start at 45 ft):		
Shale, medium-gray; slightly calcareous in places and has a few white specks; contains a few shell fragments. A medium-gray finely pyritic layer of bentonite at 55–60 ft	15	60
Shale, medium-gray; contains minute black carbonaceous specks and, here and there, white calcareous specks, bits of mollusks, or brown fish scales	30	90
Shale, medium-gray; calcareous where white specks are concentrated as thin laminae	5	95
Total Sharon Springs Member drilled	95	
Niobrara Formation:		
Smoky Hill Chalk Member:		
Shale, light-medium-gray, firm; very calcareous, abundant white specks; contains a few fish scales. Traces of white bentonite and bluish-gray pyritic bentonite	5	100
Shale, light-medium-gray; slightly lighter than overlying subunit; firm; very calcareous, abundant white specks. Sparse pyrite	5	105
Shale, medium-light-gray, very calcareous. A little white bentonite	5	110
Shale, light-gray; very calcareous, abundant white specks	50	160
Shale, like overlying subunit. Hard layer at 163 ft. A little bluish-gray bentonite	5	165
Shale, light-gray; very calcareous, abundant white specks. Trace of bluish-gray pyritic bentonite in lower 5 ft	45	210
Total Smoky Hill Member drilled	115	

LOCALITY 3. — *Partial section of the lower unit of the Sharon Springs Member of the Pierre Shale*

[SE¼ sec. 20, T. 12 S., R. 36 W., Logan County, Kans. Measured along the south meander scar of the North Fork of the Smoky Hill River]

	Feet
Pierre Shale (part):	
Sharon Springs Member (lower unit):	
16. Soil and deeply weathered shale	3.0
15. Bentonite, light-orange-brown; much limonite stain	.5
14. Shale, dark- to medium-gray, soft; upper 5.5 ft weathers brownish gray, lower 2 ft weathers light gray; coarsely laminated appearance	7.5
13. Shale or ferruginous mudstone, limonitic, orange-brown, fossiliferous; contains fragmentary inocerams and baculites (USGS Mesozoic loc. D2690). Fossils: *Inoceramus* aff. *I. barabini* Morton, *Baculites obtusus* Meek	.3
12. Bentonite, dark-orange-brown	.25
11. Shale, dark- to medium-gray; weathers gray; soft	1.4
10. Bentonite parting	.02
9. Shale, like subunit 11	3.3
8. Bentonite parting	.01
7. Shale, like subunit 11	.3
6. Bentonite parting	.01
5. Shale, like subunit 11	.3
4. Bentonite, cream to light-gray; limonite stain	.15
3. Shale, like subunit 11	4.7
2. Shale, light-gray-brown; weathers dark gray to gray brown; hard, platy to chippy; abundant jarosite	4.8
1. Shale, like subunit 11	2+
Covered.	
Total lower unit of Sharon Springs measured (rounded)	28.5

LOCALITY 4. — *Section of the lower unit of the Sharon Springs Member of the Pierre Shale and the upper part of the Smoky Hill Member of the Niobrara Formation*

[Measured in the SW¼SE¼ sec. 33, T. 12 S., R. 36 W., Logan County, Kans. Section started in Niobrara about 100 yards due west of dry oil and gas test hole and continued north along the southwest bank of the North Fork of the Smoky Hill River]

	Feet
Pleistocene deposits, not measured.	
Pierre Shale:	
Sharon Springs Member (lower unit):	
20. Shale, gray; weathers light tannish brown; soft; flaky; 0.2-ft-thick rusty bentonite 3 ft above base	8
19. Shale, dark-gray, soft, poorly exposed; one or two bentonites near base. A 1-ft bentonite bed 15 ft above base contains thin white limestone concretions; a questionable bentonite at about 19 ft above base	23
18. Shale, bluish-black, hard; weathers papery; rich in organic matter; abundant fish remains	12
17. Shale, dark-gray, bentonitic, soft; abundant jarosite throughout	2

Pierre Shale — Continued

Sharon Springs Member (lower unit) — Continued

	Feet
16. Shale, dark-brownish-gray; slightly harder than underlying shales; abundant fish remains	3
Total lower unit of Sharon Springs Member measured	48

Niobrara Formation (part):

Smoky Hill Chalk Member (part):

	Feet
15. Bentonite, white to cream, nonswelling, granular	0.1
14. Shale, gray-brown, calcareous, fissile; abundant white calcareous specks	4.0
13. Bentonite parting	.05
12. Shale, like subunit 14; brownish gray	1.9
11. Bentonite parting	.05
10. Shale, like subunit 14	1.5
9. Bentonite parting	.05
8. Shale, like subunit 14	1.2
7. Bentonite, cream; contains white nodules of kaolin(?) 0.1 ft thick by 0.15 ft in diameter; heavy limonite crust at top and base of bed	.15
6. Shale, dark-gray; weathers bluish gray; calcareous; flaky; abundant pyrite nodules	5.0
5. Shale, cemented with limonite	.2
4. Bentonite, gray; contains hairline black-shale streaks	.1
3. Shale, dark-gray; weathers bluish gray; calcareous; thin limonite layer at top	.3
2. Bentonite, white, nonswelling; with 0.05-ft-thick limonite layer at top, 0.02-ft-thick layer at base	.4
1. Marlstone, dark-gray; weathers bluish gray and shaly. Several zones of altered pyrite nodules and yellow chalk streaks; pyrite nodules 3 ft above base, pyrite nodules and chalk layer 7 ft above base, layer of pyrite nodules 8 ft above base	12.0
Total Smoky Hill Member measured	27.0

Locality 5. — *Section of the lower unit of the Sharon Springs Member of the Pierre Shale and the upper part of the Smoky Hill Member of the Niobrara Formation*

[Measured in the SE¼NE¼ sec. 32, T. 13 S., R. 37 W., Logan County, Kans.]

Pierre Shale (part):

Sharon Springs Member (lower unit):

	Feet
41. Shale, dark-gray to black; mostly covered by gravel	10.0
40. Bentonite, cream to light-yellow, granular, nonswelling	.15
39. Shale, dark-gray-brown, clayey, soft, poorly exposed, highly weathered	2.0
38. Bentonite, like subunit 40	.15
37. Shale, like subunit 39	.25
36. Bentonite, like subunit 40	.2
35. Shale, like subunit 39	1.0
34. Bentonite, like subunit 40	.4
33. Shale, like subunit 39	1.5
32. Bentonite, like subunit 40	.05
31. Shale, like subunit 39	.8
30. Bentonite, like subunit 40	.01
29. Shale, like subunit 39	.6
28. Bentonite, like subunit 40	.5
27. Shale, like subunit 39	3.3
26. Bentonite, like subunit 40	.25
25. Shale, like subunit 39	1.0
24. Bentonite, like subunit 40; true thickness indeterminate	1.0
23. Shale, like subunit 39	8.0
Total lower unit Sharon Springs Member measured (rounded)	31.2

Niobrara Formation (part):

Smoky Hill Chalk Member (part):

	Feet
22. Shale, medium- to light-gray; has thin calcareous streaks	3.5
21. Bentonite, like subunit 40; orange	.3
20. Shale, black, hard, weakly calcareous; contains a few white specks	4.0
19. Bentonite, like subunit 21	.2
18. Marlstone, bluish-gray, shaly; yellow to orange on deeply weathered surface	5.7
17. Bentonite, like subunit 21	.1
16. Marlstone, like subunit 18; has a 0.03-ft-thick bentonite bed 1.5 ft below top	3.4
15. Bentonite, like subunit 21	.05
14. Marlstone, like subunit 18	4.0
13. Bentonite, like subunit 21	.1
12. Marlstone, like subunit 18; has two zones of 0.1-ft-thick pyrite nodules	3.7
11. Bentonite, like subunit 21	.2
10. Marlstone, like subunit 18	1.2
9. Bentonite, gray, nonswelling; abundant gypsum and jarosite	.4
8. Marlstone, like subunit 18	2.5
7. Chalk, compact, yellow, lenticular	1.0
6. Marlstone, like subunit 18	7.5
5. Limonite layer, brown, persistent	.02
4. Marlstone, like subunit 18; contains numerous weathered pyrite nodules	2.4
3. Chalk, like subunit 7	.4
2. Limonite layer, like subunit 5	.2
1. Marlstone, like subunit 18	5.0
Covered.	
Total Smoky Hill Chalk Member measured (rounded)	45.9

Locality 6. — *Section of the lower unit of the Weskan and the upper unit of the Sharon Springs Members of the Pierre Shale*

[Measured at Devils Halfacre, in the SW¼SE¼NW¼ sec. 36, T. 13 S., R. 40 W., Wallace County, Kans.]

Pierre Shale (part):

Weskan Member (lower unit):

	Feet
27. Siderite concretion; weathers dark yellowish orange to dusky red	.05
26. Shale, greenish-black to olive-gray, poorly exposed	7.0

	Feet
Pierre Shale (part) — Continued	
Weskan Member (lower unit) — Continued	
25. Limestone concretions, dark-gray; weather to light-gray small chips and angular fragments; septarian; fossiliferous (USGS Mesozoic loc. D1177). Fossils: pelagic Foraminifera, *Inoceramus sublaevis* Hall and Meek, *Pteria linguaeformis* (Evans and Shumard), *Ostrea inornata* Meek and Hayden, *Anisomyon* cf. *A. borealis* (Morton), *Drepanochilus* sp., *Odontobasis?* sp., *Oxybeloceras* sp., fish scales	1.0
24. Shale, like subunit 26; bentonitic; thin bentonite bed near base, 0.5-ft-thick bed of moderate-red bentonite near top; poorly exposed	6.0
23. Limestone concretion, grayish-orange, tabular, slabby, fossiliferous (USGS Mesozoic loc. D1176). Fossils: pelagic Foraminifera, *Inoceramus* aff. *I. proximus* Tuomey, *Baculites* sp., *Didymoceras* n. sp., fish scales	.4
Total Weskan Member measured (rounded)	14.5
Sharon Springs Member (upper unit):	
22. Gypsum, fibrous, and white soft chalky basaluminite	0.2
21. Shale, grayish-brown; lower 3 ft hard and chippy, upper 1.5 ft soft; thin layer of phosphate nodules in lower 1 ft	4.5
20. Bentonite, very pale orange, hard	.01
19. Shale, grayish-brown; weathers light gray; hard; phosphatic(?); contains one layer of small phosphate nodules	.6
18. Bentonite, like subunit 20	.05
17. Shale, like subunit 19; abundant large fish scales	.4
16. Bentonite, like subunit 20	.05
15. Shale, medium-dark-gray to dark-gray; weathers papery to flaky in lower 2.4 ft, becoming grayish brown with hackly fracture in upper 5 ft; abundant jarosite throughout. Eight layers of gypsum-encrusted clayey phosphate nodules which range from 0.05 to 0.3 ft in diameter and contain rounded fragments of bones and abundant light-blue-weathering fish scales	7.4
Total upper unit of Sharon Springs Member	13.2
Sharon Springs Member (middle unit):	
14. Bentonite, grayish-yellow, soft, nonswelling; limonite stain on fractures; abundant large selenite crystals throughout	0.4
13. Shale, grayish-black, hard, buttress-forming; weathers brownish black and papery; abundant fish scales and occasional vertebrate remains; rich in organic matter; abundant jarosite on bedding planes and fracture surfaces. Upper 0.6 ft contains 0.05-ft-thick layer of clayey phosphate nodules and 0.01-ft-thick bentonite parting	1.75
12. Bentonite, like subunit 14	.25
11. Shale, like subunit 13	1.1
10. Bentonite, like subunit 14	.15
9. Shale, like subunit 13	1.2
8. Bentonite, like subunit 14	.05
7. Shale, like subunit 13	.6
6. Bentonite, like subunit 14	.1
5. Shale, like subunit 13. Has sparse septarian limestone concretions containing white calcite septa and sparse gray to pale-blue barite crystals	1.0
4. Limestone concretions, septarian, dark-gray, spherical, closely spaced; weather light gray; thick septa of dark-brown fibrous calcite coated with transparent calcite crystals. Two or more concretions may join to form lenslike masses of limestone 20 ft or more in diameter. Thick crusts of cone-in-cone limestone coat a few of the concretions	2.5
3. Shale, like subunit 13	2.4
2. Limestone concretions, like subunit 4	1.0
1. Shale, like subunit 13	3+
Total middle unit of Sharon Springs Member measured	15.5
Total Sharon Springs measured	28.7
Total Pierre Shale measured	43.1

LOCALITY 6. — *Sample log of test hole Guy Holland 1 State, Devils Halfacre*

[In the SE¼SE¼NW¼ sec. 36, T. 13 S., R. 40 W., Wallace County, Kans. Ground elevation 3,440 feet. Hole collared at the contact of the Weskan and Sharon Springs Members of the Pierre Shale. Sampled and described by W. A. Cobban]

Pierre Shale:	*Thickness (feet)*	*Depth (feet)*
Sharon Springs Member (upper unit):		
Shale, yellowish-gray; mottled medium-light-gray; weathered; contains black fish scales and bones	5	5
Shale, medium- to medium-dark-gray; has minute yellowish-gray specks	5	10
Sharon Springs Member (middle and lower units):		
Shale, medium-dark-gray and medium-olive-gray; mottled lighter brown; contains brown fish scales and bones. A little medium-bluish-gray minutely pyritic nonswelling bentonite and very pale orange to white very finely micaceous (white) nonswelling bentonite	5	15
Shale, medium-dark-gray; contains a few brown fish scales. A little bluish-gray and white bentonite	5	20
Shale, medium-dark-gray; contains fish scales and bones. Much pale-bluish-gray bentonite	5	25

Pierre Shale — Continued	*Thickness (feet)*	*Depth (feet)*
Shale, medium-dark-gray; contains a few fish scales and bones. At 27–29 ft a medium-dark-gray septarian limestone concretion has brown to white calcite veins which contain some large crystals of nearly colorless calcite	5	30
Shale, medium-dark-gray; not as dark as 10- to 30-ft subunits; contains minute black carbonaceous specks and a few fish scales	20	50
Shale, like overlying subunit; contains a bed of white bentonite	5	55
Shale, medium-dark-gray; contains minute black carbonaceous specks and a very few fish scales and bits of mollusk shell. Some laminae of gray siltstone in lower 10 ft	40	95
Shale, medium-gray; contains a layer of white swelling bentonite	5	100
Shale, medium-gray; contains carbonaceous specks and, here and there, bits of mollusks or white calcareous specks. Some white bentonite at 125–130 ft and 135–140 ft. Few fragments of inoceramid and baculitid shells at 130–135 ft	50	150
Shale, medium-gray; contains some white calcareous specks locally concentrated as thin laminae. Fish scales and bones moderately common. Some white bentonite at 155–160 ft. At 170–171 ft a medium-gray limestone concretion contains white specks and septarian concretions having thin white calcite veins	35	185
Shale, medium-gray; calcareous in parts having white specks. Traces of bluish-gray minutely pyritic bentonite; fragments of inoceramid shells	5	190
Shale, medium-gray; in part calcareous. Subunit contains a thin brown sideritic concretion	5	195
Shale, medium-gray, calcareous; contains white specks. Some medium-bluish-gray minutely pyritic bentonite in lower 5 ft	10	205
Shale, medium-gray; gradually becomes lighter downward; very calcareous, abundant white specks; contains a few fish scales. A little medium-gray to bluish-gray bentonite at 220–222 ft. (Approximate contact between Pierre Shale and Niobrara Formation picked on the electric log at 222 ft)	17	222
Total middle and lower units of Sharon Springs Member measured	222	
Niobrara Formation:		
Shale, same as overlying subunit	13	235
Shale, medium-light-gray; very calcareous, abundant white specks; contains a few fish bones. Some medium-bluish-gray bentonite at 245–250 ft	20	255
Shale, medium-light-gray; slightly darker than overlying subunit; very calcareous, abundant white specks. A little bluish-gray bentonite in upper 20 ft	45	300
Total Niobrara Formation measured	78	

Section of lower unit of Sharon Springs Member

[Measured by J. R. Gill and W. A. Cobban on the east bank of Prairie Dog Creek about 1 mile east of the town of Long Island in the E½SE¼ sec. 24, T. 1 S., R. 20 W., Phillips County, Kans.]

Pierre Shale (part):	*Feet*
Sharon Springs Member (lower unit):	
33. Bentonite; bright orange at base, pale yellowish gray at top, nonswelling	0.3
32. Shale, medium-dark-gray; weathers flaky	6.9
31. Ash, light-yellow, medium-grained, calcareous	.1
30. Bentonite, yellowish-orange	.05
29. Shale, medium-dark-gray; contains 0.1-ft-thick layer of phosphate nodules about 1 ft above base. Limestone concretion 0.2 ft thick by 0.05 ft in diameter about 1.5 ft below top; thin light-orange-weathering limonite plates throughout	5.0
28. Bentonite, pale-yellowish-gray, ashy	.1
27. Shale, like subunit 32	1.7
26. Bentonite; weathers orange; nonswelling	.1
25. Shale, like subunit 32	1.1
24. Bentonite, dark-gray, waxy, nonswelling	.2
23. Shale, like subunit 32	2.6
22. Bentonite; basal 0.15 ft weathers bright orange, upper 0.45 ft weathers pale yellowish gray; waxy, nonswelling	.55
21. Shale, like subunit 32	1.2
20. Bentonite, pale-yellowish-gray, waxy	.6
19. Shale, like subunit 32	.9
18. Bentonite, impure; limonite stain	.05
17. Shale, like subunit 32	.6
16. Bentonite, pale-yellowish-gray	.02
15. Shale, like subunit 32	2.2
14. Bentonite, pale-yellowish-gray, waxy, nonswelling; mottled with orange and brown iron stain	.6
13. Shale, like subunit 32	3.3
12. Shale, dark-gray	1.5
11. Bentonite, gray; mottled with bright-orange iron stain; nonswelling	.5
10. Shale, olive-gray; grades upward into medium dark gray; weathers into small chips	1.0
9. Shale, medium-light-gray, calcareous; weathers yellowish gray to pale yellowish gray; has hackly fracture; contains limonite-cemented bentonite layer 0.01 ft thick 1.8 feet above base	5.5

	Feet
Pierre Shale (part) — Continued	
Sharon Springs Member (lower unit) — Continued	
8. Bentonite, pinkish-gray, nonswelling	.1
7. Shale, dark-grayish-brown; weathers hackly	6.0
6. Marlstone, light-gray; persistent marker	.2
5. Shale, dark-gray to black, buttress-weathering; contains some calcareous streaks in upper part	9.7
4. Bentonite, pale-yellowish-gray, nonswelling	.02
3. Shale; weathers bluish gray and papery; upper part harder and contains thin calcareous shale layers	3.1
2. Bentonite, yellowish-gray, nonswelling	.05
Total lower unit of Sharon Springs Member measured (rounded)	55.85
Niobrara Formation (part):	
Smoky Hill Chalk Member (part):	
1. Marlstone; weathers bluish gray; abundant limonite and gypsum; a few scattered bones	1+

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PLATES 1, 2

PLATE 1

[All figures natural size except as otherwise indicated]

FIGURES 1–3. *Baculites obtusus* Meek (early form) (p. 11).

From orange-weathering limestone concretions 71 feet above base of Sharon Springs Member of Pierre Shale at USGS Mesozoic loc. D1827 (text fig. 1, loc. 1).

1. Lateral view of a large adult, × ⅔, hypotype USNM 157858.

2, 3. Lateral views of latex casts of a young adult and a juvenile, hypotypes USNM 157859, 157860.

4, 5. *Baculites obtusus* Meek (late form) (p. 11).

From lower unit of Sharon Springs Member at USGS Mesozoic loc. D2663 in the NE¼ sec. 18, T. 12 S., R. 36 W., Logan County, Kans.

4, 5. Lateral views of latex casts of specimens that show the strong ribbing characteristic of this form of the species. Hypotypes USNM 157861, 157862.

6, 7. *Inoceramus* cf. *I. subcompressus* Meek and Hayden (p. 39).

Incomplete specimens from the same locality as figs. 1–3. Figured specimens USNM 157872, 157873.


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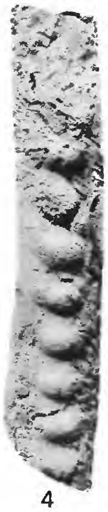
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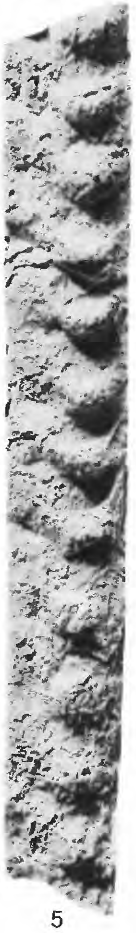
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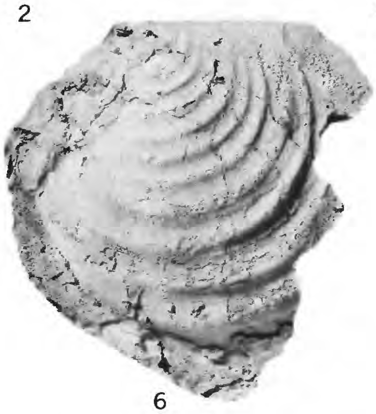
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7

MOLLUSKS FROM THE *BACULITES OBTUSUS* ZONE

PLATE 2

[All figures natural size]

FIGURES 1–11. *Baculites asperiformis* Meek (p. 5).

From a limestone concretion about 65 feet below top of Sharon Springs Member of Pierre Shale at USGS Mesozoic loc. D2591 (text fig. 1, loc. 2).

1, 2. Lateral and ventral views of a juvenile showing rise of flank nodes. Hypotype USNM 157863.

3, 4. Lateral and ventral views of a larger juvenile showing rather closely spaced nodes. Hypotype USNM 157864.

5, 6. Lateral and ventral views of a young adult showing well-developed widely spaced nodes. Hypotype USNM 157865.

7. Lateral view of a young adult with riblike nodes. Hypotype USNM 157866.

8, 9. Lateral and ventral views of a young adult showing most of the living chamber which contains a juvenile. Hypotype USNM 157867.

10. Lateral view of the aperture of an adult. Hypotype USNM 157868.

11. Lateral view of part of an adult living chamber showing reduction in lateral ornament toward the flared aperture. Hypotype USNM 157869.

12. *Trachyscaphites spiniger* (Schlüter) subsp. *porchi* (Adkins) (p. 5).

Lateral view of a fragment of a phragmocone from the same locality as figs. 1–11 showing the dense ribbing and several rows of tubercles. Hypotype USNM 157870.

13. *Inoceramus* aff. *I. cycloides* Wegner (p. 39).

Fragment showing rather even concentric folds with growth lines from a very thin gypsiferous limonite bed 71 feet above base of Sharon Springs Member at USGS Mesozoic loc. D2691 (text fig. 1, loc. 1). Figured specimen USNM 157871.


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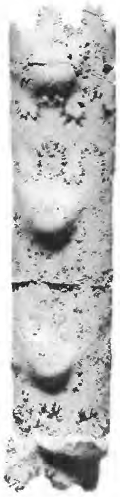
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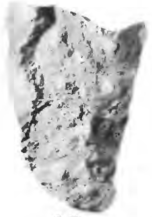
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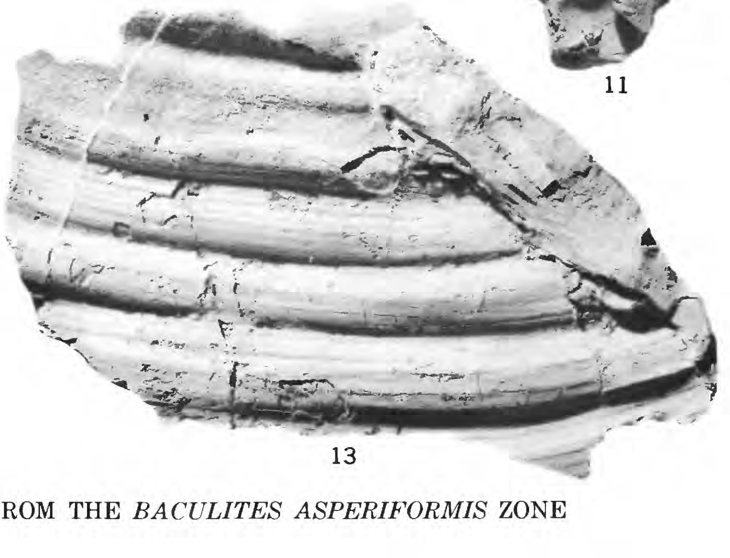
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MOLLUSKS FROM THE *BACULITES ASPERIFORMIS* ZONE