Depositional environments of the upper part of the Sentinel Butte Formation, southeastern McKenzie County, North Dakota

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DEPOSITIONAL ENVIRONMENTS OF THE UPPER PART OF THE
SENTINEL BUTTE FORMATION, SOUTHEASTERN
MCKENZIE COUNTY, NORTH DAKOTA

by

Robert Post Johnson

Bachelor of Philosophy, University of North Dakota, 1970

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Science

Grand Forks, North Dakota

May
1973
This thesis submitted by Robert Post Johnson in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(Chairman)

Dean of the Graduate School
DEPOSITIONAL ENVIRONMENTS OF THE UPPER PART OF THE SENTINEL BUTTE FORMATION, SOUTHEASTERN MCKENZIE COUNTY, NORTH DAKOTA

Department Geology

Degree Master of Science

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Date April 25, 1973
ACKNOWLEDGMENTS

I am deeply indebted to several people on the faculty of the University of North Dakota Geology Department for their advice and assistance in the preparation of this paper. These people include Dr. Art Jacob, Dr. Alan Cvancara, and Dr. Walter Moore. I am particularly indebted to Dr. Jacob for his interest, enthusiasm, and advice. Dr. Francis Ting and Dr. Lee Clayton are to be thanked for their interest and suggestions.

I am also indebted to the National Forest Service and National Park Service for their permission in gaining access to National Grassland areas and the North Unit of Theodore Roosevelt National Memorial Park. Several farmers and ranchers are to be thanked for allowing me access to their property.

Many hours of conversation with Victor B. Cherven, a fellow graduate student doing a similar study of another part of the Sentinel Butte Formation, led to a considerable exchange of valuable ideas and opinions used in formulating this paper. Other graduate students who contributed in various ways are Bill Hickey and Ron Richardson.

My wife Linda, and my parents deserve special acknowledgment for their moral support and financial assistance which made this study possible.
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19. Cyclic Units in the Sentinel Butte Formation in the Study Area
The depositional environments of a 40 meter thick interval in the upper part of the Sentinel Butte Formation in southeastern McKenzie County, North Dakota have been determined from the sedimentary structures, geometry, distribution of grain sizes, and stratigraphic relations of cyclic lithostratigraphic units. The top of the study interval is the top of the upper yellow marker bed.

An elongate, tabular sand bed was studied in detail. It is 12 meters thick and 3 kilometers wide and it is interpreted to have been deposited by lateral accretion in a high-sinuosity stream. Paleo-current indicators are parallel to the long axis of the sand bed. In this bed are bodies of interbedded silt and clay that are interpreted as channel plug deposits. Epsilon cross-strata are common. Cross-stratification grades from large-scale at the base to small-scale at the top of the bed and grain size decreases upward.

An elongate, trough-shaped sand bed 15 meters thick and 400 meters wide and an elongated trough-shaped sand bed 10 meters thick and 200 meters wide are interpreted as deposits of low-sinuosity streams. Paleo-current indicators trend parallel to the trends of the sand beds. These beds lack the silt and clay bodies and epsilon cross-strata of the elongate, tabular sand bed, but they have similar vertical distributions of cross-stratification and grain size.
Yellow- to red-brown sand, silt, and clay beds occur above and adjacent to the three sand beds. The sand, silt, and clay beds become thinner and finer away from the sand beds. These characteristics, plus little organic matter, abundant iron-stained concretions, and climbing ripple cross-stratification, indicate that these beds are natural-levee and crevasse-splay deposits.

Laterally extensive, gray and brown silt and clay beds grade laterally and vertically from the natural-levee deposits. These highly bioturbated beds contain abundant plant fragments and are generally overlain by lignite beds. The gray and brown silt and clay beds and the lignite beds are interpreted to be floodbasin deposits.
INTRODUCTION

The Paleocene Sentinel Butte Formation of McKenzie County, North Dakota has previously been studied by Clark (1966), Fisher (1953, 1954), Laird (1956), Meldahl (1956), and Royse (1967a, 1967b, 1970). All of this work, with the exception of that of Royse, is primarily descriptive with little emphasis on the interpretation of environments. Royse (1967a) interpreted the formation as being fluvial. His study is based largely on textural analysis from which he recognized a fluvial environment grading from stream channels to floodbasin swamps.

The current study is a detailed field study of the geometry, sedimentary structures, textures, lithologies and stratigraphic relationships of the beds in the upper part of the Sentinel Butte Formation to determine the depositional environments.

The study area (Figure 1) is in McKenzie County in the vicinity of the North Unit of Theodore Roosevelt National Memorial Park. The area is highly dissected by the Little Missouri River and its tributaries, and contains exposures of several hundred feet of the Sentinel Butte Formation. The semi-arid climate caused the slopes to remain relatively free of vegetation.

The field work was concentrated in areas with excellent exposures. Stratigraphic sections were measured in these areas, not more than 0.3 km. apart, and an altimeter or transit was used to establish a datum. Detailed stratigraphic cross-sections were
Fig. 1.--Study area in southeastern McKenzie County, North Dakota showing locations of measured sections for Figures 4, 11 and 15.
then constructed (Figures 4, 11, 15). Shown on the finished diagrams are detailed lateral and vertical relationships of lithologies, primary and secondary sedimentary structures, grain size, and fossils.

Sand beds were mapped in the field on aerial photographs (scale, 1:20,000). Paleocurrent indicators and orientations of large elongate concretions in the sand beds were measured and compared with the maps. Petrographic and grain size analyses were performed in the laboratory. Grain-size analyses were performed by a weight-accumulation settling tube of the type described by Felix (1969).
GENERAL STRATIGRAPHY

The Ludlow Formation (laterally equivalent to the Cannonball Formation), Tongue River Formation and Sentinel Butte Formation, in ascending order, comprise the Paleocene Fort Union Group. The Fort Union is underlain by the Cretaceous Hell Creek Formation and is overlain by the Paleocene-Eocene Golden Valley Formation. These units occur within the boundaries of the Williston Basin.

The Williston Basin generally includes western North Dakota, eastern Montana, southeastern Saskatchewan, and northwestern South Dakota. The basin contains sedimentary rocks of every geologic period from the Cambrian through the Tertiary. The basin was particularly active in controlling sedimentation from the Middle-Ordovician through the end of the Permian, but had little effect on sedimentation from the Triassic through Cretaceous Periods (Carlson and Anderson, 1966).

The Tertiary Period is represented by a wedge of predominantly nonmarine beds which thicken westward through the Rocky Mountains. Tectonic control of sedimentation of these strata is indicated by the thickening of these deposits in the center of the Williston Basin (Royse, 1967a).

The Sentinel Butte Formation is widespread in the western half of North Dakota (Carlson, 1969). The thickness of this unit ranges from approximately 65 meters along the northeast flank of the Cedar Creek Anticline to approximately 190 meters in the center of the Williston Basin (Royse, 1967a). The best exposures of
the formation occur in the badlands of the Little Missouri River. Other exposures are found along the shores of Lake Sakakawea and in other scattered areas throughout the western part of the state.

The Sentinel Butte Formation in the study area is approximately 190 meters thick (Royse, 1967a). Several key beds have been noticed in the area by several workers. These include the basal sand bed, the blue bed, and the upper and lower yellow marker beds (Laird, 1956; Fisher, 1953; Meldahl, 1956; and Royse, 1967a). The location of these beds and the stratigraphic interval studied are shown in Figure 2.
Fig. 2.—Approximate location of key beds in the Sentinel Butte Formation and the location of the study interval.
study interval

upper yellow marker bed

lower yellow marker bed

blue bed

basal sand bed

scale

20 m.
LITHOSTRATIGRAPHY

The Sentinel Butte Formation, in the study area, consists of the following basic lithostratigraphic units: (1) yellow or gray sand beds, (2) yellow- to red-brown sand, silt, and clay beds, (3) gray and brown silt and clay beds, and (4) lignite beds. The beds are poorly indurated, although locally they may be cemented by calcite or iron oxide. Limonitic, hematitic, marcasitic-pyritic, and calcareous concretions may be locally abundant.

Yellow or Gray Sand Beds

Sand bed I

Stratigraphy and Sedimentology.—Sand bed I is mapped on Figure 3. This bed is 8 to 13 meters thick (Figure 4). It is an elongate-tabular bed that may exceed 3 kilometers in width (Figure 3). Its base is in sharp contact with the underlying lignite and clay beds. Its top grades to finer silt and clay beds, which in turn, grade up into a thin lignite bed. The edges of the bed show both gradational and scoured contacts with adjacent silt and clay beds. There is little lateral variability in this sand bed except for bodies of thin interbedded silt and clay. These bodies of silt and clay have concave-up bases, do not exceed more than 200 meters across, and extend from the base to the top of the sand bed (Figure 4, sections 3 and 4).
Fig. 3. -- Map of sand bed I. Solid lines indicate areas of exposure of sand bed I (Figure 4). Dotted line indicates edge of the sand bed. Circular diagram 1 indicates directions of dip of foresets of cross-strata. Circular diagram 2 shows orientation of elongate concretions in the sand bed. (Aerial photographs AXD-4V-72-75).
Fig. 4.--Stratigraphic cross-section A. Location of measured sections are shown on Figure 1.
Petrographic analysis reveals that the sand grains are primarily sedimentary rock fragments. Angular grains of quartz and plagioclase feldspar are present. The grain size of the sand ranges from medium to very fine and the sand contains an average of 20 to 30 percent silt-clay. A few of the measured sections show considerable increases in silt-clay at the top of the sand bed (Figure 5). The sand fraction becomes finer upward in two vertical sections within the bed (Figure 6). Figure 6 also suggests more than one fining-upward cycle in the measured sections.

The cross-strata in this sand bed were classified according to McKee and Weir (1953). Large-scale trough cross-strata are found throughout the middle and lower parts of the bed. Tabular sets of planar cross-strata are also quite common (Figure 7). The height of these cross-strata never exceeded 0.7 meters although they may be several meters in width. The size of these cross-strata generally decreased upward in the bed. Plane bed may be found close to the base but it is more common in the middle and upper parts of the bed. Small-scale ripple cross-strata are only in the upper parts of the bed.

Epsilon cross-strata (Allen, 1963) are also quite common. The cross-strata are bounded by a thin (0.1 m) reddish-brown bed of alternating layers of silt and clay. The cross-strata have a dip of less than 10 degrees and may have associated tabular, calcite-cemented sandstone concretions.

Dip directions of foresets of large-scale cross-strata are unimodal and parallel the elongate trend of the sand bed (Figure 3).
Fig. 5.--Vertical distribution of silt-clay in six measured sections of sand bed I.
Fig. 6.—Vertical distribution of the median fall diameter of the sand fraction in four measured sections of sand bed I.
Fig. 7.—Tabular sets of large-scale planar cross-stratification in an elongate concretion in sand bed I. (SE\(\frac{1}{4}\) sec. 9, R. 99 W., T. 147.)
Numerous calcite-cemented concretions that may be several meters long and a few meters across are present in this sand bed. The orientations of these elongate concretions also are parallel to the elongate trend of the sand bed and are useful in predicting the trend of the bed (Figure 3).

No invertebrate or vertebrate fossils were found in this sand bed. However, small plant fragments of lignite are found near the base of the bed and may have resulted from erosion of underlying lignite beds.

Depositional Environment.—Sand bed I was probably deposited by a high-sinuosity stream. The elongate-tabular shape of the bed (Figure 4) is attributed to lateral migration of a stream channel (Figure 8) causing the lateral accretion of the sand over a wide area. Paleocurrent orientations indicate a southeasterly flow parallel to the elongate trend of the sand bed (Figure 3). The sharp contact between the base of the sand bed and the underlying clay or lignite beds is probably the result of scour at the bottom of the channel as it migrated laterally.

The fining upward grain size and the upward sequence of sedimentary structures from large-scale trough and planar cross-stratification at the base of the sand bed to plane bed and small-scale cross-strata near the top can be explained using Allen's (1970a) quantitative model of grain size and sedimentary structures in lateral deposits. In the channel bend of a stream, the velocity, shear stress, and stream power generally decrease up the point bar from the deepest part of the channel to the inner bank. Because these parameters decrease, the particle size of
Fig. 8.--Model for the origin of sand bed I. Lateral accretion in a high-sinuosity stream results in the vertical distribution of sedimentary structures and relative grain size shown. Modified after Visher, 1965)
the bed-load material also decreases up the profile of the point-bar resulting in a fining upward sequence in the deposit.

The sequence of sedimentary structures compares favorably with Allen's scheme for a highly sinuous stream, that is, a stream with a low ratio of radius of curvature to width and a concave-down point-bar profile. Such a stream would have predominantly dune and ripple cross-stratification and less abundant upper-phase plane bed. Abundant trough and planar cross-stratification occur near the base of the sand bed and probably formed under moderately high shear stress. Increased shear stress up the point-bar may have formed plane bed. The abundance of ripples near the top of the sand bed indicates low shear stress (Allen, 1970a).

The epsilon cross-strata may be traces of channel cross-sections resulting from deposition on a point-bar surface following a period of nondeposition or erosion. Epsilon cross-strata have been described in ancient sand deposits by Allen (1965a) and Moody-Stuart (1966). No known descriptions of this type of cross-stratification in recent fluvial deposits is known by the writer.

The inset bodies of thin interbeds of silt and clay with concave-up bases (Figure 4, section 4) are interpreted as being channel plug deposits. They probably resulted from the filling of an oxbow lake with silt and clay (Bernard and Major, 1963; Fisk, 1947). These bodies have the shape of the original channel unless scoured by further migration of the channel (Figure 9 and Figure 4, section 4).

A beach origin for this sand is not likely. The paleocurrent indicators are generally unimodal and parallel to the elongate
Fig. 9.--(A) Channel plug deposit (outlined in solid line) scoured by channel sand (outlined by dashed line) in sand bed I. (B) Close-up of A showing silt-clay of channel plug above dashed line (sloping surface of point-bar) with sand below. (SW¼ sec. 10, R. 99 W., T. 147 N.)
trend of the sand bed. Unimodal paleocurrent distributions are parallel to the elongate trends of sand bodies for fluvial deposits. Paleocurrent distributions are generally bimodal and perpendicular to the elongate trend of shoreline sand bodies (Klein, 1967; Selley, 1970). The vertical profiles of grain size fining upward and an upward sequence from large-scale cross-strata to small-scale cross-strata could indicate a transgressive beach deposit. However, the overlying beds do not consist of offshore silt and clay. Rather, they consist of highly bioturbated organic silt and clay that grade up into a thin lignite bed. So they are probably swamp deposits.

The large-scale trough and planar cross-strata could indicate eolian deposition. This is unlikely because of high percentages of silt-clay, small-scale ripple cross-stratification, abundant plant remains, associated lignite, and the presence of aquatic invertebrate fossils. The height of the cross-strata does not approach the height of those usually contained in eolian deposits.

Sand bed II

Stratigraphy and sedimentology.--The sand bed mapped on Figure 10 and associated with the upper yellow marker bed is an elongate bed about 400 meters wide and up to 15 meters thick (Figure 11). It has an erosional concave-up base. The body appears to fill a large depression in the underlying beds of silt and clay. The edges of the bed are not distinct, but appear to intertongue and grade laterally to beds of yellow silt and clay.

Petrographic analysis of the sand grains reveals primarily limonite-stained, subangular quartz grains and a few sedimentary
Fig. 10.--Map of sand bed II (Figure 11). Exposures are indicated by solid lines. Approximate edges of the bed are indicated by dashed lines. Circular diagram shows the directions of dip of foresets of cross-strata. (Aerial photographs AXD-4V-93, 94, and 75)
Fig. 11.---Stratigraphic cross-section B. Location of measured sections is shown on Figure 1.
B-5

L.,

8048,28,

Natural Levee

...-...............-

I[IZJ SAND CLAY

SILT

LIGNITE

B-6

K, Natural Levee

J Channel

SAND BED II

Floodplain

F Floodplain

D Floodplain

C Floodplain

B Floodplain

SCALE 4m

50 m

LARGE SCALE PLANAR CROSS STRATA

PLANAR BED

SILT

LIGNITE

SMALL SCALE RIPPLE CROSS STRATA

VERTICAL CONCRETIONS

SAND HED

FERRUGINOUS CONCRETIONS

FOSSIL INVERTEBRATES
rock fragments. The yellow color of this sand bed contrasts with the gray color of sand bed I. This contrast is attributed to a difference in mineral composition between the two beds.

Sand bed II becomes finer upward (Figure 12) from fine sand at the bottom to yellow silt and clay at the top, which, in turn, grades up to the overlying beds of highly organic, brown clay and lignite. The top is flat but a lens-shaped body of clay is located at the top (Figure 11, section 4).

Large-scale, tabular sets of planar cross-strata, small-scale ripple cross-strata, and plane bed are present. Planar cross-strata overlain by plane bed and small-scale ripple cross-strata is a common sequence in this sand bed. Dip directions of foresets of large-scale cross-strata show a unimodal distribution parallel to the elongate trend of the sand bed (Figure 10).

Depositional environment.—Sand bed II is interpreted as being fluvial. The fining-upward sequence of grain size and the vertical sequence of sedimentary structure from large-scale planar cross-stratification to plane bed and small-scale ripple cross-stratification is similar to sand bed I. Moody-Stuart (1966) discusses lenticular sand bodies deposited by low-sinuosity streams that exhibit fining-upward sequences of grain size and sedimentary structures indicative of an upward decrease in flow regime. He attributes the upward decrease in flow regime to widening and shoaling of a stream during aggradation.

Allen (1970c) disproves vertical accumulation through aggradation in stream channels. Allen showed that deposits of low-sinuosity streams are deposited by lateral accretion, because all streams
Fig. 12.--Vertical distribution of the percent silt-clay and median fall diameter of the sand fraction in sand bed II at measured section B-4, Figure 11. Vertical scale is distance above the base of the body.
possess a sinuous thalweg even though the stream may be relatively straight. Repeated lateral deposition of these deposits in the same location may produce a multi-story sand body giving the appearance of vertical accumulation.

The sequence of planar cross-stratification overlain by plane bed and ripples may be due to the development of lateral bars on the margins of a low-sinuosity stream (Allen, 1966) (Figure 13). The planar cross-stratification results from the preservation of the avalanche slopes of lateral bars migrating downstream. Plane bed and small-scale ripple cross-stratification developed and were preserved on the gentle slope on the backside of the bar as it migrated downstream. This sequence of sedimentary structures is shown in Figure 14.

The stream that deposited sand bed II occupied a depression in a floodbasin. The depression was the result of erosion as evidenced by the truncation of bed G (Figure 11). After the depression was formed, highly organic clay and lignite were deposited in the low area. Once the stream was diverted into the depression it began to deposit laterally and a multi-story sand bed resulted due to repeated lateral deposition. The exact mechanism that caused the multi-story deposit is not understood but may be related to subsidence and tectonics. The cohesiveness of the adjacent silt and clay beds may have caused the stream to be confined to the depression and wide lateral migration was kept to a minimum.

On the basis of geometry, morphology, and associated lithologies, this sand bed is similar to the deposits of low-sinuosity distributary channels in deltaic complexes as described by
Fig. 13.—Development of lateral bars in a low-sinuosity stream (Allen, 1966).
Fig. 14.—(A) Large-scale planar cross-stratification overlain by small scale ripple cross-stratification and plane bed in sand bed II. (B) Close-up of plane bed and ripple cross-stratification. (NE¼ sec. 10, R. 99 W., T. 147 N., near section B-4, Figure 11).
Donaldson (1969), Fisk (1960), Fisk and others (1954), Fisher and McGowen (1969), Jacob (1972), and Kolb and Van Lopik (1966). These sand bodies are generally described as elongate bodies, with concave-up bases, fining upward sequences of grain size, sedimentary structures that range from large-scale at the base to small-scale at the top, and associated lithologies of sand, silt, clay and lignite.

Sand bed III

Stratigraphy and sedimentology.--This light gray sand bed is 200 meters wide and up to 10 meters thick (Figure 15). The bed has a flat top and an erosional, concave-up base (Figure 16[A]). Adjacent thin beds of sand, silt, and clay are sharply truncated by the bed (Figure 16[B]).

Samples for determining grain size variations and mineral composition were not obtained from this bed. Field observations indicate that the bed becomes finer upward from medium sand at the base to very fine sand and silt at the top. A highly organic clay is present across the top of the bed.

Sedimentary structures are similar to those of sand bed II. Large-scale cross-strata are common in the lower part of the bed and small-scale ripple cross-strata and plane bed are common in the upper part of the bed. Paleocurrent-orientation data were not taken from this bed nor was the bed mapped.

Depositional environment.--This sand bed is similar to sand bed II and probably had a similar origin. It has a trough-shaped cross-section and is assumed to be elongate like sand bed II. The sequence of sedimentary structures from planar cross-strata near
Fig. 15.—Stratigraphic cross-section C. Location of measured sections is shown on Figure 1.
Fig. 16.--(A) Sand bed III outlined by dark solid lines. (B) The south edge of the sand bed truncating adjacent sand, silt, and clay beds. (S\(\frac{1}{2}\) sec. 12, R. 99 W., T. 147 N., near sections C-1 and C-1).
the base to plane bed and ripples near the top could indicate the presence of lateral bars in a low-sinuosity stream as in sand bed II. Repeated lateral deposition of a low-sinuosity stream after initial scouring, and possible subsidence allowed the vertical accumulation of sand bed III.

Yellow- to Red-Brown Sand, Silt, and Clay Beds

Stratigraphy and sedimentology.—Beds consisting of thin interbeds of yellow- to red-brown sand, silt, and clay are a few tenths of a meter to approximately 10 meters thick. They are found above sand bed I (Figure 4) and sand bed II (Figure 11) and above a few of the gray and brown silt and clay beds and lignite beds (Figure 11). Sand bed I truncates these deposits (Figure 4) or grades laterally into them (Figure 11). Sand bed II grades laterally into beds of sand, silt, and clay (Figure 11), but sand bed III truncates similar beds (Figure 15).

Small, spherical, iron-stained concretions are commonly concentrated in various horizons within these units. Larger, iron-stained, upright-cylindrical concretions (Figure 17[A]) reaching almost a meter in length and up to three-tenths of a meter across, occur in the yellow- to red-brown sand, silt, and clay beds adjacent to sand bed II. The center of these concretions are lignitic.

Small-scale ripple cross-stratification, climbing-ripple cross-stratification (Figure 17[B]) and plane bed are characteristic of these beds although they are poorly preserved except in the yellow- to red-brown sand, silt, and clay beds adjacent to sand bed II.
Fig. 17.--(A) Elongate vertical concretion in alternating beds of sand, silt, and clay adjacent to sand bed II (SE\% Sec. 10, R. 99 W., T. 147 N. near measured section B-5). (B) Climbing ripples in the alternating beds of sand, silt, and clay adjacent to sand bed II (SE\% sec. 10, R. 99 W., T. 147 N., near section B-6).
Depositional environment.—The vertical interbedding of the sand, silt, and clay beds is probably the result of repeated submergence and the intermittent construction of natural levees during flooding (Allen, 1965b; Fisk, 1947). The high relief of these deposits allowed repeated exposure and oxidation of these sediments after flooding, causing the development of the yellow- to red-brown colors. The yellow- to red-brown sand, silt, and clay beds overlying sand bed I may be poorly developed natural-levee sediments deposited on the upper surface of point-bars during flooding. Sedimentary structures are poorly preserved because of bioturbation by plants.

The highest rates of sedimentation probably occurred near the channel where these beds are the thickest and grain size is coarsest. The rates of sedimentation and grain size of modern natural-levee deposits decreases away from the channel (Allen, 1965b). The high rates of sedimentation from suspension on the natural levee during flooding could have caused the formation of climbing-ripple cross-stratification close to the channel. According to Allen (1970b), a high rate of sedimentation from suspension results in the formation of climbing ripples. McKee (1966) and Singh (1972) observed that climbing ripples are very common in natural-levee deposits.

High sedimentation rates on the natural levee may also have caused the rapid burial of tree trunks in growth position. After decaying, the organic matter served as nuclei for the precipitation of iron compounds causing the iron-stained, vertical concretions present in the natural-level deposits adjacent to sand bed II (Figure 17[A]). Smaller, spherical concretions may be of similar
origin. The occurrence of these concretions at given horizons may result from rootlet zones in ancient soils.

Some of the thin sand beds found in these units may be crevasse-splay deposits. One such sand bed is shown on Figure 15 adjacent to sand bed III. It is much coarser than the adjacent silt and clay beds. This sand bed has a sharp base and becomes thinner away from sand bed III into silt and clay beds. The bed is characterized by plane bed with small-scale ripple cross-strata and small channels near the top. The occurrence of this bed in a sequence of silt and clay beds, the thinning away from a channel-sand deposit, the sequence of sedimentary structures from plane bed at the base to small-scale ripples at the top, and the presence of small channels at the top of the bed may indicate a crevasse-splay deposit (Allen, 1965b).

Gray and Brown Silt and Clay Beds

Stratigraphy and sedimentology.—Beds of gray and brown silt and clay grade laterally from the beds of yellow- to red-brown sand, silt, and clay (Figure 11, between sections 1 and 2, bed B). The gray and brown silt and clay beds are of great lateral extent and can be traced with little variability. They overlie beds of yellow- to red-brown sand, silt, and clay and lignite beds. The gray and brown silt and clay beds become finer upward and grade from silt to highly organic clay to lignite (Figure 11, bed B). The bases of these deposits are generally horizontal but the tops may be undulatory.

The horizontal stratification of these deposits is accentuated by thin alternating beds of gray and brown silt or clay and thin beds
of red-orange clay 1 or 2 centimeters thick. The stratification is largely disturbed throughout these beds (Figure 18). Finely laminated beds of silt and clay and invertebrate fossils are present but quite rare. Well preserved plant fossils such as leaves, twigs, and rootlets are common. Many of the plant fragments are lignitized and are associated with limonitic and marcasitic-pyritic concretions.

Depositional environment.—These beds are interpreted to have formed in a floodbasin and were probably deposited from suspension in the lowest areas of the floodbasin. The predominantly gray and brown colors of the silt and clay beds indicate either low iron content due to low Eh and pH conditions unfavorable for the formation of iron compounds during deposition, or high organic matter masks the iron content, or both. Coleman and Gagliano (1965) and Fisk (1947) indicated that dark colors are typical of floodbasin deposits. The thin, red-orange beds may be the result of a periodic lowering of the water table with subsequent oxidation shortly after deposition.

The disturbed horizontal stratification is attributed to bioturbation by plants (Coleman and Gagliano, 1965). Compaction and repeated wetting and dessication may contribute to this distortion.

Small channels that drained the floodbasin after periods of flooding may explain the undulations in the upper parts of these beds (Figure 11, sections 1 and 2, bed B). The lignite beds above the gray and brown silt and clay beds tend to conform to the shape of these undulations.

The gray and brown silt and clay beds are not to be confused with prodelta silt and clay beds. Coleman and Gagliano (1964) pointed out that prodelta silt and clay beds are usually finely
Fig. 18.--(A) Exposure of weathered gray and brown silt and clay. (B) Fresh exposure of highly disturbed gray and brown silt and clay. (NE ¼ sec. 10, R. 99 W., T. 147 N., near section B-3, bed B).
laminated and generally coarsen upward from fine clay and silt and are overlain by distributary-mouth-bar sand or delta-front sand. The gray and brown silt and clay beds of the study area are poorly laminated and become finer upward from silt to clay to lignite.

**Lignite Beds**

Stratigraphy and Sedimentology.--Lignite beds in the study area are covered in most places except on fresh road cuts and slump surfaces. A lignite bed is usually indicated by the occurrence of a band of vegetation because these units are excellent aquifers and make moisture available to stimulate plant growth. The lignite beds grade up from highly organic clay of the gray and brown silt and clay units. Their thicknesses range from less than one-tenth of a meter to about two meters. They may be traced laterally for several kilometers even though the thickness of an individual lignite bed may be only one-tenth of a meter.

The lignite beds vary considerably in elevation over short distances, and they may split from one thick bed into two thinner beds, separated by a gray and brown silt and clay bed. These properties make the correlation of the lignite beds over a large area difficult.

The lignite beds are generally blocky, have a woody structure and contain little clastic material. The extremely thin lignite beds may have silicified wood fragments and occasional silicified stumps. Burned out lignite beds and resulting "scoria" (baked clay), which are so common in the Badlands, are rare in the study area.
Depositional Environment.—The lignite beds of the study area are associated with deposits that have been interpreted as being formed in rivers, on natural levees, and in floodbasins. So the lignite beds probably represent peat accumulations in alluvial backswamps. The lignite beds tend to reflect the topography of the floodbasin at the time of deposition. This accounts for the difficulties in using lignite beds for correlation.

The lateral persistence of the lignite beds and the absence of shoreline sands discounts a lagoonal origin for these beds. These lignite beds may have originated on a deltaic plain. The woody structure of the thin lignite beds may suggest deposition in the upper subaerial part of a delta where forested swamps occurred. Lignite beds that formed on the lower subaerial part of a delta should be thicker than those of the study area and should be associated with prodelta silt and clay beds and delta front sand beds (Fisher and McGowen, 1969). Prodelta silt and clay beds and delta-front sand beds are not recognized in the study area.
CYCLIC UNITS

Cyclic units were observed in the study area and were also apparent in much of the Sentinel Butte Formation elsewhere. The most common and simplest cyclic unit (Figure 19[A]) consists of a bed that fines upward from silt at the base to highly organic clay at the top. This silt and clay bed may range from a few tenths of a meter thick to eight meters thick. It is overlain by a lignite bed from one-tenth of a meter to two meters thick. Examples of the simple cyclic unit are beds B and C or D and E (Figure 4) and E and F (Figure 11).

This simple cyclic unit is interpreted to have formed by the filling of a subsiding floodbasin. When the floodbasin fills to groundwater level and the rate of clastic influx is not too great, swamps may form. Once formed, the swamps will exist until subsidence exceeds the accumulation of peat and the swamp drowns, or until enough clastic sediments are introduced to suffocate the swamps. Peat accumulation should equal the rate of subsidence in order to produce thick lignite beds. Rapid subsidence results in a higher water table which destroys the swamp and may result in a thick accumulation of clastic sediment. Slow subsidence results in the filling of the floodbasin restricting the thickness of the peat or preventing the accumulation of any peat at all. The thicknesses of the cyclic unit and the individual beds in the unit depend upon the interrelation between the rate of supply of
Fig. 19.—Cyclic units in the Sentinel Butte Formation in the study area.
KEY

- Yellow or Gray Sand
- Yellow-to Red-Brown Sand, Silt, and Clay
- Gray and Brown Silt and Clay
- Lignite
clastic sediment, the rate of subsidence, the rate of production of organic matter, the rate of decomposition, and the location of the water table.

Other cyclic units may be formed by the invasion of a stream into the floodbasin, resulting in the scouring of some floodbasin sediments and the deposition of a fluvial sand body (Figure 19[B]). After abandonment of the stream course, subsidence may allow the re-establishment of the simple floodbasin cycle. An example of this cyclic unit is shown in Figure 4 by beds A-D.

The encroachment of a stream near a floodbasin with a peat-accumulating swamp, will introduce natural-levee and crevasse-splay sand, silt, and clay and destroy the swamp; the cyclic unit is shown in Figure 19(C) will result. An example of this cyclic unit is represented in Figure 4 by beds F and G. If conditions are not favorable for the accumulation of peat, natural-levee and crevasse-splay sand, silt, and clay may be deposited directly on the gray and brown silt and clay beds of the floodbasin (Figure 19[D]). An example of this cyclic unit is shown on the stratigraphic cross-section (Figure 4) by beds I and J. A stream deposit that scours through the cyclic unit (Figure 19[E]) is represented on Figure 15 by sand bed III and beds C and D.
SUMMARY

Four types of basic lithostratigraphic units are present in the Sentinel Butte Formation in the study area. These are (1) yellow and gray sand beds, (2) yellow-to-red-brown sand, silt, and clay beds, (3) gray and brown silt and clay beds, and (4) lignite beds.

Three sand beds were studied. Sand bed I is an elongate-tabular bed. It has an erosional base, inset bodies of silt and clay interpreted as being channel plug deposits, epsilon cross-strata, and fining-upward grain size. It also shows large-scale cross-strata at the bottom and small-scale cross-strata at the top, abundant organic debris, and paleocurrent indicators that are parallel to the elongate trend of the sand bed. It is interpreted as a high-sinuosity stream deposit.

Sand beds II and III lack epsilon cross-strata and the inset bodies of interbedded silt and clay that are present in deposits of high-sinuosity streams. They are elongate, and have concave-up bases and fining-upward grain size. They have a vertical sequence of sedimentary structures from planar cross-stratification near the base to plane bed and ripples near the top, and the paleocurrent indicators parallel the elongate trends of the sand beds. These two sand beds are interpreted to be deposits of low-sinuosity streams.
The yellow- to red-brown sand, silt, and clay beds are interpreted as being natural-levee deposits. The interbedding of sand, silt, and clay, the light colors, abundance of ferruginous concretions, and climbing-ripple cross-stratification characterize these beds. The thinning of beds and fining of grain size away from the channel, little organic matter and associated channel sands and floodbasin deposits are further evidence that these beds are natural-levee deposits.

The gray and brown silt and clay beds show dark colors, highly disturbed horizontal stratification, abundant organic debris and associated channel and natural-levee deposits that characterize floodbasin deposits. The lignite beds, on the basis of association with fluvial deposits, probably accumulated in alluvial backswamps.

Cyclic units are present. The most common and simplest cyclic unit consists of a silt and clay bed overlain by a lignite bed and was formed by the filling of a floodbasin. Other cyclic units may have formed by the introduction of natural-levee and stream-channel deposits.

Deposits of high-sinuosity streams have been reported in the alluvial plain facies or the upper-deltaic plain facies, and low-sinuosity-stream deposits of deltaic distributaries have been reported in the lower sub-aerial delta facies by Donaldson (1969) and Fisher and McGowen (1969). The high- and low-sinuosity-stream deposits of the study area may have originated in an environment transitional between the alluvial plain facies and lower-subaerial deltaic facies, where the site of deposition fluctuated between these two environments.
Jacob (1972) interpreted the Tongue River Formation as representing the lower subaerial facies of a high-constructive delta. The Sentinel Butte Formation may represent the upper-subaerial deltaic or lower-alluvial plain facies of this same delta complex. Perhaps the delta-front facies of the complex is the Cannonball Formation.
REFERENCES CITED


