Fluvial Architecture of the Lower Cretaceous Lakota Formation, Southwestern Flank of the Black Hills Uplift, South Dakota

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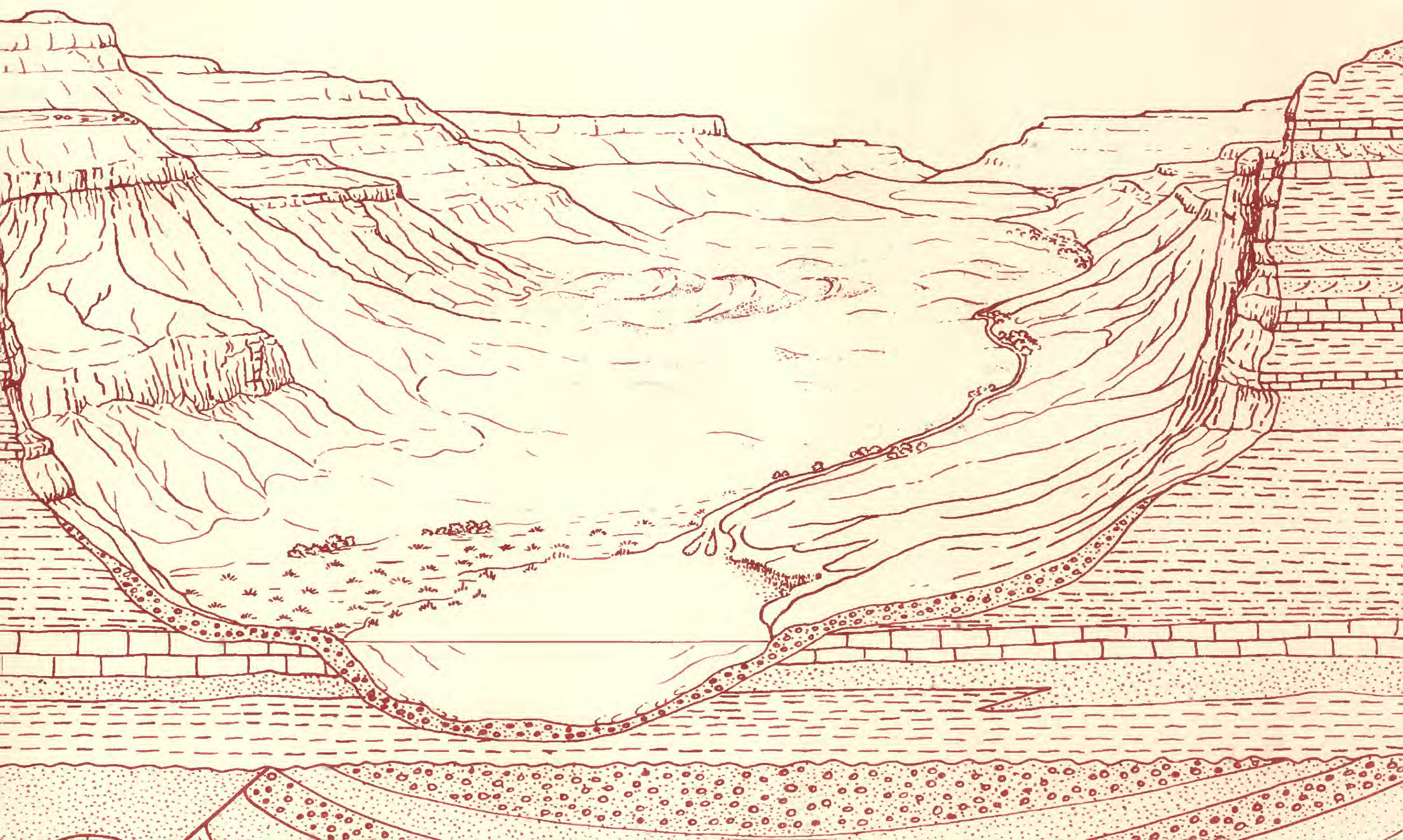

Chapter S

Fluvial Architecture of the Lower Cretaceous Lakota Formation, Southwestern Flank of the Black Hills Uplift, South Dakota

By DAVID J. DAHLSTROM and JAMES E. FOX

A multidisciplinary approach to research studies of
sedimentary rocks and their constituents and the
evolution of sedimentary basins—both ancient and modern

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FIGURES

Fluvial Architecture of the Lower Cretaceous Lakota Formation, Southwestern Flank of the Black Hills Uplift, South Dakota

By David J. Dahlstrom[1] *and* James E. Fox[2]

Abstract

In the southern Black Hills, South Dakota, the Lakota Formation consists of four distinctive fluvial units. Three of these units, identified as fluvial units 1, 3, and 4, crop out in the study area. Fluvial unit 2 crops out east of the study area.

Fluvial systems are made up of distinctive architectural elements enclosed by second-order surfaces. Fluvial unit 1 formed as a result of meander construction by a high-sinuosity, single-channel stream. At its base is a massive to cross-bedded sandstone sequence, including erosional scours and lenses of intraformational conglomerate, that formed in the deepest part of the channel under high-energy conditions. This sequence is overlain by lateral accretion elements consisting of laminated sandstone deposited as low-amplitude bedforms overlain by rippled sandstone. These lateral accretion elements are the dominant feature of fluvial unit 1.

Depositional elements of fluvial unit 3 are much thinner and more limited in areal extent than the sheetlike sandstones of fluvial unit 1 or the tabular, elongate sandstones of fluvial unit 4. Sandstones of fluvial unit 3 are very poorly sorted, have numerous erosional scours, and have cyclically interbedded lower- and upper-flow-regime structures that indicate ephemeral flow. Multiple topographic levels developed in this depositional system.

Tabular planar crossbeds dominate fluvial unit 4. Many of the sandwaves that gave rise to these crossbeds migrated over larger bars (macroforms). Fluvial unit 4 is composed primarily of lateral and bilateral accretion elements in transverse profile and foreset macroforms in longitudinal profile. Bar-top deposit elements that formed on semiemergent macroforms and sandy bedform elements from both deep (restricted) and shallow channels indicate multiple topographic levels. This fluvial unit formed in a rapidly aggrading, low-sinuosity, multiple-channel system.

INTRODUCTION

Large-scale depositional units referred to as architectural elements by Miall (1985a, b) were interpreted from outcrops of three distinct fluvial sandstone units of the Lakota Formation in the southwestern Black Hills area of Custer and Fall River Counties, South Dakota (fig. 1). These fluvial deposits formed near the end of an episode of continental deposition that began when the Jurassic Sundance sea regressed from the region and ended when the Early Cretaceous Skull Creek sea encroached from the north in Albian time. This depositional phase is represented by the Upper Jurassic Morrison Formation and Lower Cretaceous Lakota Formation and its regional equivalents (fig. 2). A transgressive disconformity of regional extent marks the contact between the Lakota and the overlying marginal-marine Fall River Formation (Waage, 1959; Haun and Barlow, 1962). Together, these two formations comprise the Inyan Kara Group. The Lakota is well exposed on the southern and southwestern flanks of the Black Hills uplift, where it is at its maximum regional thickness of about 500 ft (150.4 m). Because of the shallow dip of strata throughout much of this area, outcrops are as wide as 6 mi (9.6 km).

A light-mineral fraction dominated by rounded chert and quartz with abraded overgrowths and a heavy-mineral fraction of primarily rounded zircon and tourmaline suggest a predominantly sedimentary source terrane for the Lakota (MacKenzie and Ryan, 1962; Chisholm, 1963).

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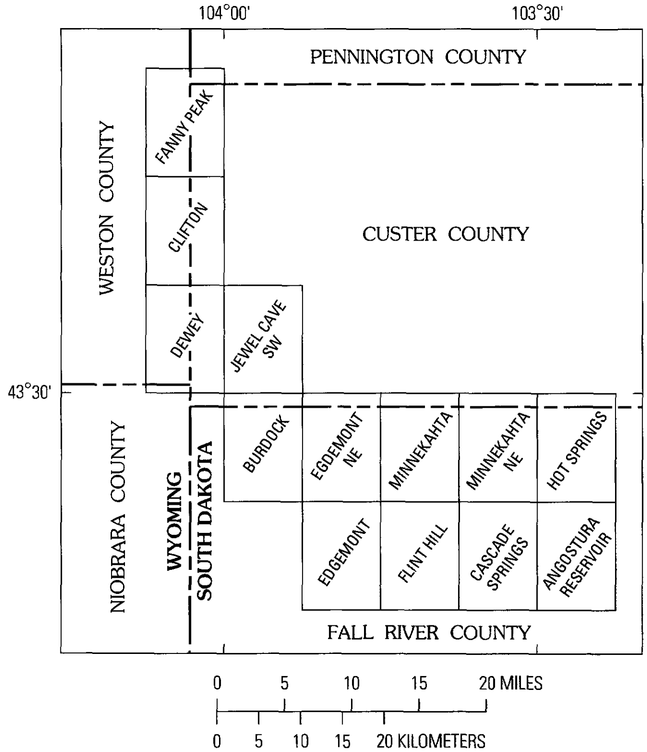

Figure 1. Index map of 7.5-minute quadrangles mapped by the U.S. Geological Survey in the study area. Modified from Gott and others (1974).

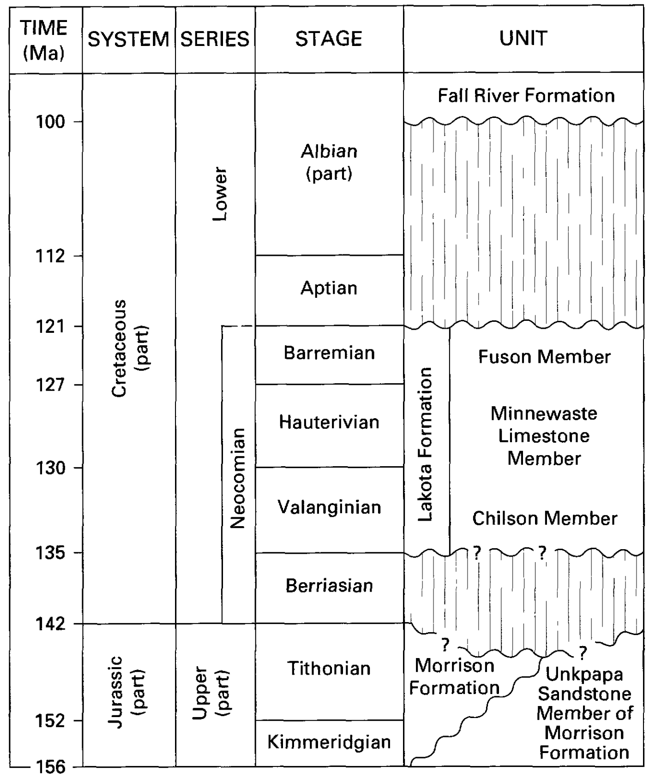

Figure 2. Chart showing stratigraphy of Upper Jurassic and Lower Cretaceous rocks in the study area. Absolute ages from Palmer (1983).

Regional paleocurrent trends and the presence of late Paleozoic fossils within chert pebbles (MacKenzie and Poole, 1962) suggest that source areas were to the west and south.

FLUVIAL UNITS IN THE LAKOTA FORMATION

The Lakota Formation contains diverse lithotypes, including conglomerate, sandstone, siltstone, fissile to massive mudstone, coal, and limestone (Dandavati and Fox, 1981). Widespread marker units are rare in this sequence, and a major mapping effort was required to decipher its stratigraphy. Thirteen 7.5-minute quadrangles containing exposures of the Inyan Kara Group were mapped by the U.S. Geological Survey (fig. 1). The stratigraphic framework of the Lakota Formation is summarized in figure 3.

General Characteristics

Four informal units of the Lakota Formation, identified as fluvial units 1–4, have similar characteristics: (1) each unit is eroded into the underlying rocks; (2) the units are elongated toward the northwest and have been traced for 25–60 mi (40–97 km) on outcrop; (3) toward its center, each unit consists primarily of sandstone; (4) in cross section units 1–3 are lenticular and unit 4 is tabular; (5) toward their edges, units 1–3 are interbedded with finer grained deposits containing freshwater fossils; and (6) crossbeds within the units dip predominantly toward the northwest. Based on these characteristics, the four units are interpreted to be fluvial in nature and were referred to as fluvial units 1–4 by Post and Bell (1961). Outcrops of fluvial units 1–3 were studied for this report; fluvial unit 2 crops out southeast of the study area.

Stratigraphic Relationships and Characteristics

Fluvial units 1 and 2 are assigned to the Chilson Member of the Lakota Formation, and fluvial units 3 and 4 are assigned to the Fuson Member. The Chilson Member is locally overlain by the Minnewaste Limestone Member of the Lakota in the southern Black Hills area.

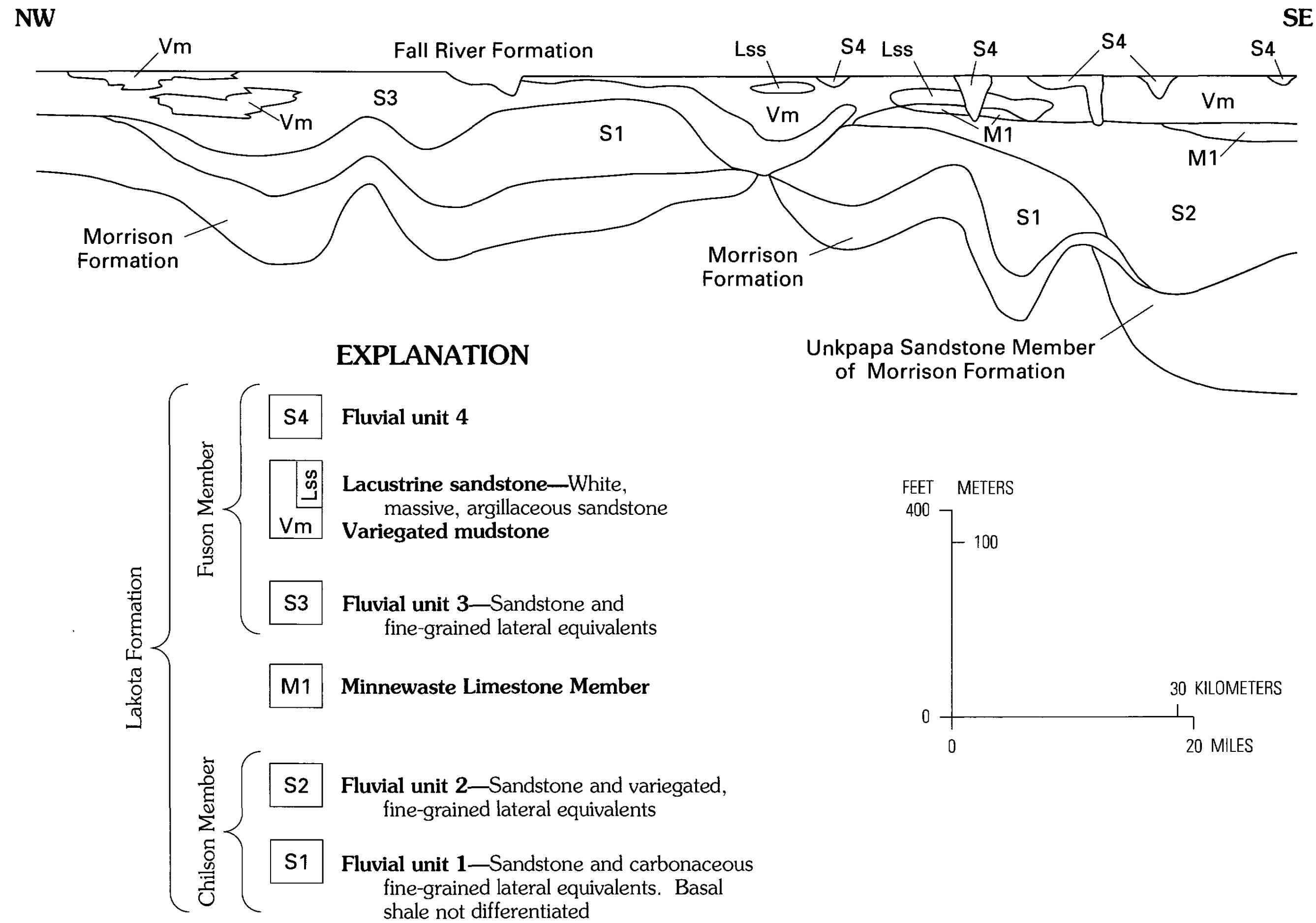

Figure 3. Cross section of the Lakota Formation in the southern Black Hills, South Dakota and Wyoming. Modified from Post and Bell (1961).

Chilson Member

A basal fissile and carbonaceous shale as thick as about 100 ft (30.5 m) is overlain by fluvial unit 1, which thins both east and northwest of its thickest section of 300 ft (91.4 m) on the border between the Flint Hill and Edgemont NE quadrangles (fig. 1) (Gott and others, 1974). In the Edgemont NE quadrangle, the axis of fluvial unit 1 trends northwesterly (Gott and Schnabel, 1963). An increase in chert content and a decrease in mica content relative to the more locally derived Upper Jurassic Unkpapa Sandstone Member of the Morrison Formation suggest increased input from pre-Cretaceous sedimentary rocks of the Cordilleran region to the west (Gott and others, 1974).

In some places, 300–400 ft (91.4–121.9 m) of strata, including fluvial unit 1 and underlying strata, may have been eroded (Gott and others, 1974) prior to deposition of fluvial unit 2. As much as 150 ft (45.7 m) of Unkpapa Sandstone Member has been removed beneath the thickest section of fluvial unit 2 (400 ft, 121.9 m) in the southeastern part of the Cascade Springs quadrangle (Post, 1967). In other places fluvial unit 2 truncates and laps onto fluvial unit 1.

An increase in the abundance of rounded zircon and tourmaline in fluvial unit 2 indicates increased input from a western source (MacKenzie and Poole, 1962; Gott and others, 1974). A period of subaerial exposure and minor erosion followed deposition of fluvial unit 2.

Minnewaste Limestone Member

The Minnewaste Limestone Member crops out continuously in the eastern part of the study area (fig. 1) and discontinuously as far west as the Burdock quadrangle. The Minnewaste grades from almost pure, lithographic limestone in its thickest sections (80 ft, 24.3 m) to sandy limestone and calcareous sandstone at its depositional pinchout. Removal of about 30 ft (9.1 m) of anhydrite reported to be present in the subsurface to the east of the study area may be the cause of brecciation common on outcrop (Gott and others, 1974). The Minnewaste intertongues with mudstones of the overlying Fuson Member (Gott and Schnabel, 1963). Freshwater sponge spicules recovered from this unit suggest a lacustrine origin (Schnabel, 1963).

Fuson Member

Three mappable units have been identified within the Fuson Member: fluvial unit 3, a variegated mudstone and sandstone, and fluvial unit 4.

Sandstone bodies within fluvial unit 3 have a maximum thickness of 120 ft (36.6 m) (Gott and others, 1974) and exhibit a range of textures from conglomeratic to fine grained. The sandstone is coarsest where incision is greatest. The thick, coarse strata trend north-northwest (Brobst, 1961). Strata of fluvial units 3 and 4 are interbedded with the variegated mudstone, and in places fluvial unit 3 contains thin interbeds of mudstone (Braddock, 1963). Relatively abundant chert and silicified limestone in fluvial unit 3 suggests continued input from a western source area (Gott and others, 1974).

The variegated mudstone unit, which is interbedded with fluvial unit 3, is the most widespread informal unit of the Lakota Formation and has probable equivalents around the entire periphery of the Black Hills (Gott and others, 1974). This floodplain mudstone is commonly gray but is mottled red, green, or brown; it lacks carbonaceous material, and it is slightly calcareous, containing minor concretionary horizons and limestone beds (Braddock, 1963). Freshwater fossils have been identified from calcareous rocks in the lower part of this unit (Bell and Post, 1971; Sohn, 1979). It has a maximum thickness of 180 ft (54.9 m) and an average thickness of 100 ft (30.5 m).

Locally developed within the variegated mudstone is a white, structureless, highly argillaceous, silty sandstone containing exotic pebbles. This sandstone has a maximum thickness of 100 ft (30.5 m) in a northwest-bearing lens in the Edgemont NE quadrangle (Gott and Schnabel, 1963).

Fluvial unit 4 overlies the variegated mudstone unit and, in places, has incised into underlying strata. It crops out continuously for approximately 35 mi (56.4 km), from the Flint Hill quadrangle to the Dewey quadrangle (see fig. 1). In the Burdock, Jewel Cave SW, and Dewey quadrangles, fluvial unit 4 occupies a northwest-trending belt 0.5–1 mi (0.8–1.6 km) wide. This unit has a maximum thickness of 165 ft (50.3 m) in the Flint Hill quadrangle and thins in its downstream direction to a maximum thickness of 70 ft (21.3 m) in the Jewel Cave SW quadrangle (Braddock, 1963). Abrupt lateral truncation of this sandstone body and abundance of large slump blocks at the base of fluvial unit 4 in the Edgemont quadrangle suggest that relief on the walls of the paleovalley in which fluvial unit 4 was deposited was great (Ryan, 1964). The mineral assemblage of fluvial unit 4 indicates input from both western and eastern source areas (Gott and others, 1974).

METHODS

Concepts and Definitions of Architectural Elements

Allen (1983) established a hierarchy for surfaces or boundaries within bedded sandstones using terms of McKee and Weir (1953) for stratification types. Zeroth-order surfaces bound individual strata or cross-strata within a set. First-order surfaces form the boundaries of individual sets. Second-order surfaces bound groups of genetically related stratified and (or) cross-stratified units (cosets or composite sets). This genetic relationship is established by consistent paleocurrent trends within similar lithofacies. Third-order surfaces bound groups of cosets, or composite sets of a larger scale, deposited by the overall channel system. Boundaries of these units are depositional and (or) erosional surfaces.

The scale of architectural elements may vary from the smallest scale, flow-regime bedforms, to the largest scale, macroforms, which approach the scale of the channel itself. A complete heirarchy of depositional features may coexist in a single fluvial system (Jackson, 1975). Lateral, vertical, and forward accretion of the macroform is commonly accomplished by migration of superimposed smaller bedforms (Allen, 1983; Friend, 1983; Haszeldine, 1983; Kirk, 1983). In this study the most diagnostic and useful units identified in the outcrop were those elements or packages of strata enclosed by second-order surfaces. The depositional processes that gave rise to the element are inferred from interpretation of internal geometry, lithofacies, and relationship with surrounding elements.

For example, figure 4*A* shows an element exposed in longitudinal section. This element is entirely enclosed within second-order surfaces. The first-order surfaces within this element descend stratigraphically in the downstream direction and terminate against the basal surface. The bedforms that resulted in the coset of planar crossbeds apparently migrated down the lee of a macroform (fig. 4*B*). The geometry of the set and coset boundaries describe the outline of the macroform.

This element is defined as the foreset macroform (Miall (1985a, b). Just as the foreset macroform is related to a specific fluvial process, Miall described seven other architectural elements related to seven distinct fluvial processes. Miall contended that all fluvial deposits can be divided into varying proportions of these eight process-controlled genetic elements.

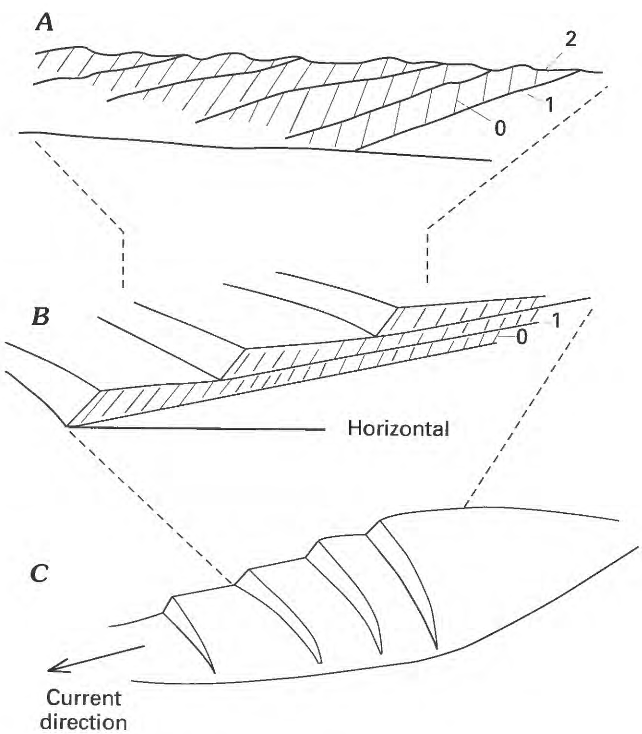

Figure 4. Drawings showing tabular planar crossbedding resulting from migration of superimposed sandwaves in the lee of a large bar. 0, zeroth-order surface; 1, first-order surface; 2, second-order surface. *A, B,* Cross sections through macroform showing crossbedding. *C,* Perspective view of macroform.

Five of Miall's elements were identified in this study: foreset macroforms (FM), lateral accretion deposits (LA), fine-grained overbank deposits (OF), channel-fill deposits of many scales (CH), and sandy bedform deposits (SB). In addition, three new elements are proposed based on depositional units identified in this study: bilateral accretion deposits (Bi-LA), massive channel deposits (MC), and bar-top deposits (BD).

Outcrop Methods

Outcrops of the three fluvial units within the study area were chosen that offer extensive three-dimensional exposure. Photographs were taken of these outcrops, enlarged, and used as a base for construction of two-dimensional lateral profiles (plate 1).

Detailed two-dimensional profiles of rock exposures were constructed in such a way that the outcrop is divided into naturally occurring packages or units made up of internally consistent or genetically related lithofacies (elements). Profile construction entailed identifying lithofacies and documenting their distribution throughout the outcrop. Second- and third-order surfaces were located and traced across the outcrop. Units enclosed by second-order surfaces were examined for the signature of macroforms. The appropriate element name was assigned to each unit composing the outcrop.

Nine lithofacies categories were established for this outcrop study. Shorthand symbols modelled after those of Miall (1977, 1978) are used on plate 1. The lithofacies include (1) massive intraformational conglomerate (Gm), (2) erosional surfaces within sandstone (Se), (3) massive sandstone (Sm), (4) laminated sandstone (Slm), (5) planar crossbedded sandstone (Sp), (6) trough crossbedded sandstone (St), (7) ripple crosslaminated sandstone (Sr), (8) fine-grained partings (Fp), and (9) carbonaceous partings (Cp). Characteristics and associations of these lithofacies in the sandstone bodies are described following.

Two types of trough crossbedded sandstone (St) were noted: solitary occurrences of cut and fill, and nested sequences of trough crossbeds. The latter type is present in all of the fluvial units, generally in medium to very coarse sand: sets are as thick as 0.5 m and as wide as 2 m. Trough crossbeds are inferred to represent migration of three-dimensional dunes in the deeper part of active channels (Allen, 1983; Miall, 1985a, b). Methods outlined by DeCelles and others (1983) were employed to determine paleocurrent directions from trough crossbedded sandstone.

Ripple crosslaminated sandstone (Sr) is generally medium to very fine grained. A variety of internal structures was noted, including small-scale trough and planar crosslaminations and climbing ripples.

Fine-grained partings (Fp) are commonly associated with rippled sandstone. The partings range from siltstone to claystone, are laminated or massive, and, in fluvial unit 1, contain variable amounts of detrital carbonaceous material. These units are inferred to have been deposited from suspension in quiet water.

OUTCROP PROFILES AND DEPOSITIONAL MODELS

Outcrop profiles of fluvial units 1, 3, and 4 are presented on plate 1. Profile 1 includes fluvial unit 1, profiles 2 and 3 include fluvial unit 3, and profiles 4 and 5 include fluvial unit 4. An index figures is included with each profile. Elements comprising each profile are outlined and sequentially numbered in these index figures. Element symbols used on plate 1 are presented in parentheses after their first appearance in the text.

In profiles 4 and 5, certain critical sets of crossbedding are numbered. These numbers are used for reference in the discussion.

Figure 5. Base of fluvial unit 1 eroded into laterally equivalent fissile, carbonaceous mudstone near the 55-m mark of profile 1 (plate 1). Massive channel fill element near the base consists of thick sets of massive sandstone interbedded with intraformational conglomerate.

Description Of Fluvial Unit 1 In Profile 1

Profile 1 was constructed based on exposures of fluvial unit 1 on the north wall of an unnamed east-trending canyon in sec. 24, T. 6 S., R. 2 E., Custer County, South Dakota. This sandstone is sheetlike in plan and averages 30–50 ft (9.1–15.2 m) in thickness.

All nine lithofacies are present in profile 1. On the left side of the profile, the basal element (element 1) of the sandstone body is dominated by massive sandstone interbedded with intraformational conglomerate. This element contains numerous intraclast-strewn erosional surfaces (fig. 5).

Element 2 comprises an interbedded sequence of laminated sandstone, ripple-laminated sandstone, fine-grained partings, and carbonaceous partings. It overlies element 1 from the left border of the profile to the 110-m mark. Strata in element 2 have a depositional dip east-southeast at 10°–19° (fig. 6). In the lower part of this sequence laminated sandstone is the dominant lithofacies, whereas in the upper part of the sequence ripple crosslaminated sandstone is the dominant lithofacies. Sets of laminated sandstone and carbonaceous partings extend downdip into massive sandstone. These sets are generally truncated and are equivalent in the downdip direction to erosional surfaces bearing intraclasts of similar composition (fig. 7).

On the basis of the inclination of strata within element 2, the upward fining of grain size in the sandy lithofacies, the vertical and updip succession from laminated sandstone to rippled sandstone, and the tabular geometry of this lithofacies assemblage, element 2 is inferred to represent lateral accretion on a point-bar macroform and is labeled a lateral accretion element (LA). Because this element volumetrically dominates profile 1, especially the left half, the point bar it represents was the major macroform in this channel. The fluvial system represented by this profile is inferred to have been a single channel having high sinuosity.

The position of element 1 at the base of a lateral accretion element (element 2), the gradation of erosional surfaces within element 1 into lithofacies of element 2, and the similarity of lithofacies in element 2 to intraclasts included in element 1 lead to an interpretation of sediment fill in the deepest, highest energy part of the channel. Erosional surfaces and massive intraformational conglomerate represent scour and lag deposits formed during high flood stages. Massive sandstone was deposited at lower water stages when erosion was not as great. The symbol MC, for massive sandstone deposited as active channel fill, is suggested for this element.

Beginning at the 75-m mark of profile 1, an anomalously coarse set of planar crossbedded sandstone (Sp) near the top of the sandstone body indicates a change in depositional conditions. In contrast to the left half of the profile, the right half contains a greater percentage of cross-stratified sandstone at its base, a smaller percentage of lateral accretion deposits, and no carbonaceous partings in its lateral accretion deposits, and it is thinner. From 110 to 125 m, the exact position of the outcrops cannot be traced because of the weathered condition of the outcrop, but a third-order contact is inferred to separate the markedly different halves of this profile.

Despite these differences, some points of similarity exist between the two halves of the profile. As on the left, the upper half of the sandstone body on the right, element 4, is composed of a lateral accretion element and capped with fine-grained overbank material (element 5, described following). Vertical sequences and lithofacies assemblages are essentially identical, and the dip of lateral accretion surfaces is comparable to that of element 2. Element 3, the

Figure 6. Outcrop of rocks at the left margin of profile 1 (plate 1). Dipping lateral accretion surfaces are prominent. Note the angular discordance between sandy lateral accretion surfaces and overlying and underlying finer grained overbank deposits.

basal element, is dominantly bedded sandstone and also includes some massive sandstone containing internal erosional surfaces (fig. 8).

Element 3 also contains planar crossbedded sandstone, solitary trough crossbedded sandstone, and nested trough crossbedded sandstone. Paleocurrents measured from smaller scale crossbeds indicate low dispersion from the channel axis as determined from the strike of accretionary surfaces within the lateral accretion element (element 4). The large-scale crossbeds indicate bedform migration at roughly right angles to the channel axis in the updip direction of the lateral accretion surfaces, which is consistent with the direction of helical overturn in a channel bend (Allen, 1985). Crosscutting erosional surfaces are also common in element 3. Element 3 represents migration of sandy bedforms in a channel that lacked larger macroforms (SB).

Similar to elements 1 and 2, elements 3 and 4 are inferred to represent a high-sinuosity, single-channel stream. Both sets of elements are capped by a composite set of fine-grained partings and very fine grained rippled sandstone (element 5). An angular discordance between set boundaries in this composite set and the underlying lateral accretion surfaces indicates a change in depositional process (figs. 6, 8). Deposition in an overbank setting is indicated by the fine-grained texture and almost horizontal attitude of the capping sequence (OF).

Depositional Model For Fluvial Unit 1

Although they do not contain identical elements, strata in both halves of this profile were deposited within high-sinuosity streams. Location of the two sandstone bodies at the same stratigraphic level within a sheetlike sandstone body suggests that the sandstone bodies are related to migration of the same stream. Studies of modern point-bar construction indicate a stepwise pattern (Hickin, 1977). Each phase is initiated due to necessity of the stream to lengthen its course to expend excess energy. Each phase is halted when the meander becomes so tight that flow separation on the concave bank prevents further

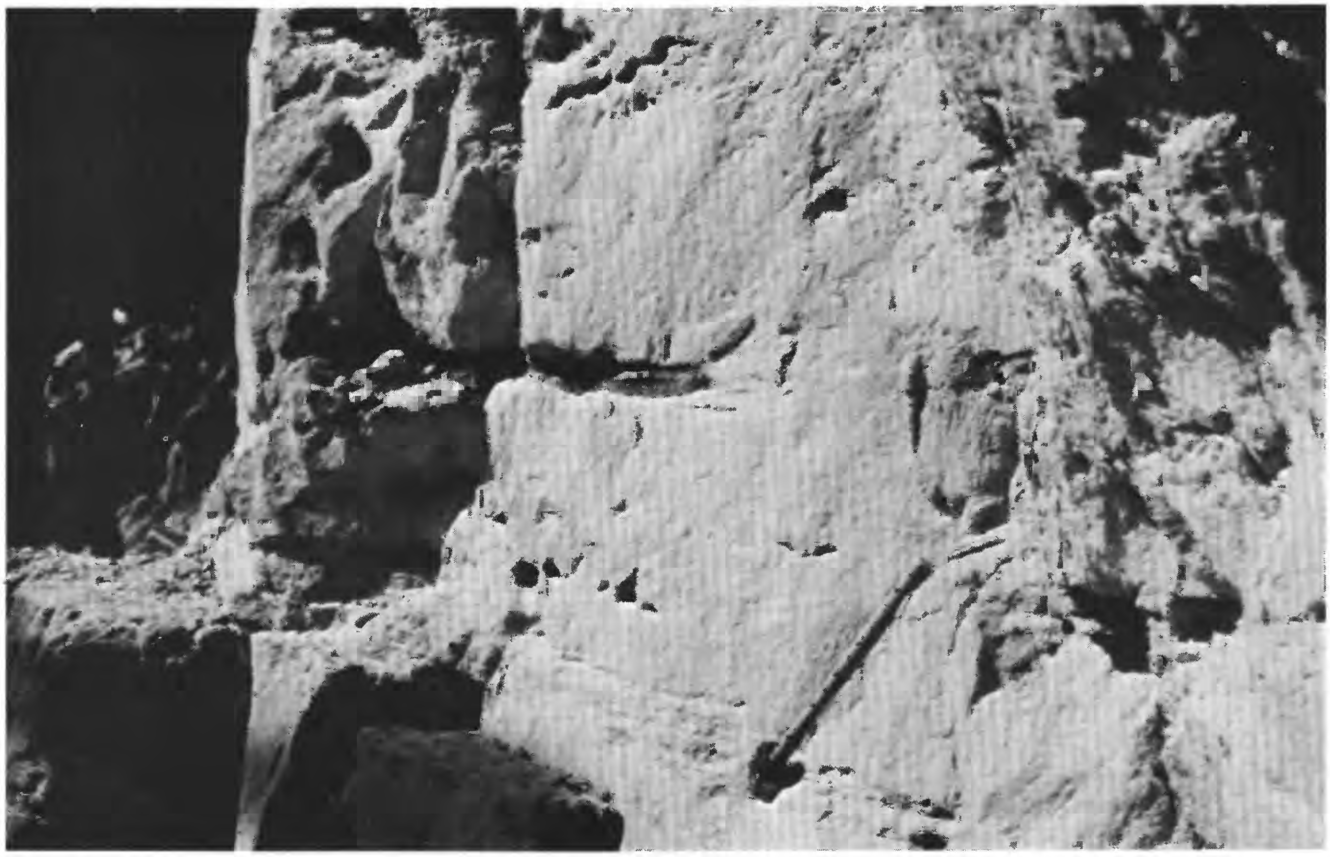

Figure 7. Abrupt erosional terminations of laminated carbonaceous sandstone of fluvial unit 1. Massive sandstone overlies and is laterally equivalent to these units. Hammer shown for scale.

erosion. Deposition of the subsequent phase commences immediately downstream, tending to increase the radius of curvature of the critical bend. Based on this scenario, a possible explanation for the geometry of the lateral accretion elements of profile 1 is shown in figure 9.

The change in depositional conditions between the left and right halves of profile 1 may be related to variability in the sediment source of the system. Although no significant change in maximum grain size was noted, an increase in the ratio of bedload to suspended load could have caused an increase in channel width (Galloway, 1985). This increase in width would have allowed the current to rework the active channel fill into bedforms, resulting in crossbedded rather than massive sandstone.

Figure 10 depicts the depositional model inferred for profile 1. In plan view, the channel was highly sinuous and lacked mid-channel macroforms. Deposition on point-bar macroforms led to formation of lateral accretion elements that volumetrically dominated the sandstone body. In transverse cross section through a point-bar macroform, the channel geometry was relatively simple: a gently sloping convex bank and a steeper, concave cut bank. Vertical (upslope) decrease in stream power on the convex bank resulted in the vertical sequence of lithofacies and elements characteristic of fluvial unit 1.

In the deepest, highest energy part of the channel, flow was variable. During periods of normal flow, great amounts of sediment were transported in suspension. Sand deposited from suspension in the deepest part of the channel was reworked to varying degrees. During deposition of the left half of the profile, little reworking occurred, and consequently element 1 is dominated by massive sandstone. In contrast, element 3 is composed primarily of crossbedded sandstone. High-flow events ripped up sediments deposited higher on the point bar and deposited the resultant intraclasts on erosional surfaces scoured into the massive to crossbedded sand downslope.

Lenses of massive intraformational conglomerate (Gm) are common in fluvial unit 1. Intraclasts are composed of massive to laminated mudstone. The conglomerate is generally clast supported and has a matrix of medium to coarse sand, and it is probably lag in origin.

Figure 8. East half of profile 1 (plate 1). Element 3 is dominated by bedded rather than massive sandstone. Note the angular discordance between the overbank deposits and the lateral accretion surfaces of element 4.

The mudstone intraclasts are believed to be derived from preexisting deposits within the active channel. Lenses of massive intraformational conglomerate are laterally gradational; erosional surfaces are enclosed within sandstone (Se) and lined with intraclasts. Generally, these surfaces are laterally gradational with in situ laminated fine-grained deposits similar in composition to the intraclasts.

Massive conglomeratic lenses and erosional surfaces of fluvial unit 1 are generally contained within massive to crudely bedded sandstone (Sm) (fig. 5). Poor sorting and an overall lack of structure indicate fallout from suspension in a sediment-choked fluid. Intraclasts included in the massive sandstone generally have their apparent maximum dimension oriented vertically. Invariably, the massive sandstone of fluvial unit 1 is at the base of the sandstone body.

The sequence of massive sandstone interbedded with erosional surfaces and intraformational conglomerate is succeeded upsection by laminated fine-grained sandstone (Slm). The laminated sandstone lithofacies includes both truly horizontal laminae and laminae deposited on inclined surfaces. Cosets of these laminae in fluvial unit 1 are inclined as much as 15° to original horizontal. Within these cosets, sets of laminae turn down and are truncated against a lower lamina. Superjacent laminae drape over and reduce the resultant relief upsection. On the basis of these observations, both fallout from suspension and bedload traction are believed to have been active in the deposition of the laminated sandstone lithofacies. Dispersion of bedding attitudes within the laminated sandstone suggests minor relief on the depositional surface. Truncation of sets of laminae indicates that this relief was due to development of low-amplitude bedforms. Whether these low-amplitude bedforms were periodic is not known, but termination of laminae indicates a component of migration updip on the depositional surface. Structures formed by these bedforms are similar to those of Allen's (1983) plane-bedded simple bars and Saunderson and Lockett's (1983) convex dunes.

Fluvial unit 1 includes a facies similar in composition to the fine-grained partings. This facies contains large amounts of detrital carbonaceous material. On the basis of

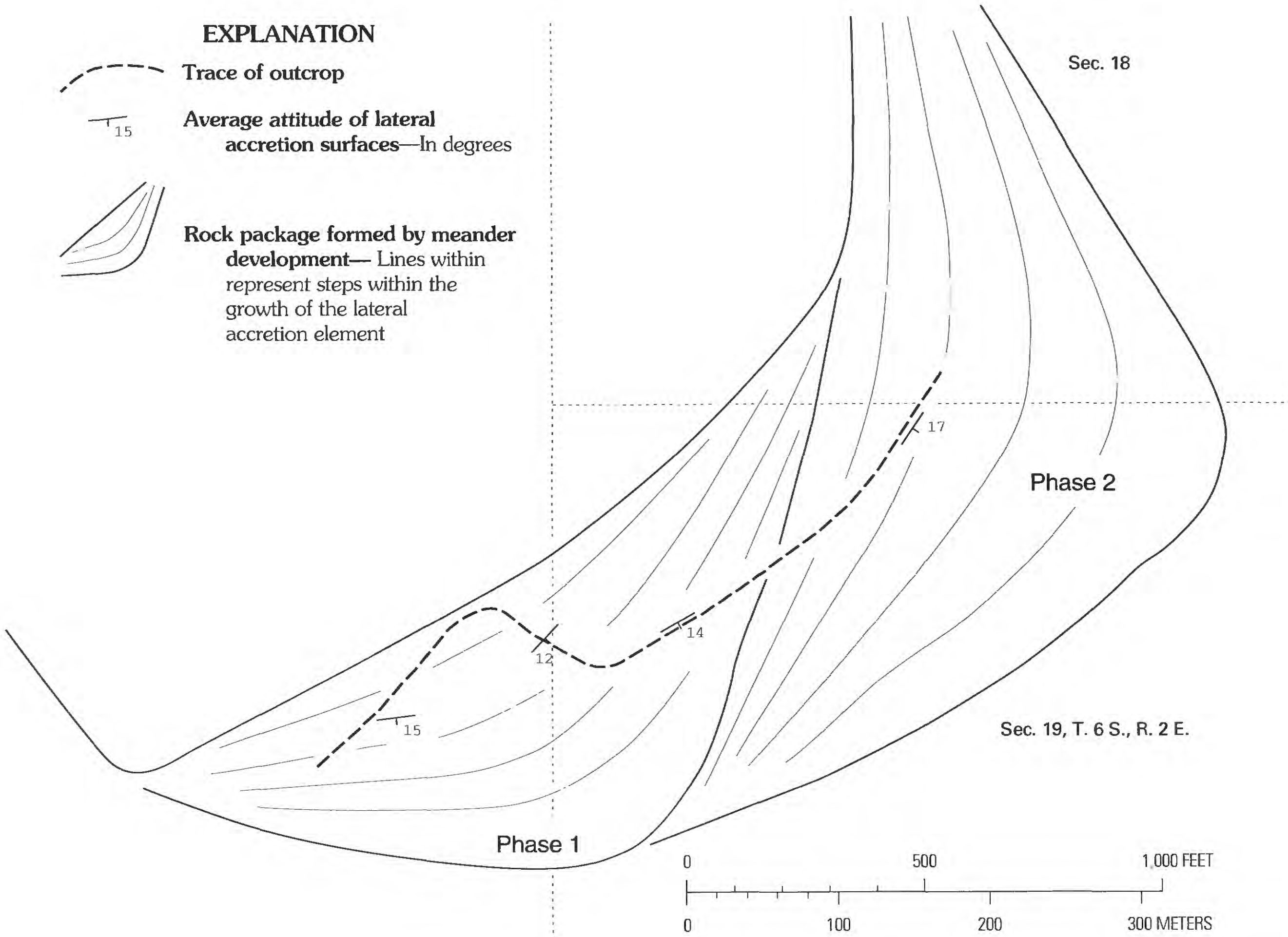

Figure 9. Plan view showing depositional model of fluvial unit 1 at profile 1. Each phase represents a period of channel meander building that began along an originally straight reach of the channel and ended when the radius of curvature of the bend reached a critical minimum. The profile is shown on plate 1, and a block diagram model for fluvial unit 1 is shown in figure 10.

its conformable interbedding with laminated sandstone, the carbonaceous parting lithofacies (Cp) is interpreted to represent deposition both from bedload traction and as fallout from suspension.

Low-amplitude bedforms developed higher on the point-bar surface, where both bedload and suspension transport occurred. Significant avalanching did not occur on these bedforms; consequently, laminated (rather than cross-stratified) sandstone was deposited. Fine-grained partings in elements 2 and 4 represent deposition of clay and silt from suspension during low-flow events. Rippled sandstone represents deposition on the uppermost, lowest energy part of the point bar.

The rippled sandstone of element 5 deposited in angular discordance over the lateral accretion deposits probably represents crevasse splays that formed as floodwater carried sand and silt from a subsequent channel in the system.

Description of Fluvial Unit 3 in Profiles 2 and 3

Exposures of fluvial unit 3 (fig. 11) are thin (15–30 ft, 4.6–9.1 m) and generally discontinuous in the study area.. Northwest of the study area, the unit is prominent and is as thick as 120 ft (36.6 m) (Gott and others, 1974). Profile 2 depicts an exposure of fluvial unit 3 in the NE¼SE¼ sec. 32, T. 6 S., R. 2 E., Custer County, South Dakota. Profile 3 depicts an outcrop of fluvial unit 3 in the SW¼NE¼ of the same section.

In contrast to the friable sandstones of fluvial units 1 and 4, sandstones of fluvial unit 3 are moderately to well cemented with hematite and silica. Liesegang banding is so extensive in parts of the outcrop that it masks primary structures. This banding is concentrated around petrified organic material. This organic material is much better preserved in fluvial unit 3 than in fluvial unit 1 or 4.

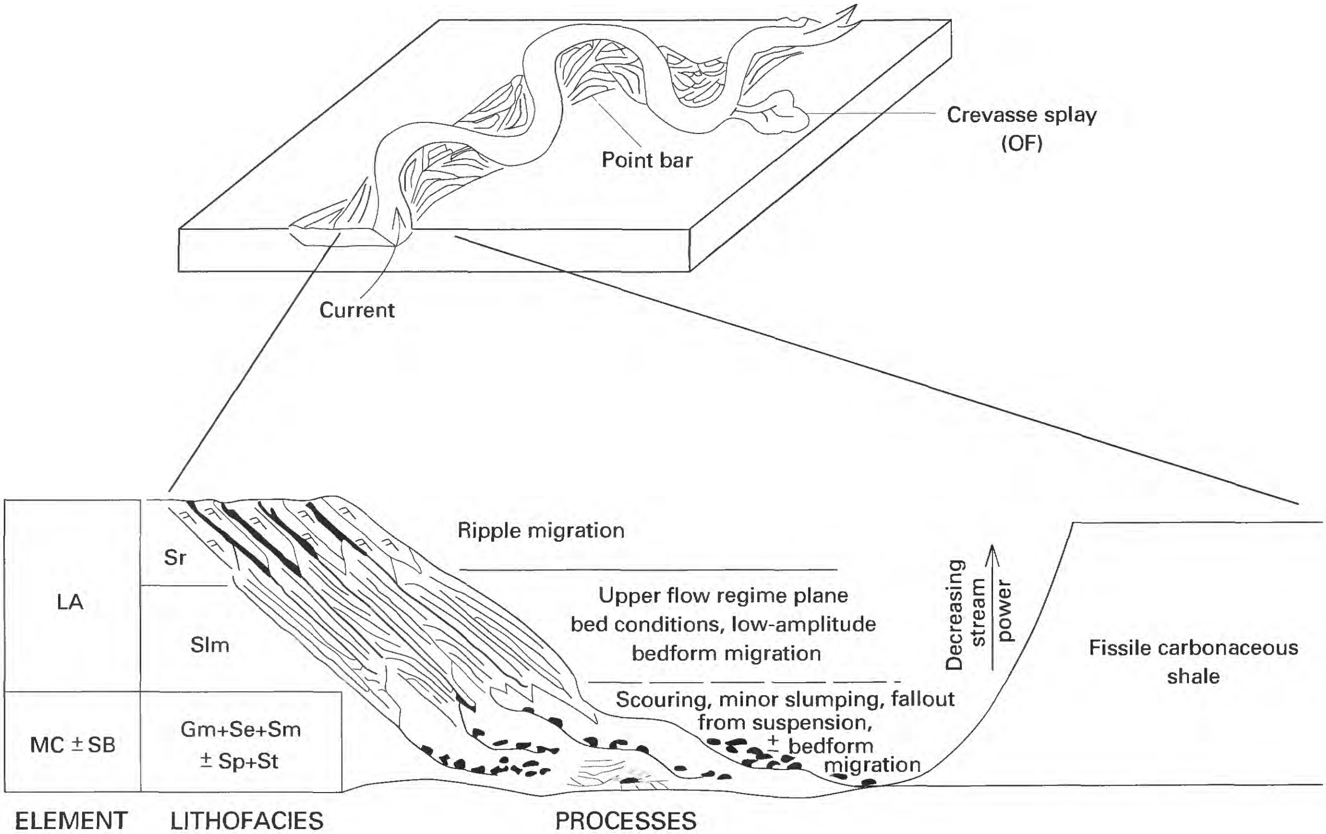

Figure 10. Block diagram model of fluvial unit 1. Elements and lithofacies: Gm, massive intraformational conglomerate; Se, erosional surfaces within sandstone; Sm, massive sandstone; Slm, laminated sandstone; Sp, planar crossbedded sandstone; St, trough crossbedded sandstone; Sr, ripple crosslaminated sandstone; LA, lateral accretion deposit; MC, massive channel deposit; SB, sandy bedform deposit; OF, overbank fine-grained deposit (crevasse splay).

Profile 2

In profile 2 (plate 1), the base of fluvial unit 3 is eroded into interbedded laminated mudstone and very fine-grained ripple crosslaminated sandstone laterally equivalent to fluvial unit 1. Element 1 is a medium- to coarse-grained, moderately well sorted sandstone consisting of nested trough crossbedding. A bimodal paleocurrent direction, with azimuths at N. 34° E. and N. 50° W., was measured for this element. Migration of three-dimensional dunes in a relatively deep channel lacking macroforms is inferred for this sandy bedform element (Allen, 1983).

Element 2 contains a sequence of laminated sandstone interbedded with small- to large-scale wedge-planar crossbedded sandstone. Contacts between these lithofacies are somewhat irregular and rise stratigraphically downstream. Cyclic interbedding of these lithofacies indicates a system in which flow velocity alternated between lower- and upper-flow regimes, with possible erosive events between cycles. Element 2 is capped with a laterally extensive surface covered with petrified organic debris.

Composed to element 2, element 3 has thicker sets of planar crossbedded sandstone and fewer laminated sandstone sets. Set boundaries in element 3 are markedly irregular, in general rising downstream. At the extreme right end of the profile, a composite set of planar crossbedded sandstone and laminated sandstone laps onto an erosional surface covered with petrified organic debris. Both elements 2 and 3 represent deposition in a relatively straight channel with variable discharge. The planar crossbedded sandstone was deposited by sandy bedforms during normal discharge, whereas the laminated sandstone was deposited during extreme discharge events.

Element 4 contains a sequence of interbedded, very fine grained, bioturbated sandstone and variegated mudstone. The contact between this sequence and the sandstone below dips 16° to the northwest. Fine-grained texture and bioturbation indicate quiet-water deposition, presumably in an abandoned channel. The northeasterly trend of this element and its restricted thickness indicate that the element does not represent a major channel within the depositional system.

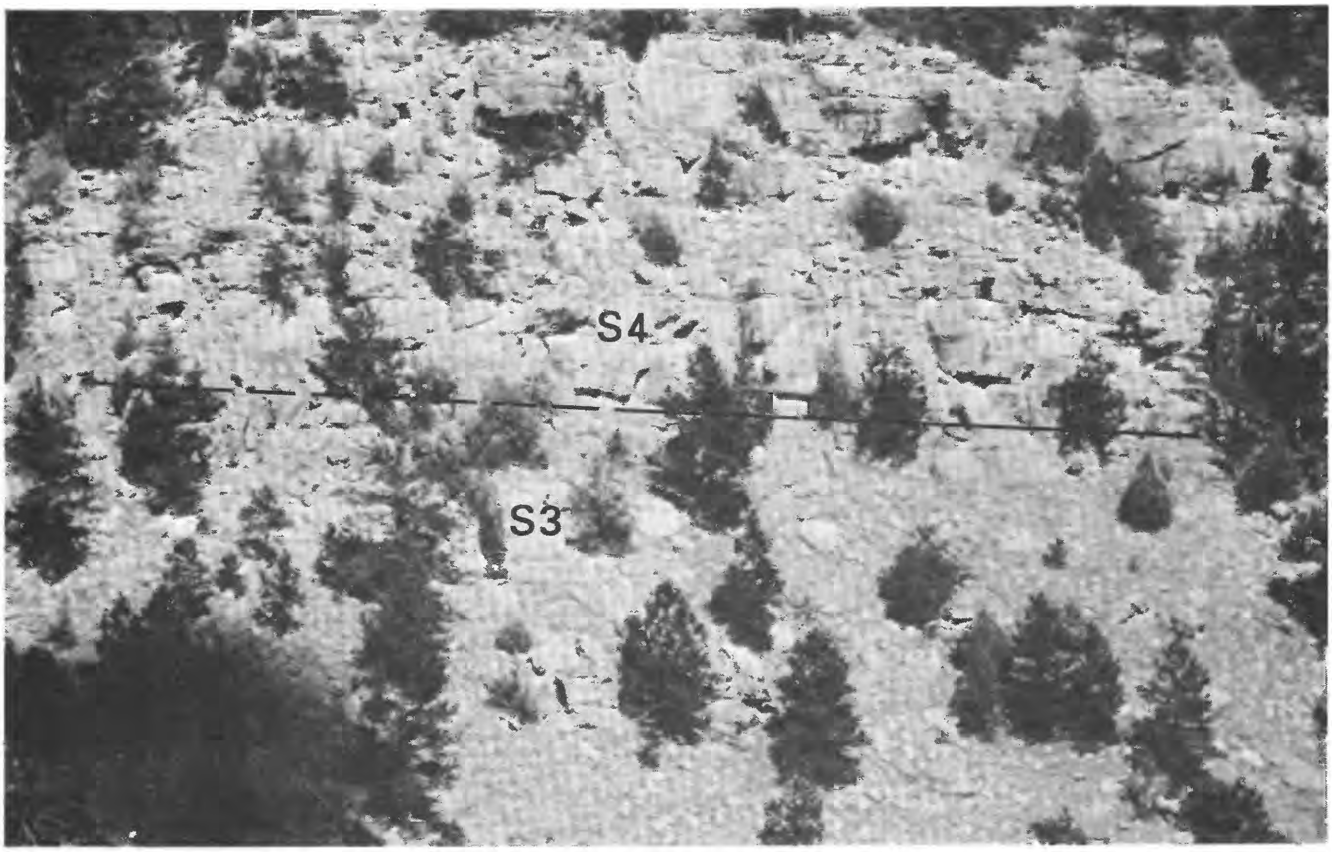

Figure 11. Fluvial units 3 (S3) and 4 (S4) at the location of profiles 2 and 4 (plate 1).

If profile 2 represents a single fluvial system, the system comprised distinct levels but probably lacked macroforms. The lowermost level, represented by element 1, was a relatively deep channel. Elements 2 and 3 represent a shallower part of the system. Element 4 represents abandonment of a minor channel atop element 3.

Profile 3

Profile 3 is from an outcrop that is thinner than but of comparable lateral extent to profile 2. Element 1 contains small- to large-scale planar crossbedded sandstone, solitary trough crossbedded sandstone, and abundant erosional surfaces. These erosional surfaces are strewn with exotic chert pebbles and cobbles (fig. 12), lithic fragments derived from the fluvial unit 1 equivalent into which this unit is incised, intraclasts, and petrified organic debris. As much as 3.9 ft (1.2 m) of relief is present on the erosional surfaces. Element 1 has the coarsest texture described in this study, yet foresets within its crossbed sets have tangential terminations that indicate deposition of very coarse sand and granules from suspension. This evidence of extreme flow velocity and an abundance of erosional scours within element 1 indicate flashy discharge.

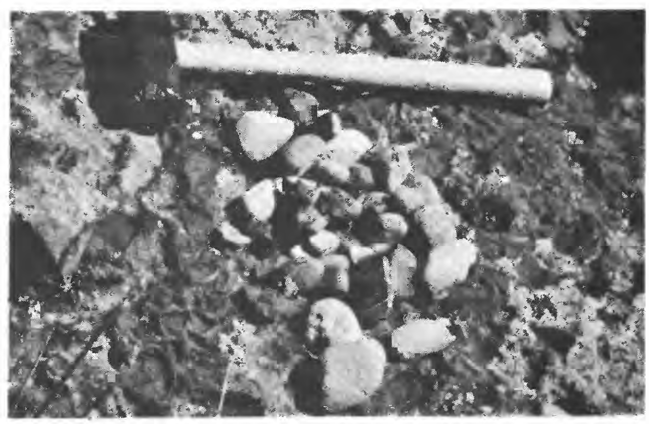

Figure 12. Exotic cobbles recovered from fluvial unit 3 at location of profile 3 (plate 1). Hammer shown for scale.

Element 2 contains small-scale planar crossbedded sandstone, laminated sandstone, and minor isolated trough crossbedded sandstone. Field observations indicate that, although element 2 of profiles 2 and 3 is similar, the paleocurrent dispersion is greater in profile 3 than in profile 2.

Element 3 caps the profile from 35 to 70 m. This thin element contains a single set of wedge-planar crossbedded sandstone that has a dip azimuth of N. 45° E., radically different from dips of element 2. A coset of planar crossbedded sandstone laps onto this single set of cross-strata from the right. This element represents bedforms migrating in two distinct directions, perhaps under the influence of macroforms in the channel system; however, no direct evidence of macroforms was observed in this profile.

Depositional Model for Fluvial Unit 3

In fluvial unit 3, erosional surfaces are lined with exotic chert pebbles and cobbles, lithic fragments derived from the fluvial unit 1 equivalent unit into which fluvial unit 3 is incised, and petrified organic debris. Laminated sandstone is interbedded with tabular and wedge-planar crossbedded sandstone (Sp). High-energy stream flow is indicated by tangential foresets developed in medium- to granule-grained sandstone.

Profiles 2 and 3 represent a depositional system having distinct levels. Element 4 of profile 2 and element 3 of profile 3 indicate the presence of minor channels incised at high angles to the main channel(s) of this system. Extreme variability in stream power and discharge suggests ephemeral flow. The depositional system lacked distinct macroforms, probably due to its limited size. Allen (1983) indicated that more complex macroforms do not develop in smaller streams. This may be the case with profiles 2 and 3.

Description of Fluvial Unit 4 in Profiles 4 and 5

In the study area, fluvial unit 4 is a tabular sandstone body that has a lateral extent of 0.25–0.5 mi (0.4–0.8 km) (Gott and others, 1974). Profile 4, oriented parallel with the axis of fluvial unit 4, depicts an outcrop of fluvial unit 4 eroded into the fluvial unit 3 outcrop depicted in profile 2 (fig. 11). Profile 5, oriented perpendicular to the axis of fluvial unit 4, is based on outcrops in the SE¼ SW¼ sec. 4, T. 7 S., R. 2 E., Fall River County, South Dakota. (fig. 13).

Profile 4

Four elements compose fluvial unit 4 at this location. The contacts between these elements are remarkably planar. Element 1 is a medium-grained to very coarse grained sandstone dominated by large-scale planar crossbeds. Set boundaries have notable relief and represent accretion of a macroform (fig. 14). Relief on the macroform is first evident in downcurrent thickening of set 1 at the expense of a subjacent coset of small-scale planar crossbedded sandstone. The termination of two superjacent sets against set 1 increases the macroform's relief. Set 2 thickens downstream where the sandwave it represents passed over the bar crest. The coset above set 2 also terminates in offlapping fashion. Above this is a coset that shows both downcurrent-ascending (onlap) and -descending set boundaries. Aggradation rates were apparently great during the life of this macroform because accretion occurred on the stoss side and the top of the macroform, as well as on the lee side. Element 1 contains both ascending and descending components of the foreset macroform element (FM) (Friend, 1983).

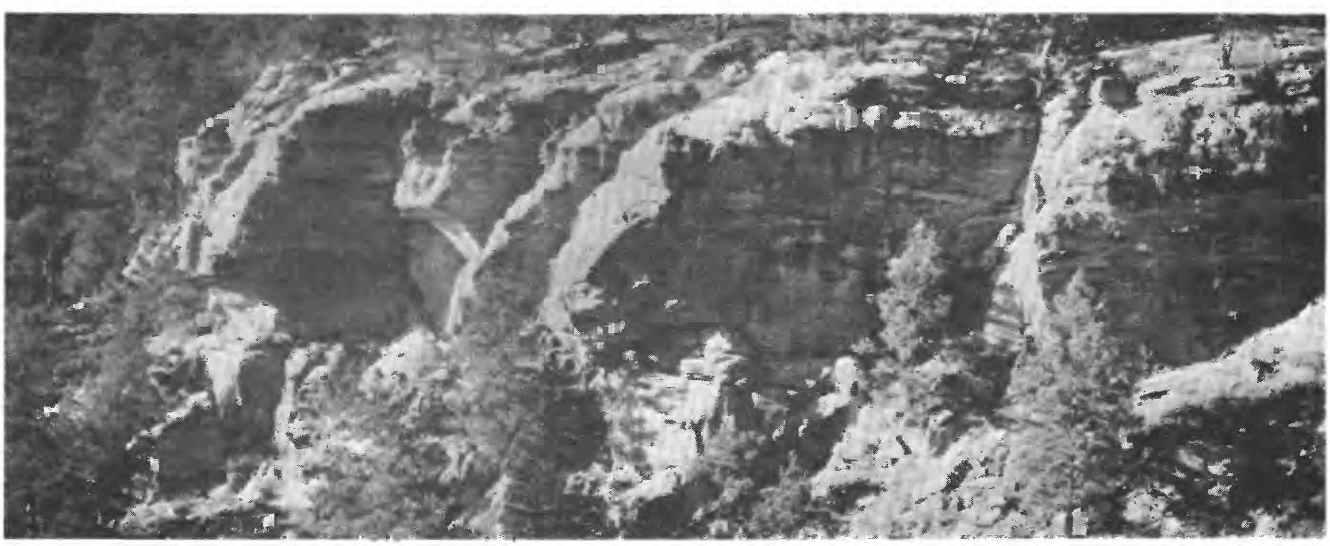

Figure 13. Fluvial unit 4 at the location of profile 5 (plate 1).

Figure 14. Oblique, upcurrent view of element 1 of profile 4 (plate 1) showing downcurrent descent of set boundaries within this foreset macroform.

No falling water level modifications were noted in element 1, yet two remarkably extensive fine-grained partings were deposited. Although flow was sluggish at times, the crest of this bar was never exposed. Haszeldine (1983) reported that the shape of a macroform's crest exerts more control on the direction of migration of bedforms in its lee than does the orientation of adjacent channel axes. The low dispersion of paleocurrent data from planar crossbed sets within this element suggests that the macroform responsible for this element must have been relatively straight crested.

A fine-grained parting in set 2 at 37 m parallels its enclosing foresets. Subsequent erosion apparently removed the topset and bottomset of this fine-grained parting, but this example is evidence that quiet-water conditions were achieved without causing modification of the sandwave represented by set 2.

Element 2 (fig. 15) is eroded into element 1. The contact reflects relief on the element 1 macroform, but this relief is subdued upsection. Fine partings and sets of small-scale planar crossbedded sandstone compose element 2 (fig. 16). These interbedded lithofacies indicate a cyclicity of low-energy and relatively high energy events. In addition, two massive, lenticular bodies are incised within element 2.

Figure 15. Closeup of bar-top deposits (element 2 of profile 4, plate 1). The vertical sequence represents waning flood, slack water and subsequent rising water. Hammer shown for scale.

Figure 16. Two small-scale foreset macroforms in element 3 of profile 4 (plate 1). Migration of the bars was toward the left.

Element 2 represents a lower energy part of the fluvial unit 4 fluvial system than does element 1. Vertical succession from a rapidly aggrading foreset macroform to lower energy deposits suggests a genetic relationship. Apparently, the reduced energy conditions represented by element 2 are a direct consequence of the aggradation achieved by element 1. During deposition of element 2 the bar was only part of an active channel at high-water stages. Sets of planar crossbedded sandstone were deposited at flood stage as sandwaves were driven over the bar top. During subsequent slack water periods, finer grained material was deposited from suspension. Lowering of water levels caused emergence of the bar top and incision of minor channels into the planar crossbedded sandstone and fine-grained parting composite sets. Infilling of these minor channels during subsequent rising water produced the element CH. In this case, the channel deposit is an integral part of a larger element. The element designation BD, for bar-top deposits, is suggested for the sequence of lithofacies in element 2. Allen (1983) described a similar sequence, dominated by fine-grained material, as tabular mudstone units.

Element 3 is composed of small-scale planar crossbedded sandstone that has downcurrent-descending set boundaries. This element represents the descending component of a much smaller macroform than that of element 1. Figure 17, from the left side of element 3, depicts a structure that may be evidence that this bar was a periodic form. The bar to the right ascended the stoss side of the bar to the left.

Figure 17. Channel element incised into the top of a foreset macroform element within element 3 of profile 4 (plate 1). Location of scour surface is shown by arrows.

Deposition of element 3 upon element 2 represents reestablishment of an active channel in this position. Lack of relief on the sharp contact between these elements indicates that this event was probably due to gradual aggradation and consequent displacement of a deep channel from a part of the system lateral to the position of the profile (in a manner similar to the element 1–2 sequence) rather than to abrupt switching and incision of an active channel.

From 27 to 55 m a channel element of larger scale than those of element 2 (3.5 ft (1.1 m) thick, 90 ft (27.4 m) minimum lateral extent) is incised into element 3 (fig. 17). Given that this channel element caps a foreset macroform element and is vertically succeeded by an element revealing a channel lacking in macroforms (and presumably smaller in scale), this channel element probably represents exposure of the element 3 bar top after aggradation again caused lateral displacement of an active (deep) channel. Element 3 is capped by a fine-grained parting that extends the entire length of the profile.

Element 4 is also composed of small-scale to minor large-scale sets of planar crossbedded sandstone. Unlike elements 1 or 3, set boundaries in this element are virtually horizontal. Unlike element 2, fine-grained partings are rare. Element 4 has no channel elements. This sandy bedform element (SB) is inferred to represent migration of sandwaves in a channel that has no macroforms. If this is the case, element 4 represents a channel diminished in size relative to elements 1 and 3. Whether or not a deeper channel coexisted elsewhere cannot be determined; however, because this element caps fluvial unit 4, it may represent the waning of this fluvial system.

Profile 5

Profile 5 was chosen to complement profile 4 by offering a section at about right angles to it. Profile 5 can be divided into eight elements. The base of element 1 is composed of a 3.0-foot (0.9 m)-thick set of poorly sorted, gravelly, laminated sandstone overlain by a coset of nested trough crossbedded, medium-grained to very coarse grained sandstone approximately 10 ft (3.0 m) thick. Migration of trains of three-dimensional dunes in a relatively deep channel is recorded by this sandy bedform element.

In erosional contact with element 1 is another element that lacks evidence of larger macroforms. Element 2 is composed of cosets of small- to large-scale planar crossbedded sandstone. Although paleocurrent dispersion of as much as 45° is recorded in this element, the set and coset boundaries show no relief trends and display only minor erosion. A laterally extensive surface dissects element 2. To the right, this surface is capped with a laminated fine-grained parting. To the left, it is erosional, encrusted with hematite, and exhibits desiccation cracks. Despite apparent subaerial exposure, this surface has little relief. Element 2 contains other less extensive erosional surfaces. Migration of small bars at various low angles to the channel axis in a relatively shallow channel that had variable discharge is suggested by element 2. Together, elements 1 and 2 probably represent a single aggrading channel system.

Element 3 shows evidence of macroforms. Set 1 forms the nucleus for deposition of element 3. The boundaries of sets 2 and 3 descend on either side of this nucleus and truncate against the base of element 3. On the left flank of this element, sets 4 and 5 also descend away from the nucleus. A bar apparently formed that grew sideways in both directions. The element name bilateral accretion (Bi-LA) is proposed for this type of deposit.

Development of the right flank of element 3 is incomplete due to onlap of sets of planar crossbedded sandstone representing leftward-migrating sandwaves. Relief on the upper boundary of set 6 and offlap of sets above suggest the presence of another laterally accreting bar. This coset of strata (element 4) is interpreted as a separate and distinct lateral accretion element. The fluvial system apparently contained multiple contemporaneous macroforms.

Element 5 (fig. 18) truncates elements 3 and 4. Its base descends 7.5 ft (2.3 m) to the left. A second erosional scour, included within this element, descends to the same level. Fill within these channel elements is dominated by laminated sandstone and includes planar and trough crossbedded sandstone. Aggradation due to bar development of element 4 may have displaced an active channel toward the left and caused the scouring represented by element 5. The second channel element is interesting because, although infilling of the earlier channel represents considerable aggradation, erosion back to the same level occurred (fig. 19). Aggradation rates in this part of the fluvial unit 4 system were apparently not as great as in the part represented by profile 4.

Element 6 has a base that is gently concave upward. Within element 6, the first two laterally extensive sets of planar crossbedded sandstone (7 and 8) lap onto this surface toward the right (fig. 20). Sets 9 and 10 form an offlapping lateral accretion sequence that, in turn, is lapped onto from the right by sets 11 and 12. In the same way that element 4 is related to element 3, sets 11 and 12 may be related to another macroform located to the right of the profile; however, insufficient evidence for such a macroform exists in this profile. Sets 13 and 14 represent continued lateral accretion of the macroform into deeper water to the right.

A silty to very fine grained sandstone parting separates elements 6 and 7. Element 7 contains an interbedded sequence of fine-grained partings and sets of tabular planar crossbedded sandstone of smaller scale than element 6. Element 7 represents lower energy deposition atop a bar macroform that has displaced the active channel (element 6).

Element 8 represents a final scour and fill event. The base of the fill consists of concordant laminated sandstone. The rest of the fill consists of planar crossbedded sandstone.

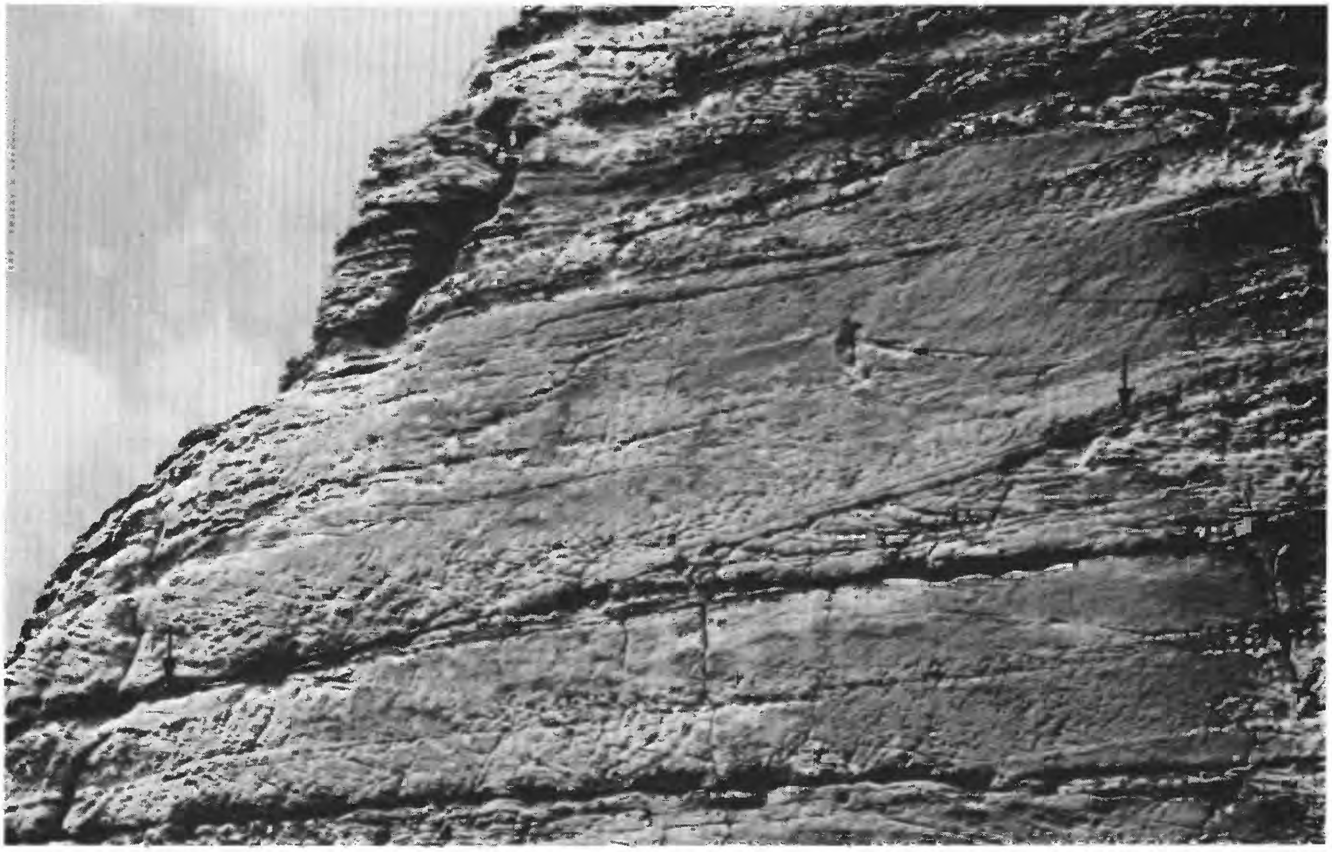

Figure 18. Channel scour and fill within element 5 of profile 5 (plate 1). Location of scour surface is indicated by arrows.

Descent of this channel element below the contact between elements 6 and 7 suggests that the fluvial system had multiple levels.

Depositional Model for Fluvial Unit 4

Figure 20 shows a hypothetical distribution of the macroforms, erosional processes, and depositional processes inferred for fluvial unit 4. Any given cross section through the fluvial unit 4 system probably would show numerous contemporaneous examples of each macroform. No implications as to channel widths are intended by this figure.

Macroform 1 is a semiemergent bar such as formed element 2 of profile 4 and element 7 of profile 5. Sets of planar crossbeds were deposited by sandwaves driven over the bar at high-water stage. Deposition from suspension during slack water formed fine-grained partings. Emergence of the bar top caused scouring. Infill of the scour resulted in a minor channel element within the larger bar-top deposit element.

The second feature is a large-scale erosional scour caused by diversion of flow around a bar macroform. Infill of the scour resulted in a channel element of higher order than that in cross section *A–A'* (for example, element 5 of profile 5).

Macroform 3 is a totally submerged bar over which sandwaves migrate. Two types of elements were formed by this process, depending on the orientation of the exposure. In transverse section *C–C'*, a bilateral accretion element formed (for example, element 3 of profile 5). In longitudinal section *D–D'*, a foreset macroform formed (for example, elements 1 and 3 of profile 4). In this way, a single set of cross-strata can be part of two elements because the three-dimensional geometry of the set indicates both lateral and downstream (forward) growth of a macroform. Incomplete exposures of a bilateral accretion element or lateral accretion of midchannel bar resulted in lateral accretion elements (for example, elements 4 and 6 of profile 5)

The fourth feature of the system is a deep, restricted part of the channel dominated by trains of dunes. Section *E–E'* shows sets of nested trough crossbeds in the sandy bedform element formed by migration of these dunes (for example, element 1 of profile 5). Deposition due to migration of periodic sandwaves in shallow parts of the channel lacking macroforms resulted in sandy bedform elements (for example, element 4 of profile 4 and element 2 of profile 5).

Figure 19. Onlap onto a concave-up erosional surface due to lateral accretion of a bar macroform. Location of concave-up erosional surface is indicated by arrows.

CONCLUSIONS

Architectural element analysis is an effective method for determining the depositional processes represented in fluvial sandstones and yields more definitive results than do vertical profiles. The process is most effective, however, when used on well-preserved outcrops, and it is not easily applied to the subsurface.

The Lower Cretaceous Lakota Formation in the southern Black Hills of South Dakota is anomalously thick and includes four major erosional events, each followed by a fluvial depositional phase, represented by fluvial units 1–4. Commencement of Lakota deposition is correlated with a rise in sea level recorded in Canada as marine strata of the Clearwater transgression. This rise in sea level and an accompanying change in climate resulted in rising base level and the stabilizing influence of vegetation in interfluvial areas. In the southern Black Hills area carbonaceous shale of the Chilson Member was deposited.

Displacement of major drainages around topographic highs created by dune fields of the Unkpapa Sandstone Member of the Morrison Formation was responsible for location of the fluvial unit 1 channel system. Deposits of this system represent high-sinuosity channels laterally accreting within a wide valley of low gradient. Rates of aggradation were sufficient to prevent beheading of these active channel-fill deposits.

Spatial relations between fluvial unit 1 and fluvial unit 2 (both in the Chilson Member) may represent the diversion of a river system around older deposits. The erosional event separating these units may be the result of local aggradation within a given reach of the system leading to excessive relief at the downstream end of that reach. Eventually, valley gradients at the toe exceeded limits for stability and incision began. As the resulting wave of erosion passed upstream, increased sediment influx again led to local deposition.

Tectonic impoundment is inferred to have caused the internal drainage and deposition of the Minnewaste Limestone and parts of the Fuson Members. Displacement along high-angle faults is believed to have influenced sedimentation throughout the Western Interior basin during the Early Cretaceous (Stelck, 1975; Slack, 1981; Weimer and others, 1982; Weimer, 1983). Differential vertical movement may also have resulted from isostatic readjustment to loading (deposition) and unloading (erosion).

In general, fluvial sandstones of the Fuson Member (fluvial units 3, 4) are much coarser than those of the Chilson Member (fluvial units 1, 2), probably because of distal

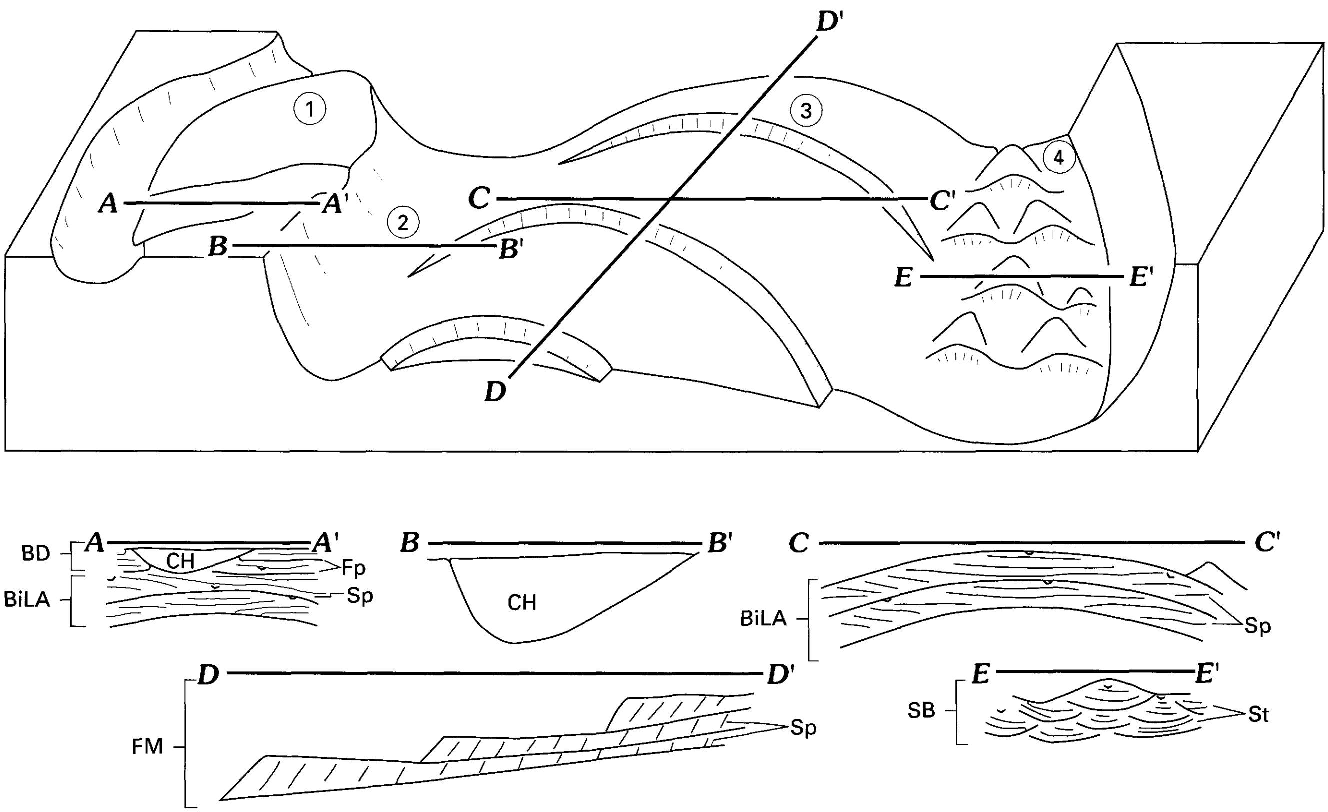

Figure 20. Block diagram and cross sections showing depositional model for fluvial unit 4. Macroforms shown on block diagram: 1, semiemergent bar; 2, erosional scour adjacent to large bar; 3, totally submerged, forward and laterally accreting bar; 4, deep channel. Lithofacies and elements shown in cross sections: BD, bar-top deposit; Bi-LA, bilateral accretion deposit; CH, channelized element; Fp, fine-grained parting; Sp, planar crossbedded sandstone; St, trough crossbedded sandstone; FM, foreset macroform; SB, sandy bedform deposits.

source area uplift. Incision prior to deposition of fluvial unit 3 was the most significant Lakota erosional event. Profiles 2 and 3 represent a minor high-energy, ephemeral tributary within the fluvial unit 3 system.

Valley gradients were also high during deposition of fluvial unit 4. On the basis of exposures in the Edgemont NE quadrangle in which fluvial unit 4 truncates the thickest section of the Fuson massive sandstone unit, the configuration of the local topography is assumed to have remained unchanged. Fluvial unit 4 represents a low-sinuosity system that had multiple, mobile channels. A paucity of fine-grained material within the valley fill and the resulting lack of cohesiveness favored this channel behavior. Aggradation rates were high, and multistoried sandstone bodies formed.

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