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High- and low-sinuosity stream deposits of the Sentinel Butte Formation (Paleocene) McKenzie County, North Dakota

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HIGH- AND LOW-SINUOSITY STREAM DEPOSITS OF THE SENTINEL BUTTE FORMATION (PALEOCENE) MCKENZIE COUNTY, NORTH DAKOTA

by
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This thesis submitted by Victor B. Cherven 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.

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Department Geology

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TABLE OF CONTENTS

Acknowledgements	iv
List of Tables	vi
List of Illustrations	vii
Abstract	ix
Introduction	1
Geologic Setting	5
Lithostratigraphy	9
Cyclic Units	63
Literature Cited	69

LIST OF TABLES

Table		Page
I.	Mean values of amount by weight of silt and clay in elongate-tabular and elongate-trough-shaped sand beds of the study area	21

LIST OF ILLUSTRATIONS

Figure		Page
1.	Location of study area and measured sections	2
2.	Generalized stratigraphic column of the Sentinel Butte Formation in McKenzie County, North Dakota . .	8
3.	(A) Edge of sand bed A and natural-levee deposits adjacent to sand bed B	11
	(B) Base of sand bed B	11
4.	Epsilon cross-strata and channel-plug deposit in sand bed B	13
5.	Channel-plug deposit in sand bed C	14
6.	Map of channel-plug deposit in sand bed B	16
7.	Map of sand bed B	18
8.	Vertical distribution of silt and clay in sand bed B	19
9.	Vertical distribution of silt and clay in sand beds A and C	20
10.	Vertical distribution of grain size in sand bed B	22
11.	Vertical distribution of grain size in sand beds A and C	23
12.	Model for the origin of elongate-tabular sand beds . . .	25
13.	Map of sand bed 1	29
14.	Map of sand bed 3	30
15.	Erosional base of bed 1	31

16. (A) Epsilon cross-strata in bed 1 33

(B) Tabular concretions in bed 1 33

17. Elongate concretion 36

18. Vertical distribution of silt and clay in sand beds 1 and 2 37

19. Vertical distribution of grain size in sand beds 1 and 2 38

20. Deposition of elongate-trough-shaped sand bed 1 . . . 41

21. Tabular silt bed overlying sand bed B 45

22. Petrified forest west of Sperati Point 47

23. (A) Erosional base of wedge-shaped silt bed 50

(B) Wedge-shaped silt bed becoming thinner away from sand bed 1 50

24. Horizontally-stratified clay beds west of Sperati Point 53

25. Silicified stump in growth position 54

26. Lensoidal sand beds within clay beds 56

27. Paleocurrent diagram for lensoidal sand beds 58

28. Vertical distribution of silt and clay in lensoidal sand beds 59

29. Diagrams of cyclic units of high-sinuosity stream deposits of study area 64

30. Cyclic low-sinuosity stream deposits of study area 66

31. Diagrams of cyclic low-sinuosity stream deposits of study area 67

Plates

1 and 2 Stratigraphic cross-sections of the Sentinel Butte Formation . . . . in pocket

ABSTRACT

High-sinuosity channel deposits in the Sentinel Butte Formation occur as elongate, tabular beds of sand that fine upward from an erosional base. The sand beds contain epsilon cross-stratification, within which stratification changes upward from large-scale trough cross-stratification to horizontal stratification and small-scale cross-stratification, indicating upward decrease in flow regime due to accretion of laterally-migrating point bars. Inset in the sand beds are channel-plug deposits that are narrow and arcuate in map view and asymmetrically trough shaped in cross-section, and consist of sandy silt and clay. Low-sinuosity channel deposits occur as elongate, trough-shaped sand beds that fine upward from a deeply-channeled base. The abundant high-angle planar cross-stratification and horizontal stratification probably originated in transverse bars. Epsilon cross-stratification and channel plugs are absent except in one bed that is transitional to a high-sinuosity channel deposit.

Silt beds, containing sandy or clayey lenses, occur in tabular beds overlying high-sinuosity-channel deposits and in wedge-shaped beds adjacent to low-sinuosity channel deposits, and are interpreted to be natural levee deposits. Silt beds become thinner and finer-grained away from channel deposits and interfinger with clay beds. Horizontal

stratification, small-scale cross-stratification, distorted lamination, and climbing ripples may be present in the silt beds.

Natural-levee sediment grades vertically and laterally to tabular beds of clay that contain distorted laminations, abundant plant fragments, and lignite lenses, and are overlain by lignite beds. The clay and lignite beds were probably deposited in floodbasins and backswamps.

Lensoidal beds of very fine sand occur in the natural levee and floodbasin deposits and are probably crevasse-splay deposits. Lensoidal sand beds contain horizontal stratification, high-angle planar cross-stratification, and small-scale cross-stratification. Paleocurrent data indicate highly variable current directions.

Vertically stacked low-sinuosity channel deposits that appear to diverge downstream from high-sinuosity channel deposits may be distributaries of highly sinuous streams on a delta. The delta may have prograded into the Paleocene sea in which the marine Cannonball Formation was deposited.

INTRODUCTION

Statement and Scope of the Problem

This is one of several studies that are being conducted by students and faculty at the University of North Dakota to interpret the depositional environment of the Paleocene sediment in western North Dakota. The major emphasis in this study has been on a detailed interpretation of the depositional environments of a small part of the Sentinel Butte Formation. Previous studies of the Sentinel Butte and other Paleocene formations have dealt mainly with stratigragraphic correlation (Laird, 1946, 1956; Brown, 1948; Fisher, 1953, 1954; Meldahl, 1956; Clark, 1966; Crawford, 1967; Royse, 1967a) or with the location and description of lignite beds (Taff, 1909; Laird, 1944). Only Royse's 1967a and 1970 studies dealt with environments of deposition in any detail.

Location of the Study Area

The area is located in and around the North Unit of Theodore Roosevelt National Memorial Park in southwest McKenzie County, North Dakota, 20 road miles south-southwest of Watford City (Figure 1). The Little Missouri River and its tributaries have cut down through 200 m of strata and created some of the most scenic badland topography in the Dakotas. Here the river forms the southern boundary of the glaciated

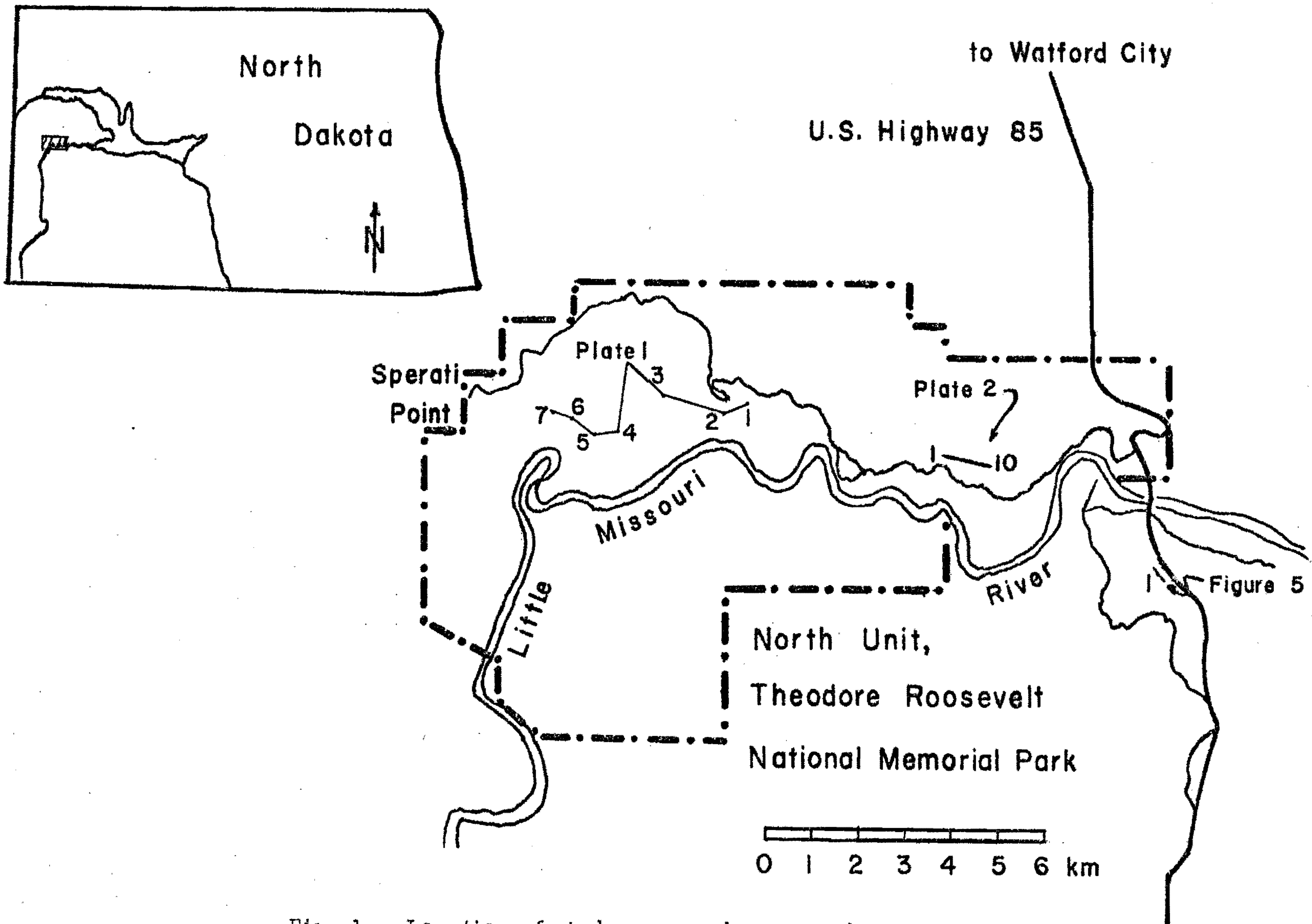


Fig. 1.--Location of study area and measured sections.

portion of the Great Plains.

The area was chosen because of its accessibility, persistent marker beds, excellent exposures along the Little Missouri and its tributaries, and, most importantly, for its varied and complex lithology. The recognition of a depositional environment requires that all of its sedimentary facies be studied, and the extent of outcrop in this area made this possible. Robert P. Johnson, a fellow graduate student at the University of North Dakota, also spent the summer of 1972 studying the depositional environments of the Sentinel Butte Formation in a nearby area, and the opportunity to regularly compare and discuss our findings also influenced my choice of study area.

Methods

Initial field work consisted of locating and mapping on aerial photographs several major sand beds. Stratigraphic sections were then measured at 50 m to 1500 m intervals across these sand beds. An altimeter was used to determine a datum horizon. Two detailed cross-sections were drawn using these measured sections for control. Unless otherwise indicated, all correlations were made in the field and none are hypothetical.

Sand samples were collected in vertical intervals of either 0.5 m or 0.25 m through the sand beds. The grain size of 209 samples was determined in the laboratory using a weight-accumulation settling tube of the type described by Felix (1969), but modified with a shutter release mechanism. Median fall diameter was then determined using charts prepared by Gibbs and others (1971).

The amount of silt and clay in the sand beds was determined by wet-sieving through a 4-phi sieve after soaking the weighed sample in a 7% calgon solution. Nine thin sections were made, and sand composition was determined with petrographic and binocular microscopes.

Stratification Terminology

The descriptive terminology of McKee and Weir (1953) is used, except that sets of cross-strata more than 5 cm thick are called large-scale cross-strata; sets less than 5 cm thick are called small-scale cross-strata.

Trough cross-stratification in the study area is lenticular, plunging or non-plunging, symmetric, concave, low angle, and either small or large in scale. Where used alone, the term trough cross-stratification refers to large-scale sets of cross-strata. Planar cross-stratification is wedge-shaped, plunging, asymmetric, concave, high angle, and large in scale.

Horizontal stratification refers to stratification that is either flat or slightly dipping. Climbing ripple cross-stratification is small-scale trough cross-stratification in sets that appear in the cross-section parallel to the dip direction of the cross-strata to be climbing over one another. Epsilon cross-stratification (Allen, 1963, 1965a) was also observed and is described in detail on page 12.

GEOLOGIC SETTING

Williston Basin

The Paleocene sediments in the study area occur near the top of a post-Precambrian stratigraphic section 4,750 m thick in the Williston Basin. This basin lies in parts of eastern Montana, northwestern South Dakota, southern Saskatchewan, and most of North Dakota. Carlson and Anderson (1965) have given a generalized summary of the tectono-stratigraphic history of the North Dakota part of the basin.

During much of geologic time the Williston Basin area was occupied by shallow epicontinental seas in which clastic and nonclastic sediments were deposited. Nearshore clastic sediments were deposited in the Late Cambrian. Between Cambrian and Mississippian time the basin was subsiding more rapidly and thick sequences of carbonate and evaporite deposits were laid down. Conditions of shallow marine-clastic deposition returned in the Late Mississippian and prevailed through the Cretaceous.

Following the regression of Late Cretaceous seas from the central plains area subsidence slowed again and a thick wedge of predominantly nonmarine clastic sediment was deposited eastward from the Rocky Mountains. Paleocene deposits in the wedge include the Sentinel Butte Formation.

Generalized Paleocene Stratigraphy

Nomenclature

Conformably overlying the Cretaceous Hell Creek Formation are more than 300 m of Paleocene strata of the Fort Union Formation according to United States Geological Survey nomenclature. Royse (1967a) gave an excellent review of the history of the Paleocene stratigraphic nomenclature in North Dakota and recommended that the Ludlow, Cannonball, Tongue River, and Sentinel Butte Formations be considered part of the Fort Union Group.

The lowermost unit in the Fort Union Group is the Ludlow Formation. The Ludlow outcrops in southwestern North Dakota. Farther east these lignite-bearing nonmarine beds interfinger with the fossiliferous marine mudstones and sandstones of the Cannonball Formation.

Overlying the Ludlow and Cannonball Formations is the Tongue River Formation. Jacob (1973a) has recently interpreted the elongate sand beds and the silt, clay, and lignite beds of this formation to be fluvial deposits, possibly on the downstream part of a delta.

Sentinel Butte Formation

The uppermost unit in the Fort Union Group is the Sentinel Butte Formation. Its base is conformable with the Tongue River Formation, but the unit is disconformable with the overlying Golden Valley Formation of Eocene and Paleocene age (Royse, 1967a).

The Sentinel Butte Formation outcrops throughout most of the central part of the Williston Basin. It is excellently exposed in the Little Missouri Badlands between Marmarth and the Missouri River, making detailed study feasible. It is also present in Montana, where it is much thinner (Royse, 1967a).

In North Dakota, the formation reaches its maximum thickness of nearly 200 m in the present study area (Royse, 1967a). Four marker horizons are useful for correlation throughout this area. The lowest of these is the basal sand bed, which overlies the Tongue River Formation; 50 m above this is the blud bed and above this are the lower and upper yellow beds (Figure 2).

The blue bed and lower yellow bed are the only marker beds used in this study. The blue bed has a maximum thickness of 6 m in the area and is a montmorillonite-rich clay. The lower yellow bed bears a striking resemblance to the buff-colored beds of the Tongue River Formation and stands out in bright contrast to the darker gray and brown of the typical Sentinel Butte beds. For these reasons the lower yellow bed was chosen as the top of the stratigraphic interval to be studied.

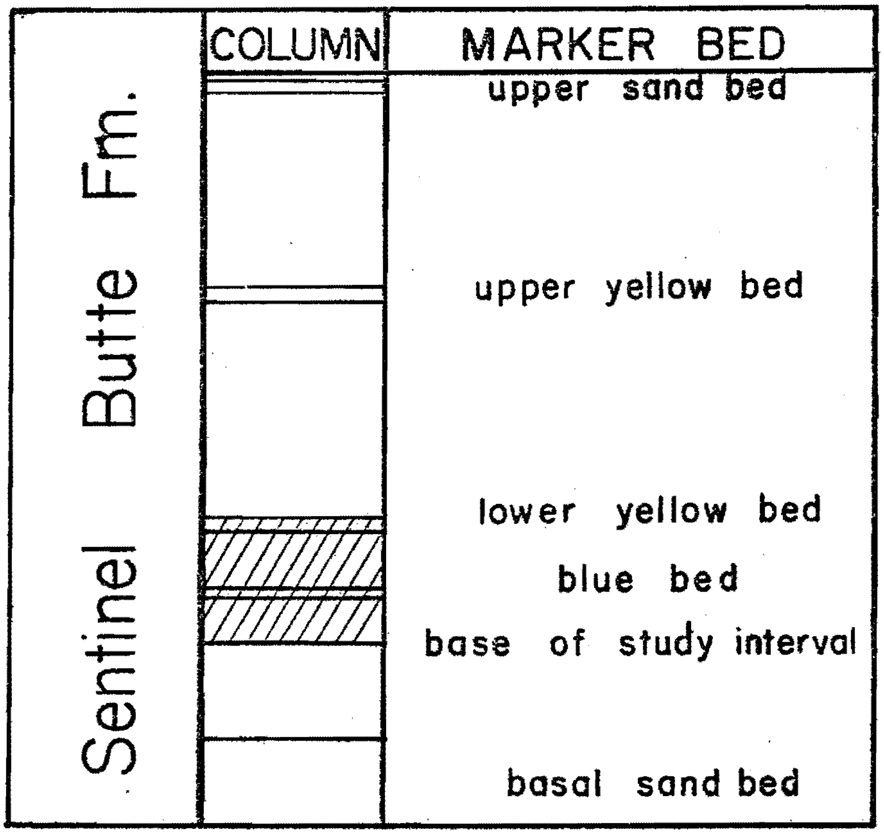


Fig. 2.--Generalized stratigraphic column of the Sentinel Butte Formation in McKenzie County, North Dakota (modified from Royse, 1970).

LITHOSTRATIGRAPHY

General

Three types of sand beds occur within the Sentinel Butte Formation in Theodore Roosevelt National Memorial Park: beds that are elongate in map view and tabular in cross-section; beds that are elongate in map view and trough shaped in cross-section; and beds that are lensoidal in map view and cross-section. Sand beds are associated with silt beds that are either tabular or wedge shaped in cross-section, clay beds that are tabular in cross-section, and lignite beds that are blanket like in cross-section. Bodies of sandy silt and clay are arcuate in map view and asymmetrically trough shaped in cross-section and are inset into elongate-tabular sand beds.

Elongate-tabular Sand Beds

Geometry

Two elongate-tabular sand beds are shown in cross-section in Plate 1. Elongate-tabular sand beds range from 5 to 25 m in maximum thickness and may be more than 2 km wide. They can be traced for several kilometers along their length.

The base of a tabular bed of sand is irregular and erosional except where the bed is underlain by a lignite bed, in which case the base is flat. A concentration of lignite fragments in the sand is the only indication of erosion in this case. The margins of elongate-tabular sand beds are generally erosional (Figure 3A) but gradational or partly gradational, partly erosional contacts occur (Figure 3B). The sand is gradationally or sharply overlain by silt, which in turn is succeeded by clay and lignite.

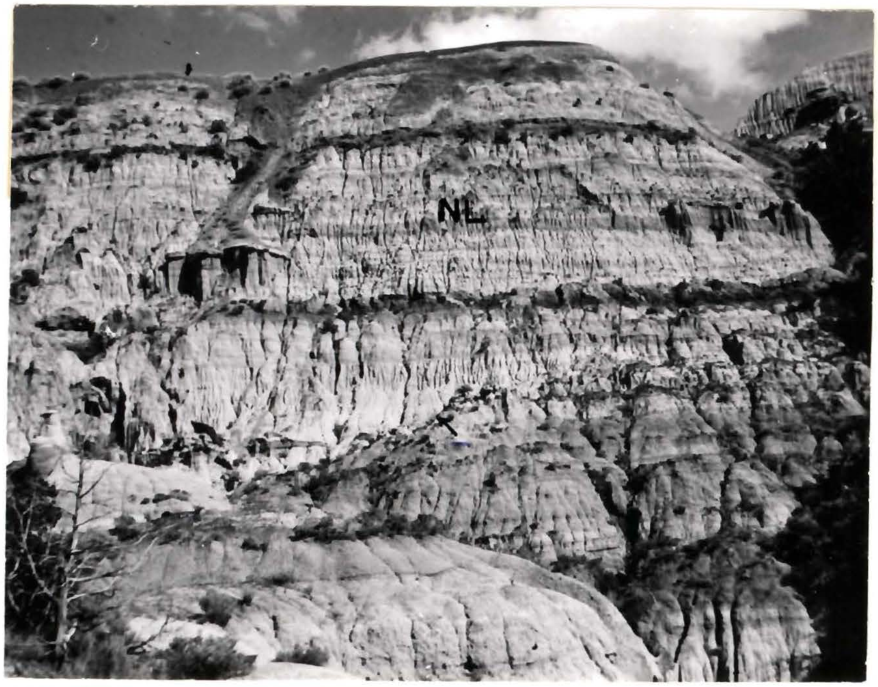
Color

Fresh exposures of the sand beds are light gray, although thin silty or clayey layers near the top of the sand beds are slightly darker. The sand is brownish in slopewashed outcrops. Red colors accentuate stratification in which plant debris is present. Particles of plant debris may have served as nuclei for the precipitation of the reddish iron-oxide stains.

Sedimentary Structures

The vertical sequence of sedimentary structures is surprisingly simple (Plate 1). Trough cross-stratification (McKee and Weir, 1953) in sets 0.5 to 1.5 m thick and 3 to 10 m across are common in the lower part of the sand beds. This type also dominates the middle and upper parts of the sand beds, although set size decreases upward to a few centimeters in thickness and less than 1 m across.

Horizontal stratification occurs with trough cross-stratification in the upper part of elongate-tabular sand beds. In some places the sand appears unstratified, but it may actually be indistinctly horizontally stratified or small-scale cross-stratified. No primary current



A

B

Fig. 3 (A).--Erosional margin of elongate-tabular sand bed A is marked by the arrow. The tabular silt bed marked NL, a natural-levee deposit lateral to tabular sand bed B, becomes finer grained upward and is overlain by a lignite bed. Measured section 5, Plate 1.

(B).--The base of sand bed B is erosional at arrow, but becomes conformable and laterally-gradational to the natural-levee deposits of the tabular silt bed to the left. Near measured section 5, Plate 1.

lineation was observed. Small-scale cross-stratification is fairly common near the tops of elongate-tabular sand beds. High-angle planar cross-stratification is rare in elongate-tabular sand beds. A few high-angle planar cross-stratification sets were observed near the margins of one elongate-tabular sand bed (bed A in Plate 1). Royse (1970) and Johnson (1973) also observed both high-angle planar cross-stratification and horizontal stratification in other elongate-tabular sand beds of the Sentinel Butte.

Although the sand beds are, for the most part, uncemented, concretions of various types occur in them. Particularly remarkable are tabular calcite-cemented concretions (Figure 4) that transect sand bed B (Plate 1).

These tabular concretions accentuate enormous low-angle cross-strata, which when unconcreted, are rarely visible except in fresh outcrops such as roadcuts. These large-scale, low-angle cross-strata are sigmoidal in form and dip at angles less than about 25° from the tops of elongate-tabular sand beds to about two-thirds of the distance to the base (Figure 4 and measured sections 2.5 and 3, Plate 1). Perpendicular to their strike the cross-strata range from 18 to 28 m across in sand bed C (Figure 5) and 150 to over 200 m across in bed B (Plate 1). The cross-stratification may be accentuated by gray, swelling clay or reddish plant debris and iron oxides along the bedding planes. Stratification is well preserved in tabular concretions and changes updip from large sets of large-scale trough cross-stratification to small sets of large-scale

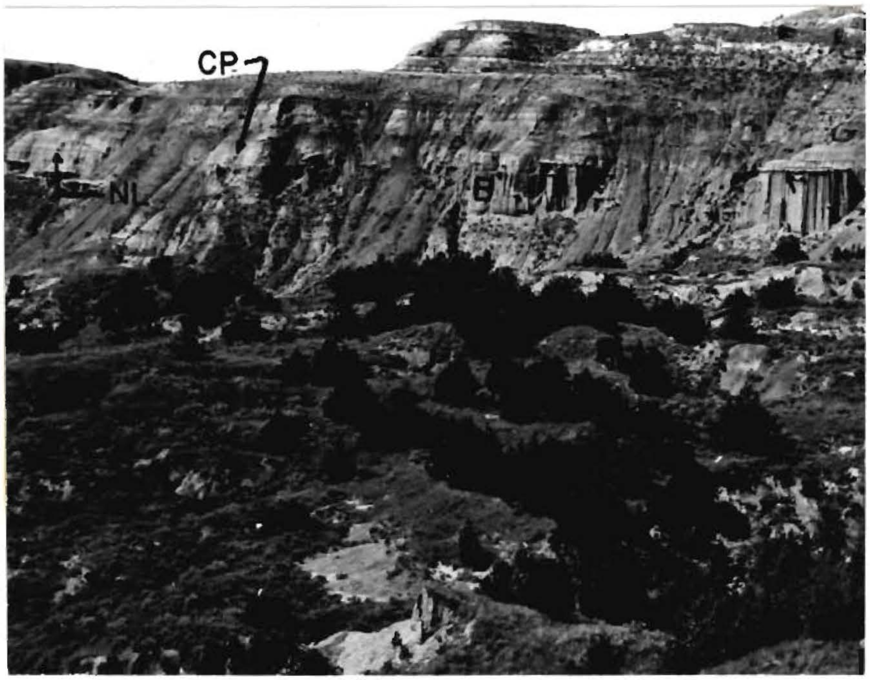
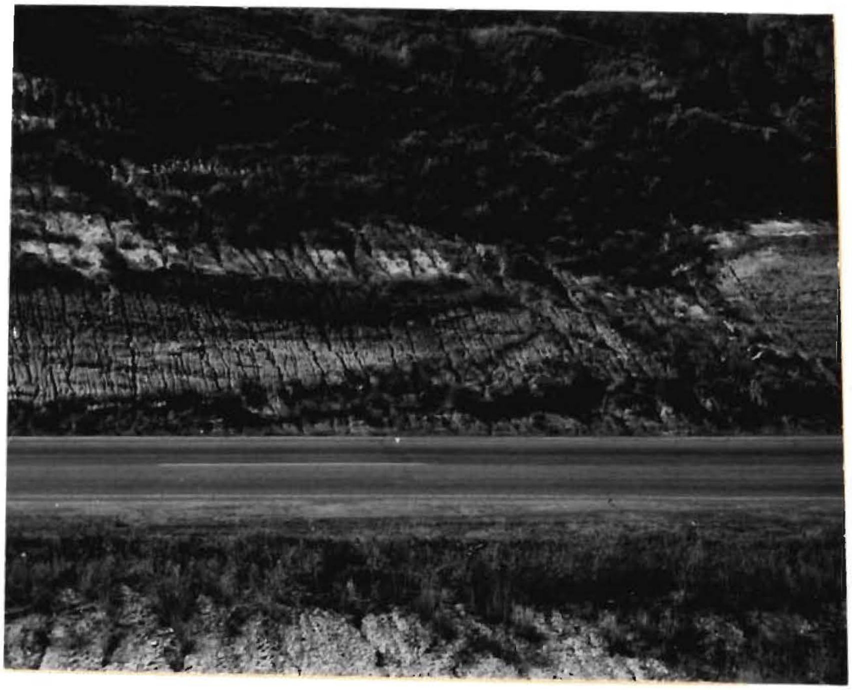
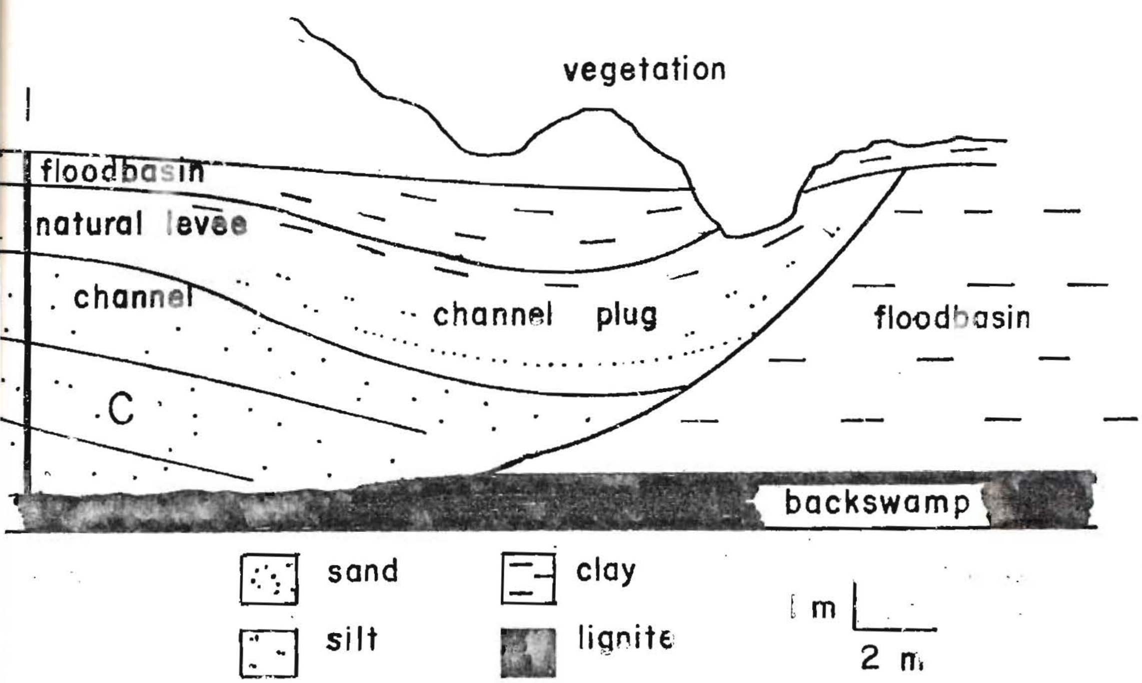


Fig. 4.--Elongate-tabular sand bed B, Plate 1, measured section 3.5. Epsilon cross-strata marked by tabular concretions (arrow) that dip toward channel-plug deposit (CP). Point bar migration was right to left. Thick natural-levee deposits (NL) on cut bank consist of silt and fine sand.



A



B

Fig. 5 (A).--Channel-plug deposit at edge of elongate-tabular sand bed C along U.S. Highway 85, 0.7 km south of Long X Bridge.

(B).--Interpretive diagram of (A).

trough cross-stratification to mixed horizontal stratification and small-scale cross stratification.

The large-scale sigmoidal cross-stratification described here is the type called epsilon by Allen (1965a); it was not recognized by McKee and Weir (1953).

In some cases an epsilon cross-stratum occurs at the top of an elongate-tabular sand bed and the sand bed pinches out laterally in the direction of the dip of the epsilon cross-stratum (Figure 4). In these cases a very large asymmetrical trough filled with sandy silt and clay overlies the epsilon cross-stratum (Figure 5). Due to the fact that these trough-shaped bodies occur within elongate-tabular sand beds and overlie epsilon cross-strata and are particularly important in the interpretation of elongate-tabular sand beds, a brief description of these bodies will be given here.

Bedding within trough-shaped bodies is concordant with their concave-up base and ranges from a few centimeters to a few tens of centimeters in thickness. The trough-shaped bodies become finer grained and organic upward and may be overlain by a lignite bed. In map view the bodies are narrow (less than 300 m across) and arcuate (Figure 6).

Paleocurrent Directions

Paleocurrent directions, assumed to be the direction of maximum dip of high-angle planar cross-strata or axes of trough cross-strata, were measured in sand bed B and was found to be generally southeast, parallel

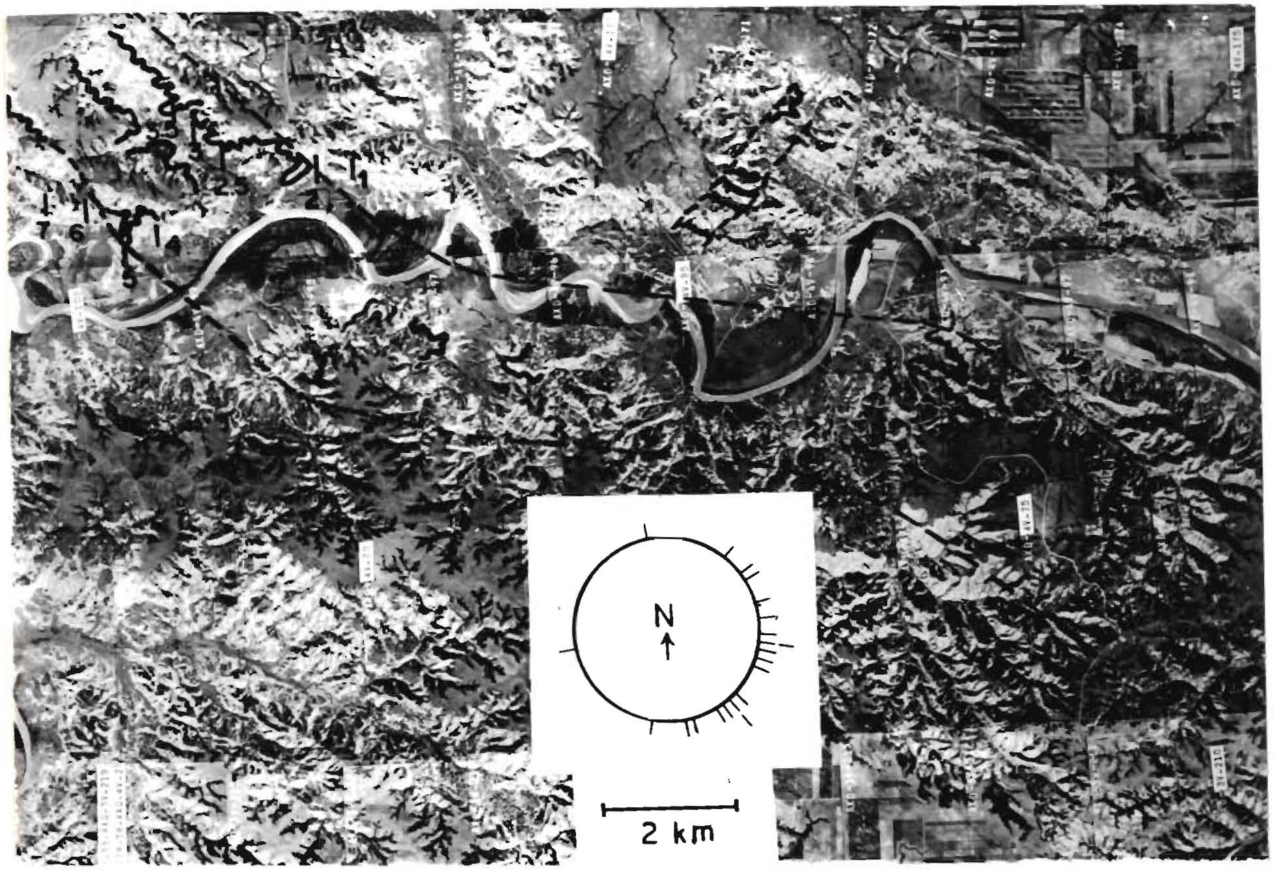


Fig. 7.--Map of elongate-tabular sand bed B. Solid lines indicate outcrop, dashed lines indicate approximate edge of sand bed. Circular diagram shows paleocurrent directions taken from trough cross-stratification. Elongate-trough-shaped sand bed 1 (narrow bed trending northeast) is also shown. Measured section numbers refer to Plate 1. Aerial photographs ASD-4V, 70-76, 92-101, 165-171.

to the elongation of the sand bed (Figure 7). Epsilon cross-strata, on the other hand, dip perpendicular to the elongation of the bed and suggest lateral accretion.

Texture

Total amount by weight of silt and clay (finer than 4-phi) for five measured sections through elongate-tabular sand beds is shown in Figures 8 and 9. A marked upward increase in silt and clay is apparent at four of the sections, but silt and clay become abundant only within the upper meter of sand in Figure 8B.

Average amounts of silt and clay are shown in Table I. Values for elongate-trough-shaped sand beds are included for comparison. There is considerable overlap, and these values cannot be used to differentiate elongate-tabular and elongate-trough-shaped sand beds.

The median fall diameter of the sand fraction in these five measured sections is shown in Figures 10 and 11. Figures 10A and 11A and B show several upward-fining cycles. These cycles are initiated at the base of an epsilon cross-stratum where it overlies the finer-grained upper part of the next-lower epsilon cross-stratum (Figure 11B). No appreciable vertical change is apparent in Figures 10B and C. The significance of this is unknown.

Mineralogy

Beds A and B are litharenites (Folk, 1968). Sedimentary rock fragments are the most common type of rock fragment, and chert

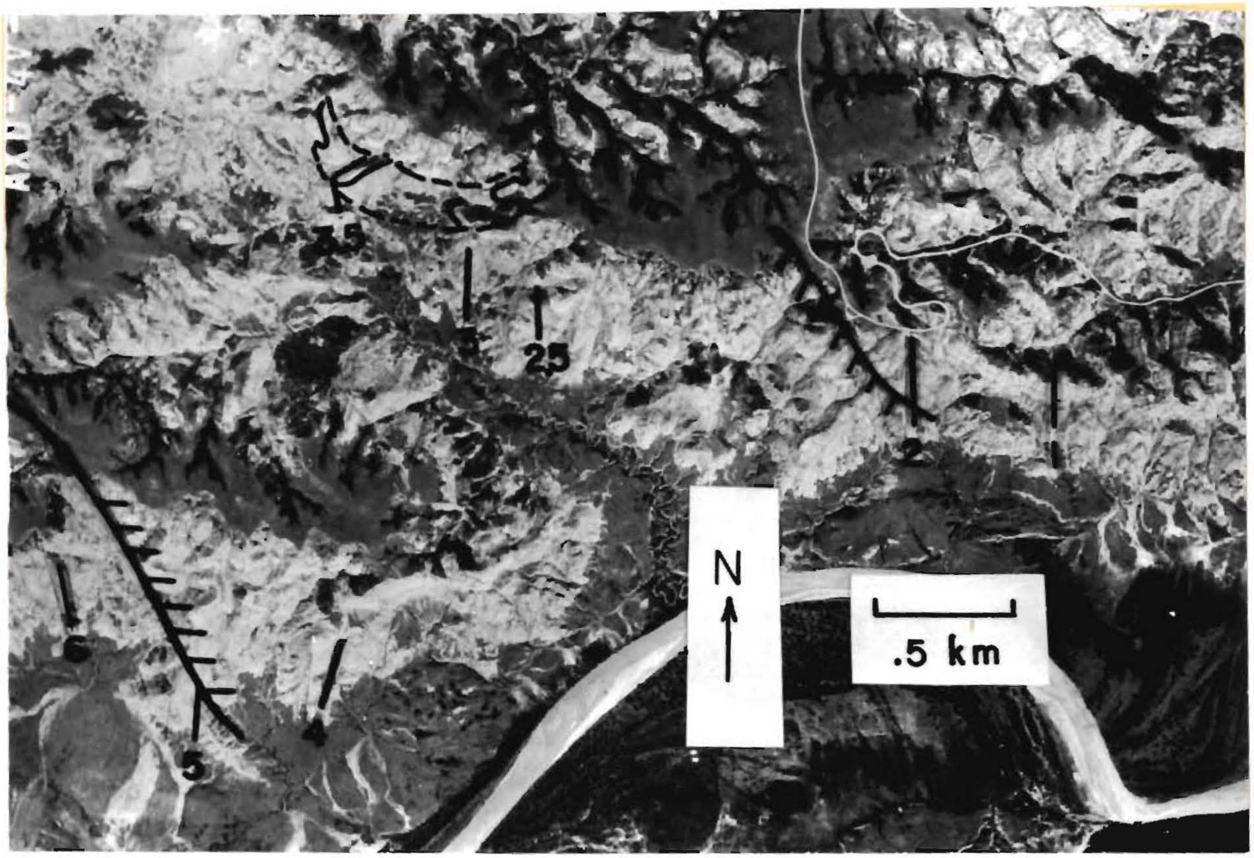


Fig. 6.--Map of channel-plug deposit in elongate-tabular sand bed B. Solid line indicates outcrop of channel plug, and dashed line indicates approximate edge of channel plug. Hatchured line indicates edge of bed B. Measured section numbers refer to Plate 1. Aerial photograph AXD-4V-166.

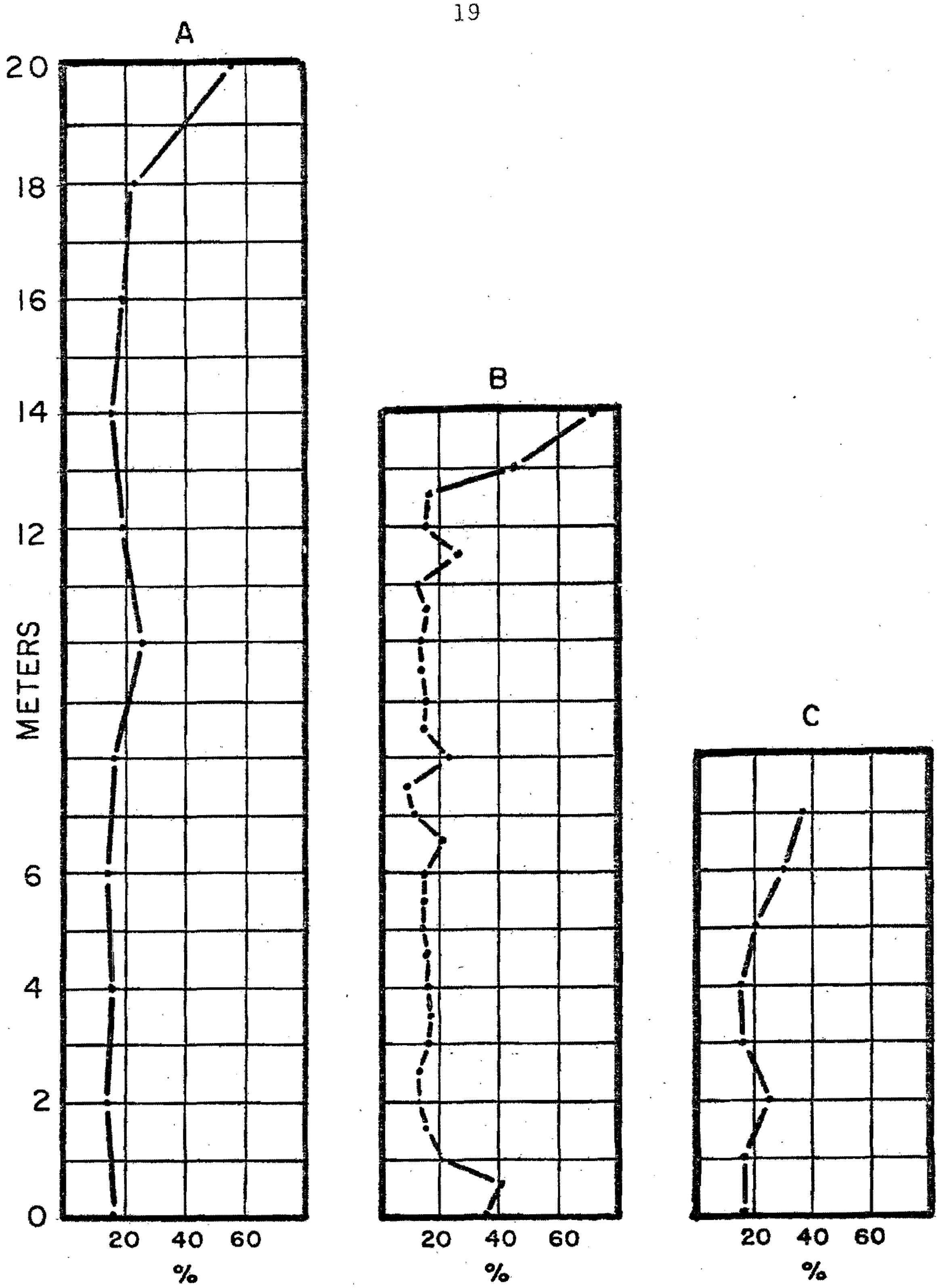


Fig. 8.--Vertical changes in amount by weight of silt and clay (finer than 4∅) in elongate-tabular sand bed B, Plate 1. (A) Measured section 2.5. (B). Measured section 3. (C). Measured section 3.5.

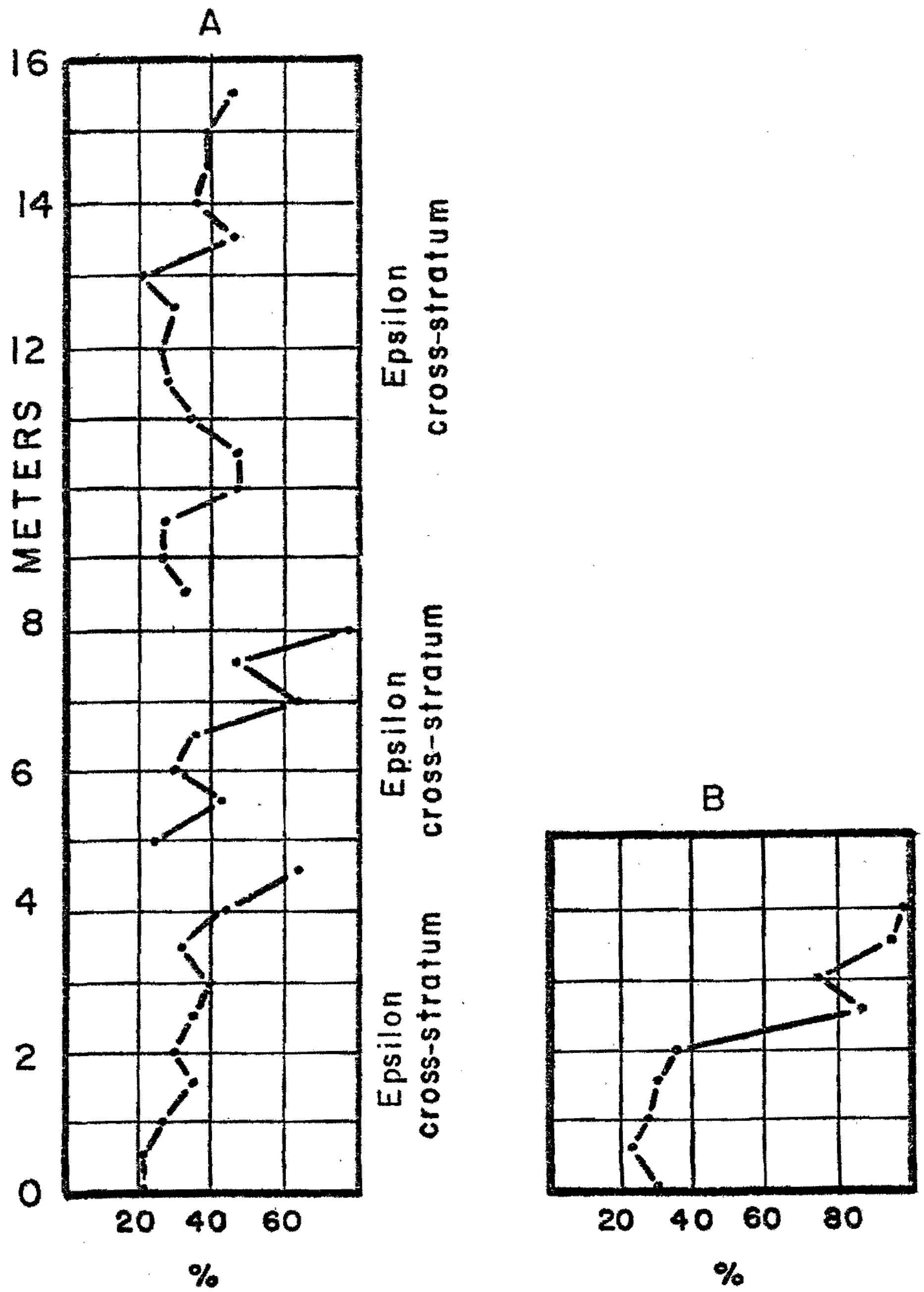


Fig. 9.--Vertical changes in amount by weight of silt and clay (finer than 4Ø). (A) Elongate-tabular sand bed A, measured section 2, Plate 1. (B) Elongate-tabular sand bed C, measured section 1, Figure 5.

TABLE I

MEAN VALUES OF AMOUNT BY WEIGHT OF SILT AND CLAY IN ELONGATE-TABULAR AND ELONGATE-TROUGH-SHAPED SAND BEDS OF THE STUDY AREA

Bed	Location	Number of Measured Section	Weight Percent Silt and Clay
Tabular Sand Bed B	Plate 1	2.5	19
Tabular Sand Bed B	Plate 1	3	20
Tabular Sand Bed B	Plate 1	3.5	21
Tabular Sand Bed A	Plate 1	2	37
Tabular Sand Bed C	Figure 5	1	55
Trough-shaped Sand Bed 1	Plate 2	3	33
Trough-shaped Sand Bed 1	Plate 2	5	36
Trough-shaped Sand Bed 2	Plate 2	4	45

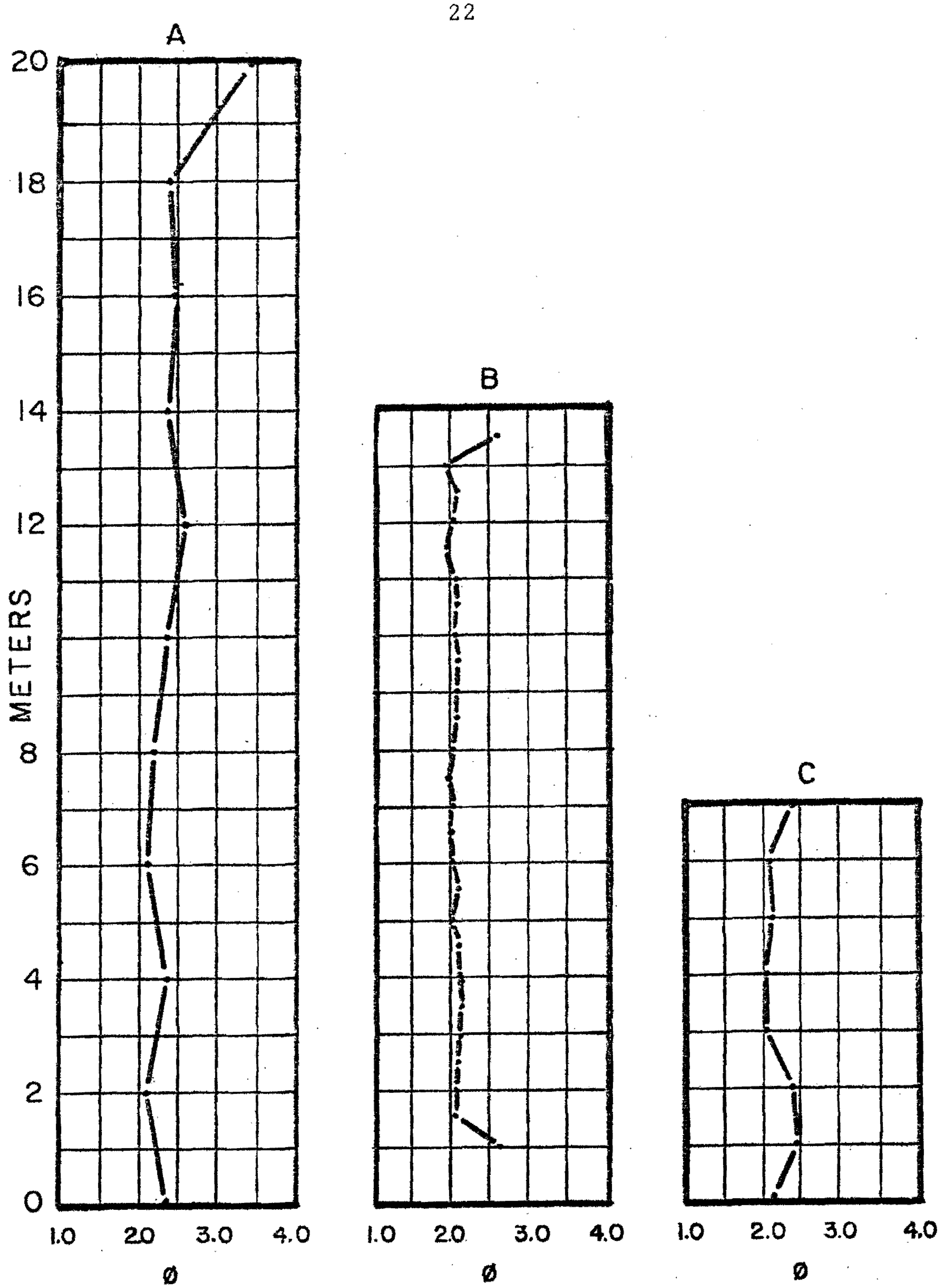


Fig. 10.--Vertical grain-size distribution of sand fraction plotted as median fall diameter for elongate-tabular sand bed B, Plate 1. (A) Measured section 2.5. (B) Measured section 3. (C) Measured section 3.5.

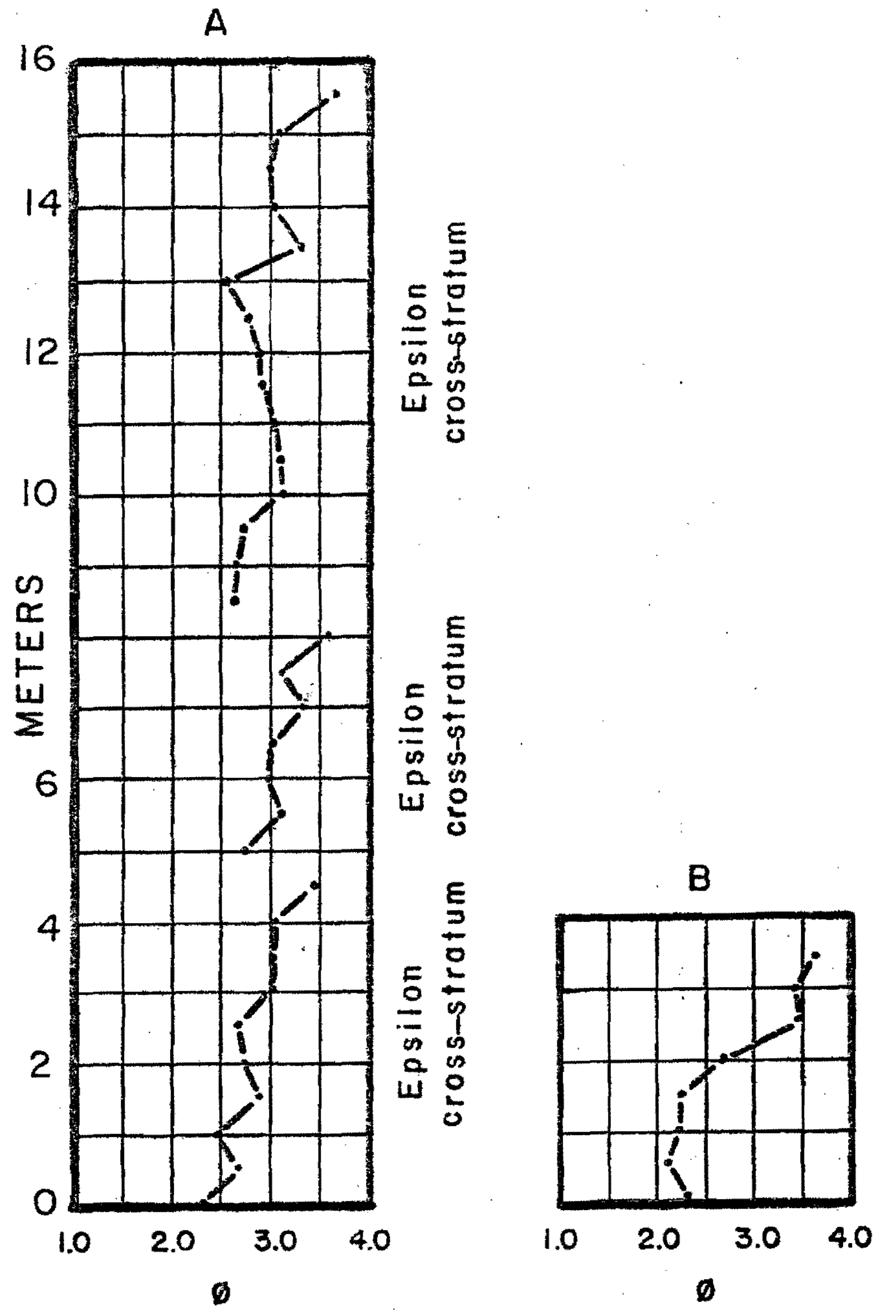


Fig. 11.--Vertical grain-size distribution of sand fraction plotted as median fall diameter. (A) Elongate-tabular sand bed A, measured section 2, Plate 1. (B) Elongate-tabular sand bed C, measured section 1, Figure 5.

predominates over other types. These sand beds lack the yellow (limonite-stained?) quartz grains and calcareous matrix that finer-grained sand beds contain; this accounts for the gray color of elongate-tabular sand beds. Small globular grain masses are cemented by red-brown iron-oxides.

Interpretation

Elongate-tabular sand beds were deposited by currents, which at any individual locality, weakened with time. This is indicated by the upward decrease in grain size and upward decrease in size of sedimentary structures. Orientations of trough cross-strata indicate that these currents were unidirectional and parallel to the elongation of the sand bed but perpendicular to the direction of lateral deposition indicated by epsilon cross-strata. A model for the origin of lateral accretion deposits is shown in Figure 12.

This diagram shows that erosion of the convex bank in the bend of a meandering stream channel and simultaneous deposition of sand on the concave bank (point bar) results in sediment accretion toward the convex bank and deposition of a bed of sand that is tabular in cross-section. The bed will be elongated in the direction of streamflow. The diagram also shows that the bedding plane between two epsilon cross-strata is the trace of the point bar at an earlier time; bedding planes, therefore, are approximate time-lines. Red or dark gray layers of clay and plant debris and layers of concretions make clearly-visible bedding planes between epsilon cross-strata, but where clay and plant debris are

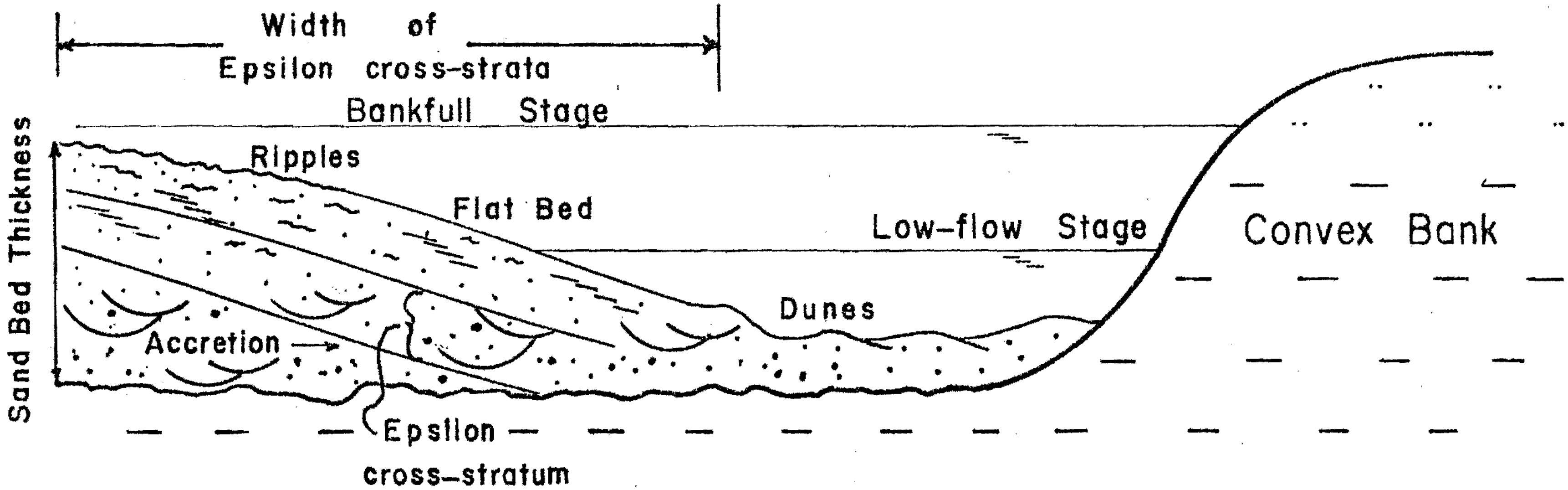


Fig. 12.--Model for lateral accretion in high-sinuosity stream channels and deposition of elongate-tabular sand beds.

lacking, epsilon cross-strata cannot be distinguished. The clay and plant debris may have been deposited when the point bar was stabilized by plant growth during low-flow periods. Another possibility is that clay and plant debris were deposited during falling flood stages. This is suggested by Carey and Keller's (1957) observation that deposition occurs on point bars during falling flood stages. Continuous accretion of the point bar without erosion probably results in thick epsilon cross-strata without well-defined bedding planes. This may account for the relatively few positive identifications of epsilon cross-strata in the elongate-tabular sand beds discussed in this report and the absence of reported occurrences of epsilon cross-strata from modern high-sinuosity stream deposits. The difficulty of digging sufficiently large trenches through modern point bars also helps to explain the lack of reports of epsilon cross-strata in modern stream deposits. Epsilon cross-strata have, however, been observed in ancient stream deposits by Allen (1965a, 1970b), Moody-Stuart (1966), Fisher and McGowen (1969), Beutner, Flueckinger, and Gard (1967), and Jacob (1973a).

Figure 12 also illustrates how the fining-upward sequence is produced. This sequence has been noted by Visher (1965); McDowell (1960); and Allen (1964b, 1965c, 1970a, 1970b) from high-sinuosity stream deposits.

Erosion of the underlying deposits occurs in the deepest part of the channel and causes the base of the channel deposits to be erosional. Scours in the bed are filled in by dunes migrating downstream in the deeper parts of the channel, and large-scale trough cross-strata are deposited. Higher up on the point bar, where stream depth and velocity are less, grain size is less and dunes do not form; instead, the surface of the bar is flat and sand is deposited in horizontal strata. If the downstream edge of the point bar is steep, a slipface may develop and planar cross-strata may be deposited. On the upper part of the point bar, bed shear stress is low due to low depth and velocity, and ripples form and deposit small-scale cross-strata. Further lateral migration of the channel causes a gradual change to predominantly overbank deposition at this locality and the point-bar deposits are buried beneath overbank sediment.

Diversion of the channel (neck cutoff) results in the creation of abandoned meanders, which are concordantly-filled by plugs of sandy-silt and clay deposited during flood stages. An example of a channel-plug deposit is shown in Figure 5. This channel-plug deposit is 20 m across; the epsilon cross-strata in the subjacent sand bed have a width (see definition of "width" in Figure 12) that ranges from 15 to 23 m across. This indicates that the channel was about 20 m wide in the bend at the time of abandonment and the point bar varied from 15 to 23 m across (3/4 to 6/5 of the average channel width of 20 m). The sand bed is about 5 m thick; this represents the bankfull depth in the bend (Figure 12). These figures suggest a rather small stream which probably did not meander extensively.

The channel-plug deposit in elongate-tabular sand bed B at measured section 3.5, Plate 1 is 190 m across; the subjacent epsilon cross-strata are about 155 m wide (4/5 of the channel width); and the sand bed is 8 m thick. This channel was also fairly small. Other epsilon cross-strata in thicker parts of sand bed B suggest channels which were 300 m across and 20 m deep (Plate 2, section 2.5). The vertical stacking of tabular sand beds A and B (Plate 1) and their association with elongate-trough-shaped sand beds suggest that moderate to high-sinuosity rivers and low-sinuosity distributaries were closely associated on the upstream part of a deltaic plain (Brown, 1969).

Elongate-trough-shaped Sand Beds

Geometry

Elongate-trough-shaped sand beds are quite narrow and can easily be mapped in the Little Missouri Badlands, since the beds are generally entirely exposed in cross-section. Sand beds may be vertically stacked, allowing several to be studied over a relatively small area.

Plate 1 and Plate 2 both show two elongate-trough-shaped sand beds in cross-section. These beds range from 200 m to 300 m wide and 8 m to 22 m thick. In map view, they range from straight to curvilinear and may be traced for a few kilometers (Figures 13 and 14).

Elongate-trough-shaped sand beds have bases that are concave-up and deeply erosional into underlying beds (Figure 15). The tops of the sand beds are relatively flat except in one case (Bed 1, Plate 2).

Fig. 15.--Elongate-trough-shaped sand bed 1 (gray) about 1 km northeast of Plate 2. Arrow marks deeply-erosional base. Swale (S) in gray clay at top of sand bed is partly-filled abandoned channel.

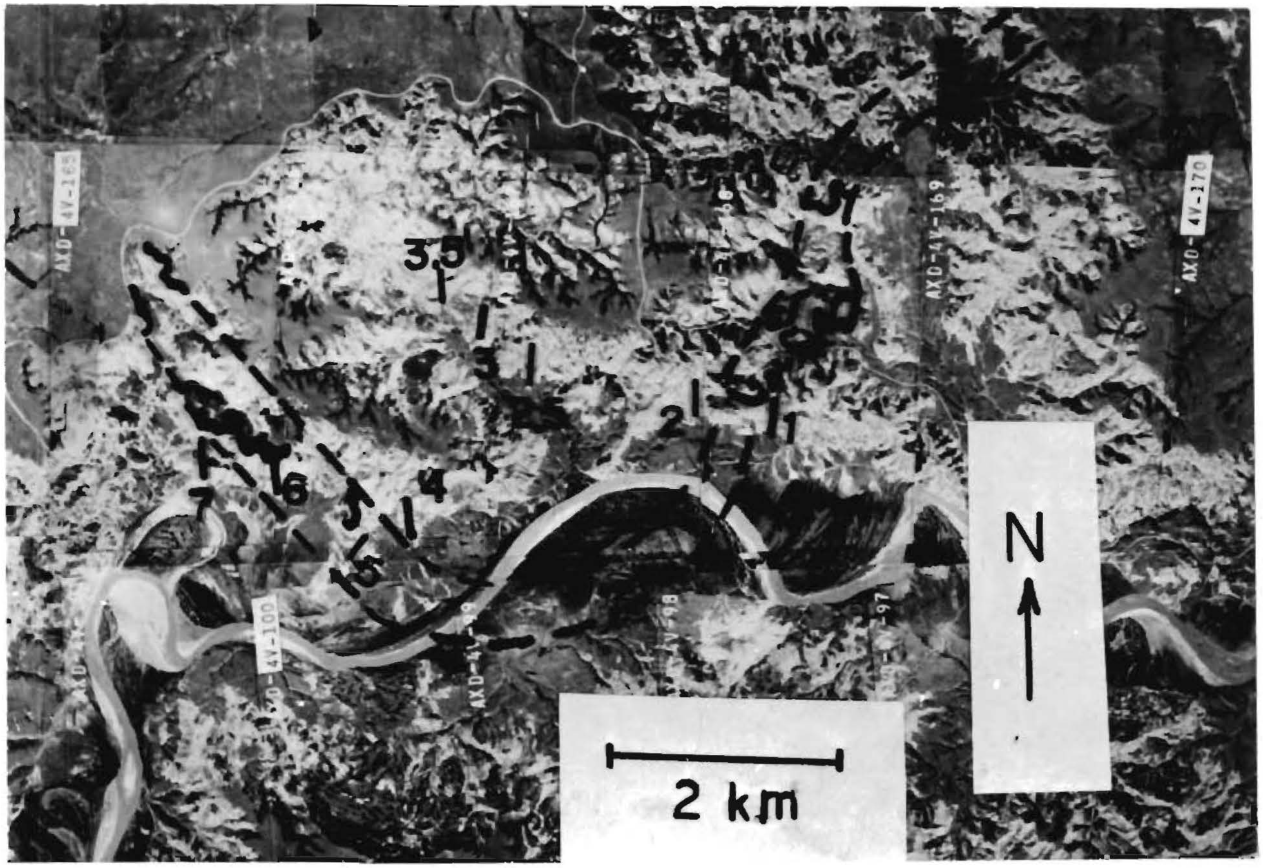


Fig. 14.--Map of elongate-trough-shaped sand bed 3. Solid lines indicate outcrop, dashed lines indicate approximate edge of sand bed. Measured section numbers refer to Plate 1. Aerial photographs AXD-4V, 98-100, 165-168, 194-195.

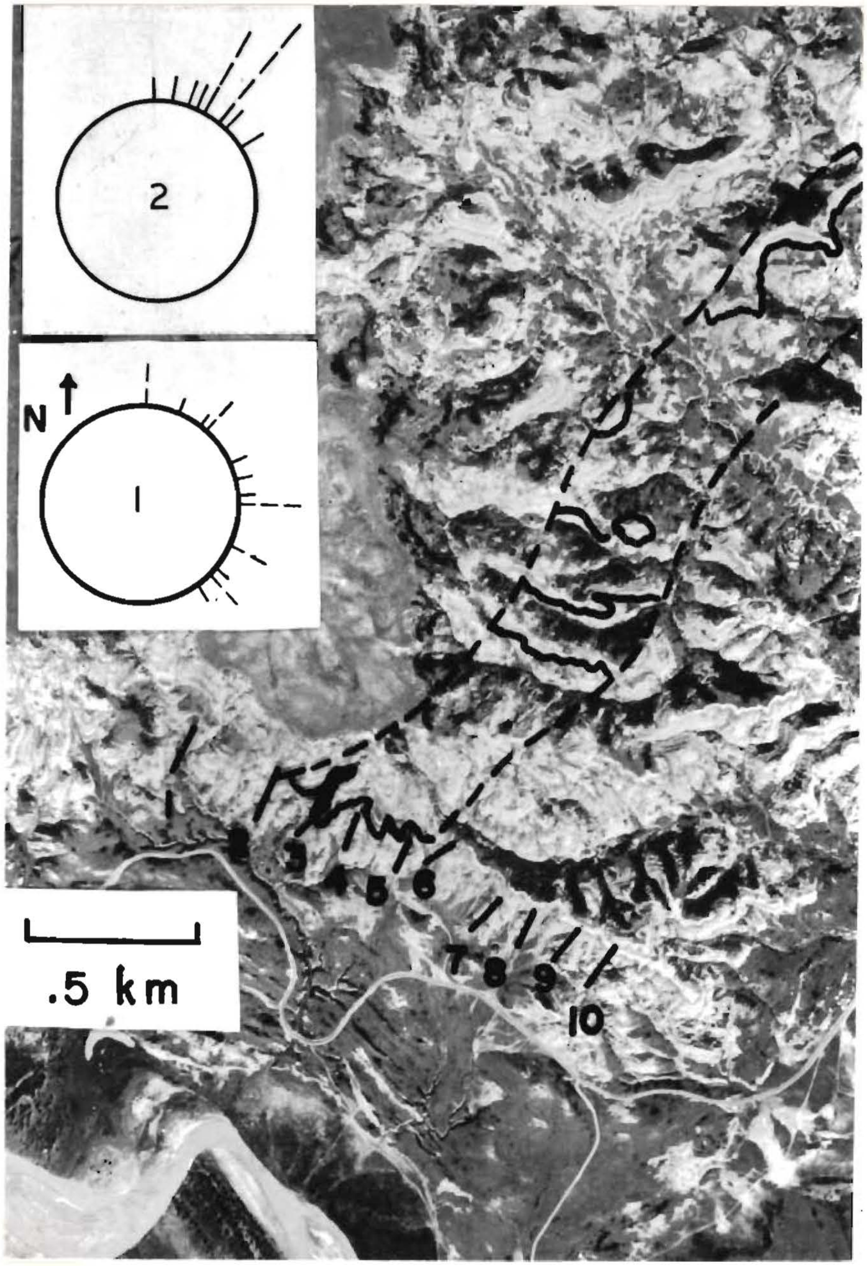


Fig. 13.--Map of elongate-trough-shaped sand bed 1. Solid lines indicate outcrop, dashed lines indicate approximate edge of sand bed. Circular diagram 1 records paleocurrent directions taken from large-scale cross-stratification. Circular diagram 2 shows trend and plunge direction of elongate concretions. Measured sections refer to Plate 2. Aerial photograph AXD-4V-170.

Bed 1 has a depression in its top between measured sections 4 and 5.

Color

Two elongate-trough-shaped sand beds in the study area are medium gray, although plant debris and clay layers along bedding planes are chocolate-brown or orange (beds 1 and 3, Plates 1 and 2). The other two sand beds (beds 2 and 4, Plates 2 and 1) occur in the lower yellow bed that caps the stratigraphic interval studied in this report. The sand in these beds is buff to light gray, but all outcrops of beds 2 and 4 are slopewashed and covered by yellow silt.

Sedimentary Structures

Bed 1.--Trough cross-stratification is the most abundant type of large-scale cross-stratification in this bed, except near the margins of the bed (Plate 2). Set size decreases upward only slightly. High-angle planar cross-stratification is common, especially at the base of epsilon cross-stratification along the margins of the bed. Small-scale cross-stratification and climbing-ripple cross-stratification are also present along the edges and top of the bed. Horizontal stratification is well-developed in the upper part of the bed and within epsilon cross-strata.

Epsilon cross-strata are not as thick in this sand bed as they are in elongate-tabular sand beds. As a result, bedding planes of epsilon cross-strata are much more abundant in bed 1 and epsilon cross-strata are clearly visible (Figure 16). Unlike epsilon cross-strata bedding planes in elongate-tabular sand beds, bedding planes in bed 1 can not

A

B

Fig. 16 (A).--Elongate-trough-shaped sand bed 1 between measured sections 2 and 3, Plate 2. Epsilon cross-strata bedding planes are the darker bands dipping to the right. Natural-levee deposits are the horizontal strata above the sand bed. Blue-black floodbasin clay and lignite beds are masked by vegetation.

(B).--Fifty meters east of (A). Tabular concretions accent epsilon cross-strata, whose left-to right dip indicates that lateral accretion of the sand bed was left to right.

be traced from the top of the bed to its base (Plate 2). Bedding planes also tend to dip more steeply than their counterparts in elongate-tabular sand beds and may exceed 25°. Although most epsilon cross-strata in bed 1 dip southeast in Plate 1, a few dip northwest in the upper part of the bed at measured section 5.

Vertical sequences of sedimentary structures within epsilon cross-strata are highly varied in bed 1, but large-scale trough cross-strata and high-angle planar cross-strata are more common in the lower parts and small-scale cross-strata are more common in the upper parts. Horizontal strata are common throughout epsilon cross-strata. Clay and plant debris are common along the bedding planes of epsilon cross-strata and stand out as orange or chocolate-brown layers. Tabular concentrations are not common, although a few are present (Figure 16B).

Beds 2, 3, and 4.--Trough cross-stratification is not common in these sand beds. High-angle planar cross-stratification is abundant, especially at the base of the beds; sets range from 0.3 m to 1 m thick and reach several meters in length. They are overlain by horizontal stratification, which is the most abundant stratification type in these beds. Epsilon cross-stratification was not observed in these beds.

Paleocurrent Directions

Paleocurrent data for elongate-trough-shaped sand bed 1 indicate a current direction that was, in general, parallel to the long axis of the bed (Figure 13). Trend and plunge of a number of elongate concretions were measured (Figure 17). The trends, shown in Figure 13, are remarkably parallel to both current direction and sand bed elongation direction. These concretions make useful trend indicators of elongate-trough-shaped sand beds, as shown by Jacob (1973b), but are too rare in elongate-tabular sand beds to be useful in predicting their trends.

Texture

Figures 18 and 19 show the vertical changes in amount by weight of silt and clay (finer than 4-phi) and median fall diameter for three measured sections through elongate-trough-shaped sand beds. It is apparent that in bed 1 (Figures 18A and B and 19A and B) at least four upward-fining cycles are present and are delineated by bedding planes of epsilon cross-strata. Bed 2 (Plate 2) shows a single upward-decrease in grain size, and bed 3, though not sampled, also appeared to become finer upward. Mean values of the amount of silt and clay are tabulated in Table I (page 21).

Mineralogy

Five thin sections were cut from bed 1. Two are feldspathic litharenites, two are shale-arenites, and one is a chert-arenite (Folk, 1968). Thin sections of elongate concretions are strongly enriched in secondary calcite as cement and overgrowths on quartz grains. Yellow (limonite-stained?) quartz grains are present but not abundant.

Fig. 17.--Elongate concretion. Pick is 1 m long.

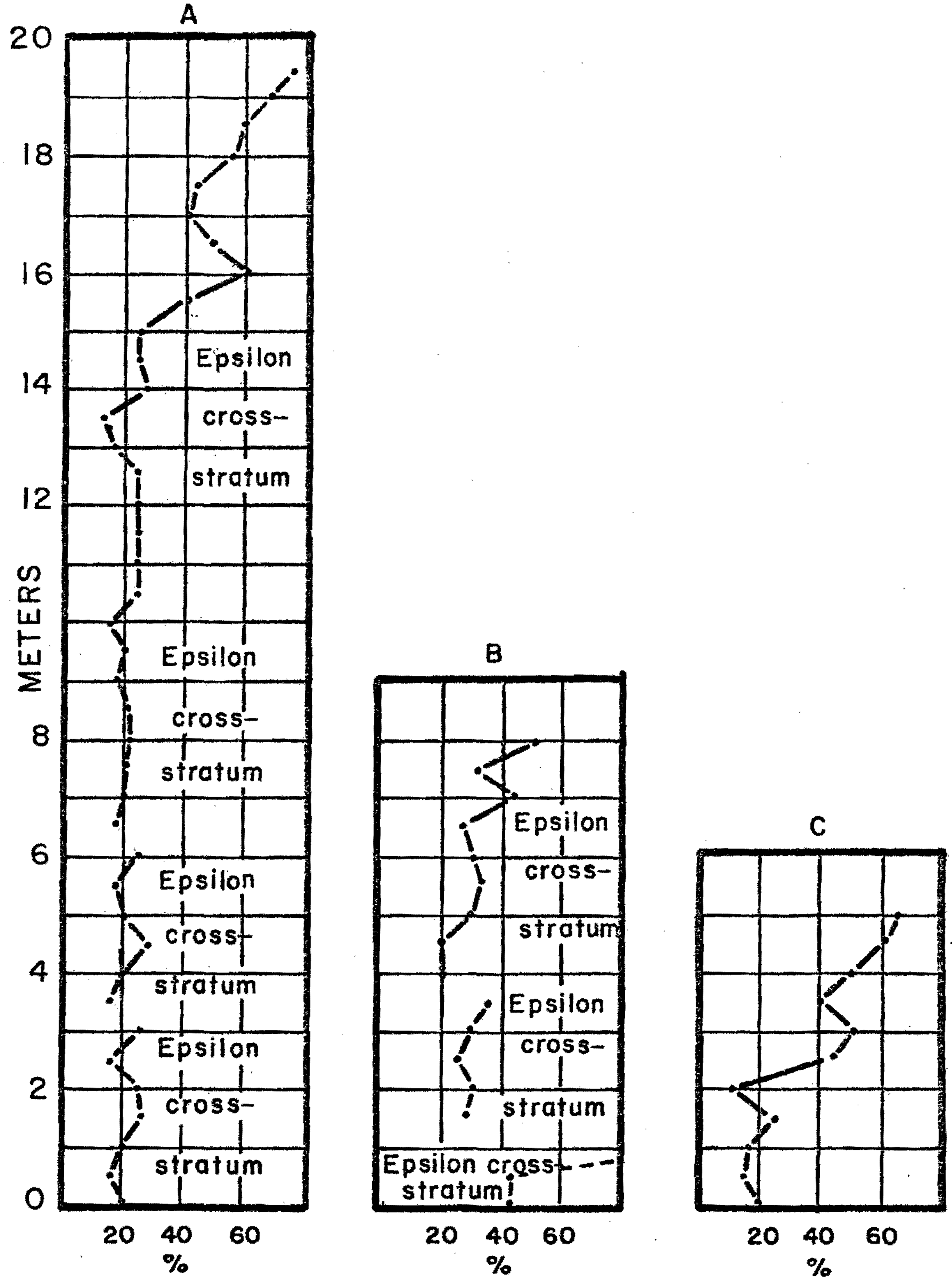


Fig. 18.--Vertical changes in amount by weight of silt and clay (finer than 4Ø). (A) Elongate-trough-shaped sand bed 1, Plate 2, measured section 3. (B) Elongate-trough-shaped sand bed 1, Plate 2 measured section 5. (C) Elongate-trough-shaped sand bed 2, Plate 2, measured section 4.

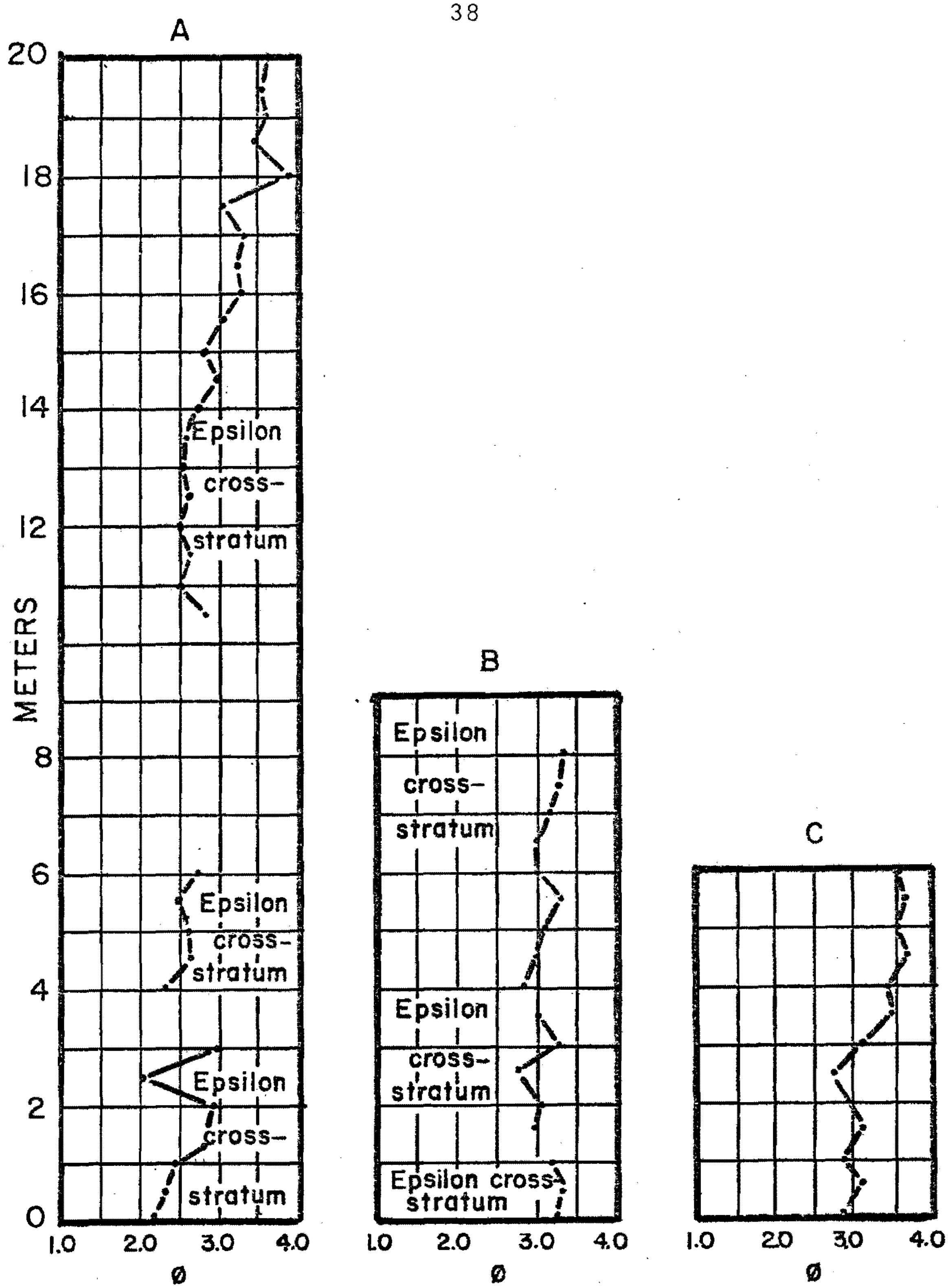


Fig. 19.--Vertical grain size distribution of sand fraction.
(A) Elongate-trough-shaped sand bed 1, Plate 2, measured section 3.
(B) Elongate-trough-shaped sand bed 1, Plate 2, measured section 5.
(C) Elongate-trough-shaped sand bed 2, Plate 2, measured section 4.

Three thin sections were cut from bed 2. The samples are chert-arenites. Quartz is more abundant and feldspar and rock fragments are less abundant than in other sand beds of the study area. The yellow color of the sand is due to the abundance of limonite-stained quartz grains. These beds have a highly-calcareous matrix, and elongate concretions are cemented by sparry calcite.

Interpretation

General.--Overall unidirectional flow in narrow, deeply-eroded channels is indicated by paleocurrent indicators that are parallel to elongation directions of these deeply-channeled, narrow sand beds.

Bed 1.--In a recent paper, Keller (1972) showed how originally-straight channels develop a meandering pattern with time due to the channeling effect that "asymmetric shoals" (transverse bars) have on the talweg. As the talweg begins to meander, "pools" and "riffles" form and erosion is concentrated between the bars, further strengthening the tendency to meander. Eventually the channel may reach a highly-sinuous state and transverse bars break up into point bars.

A similar progression appears to have occurred in the development of the stream that deposited bed 1. The channel was probably confined between measured sections 2 and 4 (Plate 2) during its early stages, and deep scouring occurred. High-angle planar cross-stratification and climbing ripple cross-stratification along the margins of the bed suggest that depositional rates were very high on transverse bars along the banks of the stream (Harms and Fahnestock, 1965; Allen, 1971; McKee, 1966). The development of these bars may have initiated meandering, which occurred later, as indicated by the abundance of epsilon cross-stratification in the upper part of the sand bed and the greater width of the upper part of the bed. Bedding planes of epsilon cross-stratification are clayey or organic, suggesting that low-flow periods were common and point bars were often emergent.

The meandering stage was short-lived, however, and before a broad meander belt could be formed avulsion of the channel occurred, leaving (near measured section 5) an abandoned channel that was later filled with fine sand, silt, and clay. The channel-plug deposit is about 150 m across and 5 m thick; these dimensions represent the bankfull width and depth of the channel. Figure 20 is a sequential diagram illustrating the development of this stream.

Figure 7 suggests that elongate-trough-shaped sand bed 1, which occurs in the same stratigraphic horizon as elongate-tabular sand bed A (several meters below the blue bed clay), may have been deposited by a distributary of the stream which deposited bed A. The two beds converge to the west (upstream), but were not seen to join. The distributary-channel sand bed is straight for over 2 km (Figure 13). Straight distributaries are typical of high-constructive deltas (Scott and Fisher, 1969). A distributary origin for sand bed 1 accounts for its deeply-scoured base, formed during the rapid bifurcation of the main channel and subsequent downcutting of the distributary. The asymmetrical shape of the bed in

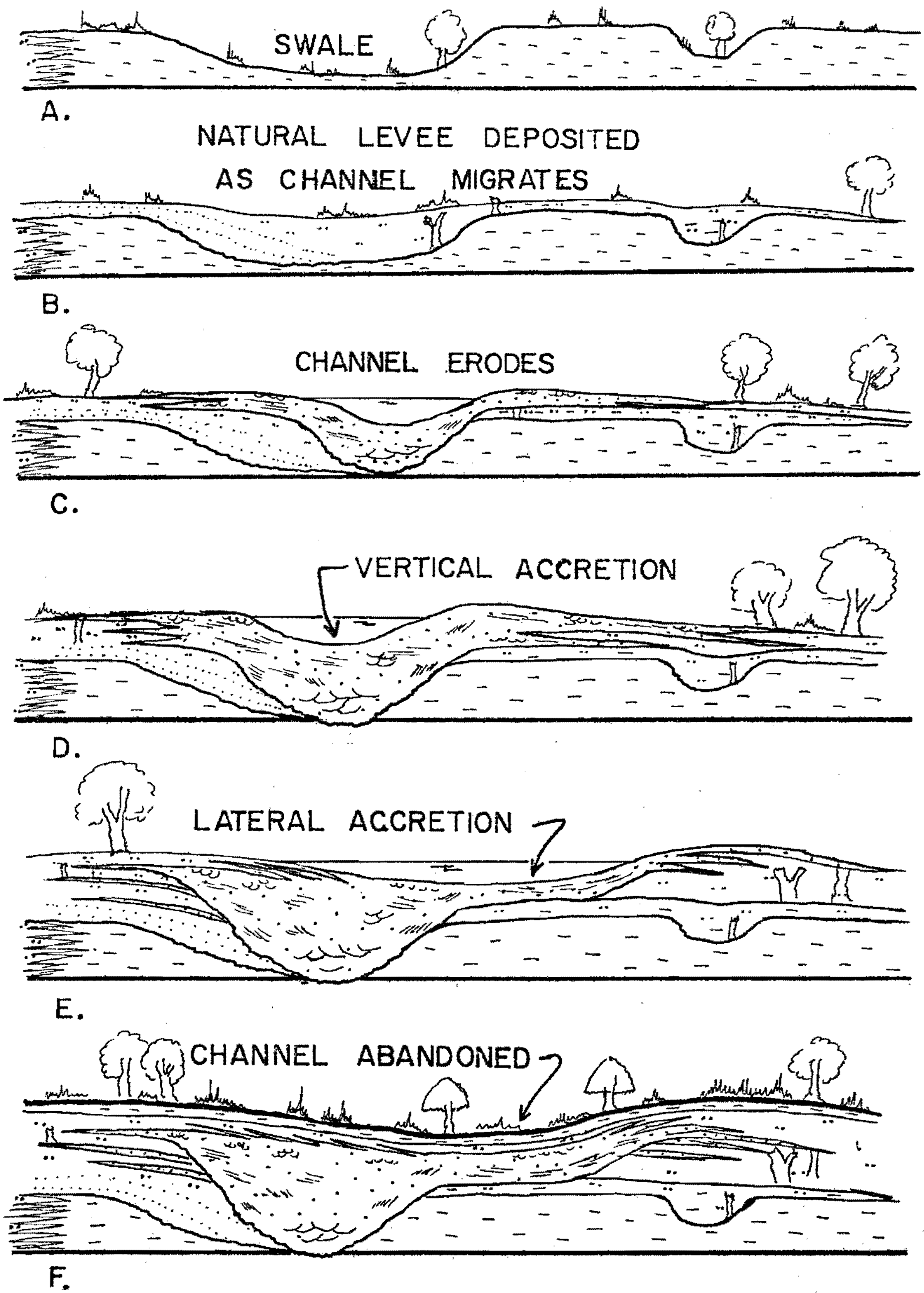


Fig. 20.--Deposition of elongate-trough-shaped sand bed 1.

cross-section and the epsilon cross-stratification suggest that the distributary retained a meandering tendency for a few kilometers downstream; unfortunately the bed cannot be traced farther than this.

Vertically-offset stacking of elongate-trough-shaped sand beds, such as occurs at measured section 4, Plate 2, has been described by Brown (1969) where compaction of interdeltaic mud overlying distributary channel sand produced depressions that made highly favorable sites for reoccupation by later distributary channels. A depression was formed when the channel was abandoned at measured section 5 (Plate 2). Thin and undulatory bedding in the clay plug that fills this depression suggests that the plug was compacted. This depression formed a favorable site for later occupation by the channel which deposited elongate-trough-shaped sand bed 2.

Beds 2 and 4.--Beds 2 and 4 are probably more typical of distributary-channel sand beds deposited in a high-constructive delta. The units are narrow, epsilon cross-stratification and trough cross-stratification are very rare or absent and high-angle planar wedge-shaped cross-stratification and horizontal stratification are abundant. This suggests that the streams that deposited these sand beds had only transverse bars and that these bars gave the talweg a very low sinuosity (Keller, 1972; Allen, 1968; Moody-Stuart, 1966; Harms and Fahnestock, 1965; Bernard and Major, 1963; Frazier and Osanik, 1961). As in the case of bed 1, the deeply-eroded bases of beds 2 and 4 are probably the result of avulsion of a very low-gradient channel into a lower area, where gradients would be sufficient to maintain the channel.

The abundance of clay associated with sand beds 2 and 4 suggests that these sand beds were deposited in low-sinuosity streams near the downstream terminus of a high-constructive delta, where distributaries are widely-separated by marshes, swamps, and interdistributary bays (Scott and Fisher, 1969).

Bed 3.--This bed is also narrow and deeply channeled into underlying sediment (Plate 1, measured section 1). The curvilinear geometry of the sand bed (Figure 14) is unlike that of other distributary-channel sand beds in the study area. The change in trend of the bed from southeast to northeast to east may represent avulsions of the channel and establishment of new stream courses. An alternative possibility is that this bed was deposited in one of the narrow, meandering distributaries common in high-destructive deltas (Scott and Fisher, 1969). The cross-sectional symmetry of bed 3 agrees with descriptions of distributary-channel sand beds by Fisher and McGowen (1969) and Brown (1969). The blue bed clay beneath it and the chocolate-brown lignitic (marsh ?) clay above it further suggest subsidence of the (abandoned) distributary beneath marsh clay. Confirmation of a delta-destructive phase will require detailed study of the interval between the base of the blue bed and the top of the lower yellow bed over a large area.

Tabular Silt Beds

Color and Texture

Light brown, tan, buff, and orange silt lenses dominate these beds. Strongly weathered and cemented lenses are bright orange. Dark gray clay lenses and light gray sand lenses are also present. Sandy lenses adjacent to channel-plug and channel-sand deposits intertongue laterally with silt lenses and clay lenses.

Geometry

Tabular silt beds overlie and extend laterally beyond elongate-tabular sand beds. Silt beds are so widespread in the study area that it is difficult to recognize an elongation direction. The beds can be traced for hundreds to thousands of meters laterally. They are rarely more than a meter thick where they overlie elongate-tabular sand beds, but are much thicker (2 to 10 m) adjacent to channel-plug deposits (Plate 1, measured section 3.5).

The bases of silt beds are undulatory and distinct or gradational with underlying sand or clay beds (Figures 3A and 21). Their tops may be undulatory and are commonly vertically and laterally gradational to clay beds. In places they are unconformably overlain by channel-plug deposits (Plate 1, measured section 3.5).

Sedimentary Structures

Horizontal lenses are dominant (Figure 3A). They range from 5 to 40 cm thick and average 10 cm. Silt lenses are thicker, more extensive

Fig. 21.--Tabular silt bed (natural-levee deposits) (arrow) overlying tabular concretion at top of elongate-tabular sand bed B, measured section 3.5, Plate 1. Darker gray bed overlying silt bed is floodbasin clay.

and more abundant than sand and clay lenses; interbedding of the three types is very repetitious. When dry, individual lenses appear unlaminated, but indistinct, horizontal or distorted lamination and small-scale cross-stratification are visible in places when the sediment is wet. Large-scale structures are very rare and only a few solitary sets of simple cross-stratification (McKee and Weir, 1953) were observed.

Small concretions with tabular, columnar or other shapes are common. Most are composed of calcite, although dense, dark-brown "ironstone" concretions are also present. The upper surfaces of concreted layers are bright red; color intensity decreases downward. Perhaps they are concreted soil horizons.

Organic Material

Organic material is generally rare; this may be due to oxidation shortly after deposition, as suggested by the iron-oxide staining on the concretionary layers and abundance of organic debris in other, less oxidized beds. A number of petrified tree stumps do occur in growth position in the deposits about 1.5 km west of Sperati Point, Theodore Roosevelt National Memorial Park (Figure 22). These stumps are rooted in clay immediately below the lignite bed that underlies the silt bed, and apparently were buried by deposition of the silt.

Interpretation

Tabular silt beds probably were deposited in a highly-oxidizing environment above and lateral to the highly sinuous channels described

Fig. 22.--Petrified stumps in growth position near the edge of the blue bed, about 1 km west of Sperati Point. Stumps are rooted in the lower part of the blue bed, which intertongues with silt and sand beds that are possibly of natural levee origin. Upper part of the blue bed caps butte.

above. Currents were weak in this environment and deposited fine sand, silt and clay in small-scale cross-stratified sets and horizontal lenses and laminations. Thin and repetitive bedding indicates that these currents increased and decreased repeatedly. Thinning and fining of the beds away from elongate-tabular sand beds suggest that currents originating in the main channel flowed out over the silt deposit and decreased as they traversed it. Leaching by downward-percolating soil moisture and high Eh conditions caused oxidation of organic and inorganic materials, including iron oxides, and led to the light colors of the deposit.

These characteristics best describe deposits of natural levees adjacent to high-sinuosity streams as described by Fisk (1947), Lattman (1960), Allen (1964a), Kolb and van Lopik (1966), and summarized by Allen (1965b). Periodic overbank flooding results in the building of elevated natural levees composed of sand, silt, clay, and organic matter. Plants rework the sediment and contribute to soil formation. Organic material may later be oxidized as suggested by Allen (1965b) and soil horizons may form.

Wedge-shaped Silt Beds

Description

These beds range from silty sand to silty clay in lenses generally less than 50 cm thick. Some of the sandier lenses are over a meter thick and are tongues of channel sand extending into the silt. Sand is less abundant and clay and silt are more abundant farther from the channel sand (Plate 2, unit 1, measured sections 6, 7, 8). Both graded and inversely graded lenses occur, but sharp contacts of sand lenses on silt lenses are more common. Wedge-shaped silt beds become finer-grained upward.

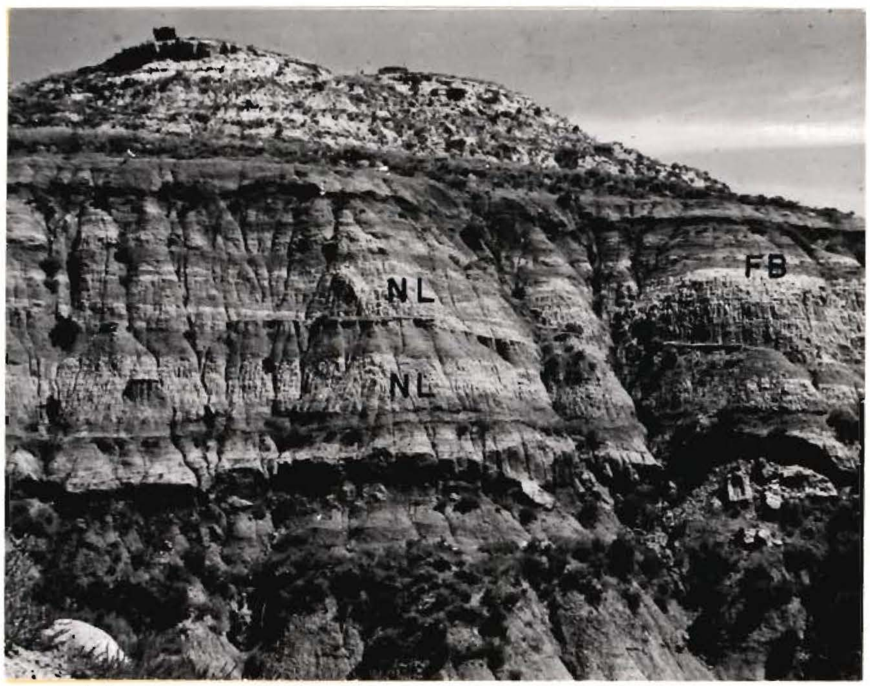
The color of these lenses is highly variable. Light brown, orange, gray, dark gray and yellow lenses can be found. The darker colors occur in the clayey upper parts of wedge-shaped silt beds. Color can be used as a supplementary tool for recognizing these beds, which are lighter-colored than clay beds and browner than sand beds. Twigs, leaves, roots, logs, and stumps are present but are not abundant. Several gastropods and pelecypods and a turtle carapace were found along the scoured base of the silt bed adjacent to bed 1 at measured section 2, Plate 2 (Figure 23A).

Unlike tabular silt beds, wedge-shaped silt beds border elongate-trough-shaped sand beds and do not overlie the sand beds. They may be as thick as or thicker than the sand bed they border. Figure 23B illustrates the wedge-shaped geometry of a silt bed as it thins laterally from bed 1 of Plate 2.

The silt beds drape over the underlying topography (Figure 15) except in a few places (Figure 23A). The tops of the beds are gradational to the overlying clay beds.

Thin, massive and repetitive lenses are the most common internal structure, although horizontal stratification and small-scale cross-stratification occur throughout the deposit. Climb angles on

A



B

Fig. 23 (A).--Rare erosional contact between wedge-shaped silt bed (natural-levee deposits) and underlying floodbasin-clay beds. Mattock marks broken fossil layer at contact, measured section 3, Plate 2.

(B).--Two wedge-shaped silt beds (NL) adjacent to elongate-trough-shaped sand bed 1 (off picture at left) become thinner from left to right and intertongue with floodbasin clay beds (FB), measured section 7, Plate 2.

climbing-ripple cross stratification may reach 70°. Wavy laminations are present.

Interpretation

Wedge-shaped silt beds are thickest and coarsest directly adjacent to margins of elongate-trough-shaped sand beds, indicating that depositional rates were high at the edge of the low-sinuosity channels that deposited the sand beds. High-angle climbing ripple cross stratification within sand lenses in wedge-shaped silt beds near the channel sand support this interpretation (Allen, 1971). The fine grain size and absence of large-scale cross-stratification suggest overbank deposition. The absence of organic matter may suggest highly oxidizing conditions.

These characteristics are suggestive of natural-levee deposits. Welder (1959) described the wedge-shaped geometry of natural levees adjacent to distributary channels of the Mississippi River, and Allen (1965d) noted that natural levees of Niger River deltaic distributaries become finer-grained away from the channel. He also found horizontal stratification and small-scale cross stratification in the deposits. McKee (1966) concluded that climbing ripple cross-stratification is abundant in natural-levee deposits, and both Welder (1959) and Allen (1965d) observed gray, brown, or red mottling in the sediments. These descriptions support the interpretation of these sediments as natural-levee deposits. The natural-levee deposits adjacent to elongate-trough-shaped sand bed 2 are relatively small (measured sections 2 and 6, Plate 2) and suggest that this sand bed was deposited in the downstream part of a deltaic plain, where natural levees are poorly-developed (Kolb and van Lopik, 1966).

Clay Beds

Description

Clay beds are either unstratified or consist of interstratified silt and clay lenses, but clay lenses predominate. Sand lenses are present in clay beds that grade laterally to wedge-shaped silt beds, but were not found in clay beds associated with tabular silt beds. The clay may be brown, gray, blue-black, white, orange, or chocolate-brown. Black or brown clay is associated with lignite beds. Silt is generally gray or light brown, but may be orange (Figure 24). Clay beds contain abundant twigs, leaves, rootlets, and stumps (Figure 25). Lignite lenses are common in some clay beds but are generally rare. Fresh-water gastropods and pelecypods (Delimata, 1969) occur only in the clay of the lower yellow bed in association with elongate-trough-shaped sand beds.

Clay beds are tabular in cross-section and are 1 m to 10 m thick. They grade downward and laterally to tabular or wedge-shaped silt beds and upward to lignite beds. They are thinner under some sand beds (Plate 2, measured section 4, beneath bed 2).

Clay beds appear horizontally stratified or unstratified when viewed at a distance. Closer inspection reveals that individual lenses may contain wavy or distorted lamination or small-scale cross-stratification. Low-angle climbing ripple cross-stratification may be present in silt

Fig. 25.--Stump rooted in chocolate-brown lignitic clay, and overlain by lignite and blue-gray floodbasin clay. Measured section 6, Plate 2 at base of study interval.

Fig. 24.--Lenses of clay and silt in clay bed lateral to tabular sand bed B, near west entrance to Theodore Roosevelt National Memorial Park (Figure 1).

lenses in clay beds that are associated with elongate-trough-shaped sand beds. Load casts and small slump structures are very rare.

Interpretation

The abundant organic material and the distorted and irregular laminations suggest extensive bioturbation by plants and animals. The stratigraphic position between natural levee deposits and backswamp deposits (lignite) favors a floodbasin origin for the clay beds. The very widespread blue bed clay may be a lacustrine or interdistributary bay deposit, as suggested by its thickness and low organic material content except around its margins, where petrified stumps suggest swamps or marshes were present in shallow water.

Lensoidal Sand Beds

Description

Thin, lensoidal sand beds occur within clay or silt beds. The beds of sand are a few tens of centimeters thick and up to 150 m wide (Figure 26 and measured sections 8 and 9, Plate 2). Several beds are vertically stacked at measured section 8 (Plate 2). Thicker sand beds at the base of the stack have slightly erosional bases; other beds show no evidence of erosion. Clay chips and wood fragments are found near the bases of the lower beds and form discontinuous intraformational conglomerate.

Horizontal stratification overlain by small sets of large-scale planar or simple cross-stratification capped by small-scale

Fig. 26.--Lensoidal sand beds in stacked crevasse channels in clay beds, measured section 8, Plate 2. Arrow marks base of one sand bed, X marks base of basal sand bed.

cross-stratification or climbing ripple cross-stratification is the dominant vertical sequence within lensoidal sand beds.

Paleocurrent data, though scarce, show a wide variation in direction (Figure 27). Sand beds are too thin and discontinuous to be mapped.

Sand beds are very light gray and are separated by light brown or orange silty clay lenses. Sand bed thickness decreases upward and silty clay lenses become more abundant. The grain size of individual sand beds decreases upward slightly (Figure 28), and is considerably less than the grain size of elongate-tabular or elongate-trough-shaped sand beds.

Interpretation

Welder (1959) described how floodwaters breach the natural levees of Mississippi River distributaries, forming small crevasse channels through which turbid water reaches the floodbasin and deposits sediment in fan-shaped splays. Waning flow should record a vertical sequence of grain size and sedimentary structures indicative of decreasing flow regime, such as is suggested by the large-scale and small-scale cross-stratification overlying horizontal stratification in the lensoidal sand beds.

Lensoidal sand beds, resulting from crevassing of natural levees, were only found associated with elongate-trough-shaped sand beds and wedge-shaped silt beds. This may reflect the decreased stability of natural levees in deltaic plains as compared to upstream areas (Kolb and van Lopik, 1966). Lensoidal sand beds are particularly abundant in the

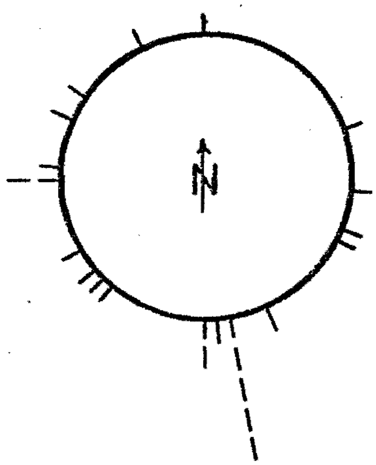


Fig. 27.--Paleocurrent directions determined from planar and small-scale cross-strata orientations, lensoidal sand beds, Plate 2, measured sections 8, 9 and 10.

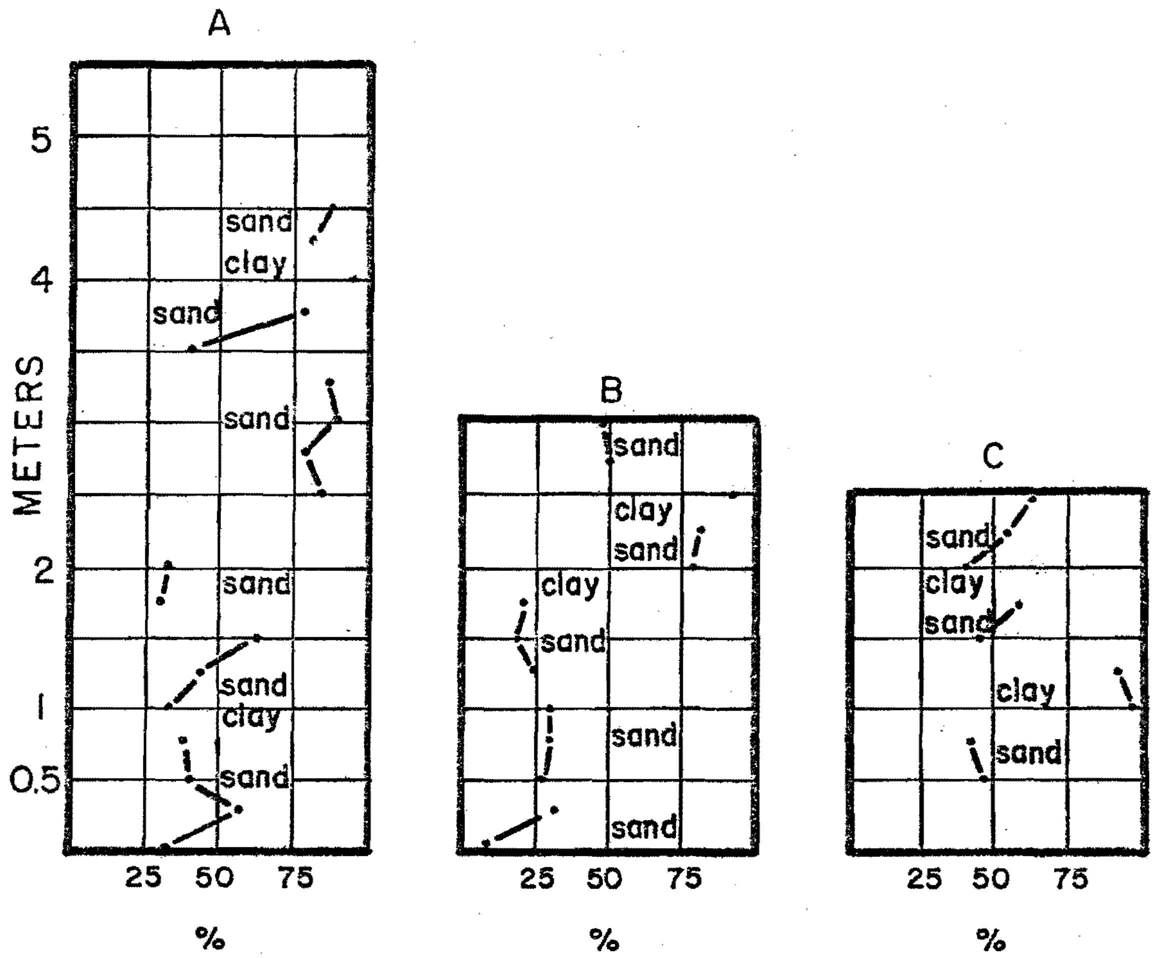


Fig. 28.--Vertical change in weight-percent silt and clay (finer than 4∅) for stacked lensoidal sand beds, Plate 2. (A) Measured section 9. (B) Mid-way between measured sections 9 and 10. (C) Measured section 10.

clay beds lateral to the small natural levee deposits associated with elongate-trough-shaped sand bed 2 (Plate 2, measured sections 6, 7, 8, and 9) and support earlier suggestions that this sand bed was deposited in the downstream part of a deltaic plain.

Lignite Beds

Description

Lignite beds generally occur at the top of clay beds and form the base of an overlying silt or sand bed. Lignite beds are quite thin throughout the study area, not exceeding 80 cm. They are remarkably laterally persistent; beds only 10 cm thick can be traced 3 km without reaching their pinch-outs. They serve as excellent marker beds over such distances, but their thicknesses may change by 50% over longer distances making them difficult to recognize in widely separated outcrops.

Contacts with underlying sediment are generally sharp and conformable, though gradation contacts are also found. Upper contacts are sharp, and may be slightly erosional if the lignite is overlain by sand. No attempt was made to study the composition of the lignite beds, but stumps and large chunks of wood were observed in the field. Vegetation and slumping obscure the beds in most places.

Lignite beds appear to be more common between clay beds in areas where elongate-trough-shaped sand beds are present. They also appear to change elevation more abruptly than lignite beds in areas where elongate-tabular sand beds are present. Swale-filling such as at measured sections 4 and 6, Plate 2, is a fairly common phenomenon of lignite beds near elongate-trough-shaped sand beds.

Interpretation

If these lignite beds had a lagoonal origin, they should be restricted to back-beach areas. This is not the case; they extend for several kilometers on both sides of sand beds (Plates 1 and 2). Also, the characteristics of the sand beds are not consistent with barrier-beach deposits.

The possibility of a deltaic-plain origin for some of the lignite beds is suggested by their abundance and lateral continuity, and association with deposits of low-sinuosity channels and crevasse-splays. The chocolate-brown lignitic clay bed underlying the lower yellow bed is particularly suggestive of a deltaic-plain marsh deposit because it lacks wood or leaves, it is quite thick and very widespread, and fresh-water molluscs may be present in the overlying clay beds. These characteristics describe marsh lignite beds according to Scott and Fisher (1969). Van Alstine (1973) has suggested that similar chocolate-brown lignitic clay beds in the Ludlow Formation may be brackish- to fresh-water deposits based on the occurrence of oysters and molluscs in the deposits. Jacob (1972) has suggested that the thick (4 m) lignite beds in the Tongue River Formation near Medora may have been deposited in the downstream part of a delta. The stratigraphic position of the lignitic clay bed above elongate-trough-shaped sand bed 3 supports earlier suggestions that this sand bed may have been deposited in an area that subsided beneath a marsh.

Some of the lignite beds were probably deposited in floodbasins and backswamps adjacent to the moderately-high-sinuosity streams that deposited sand in elongate, tabular beds. These lignite beds are thin, laterally extensive, and woody, characteristics that are common in swamp lignite beds (Fisher, 1968; Kolb and van Lopik, 1966).

CYCLIC UNITS

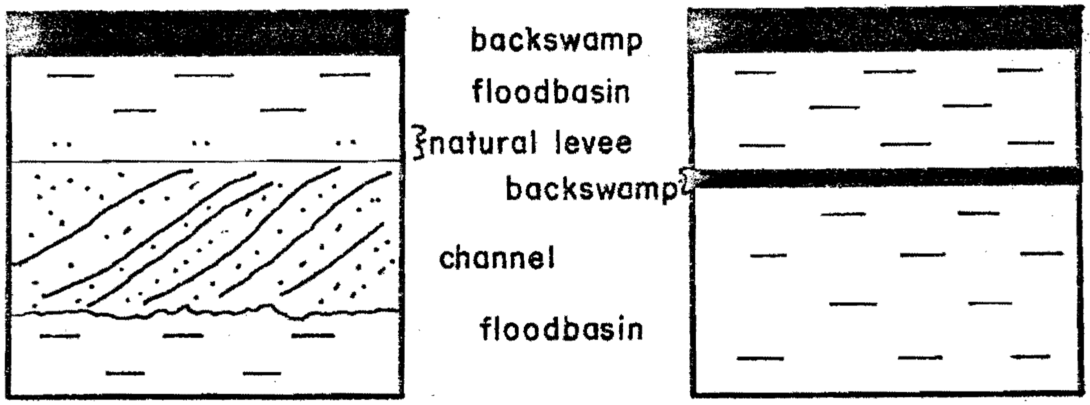
General

Cyclic sedimentation is not obvious within the study area because the stratigraphic interval studied is only 35 to 65 m thick. When thicker intervals are examined both Tongue River and Sentinel Butte strata show cyclic patterns. Although few cyclic units were studied, cyclic units exhibited by high-sinuosity stream deposits appear different from those of low-sinuosity stream deposits.

Cyclic High-sinuosity Stream Deposits

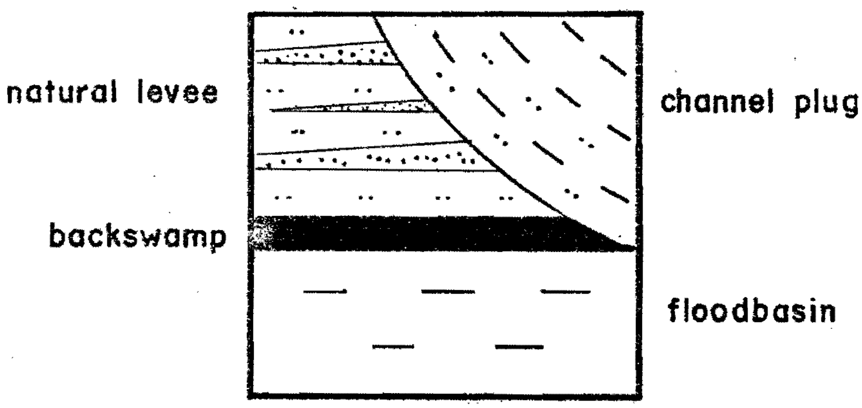
According to Jablokov and others (1961), Allen (1964b, 1965c, 1970a, 1970b), and others, the erosional base of a fluvial channel sandstone forms the base of an alluvial cycle, and channel, natural-levee, and floodbasin deposits constitute the normal upward sequence of deposits within an individual complete cycle (Figure 29A). Lateral and vertical deposition produce this fining-upward cycle. Two fining-upward sequences of high-sinuosity stream deposits are visible in Plate 1. Bed A fines upward from its erosional base and is overlain by overbank deposits, except where they have been truncated by a later cycle initiated when the channel migrated back into the area and deposited bed B.

Incomplete cycles occur in some areas that were never reached by the channel. Figure 29B shows two cycles of floodbasin deposition



(A) Normal cyclic unit in high-sinuosity stream deposits, formed by lateral accretion in a channel migrating from right to left, followed by overbank (natural levee and flood-basin) deposition.

(B) Cyclic unit formed when a backswamp (lower lignite) is drowned, clay is deposited and then the swamp is re-established.



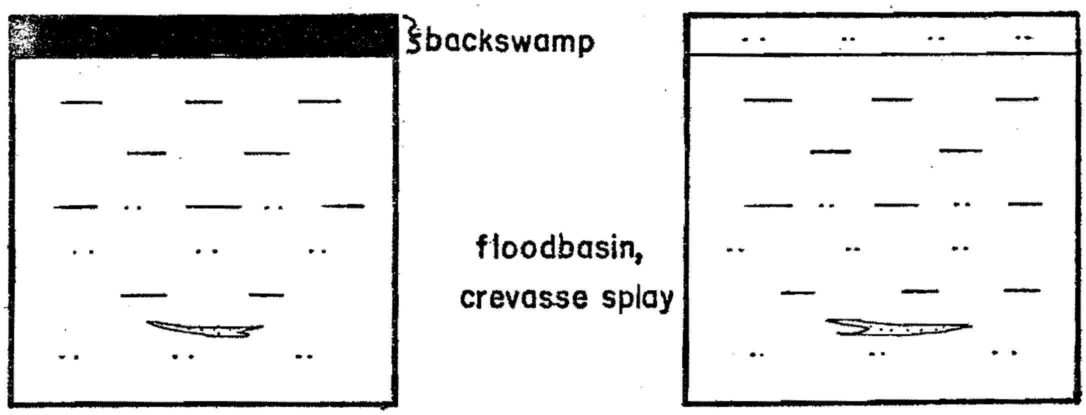
(C) Sequence found when channel was abandoned and plugged. Thick natural-levee deposits (silt and sand) occur adjacent to cut bank. The channel was migrating from right to left.

Fig. 29.--Cyclic units of high-sinuosity stream deposits of study area. Legend on Plate 1.

uninterrupted by channel deposits. Figure 29C shows the case in which the channel just barely migrated into the area and then was abandoned, leaving thick natural levee deposits adjacent to the cutbank and a channel-plug deposit overlying floodbasin sediment. An example of this occurs at measured section 3.5, Plate 1.

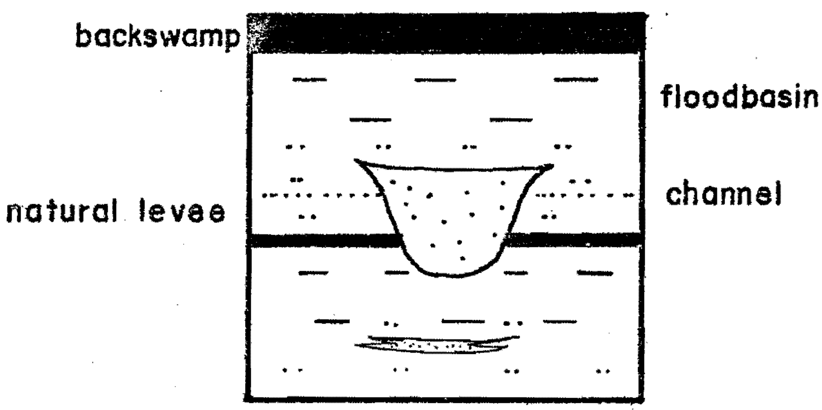
Cyclic Low-sinuosity Stream Deposits

Cyclic sequences in low-sinuosity stream deposits are more variable due to the confinement of the channel. The result is several successive cycles of floodplain deposits that may or may not be interrupted by channel deposits (Figure 30). The normal sequence is beds of tan and gray silt and clay overlain by beds of gray clay grading up to blue-black and chocolate-brown lignitic clay overlain by beds of lignite (Figure 31A). This sequence results from the gradual subsidence of the floodbasin beneath the water table and decrease in sedimentation rates, causing the light-colored silty clay to be covered by dark-colored organic clay and peat as a swamp develops. On the other hand, if depositional rates remain great enough to prevent the development of swamps, thick beds of interstratified silt and clay may develop (Figure 31B). Diversion of a low-sinuosity stream into the area produces an erosional contact that forms the base of a fining-upward cycle (Figure 31C) such as in the case of beds 1 and 2, Plate 2).



(A) Normal cyclic unit of low-sinuosity stream deposits. Silty-clay deposited prior to subsidence below water table and deposition of floodbasin and backswamp clay and lignite.

(B) Backswamp did not form because sedimentation rates were too high. Lignite bed is absent.



(C) Normal cyclic unit truncated by low-sinuosity stream when it was diverted into this area. Erosional base of the channel deposits forms the base of a fining-upward cyclic unit.

Fig. 31.--Cyclic units of low-sinuosity stream deposits of study area. Legend on Plate 2.

Larger Cycles

The alternation of cyclic high- and low-sinuosity stream deposits results in larger cycles that record the change from high- to low-sinuosity stream deposition within an area. Deposits of low-sinuosity streams overlie deposits of high-sinuosity streams within the study area (Plate 1). This sequence is repeated higher in the stratigraphic section (Johnson, 1973). Jacob (1973a) found high-sinuosity stream deposits overlying low-sinuosity stream deposits in the Tongue River Formation.

Rapid channel and natural-levee deposition, producing alluvial ridges elevated above the floodbasin, may have caused avulsion of moderately-high-sinuosity streams into lower areas and the initiation of new cycles of alluvial deposition. Differential subsidence of deltaic deposits may have resulted in the diversion of low-sinuosity distributary channels into lower areas with steeper, more stable gradients and the subsidence of abandoned distributary courses beneath marshes or inter-distributary bays. This lateral shifting of sites of active delta progradation may account for the superposition of high- and low-sinuosity stream deposits within the Sentinel Butte Formation.

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Plate 1. Stratigraphic cross-section of part of the Sentinel Butte Formation, North Unit Theodore Roosevelt National Memorial Park. Locations of measured sections are shown in Figure 7.

Plate 2. Stratigraphic cross-section of part of the Sentinel Butte Formation, North Unit of Theodore Roosevelt National Memorial Park. Locations of measured sections are shown in Figure 13.