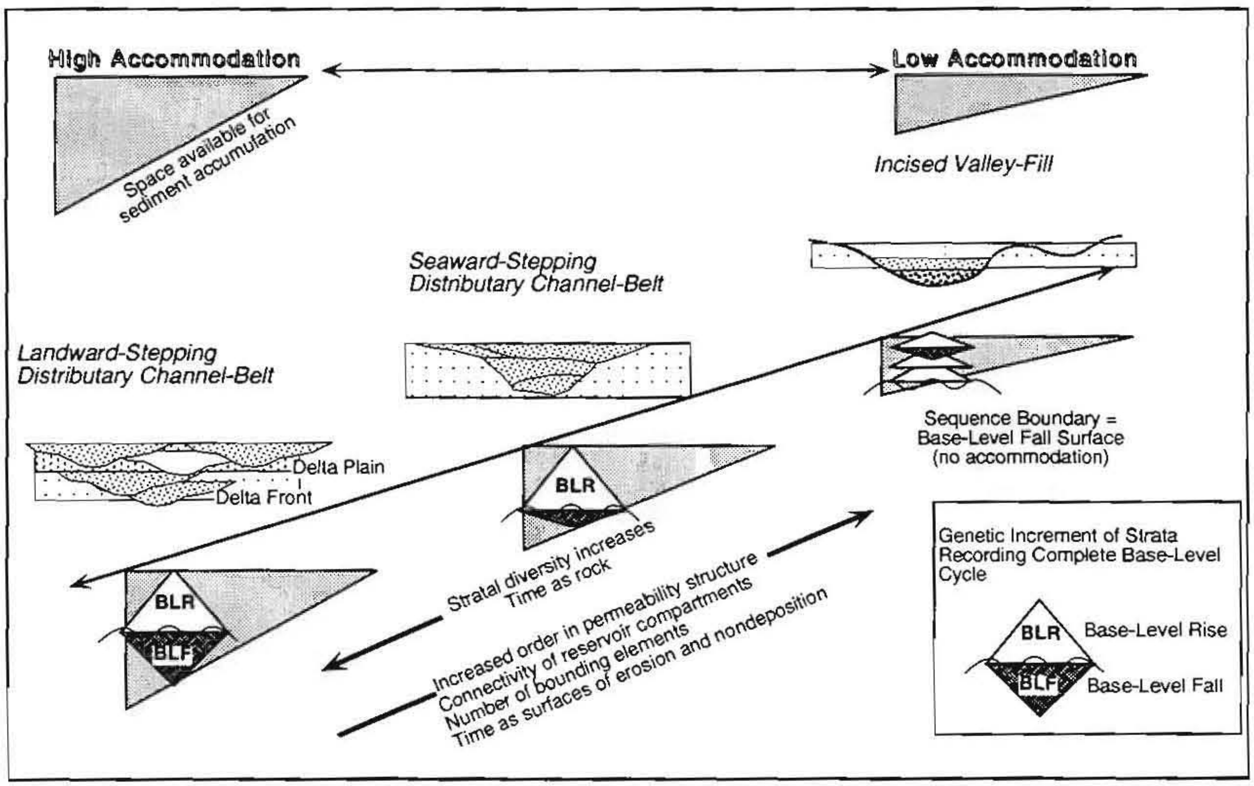
# Bureau of Economic Geology
# Deltas Industrial Associates
# Field Trip

# Outcrop Characterization of Low-Accommodation Fluvial-Deltaic Reservoir Analogs: Field Guide to Selected Outcrops of the Lower Cretaceous Fall River Formation, Black Hills of South Dakota and Wyoming





by

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## Rationale

Hydrocarbon recovery efficiency is controlled by reservoir heterogeneities resulting from geometric arrangements of strata, or "stratal architecture." Maximizing recovery requires an increased understanding of geologic processes that govern stratal architecture. Reservoir characterization studies integrate geologic descriptions of reservoir architecture with reservoir engineering to more effectively recover hydrocarbons. Fluvial-deltaic strata form the most heterogeneous class of siliciclastic reservoirs, with an average recovery efficiency ranging from 24 to 69% and averaging 40% (Galloway and others, 1988). Accordingly, it is of particular interest to determine controls on stratal architecture in fluvial-deltaic reservoirs.

Traditional reservoir characterization relates depositional systems to variations in stratal architecture (Fisher and others, 1969). Depositional systems are a three-dimensional linkage of contemporaneous facies assemblages that are governed by a common suite of depositional processes (Brown and Fisher, 1977) This approach has provided important insights, but fails to view heterogeneities within a stratigraphic context.

High-resolution sequence stratigraphy provides a chronostratigraphic framework for evaluating depositional controls on stratal architecture. The BEG has initiated a research program examining outcrop analogs to specific classes of subsurface reservoirs using a chronostratigraphic framework to document architectural styles and heterogeneity distributions in fluvial-deltaic reservoirs. An ongoing BEG study of the Upper Cretaceous Ferron Sandstone of central Utah demonstrates this basic approach. These outcrop analogs to high accommodation Gulf Coast fluvial-deltaic reservoirs show that stratal geometries, facies arrangements, and rock properties vary with stratigraphic position (Gardner et. al., 1992; Barton and Gardner, 1992; Barton and others, 1993, Gardner, 1993). Variations in stratal architecture and heterogeneity distributions are related to changing preservational conditions of depositional systems. *Hence, reservoir descriptions must be calibrated to preservational conditions of depositional systems.*

Sequence stratigraphy provides a conceptual framework for understanding how depositional units are modified by changing preservational conditions. Key stratigraphic surfaces and/or correlative strata define a hierarchy of chronostratigraphic units of different periodicities.

Our studies of the Ferron Sandstone show that sandstone bodies containing distinct facies associations, termed depositional elements, are the most important reservoir unit affecting fluid flow (flow units). Such depositional elements exhibit a characteristic permeability structure, facies association, and stratal geometry. These attributes vary systematically as a function of the elements stratigraphic position.

The Ferron Sandstone was deposited in conditions of high accommodation and sediment supply, reflecting high subsidence rates along an tectonically active foreland basin. Major unconformities are absent and depositional elements are fully preserved. These preservational conditions emphasize depositional controls on stratal architecture. Preservational conditions will have a greater control on reservoir heterogeneity in strata deposited in a low accommodation setting. Our current research addresses the role of depositional and preservational processes on the stratal architecture of fluvial-deltaic strata deposited in a low accommodation setting (i.e., an opposite "end member" of the Ferron Sandstone).

The Lower Cretaceous Fall River Formation was chosen as an analog to low accommodation fluvial-deltaic reservoirs because: (1) previous work indicated a fluvial-deltaic depositional system (Waage, 1959; Donanville, 1963; Boylard and McGregor, 1966; Gott and others, 1974; Ryer and Gustason, 1985a,b; Rasmussen and others, 1985; Bovee, 1989; and Haerter, 1990); (2) it was deposited along the low subsidence cratonic margin of the Western Interior Cretaceous Seaway; and (3) good exposures in the Black Hills can be directly related to nearby production in the adjacent Powder River basin, thereby testing the portability of outcrop data to subsurface reservoirs (see companion reservoir characterization study of Buck Draw Field).

This field trip examines outcrops of the Fall River Formation and presents preliminary results from our 1994 work. The Fall River Formation comprises an intermediate-term stratigraphic sequence consisting of six short-term stratigraphic cycles. The lower five short-term cycles are unconformity-bounded. Each short-term stratigraphic cycle contains thin tidal- to storm-dominated shallow-marine deposits locally incised by valley-fill deposits changing upward from low-sinuosity fluvial to estuarine. Valley-fill sandstones form significant reservoirs contributing to the 300 MMBOE produced from the Fall River Formation across Wyoming to date (Dolson and Muller, 1994). Detailed outcrop study of valley fill strata shows unconformities controlling permeability distributions, segregating the reservoir, and juxtaposing low and high permeability strata. This is particularly prevalent in stacked, or nested valley fills which are truncated by multiple, irregular and high-relief unconformities. Hence, in low accommodation fluvial-deltaic strata the most important stratal element affecting fluid flow may be unconformity bounded short-term stratigraphic cycles (Fig. 1). This contrasts with the Ferron Sandstone of Utah, where the most important stratal element were smaller-scale depositional elements comprising individual short-term stratigraphic cycles.

Geologic descriptions derived from this outcrop study constrain a reservoir model for Buck Draw Field. The objective is to characterize changes in stratal architecture producing interwell heterogeneities, to understand and predict the geometry of reservoir compartments, and to provide the means for calibrating and integrating outcrop data in reservoir descriptions. This approach involves six steps: (1) erect chronostratigraphic framework; (2) map reservoir sandstone bodies and bounding surfaces within chronostratigraphic units; (3) define flow units based on stratigraphic, sedimentological, petrologic and petrophysical attributes; (4) conduct geologically optimized petrophysical sampling linking permeability structure to a sedimentological hierarchy in chronostratigraphic units; (5) develop a geologically constrained reservoir model; and, (6) model spatial distributions of flow units and heterogeneities using geostatistical methods.

## Introduction

Field stops discussed in this guide are arranged from northwest to southeast across the Black Hills of Wyoming and South Dakota. This arrangement corresponds to a progression from generally more seaward to more landward paleoenvironments in the Lower Cretaceous Fall River Fm. Location of field stops (Fig. 2), a chart of lithostratigraphic nomenclature (Fig. 3), and sequence stratigraphic and biostratigraphic relations of Early Cretaceous strata in the Black Hills (Fig. 4) are shown.

Our studies of the Fall River Fm. suggest deposition within a storm- and tidally-dominated deltaic depositional system. Shallow-marine deposits are incised by regional erosional surfaces locally flooring fluvial to estuarine facies successions confined to paleovalleys (30 m maximum incision). Shallow-marine strata in successive short-term stratigraphic cycles change upward from tidal-fluvial-dominated to storm-dominated facies successions recording increased sandstone and decreased total sediment volume. Similarly, valley-fill deposits change upward from low-sinuosity fluvial to estuarine. Our interpretations differ from previous investigators, who suggested a fluvial-deltaic depositional system. Campbell and

# ARCHITECTURAL STYLES IN *LOW* ACCOMMODATION SILICICLASTIC DEPOSITIONAL SYSTEMS

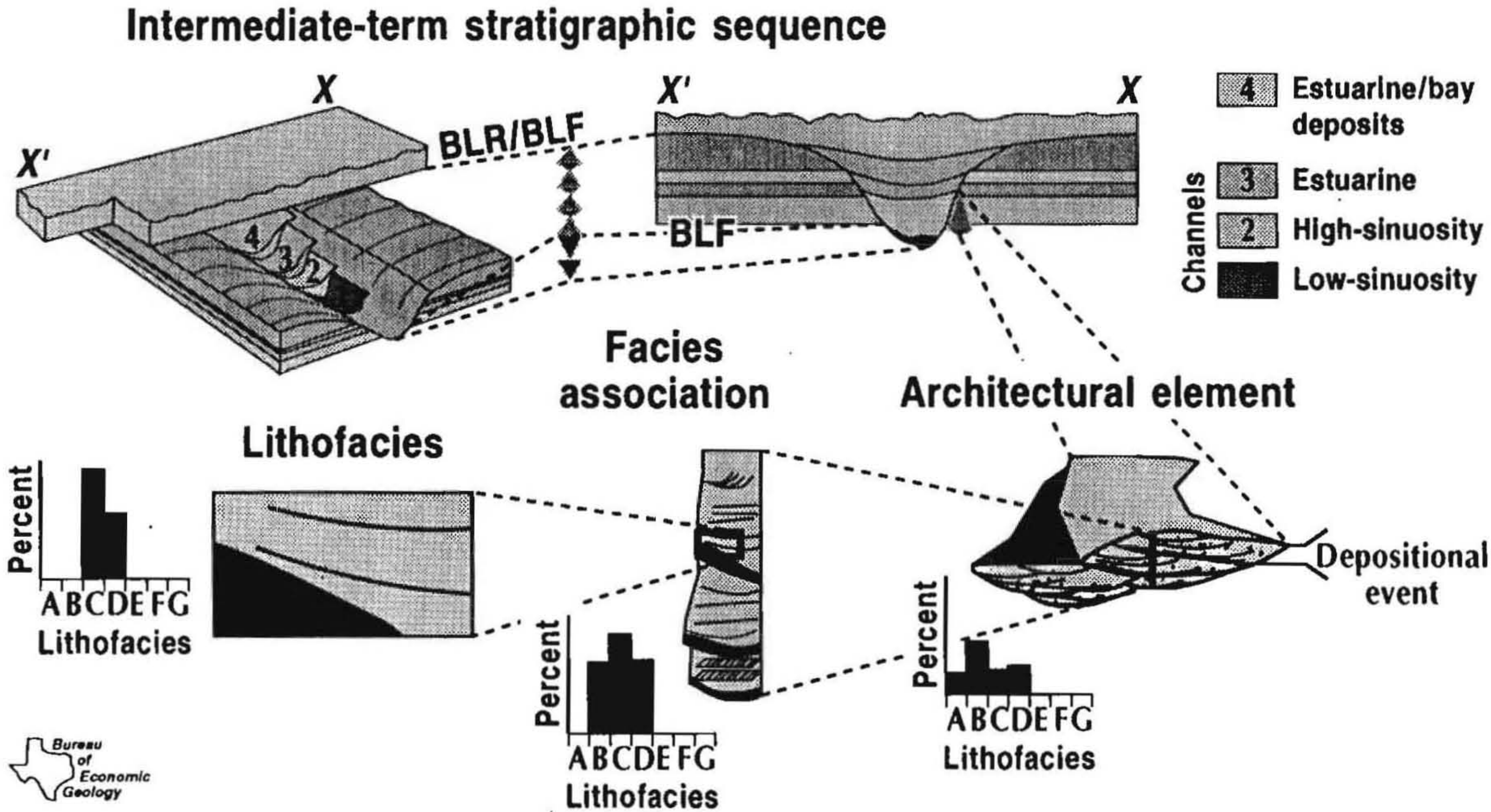



Figure 01–

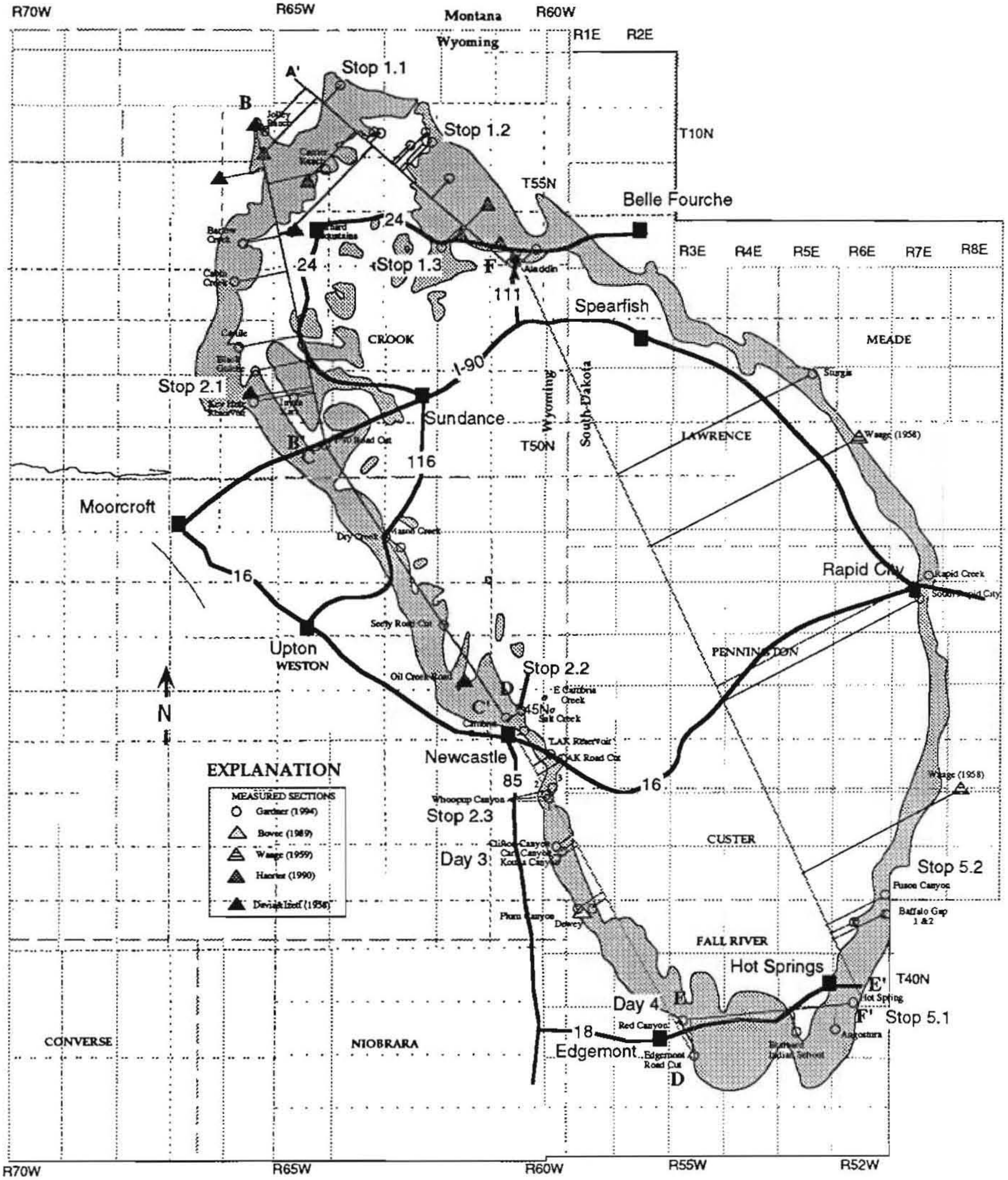



Figure 2—Location map showing line of sections and field trip stops

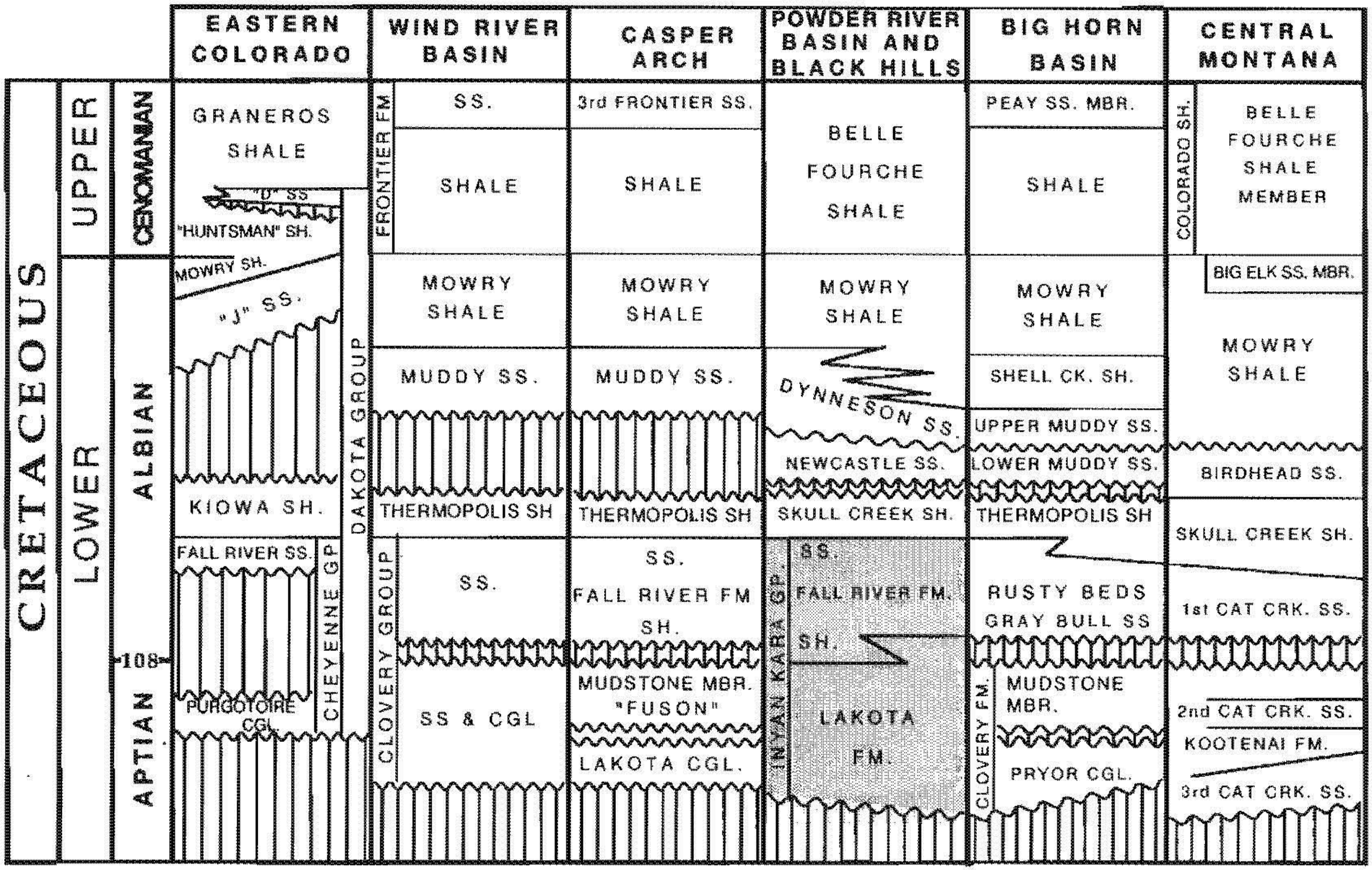



**Figure 3**—Lithostratigraphic nomenclature for Aptian, Albian and Cenomanian strata from the northern Western Interior Cretaceous Seaway.

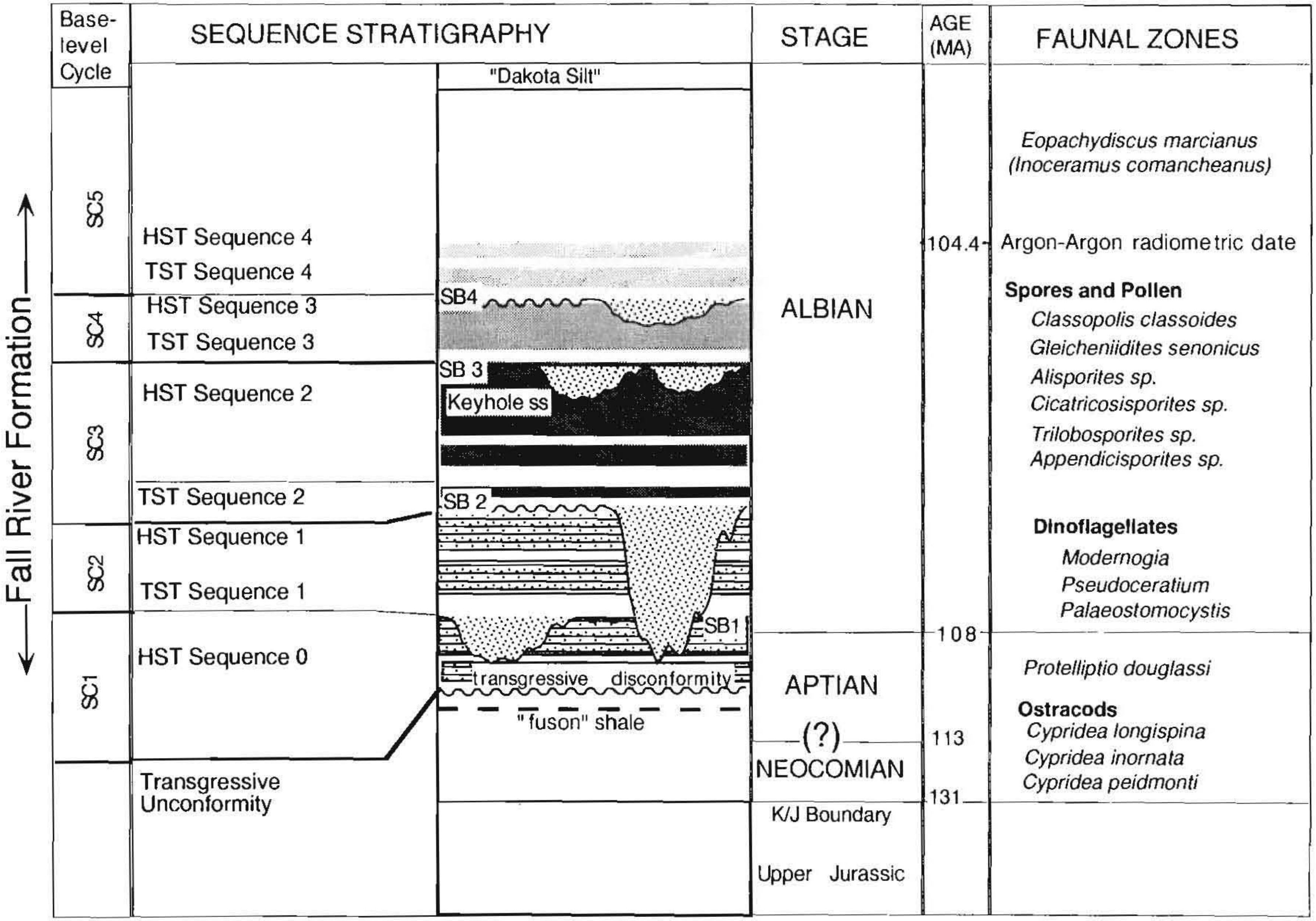



**Figure 4**—Lithostratigraphic Chart showing nomenclature for Early Cretaceous strata of the Black Hills region

Oaks (1973), however, recognized tidal flat and estuarine channel facies here.

Across the Black Hills (7,500 $mi^2$), the Fall River Fm. consists of two spatially distinct deltaic depocenters separated by a broad interdeltaic region. A northwest to southeast decrease in the proportion of marine mudstone, and increase in both the thickness of short-term cycles and the proportion of nonmarine facies, and a change from unnested to nested valley fills reflect a southeastward progression to more landward paleoenvironments. Six short-term stratigraphic cycles are recognized across this region, although they are not resolved at every locality (Fig. 5). We will focus on comparison of sedimentologic and stratigraphic attributes of shallow-marine and valley-fill deposits comprising the lower four unconformity-bounded short-term stratigraphic cycles (Figs. 6 and 7). In the northern Black Hills, unconformity-bounded short-term cycles consist of discrete unnested valley fills capped by a thin succession of marine mudstones; whereas coeval valley-fill deposits in the southern Black Hills are amalgamated and nested (Fig. 8).

Over the course of the field trip we will examine stratigraphic changes in the stratal architecture and facies of short-term stratigraphic cycles correlated across a broad spectrum of shelf, shallow-marine, coastal-plain, alluvial-plain and valley-fill deposits. Changes in facies architecture within strata recording short-term base-level cycles are emphasized. Recognition of base-level cycles helps define genetic increments of strata recording similar depositional and preservational conditions. Sedimentological and petrophysical attributes of reservoir and nonreservoir strata are linked in this chronostratigraphic framework to isolate statistically distinct changes in reservoir architecture. This addresses deposit nonstationarity, or the nonconstant spatial variance of rock properties, lithofacies, and facies associations.

## Physiographic Setting

The Fall River Formation is exposed along hogbacks rimming the Black Hills uplift in Wyoming and South Dakota. The Black Hills form the northeastern margin of the Powder River Basin. The Black Hills are a north-northwest trending uplift about 125-mile long and 60-mile wide. Precambrian igneous and metamorphic rocks are exposed in the central core. The uplift consists of two main structural features, the north-trending Fanny Peak monocline that cuts the northwest-trending Black Hills monocline. Along the western margin of the central Black Hills, at the intersection of these monoclines strata dip from 65 to 80° (Weimer and others, 1982). The

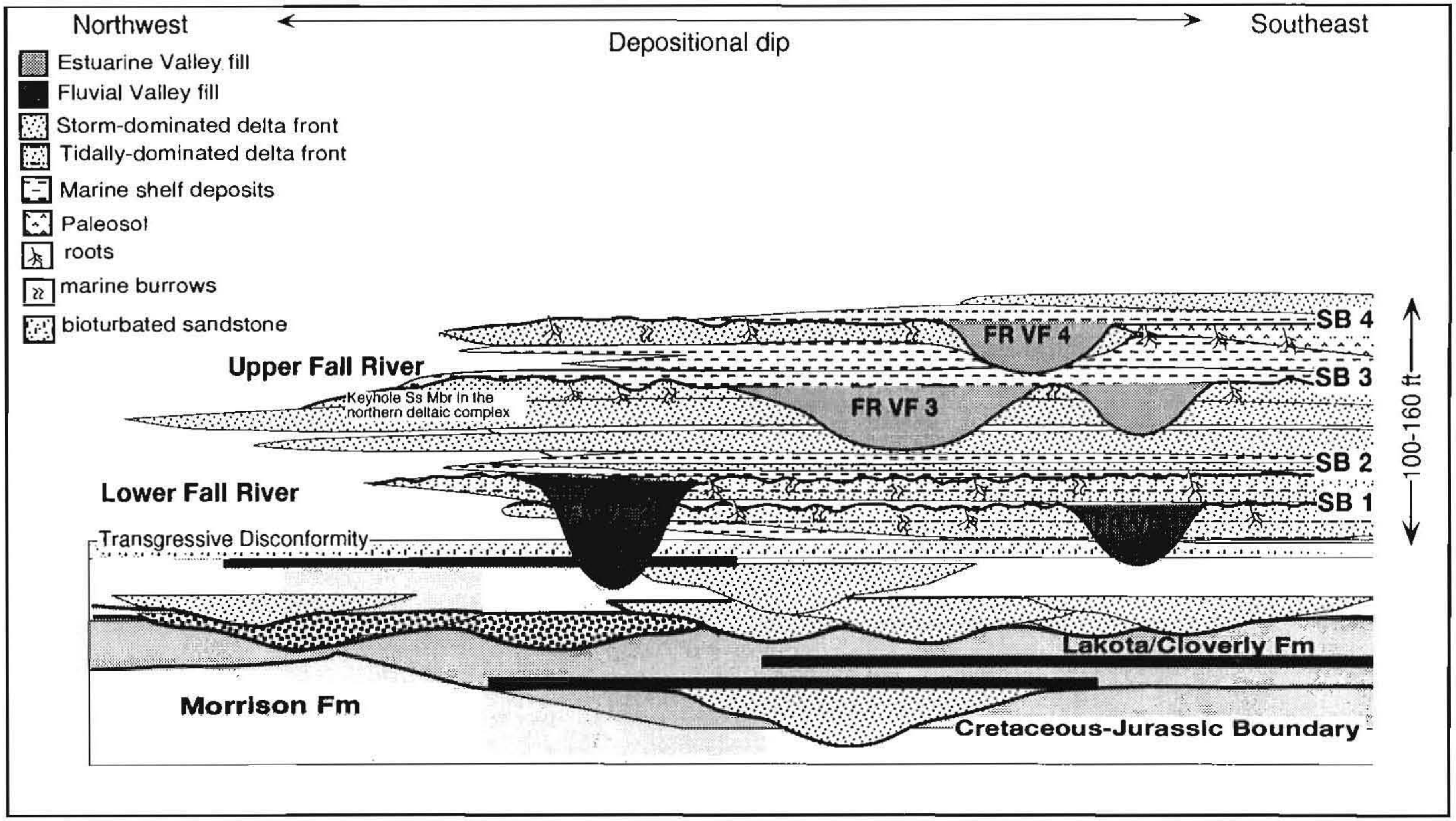



**Figure 5**—Schematic stratigraphic cross section across the Black Hills showing the arrangement of shallow-marine and valley-fill facies tracts in short-term strtigraphic cycles that comprise unconformity-bounded depositional sequences in the Fall River Formation. In the Black Hills region, these sequences are correlated across two deltaic complexes that are separated by a paleohigh, the Belle Fourche Arch. The northern deltaic complex contains the Keyhole Sandstone Member.

## Paleogeographic Maps of Seaward-Stepping Short-Term Cycles, Fall River Formation, Black Hills

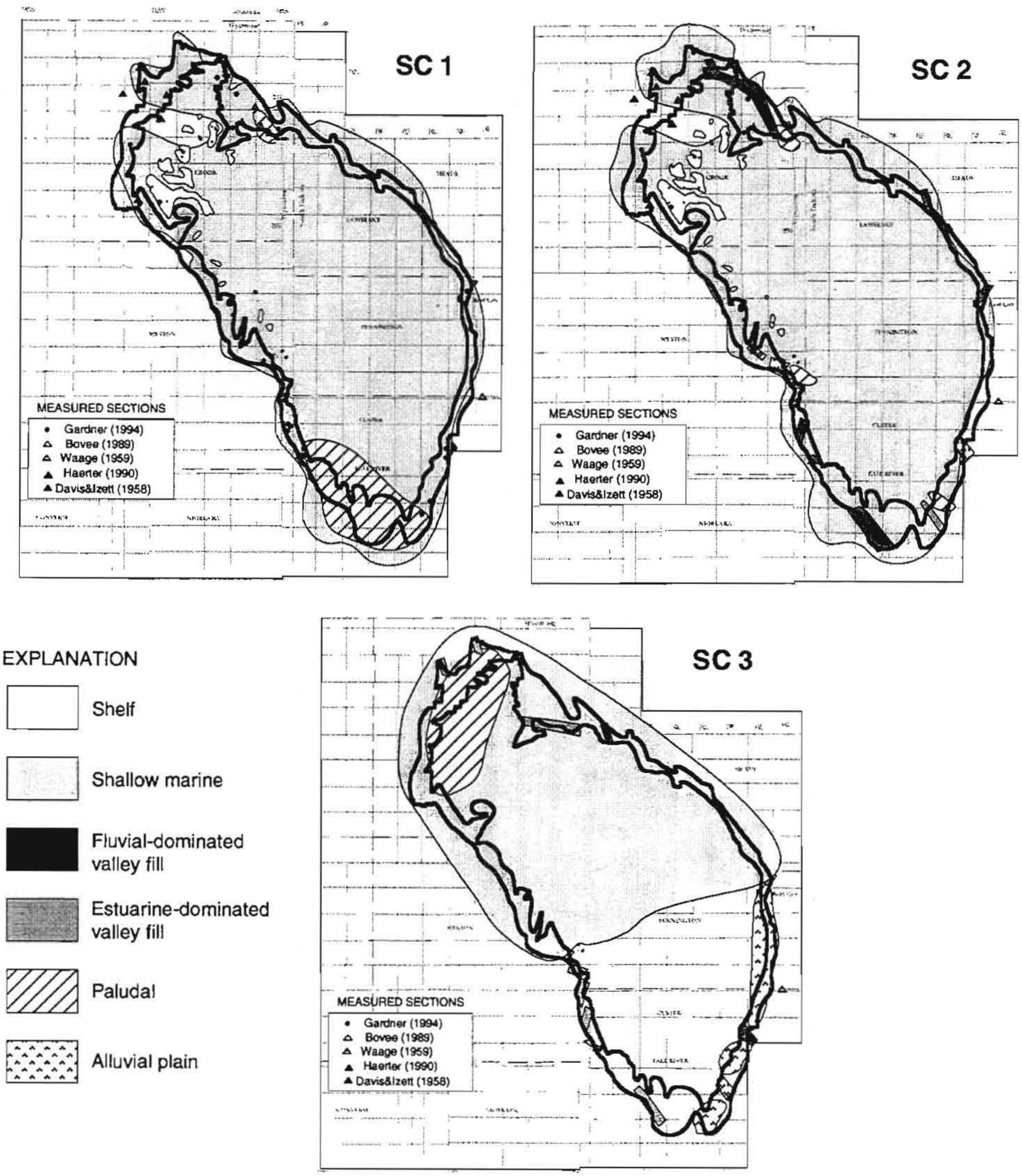



Figure 6

# Paleogeographic Maps of Landward-Stepping Short-Term Cycles, Fall River Formation, Black Hills

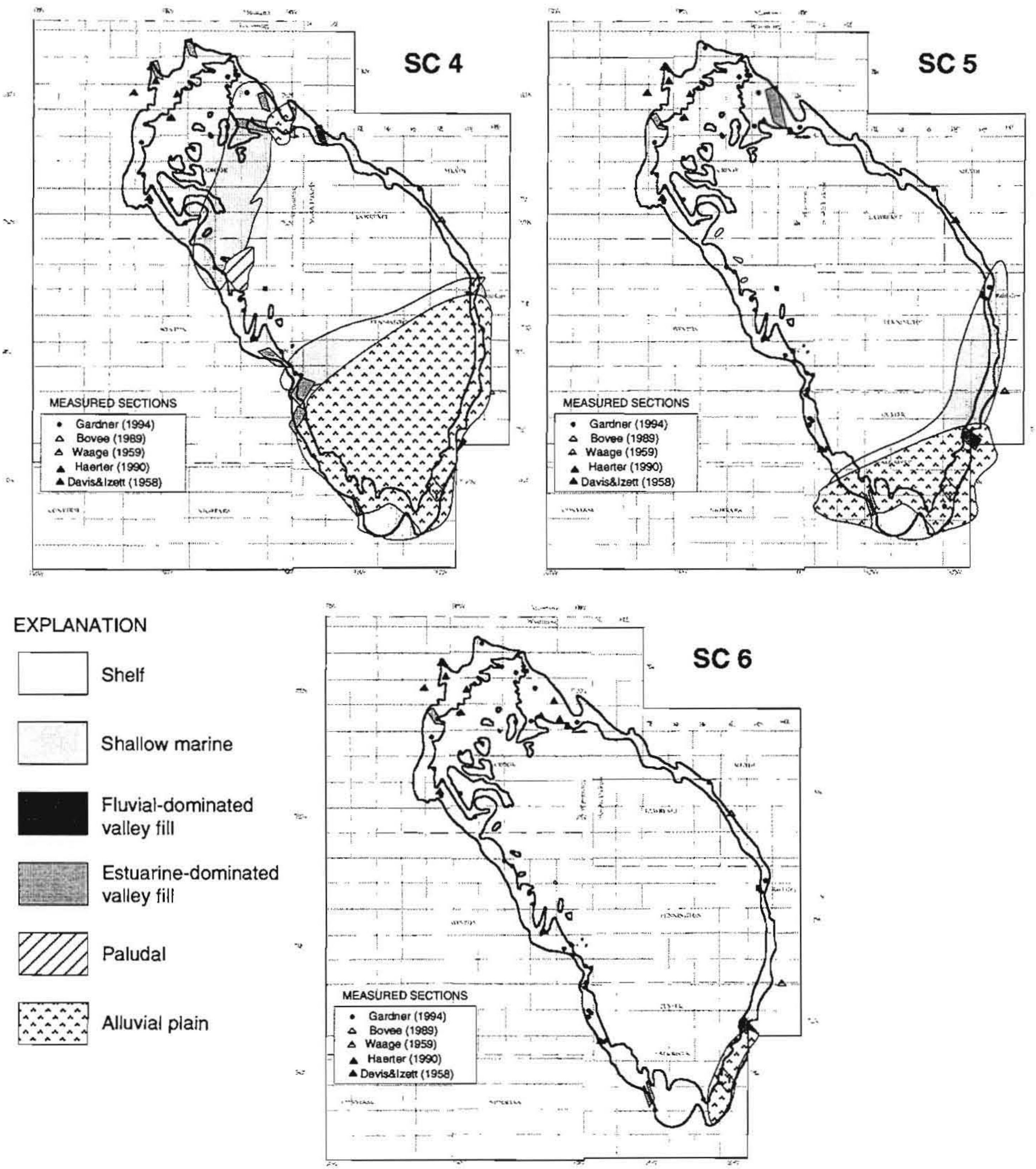



Figure7

# STRATAL ARCHITECTURE OF VALLEY-FILL SYSTEMS
## SHORT-TERM CYCLES

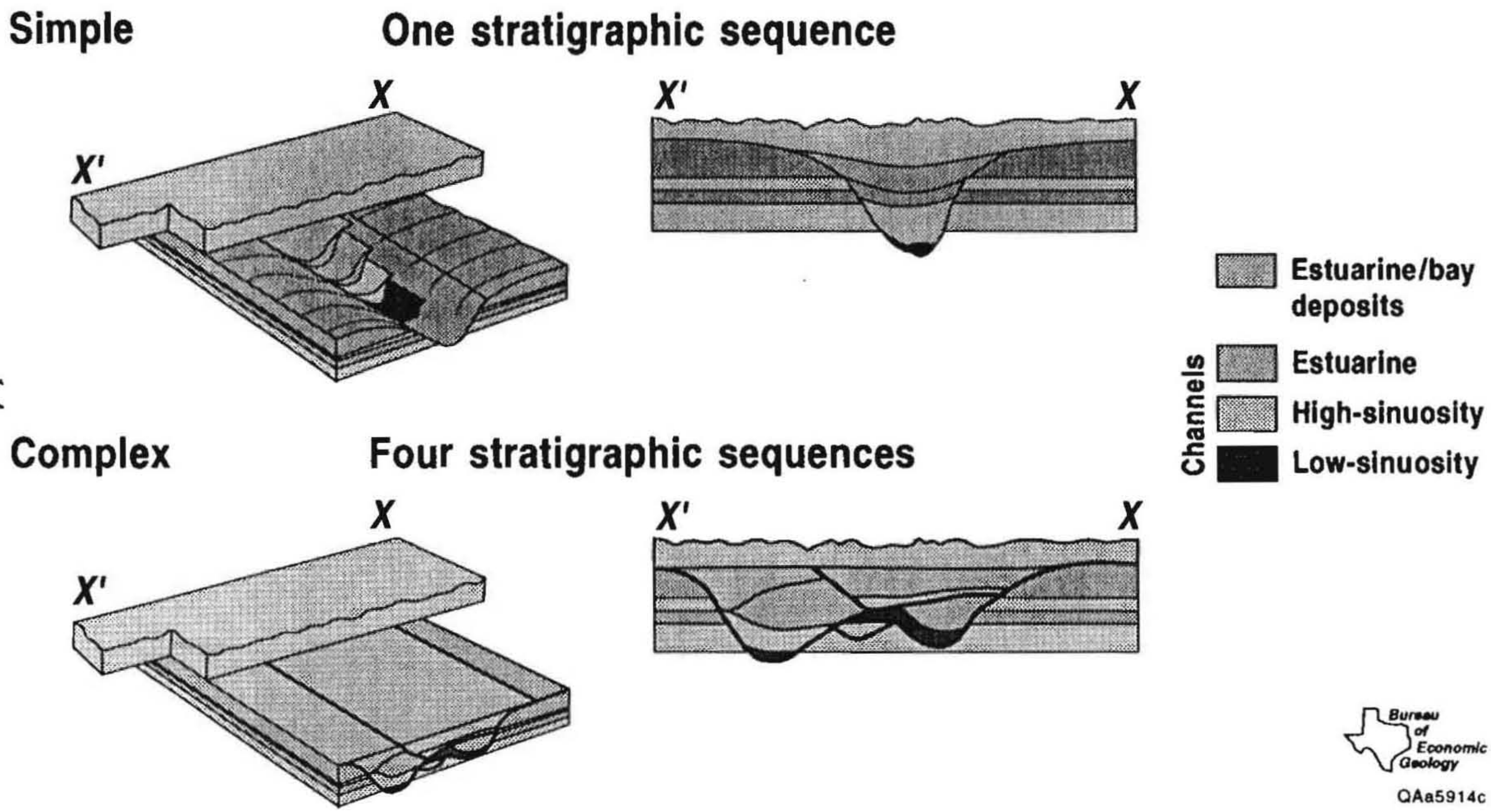



Figure 08-

Black Hills formed during the Paleocene as one of the last and easternmost Laramide uplift with surface expression (Lisenbee, 1978; Shurr and others, 1988). The Fall River Formation crops out in a outcrop belt up to ten miles wide, with typical sandstone exposures forming resistant cliffs capping bluffs and canyons. Minor faults with up to 20 m of displacement locally cut the outcrop belt.

### Age and Stratigraphic Setting

The Lakota and Fall River Formations in the Black Hills comprise the Early Cretaceous Inyan Kara Group (Rubey, 1930). The Inyan Kara Group and equivalents overlie the Late Jurassic Morrison Formation across Wyoming, but the nature of this contact is disputed. An unconformable relationship is advanced based on meager paleontological criteria, evidence of local erosional scour (Mapel and Gott, 1959; Mirsky, 1962; Ostrom, 1970; Reyments and Bengston, 1986), and more recent fission-track and paleomagnetic data (Meyers and others, 1992). Other workers have suggested a generally conformable contact based on the lack of regional erosional scour at the contact (Darton, 1904; Moberly, 1960; Weimer, 1962; Suttner, 1969; Winslow and Heller, 1987). For example, regional subsurface cross sections from central Wyoming to central Colorado show over 150 m of stratigraphic rise in Lower Cretaceous strata and suggest a conformable and interfingering relationship between Jurassic and Early Cretaceous strata (Weimer, 1962). Lower Cloverly mudstones (below chert pebble conglomerates and the lithostratigraphic boundary with the Morrison Fm) contain several volcanic ash beds yielding fission-track dates (129± 27 Ma) that are consistent with associated palynomorph assemblages. This suggests Early Cretaceous strata are Valanginian in the eastern Wind River and Bighorn Basins (DeCelles and Burden, 1992).

An Early Cretaceous age for the Inyan Kara Group in the Black Hills is suggested by Aptian plant fossils (Robinson and others, 1964; Waage, 1959, Sohn, 1979) from the Lakota Formation and Albian marine fossils and isotopic age dates from bentonites in the basal Skull Creek Shale (Waage, 1959, Cobban and others, 1994). There are conflicting biostratigraphic dates, however, for the Lakota Formation in the Black Hills including: an Albian age (108 Ma) based on palynological analysis of 16 coal samples from the lower Lakota at Cambria Creek (Pish, 1988); and an Aptian age (113 Ma) based on fossil cycads, ferns, and charophytes from lower Lakota coal-bearing strata, including Cambria Creek coal beds (Ward, 1896; Fontaine, 1899, Robinson and others, 1964); and, a Barremian to Valanginian age (124 to 138 Ma) based on 46 ostracod collections from the lower Lakota Fm (Sohn, 1979). Thus the Lakota Formation ranges from either Valanginian to Aptian (131 Ma to 113.0 Ma), or is entirely Albian in age (108.0 Ma) and represents from 4 to 9 million years.

A transgressive disconformity separates Lakota from overlying Fall River strata and records the initial marine transgression of the southward directed boreal arm of the Early Cretaceous seaway (Waage, 1959). Freshwater clams (*Protelliptio douglassi*) collected from the basal foot of the Fall River Formation in the northwestern Black Hills (Waage, 1959, p. 63, assigns an Albian age to these fossils) are a late Aptian index fossil (Katich, 1962). The Skull Creek Shale, overlying the Fall River Formation, contains fossils of the *Inoceramus comancheanus - Inoceramus bellvuensis* zone (now named *Eopachydiscus marcianus* zone, Cobban and others, 1994) Bentonite from the basal Skull Creek Shale in the northern Black Hills yields an argon-argon isotopic date of $104.4 \pm 0.5$ Ma. These data suggest the Fall River Formation ranges from late Aptian to mid-Albian (minimum 108.0 Ma top Lakota to 104 Ma top Fall River) in age and represents a minimum 4 million years. This 4 million year duration correlates a late Aptian eustatic sea-level rise to the initial marine incursion of the Western Interior Seaway into North America and the basal Fall River (Scott et. al., 1988). If the Albian age for the lower Lakota from Pish (1988) is correct, a 4 million year maximum duration for the Inyan Kara Group suggests a significantly shorter duration for the Fall River Formation. Inasmuch as Pish's (1988) dates differ with all biostratigraphic data from this interval, they must be considered tentative.

## Stratigraphic Framework

Despite poor biostratigraphy in the Fall River Formation a high resolution chronostratigraphic framework can be constructed from cycle stacking patterns, unconformities, and changes in facies architecture and stratal geometry. Four scales of stratigraphic cyclicity, three allocyclic and one autocyclic, are recognized in Lower Cretaceous strata of the Black Hills. Allocyclic stratigraphic cycles are correlated across the Black Hills and are referred to as "long-," "intermediate-," and "short-term" to emphasize comparable scales. Autocyclic stratigraphic cycles are referred to as parasequences (Van Wagoner, 1985) and represent cyclic stratal successions of local extent and restricted to a specific depositional environment, or facies tracts, in short-term stratigraphic cycles.

Cycle durations were estimated from overlapping biozones within marine strata and from isotopic ages of volcanic ashes. Stratigraphic cycles are assumed to record synchronous base-level cycles, and thus can be used to extend chronostratigraphic frameworks based on biochronozones and isotope data. Biostratigraphic data are integrated with physical stratigraphic relations to develop a chronostratigraphic framework utilizing two stratigraphic concepts: accommodation and stratigraphic base level.

*Accommodation*, the potential space available for sediment accumulation, controls preservational trends in chronostratigraphic units. Accommodation is the sum of tectonic movement, lithospheric compensation to loads, compaction, and sea level (Sloss, 1963; Cross, 1988; Jervey, 1988; Posamentier and Vail, 1988). Accommodation regulates the volume of sediment preserved in different facies tracts. Temporal and geographic variations in accommodation produce sediment volume changes across a series of laterally linked depositional environments. Such accommodation variations control the proportion of time as rock relative to stratal surfaces of erosion and nondeposition.

The concept of *stratigraphic base level* (modified from Wheeler, 1964) provides a means for describing the balance between accommodation and the transfer of sediment mass across the Earth's surface by surficial processes that erode, transport and deposit sediment. Stratigraphic base-level is not the same as geomorphic base level (e.g., Schumm, 1993). Stratigraphic base level is neither sea level nor a geomorphic profile of equilibrium. Stratigraphic base level is an abstract, nonplanar, nonhorizontal potentiometric surface describing the energy required to move the Earth's surface to attain a condition of minimum energy expenditure where gradients, sediment supply, and accommodation are equilibrated (Fig. 9). The Earth's surface may move up toward base level by deposition, and down toward base level by erosion. Changes in accommodation during base-level cycles produce progradational/aggradational stratal units. These units conform to Walther's law (1896; translated by Middleton, 1973) and are fundamental building blocks of the stratigraphic record.

Regardless of scale, each stratigraphic cycle records a complete base-level cycle *sensu* Wheeler (1964). During a base-level cycle, the accommodation/sediment-supply ratio decreases to a limit (base-level fall), then increases to another limit (base-level rise). The limits, or "turnaround" points, of these accommodation/sediment-supply ratio changes are synchronous throughout the spatial extent of each stratigraphic cycle. Thus, stratigraphic cycles at each scale

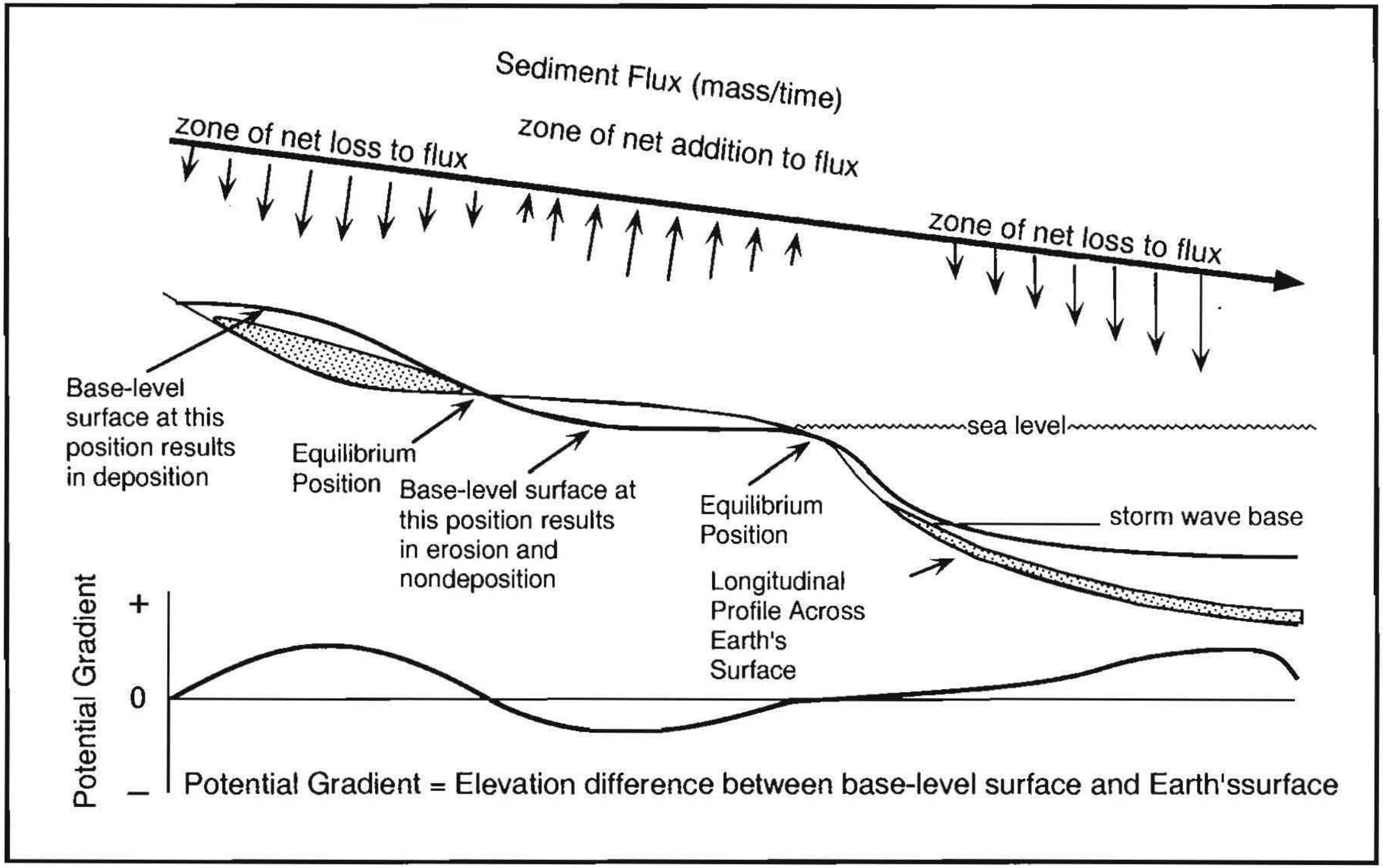



**Figure 9**–Base level is an imaginary potentiometric surface that fluctuates up and down with respect to Earth's surface in response to the energy budget of sediment supply and transfer.

are time-bounded rock units and comprise all strata accumulated during a base-level cycle. Such base-level cycles are recorded by both rock and hiatal surfaces, because sediment accumulation is not constant and continuous everywhere. Parts of the same base-level cycle can be preserved as rock, while other parts are preserved as surfaces of stratigraphic discontinuity.

Selection of the initiation point of a stratigraphic cycle is arbitrary, but must be consistent. Although both base-level turnarounds are correlated in this study, the turnaround point from base-level fall to rise is used to define cycles of all scales. This is the position of a minimum accommodation/sediment supply ratio. The base-level fall-to-rise turnaround point is the most practical cycle initiation point within a low accommodation succession, because it is the associated with unconformity development. In more conformable succession, it might be preferable to select the base-level rise-to-fall turnaround point (e.g., cycle boundaries of short-term stratigraphic cycles in the Ferron Sandstone Gardner, 1993).

*Parasequence*

The smallest scale stratigraphic unit is the meter-scale progradational/aggradational facies succession of local extent (lateral dimensions generally less than 1 km). The limits of such stratal units are confined to the depositional environment recording intrinsic depositional processes (i.e. delta switching or fluvial avulsion; Beerbower, 1964). In shallow-marine deposits, such upward-shoaling successions bounded by marine flooding surfaces resemble parasequences (Van Wagoner, 1985); whereas in valley fills they are erosive-based sandstone bodies resembling discrete channel stories or macroforms (Jackson, 1976; Friend, 1983; Crowley, 1983; Miall, 1985). Although parasequences are present in all depositional environments, they can not be correlated across environments, and variable numbers of parasequences occur in different depositional environments recording the same short-term stratigraphic cycle. Successive parasequences stack to form short-term stratigraphic cycles, and record lower magnitude water depth changes in conformable Walther's (1896) law facies successions (Fig. 10). Such autocyclicity records the episodic nature of deposition, punctuated migration of depositional environments across a geomorphic profile, and sedimentological feedback responses to accommodation changes in short-term base-level cycles.

*Short-Term Stratigraphic Cycle*

The smallest scale chronostratigraphic unit is a progradational/aggradational facies succession conforming to Walther's (1896) law. These

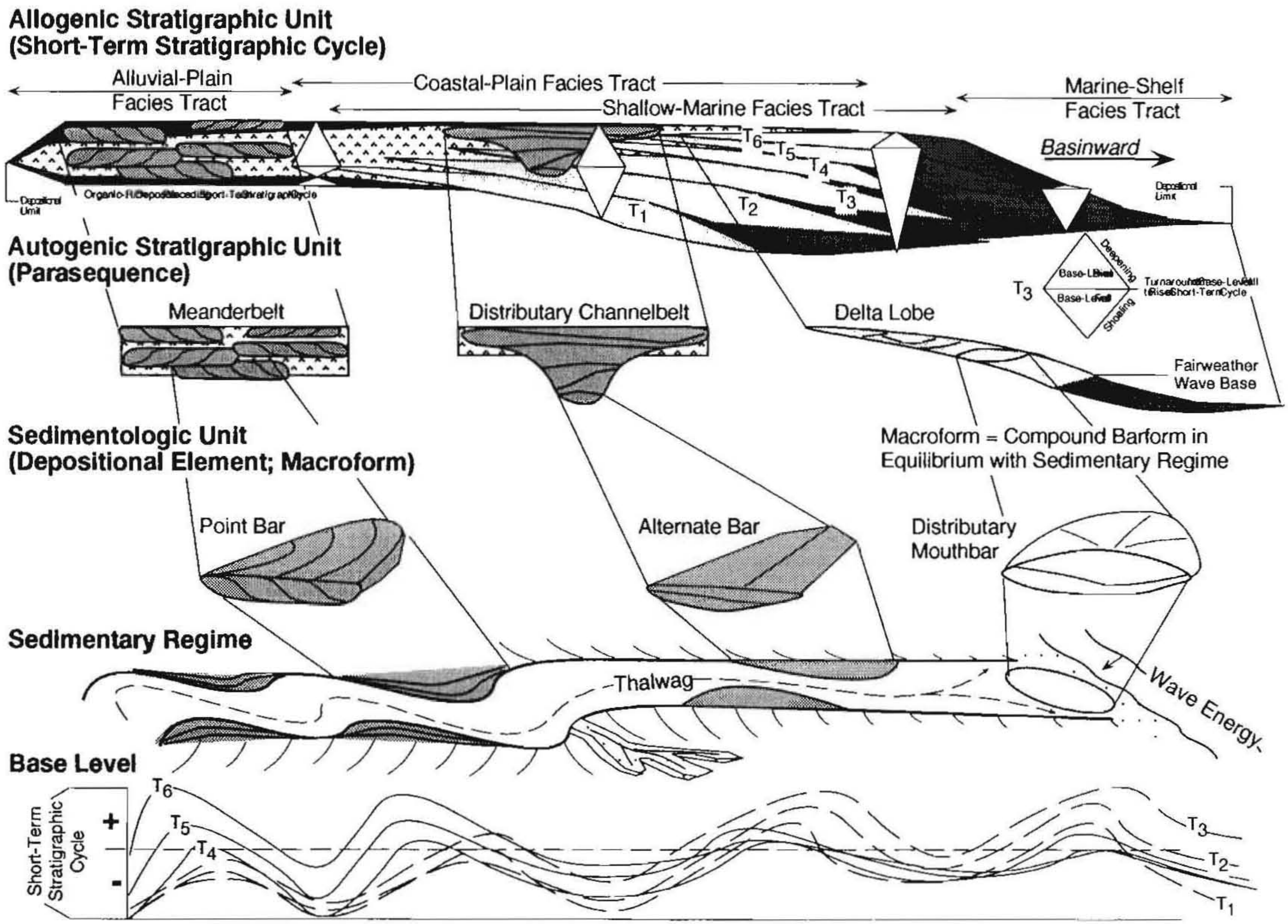



**Figure 10**—Hierarchy of Architectural Elements in Fluvial-Deltaic Depositional System

stratigraphic cycles include deposits and surfaces formed across all depositional environments during a short-term base-level cycle (Wheeler, 1964). Successive short-term cycles can be separated by surfaces of stratigraphic discontinuity marked by a facies offset. Such surfaces represent erosional unconformities, sediment bypass surfaces, or nondepositional hiatal surfaces formed during either base-level rise or fall. Alternatively, successive short-term cycles can be separated by conformable strata that record the turnaround from base-level fall to rise. In such cases, a short-term cycle is marked by a progressive change in stratal geometry and facies architecture that records a history of first decreasing and then increasing accommodation/sediment-supply ratio. Short-term cycle boundaries occur at the top of subariel exposure surfaces capping shallow-marine deposits, and at the base of valley-fill deposits. Successive short-term cycles show an upward increase in paleovalley width-to-depth ratio, decreased erosional truncation of underlying strata, and increased shallow-marine sandstone-mudstone ratio. In the Fall River Fm., such chronostratigraphic units resemble depositional events (Frazier, 1974); fourth-order high-frequency sequences (Mitchum and Van Wagoner, 1991), and short-term stratigraphic cycles in the Ferron Sandstone (Gardner, 1993).

*Intermediate-Term Stratigraphic Cycle*

*(Stratigraphic Sequence)*

The boundaries of the intermediate-term stratigraphic sequences occur at the same base-level fall-to-rise turnaround of lower and higher frequency base-level cycles (e.g., long- and short-term stratigraphic cycles). Changes in accommodation during intermediate-term base-level cycles produce distinct stacking patterns of short-term cycles described geometrically as seaward stepping, landward stepping, and vertically stacked (Cross, 1988). Seaward-stepping cycles are deposited during intermediate-term base-level fall. Vertically stacked cycles can be deposited at the beginning of intermediate-term base-level rise. Landward-stepping cycles are deposited during intermediate-term base-level rise (Fig. 11). In the Fall River Formation, such chronostratigraphic units resemble depositional episodes (Frazier, 1974); third-order composite sequences (Mitchum and Van Wagoner, 1991), and intermediate-term stratigraphic sequences in the Ferron Sandstone (Gardner, 1993). Despite the low accommodation setting, intermediate-term base-level fall is recorded in the Fall River stratigraphic sequence as a basinward shift in successively short-term stratigraphic cycles, rather than as an intermediate-term

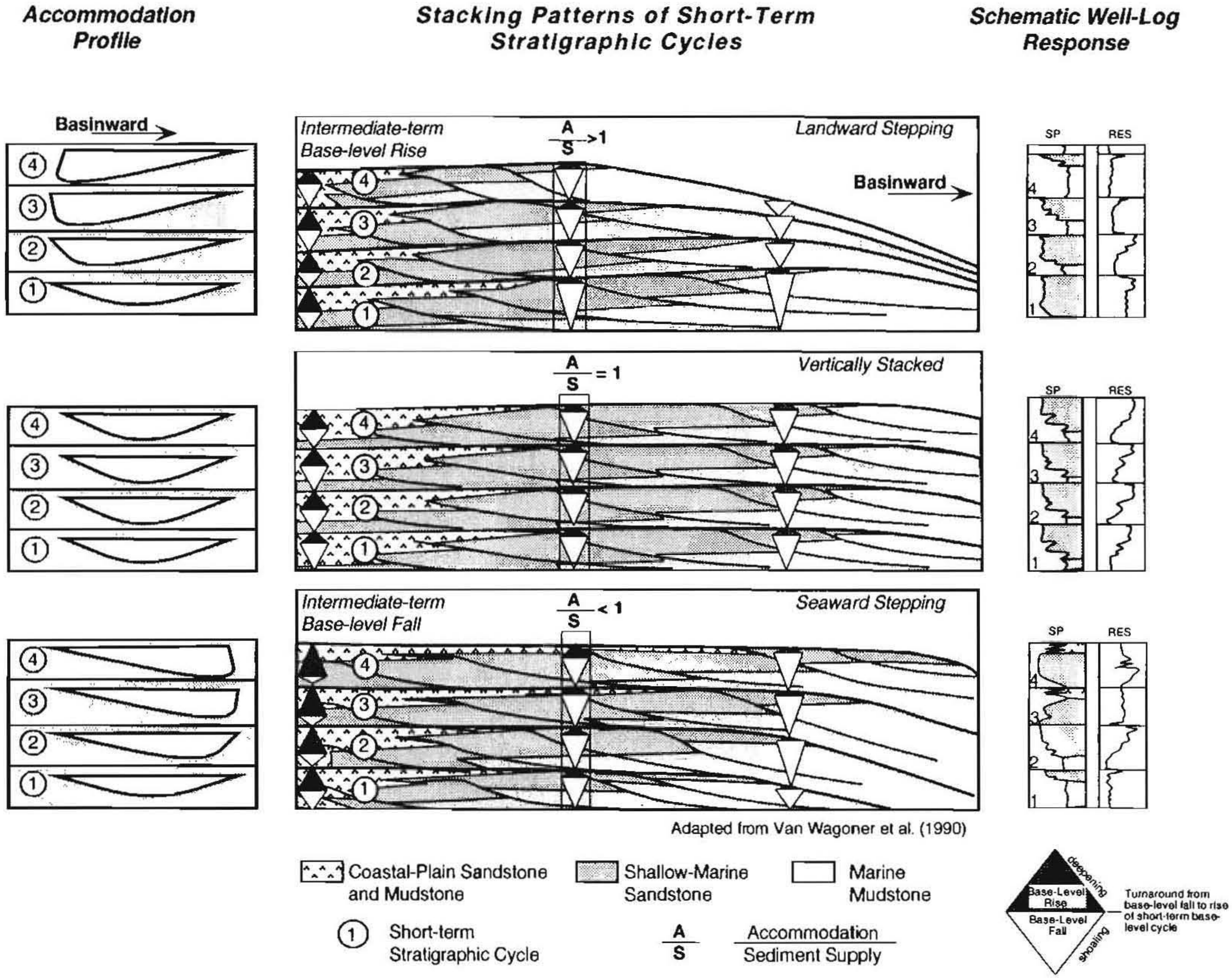



Figure 11–Diagram showing stacking patterns of short-term stratigraphic cycles

base-level fall unconformity, or third-order sequence boundary.

### *Long-Term Stratigraphic Cycle*

Late Jurassic to Early Cretaceous strata of northern Wyoming comprise one long-term stratigraphic cycle containing multiple intermediate-term stratigraphic sequences. This long-term base-level cycle is a 400-m-thick upward-coarsening succession of progradational nonmarine strata overlain by upward-fining marine strata bounded by deposits formed during eustatic transgressions. Progradation and a basinward shift in sediment accumulation is punctuated by long-term base-level rise and episodic southward transgression of the Boreal seaway. Long-term base-level rise deposits are represented by carbonates and mudstones in the late Jurassic Sundance Formation and equivalents, and the Early Cretaceous Mowry Shale (Weimer, 1962). In the Black Hills, such deposits record eustatic sea-level rise punctuating long-term base-level fall and episodic westward (basinward) progradation into the basin.

Long-term base-level fall is marked by a stepwise progradation of nonmarine sandstones and mudstones in the Morrison Fm., and sandstones and conglomerates in the Lakota Fm. and equivalents recording over-filled foreland basin conditions (Decelles, 1992; Fig. 12). Black chert-pebble conglomerates in the Lakota Fm. in the Black Hills record 600 km of eastward sediment transport from their inferred western source and the inferred maximum long-term base-level fall (Heller and Paoloa, 1989). The turnaround from long-term base-level fall to rise is marked by the transgressive disconformity separating the Lakota and Fall River Fms. Intermediate-term base-level cycles superimposed on long-term base-level rise are most apparent as successive stratigraphic sequences of the Fall River and Plainview Fms., Muddy-J-Newcastle Sandstone, and D Sandstone across Wyoming and Colorado (Fig. 13). The Skull Creek Shale capping the Fall River Fm. records marine transgression and a southward shift in depocenters to central Colorado culminating in deposition of the Plainview Fm. The Plainview Fm. is inferred to be correlative with the Dakota Silt, a regional subsurface marker in the Powder River basin about 24 m above the Fall River Fm. The Skull Creek Shale above the Dakota Silt records the initial joining of Boreal and Tethyan water masses creating the first contiguous seaway in the Cretaceous Western Interior. Overlying valley-fill deposits in the Muddy-J-Newcastle interval (96 Ma) record the next intermediate-term base-level cycle with paleovalleys incised into the Skull Creek Shale across Wyoming. The Mowry Shale records the final intermediate-term sea-level rise in Early

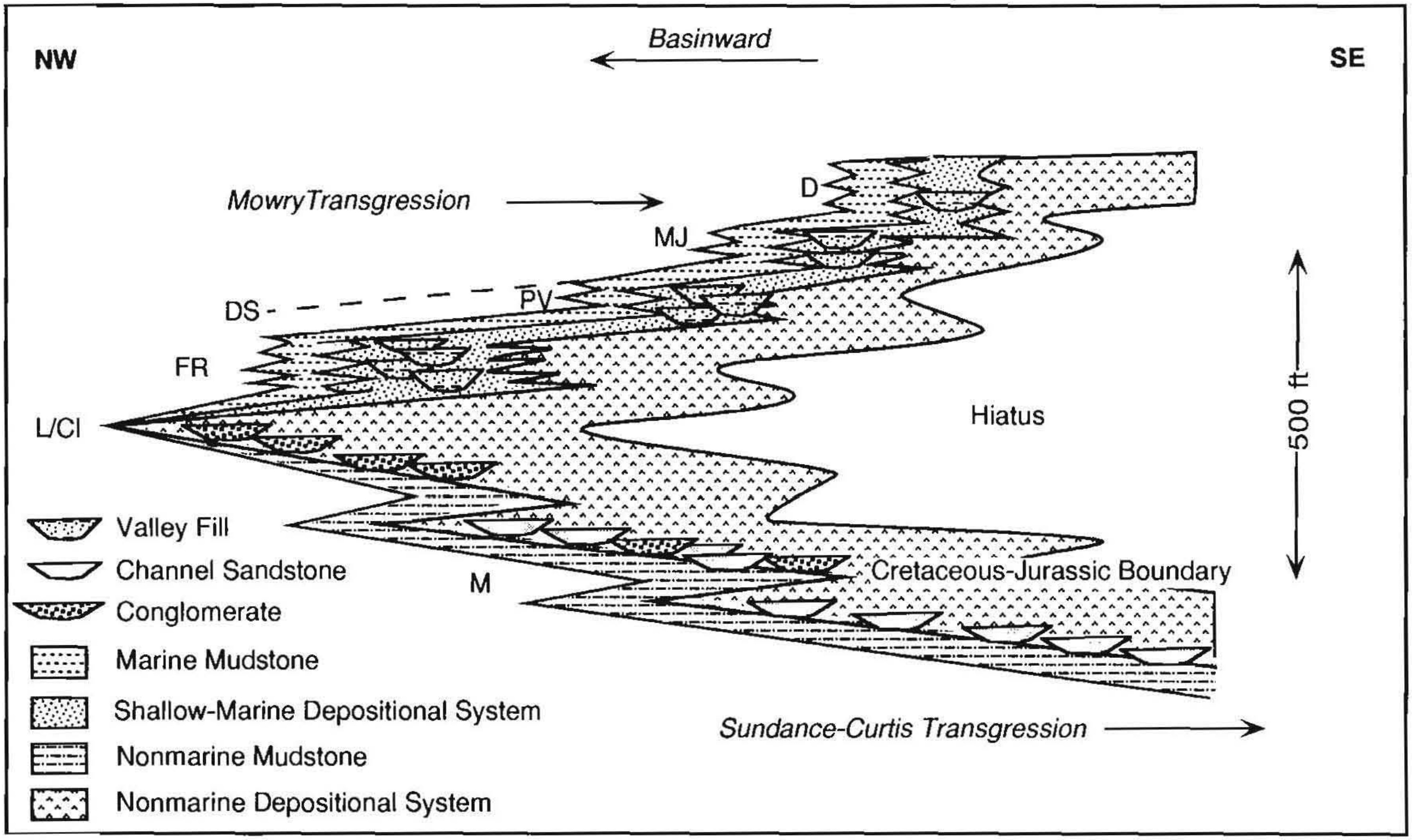



**Figure 12**—Diagramatic cross section showing four scales of cyclicity recognized in the Lower Cretaceous in the Black Hills. The long-term cycle is recorded by mayor marine transgressions of the Jurassic Sundance Formation and overlying Mowry Shale. Base-level fall of the long-term cycle is recorded by the successive offlap of intermediate-tehm base-level cycles in nonmarine strata of the Morrison (M) and Lakota/Cloverly (L/Cl) Formations. Maximum base-level fall is recorded by black chert pebbles conglomerates of the Lakota Formation. The turnaround from long-term base-level fall to base-level rise is marked by a transgressive disconformity that separates the Lakota Formation from the Fall River Formation. Intermediate-term base-level cycles that are superimposed on the base-level rise of the long-term cycle are recorded by successive clastic wedges of the Fall River Formation (FR), Muddy Sandstone (M), Planview Formation (PV) and Dakota Silt (DS) equivalents, and D Sandstone (D) of the Denver basin. The intermediate-term base-level cycles consist of several shorter term unconformity-bounded depositional sequences.

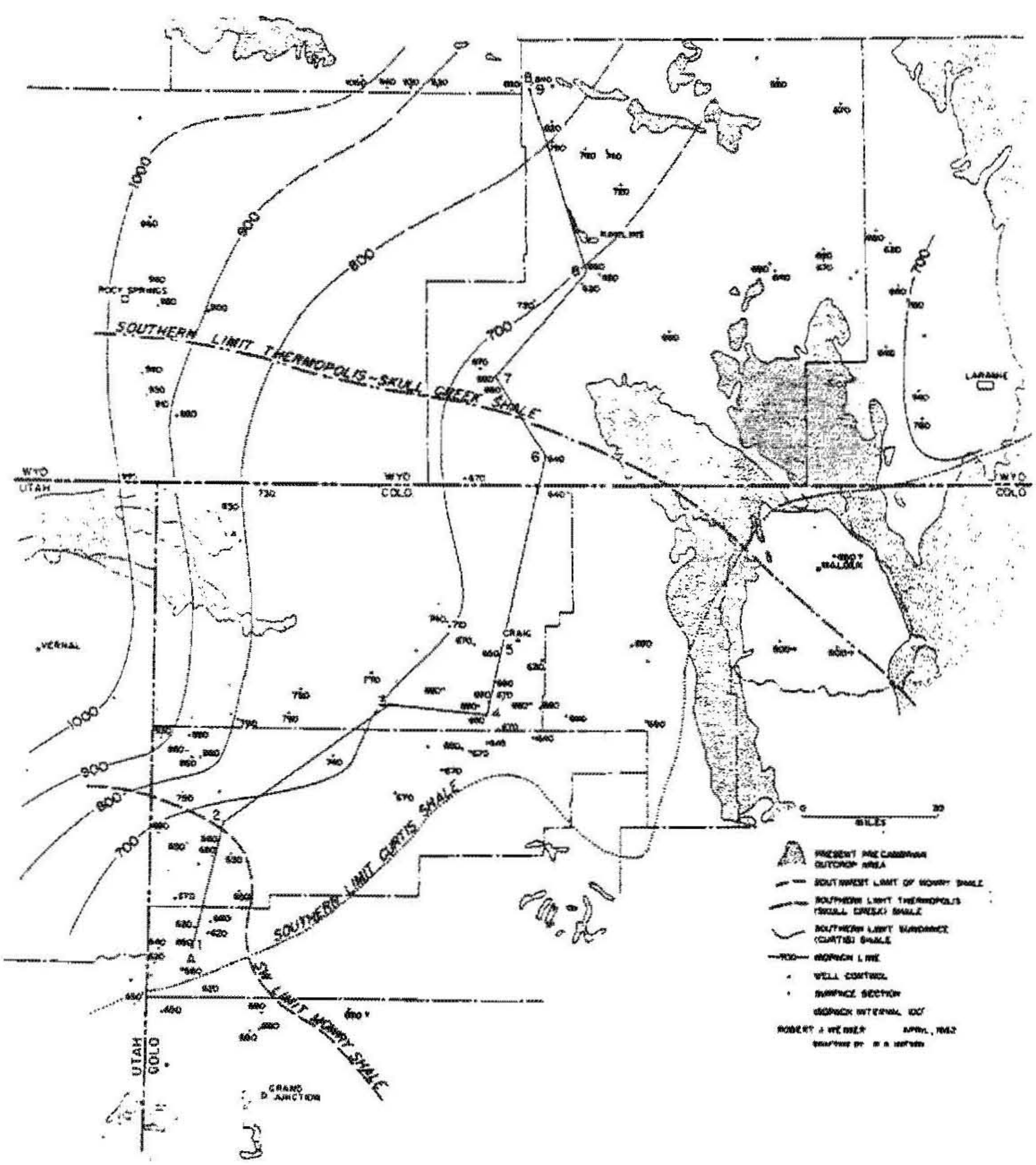



**Figure 13**– Map from Weimer (1962) showing the terminal onlap positions of the Mowry and Skull Creek marine transgressions. Although the Skull Creek Shale records the initial joining of the southward directed boreal and northward directed Tethyan transgressions, producing the first connected seaway (suggesting a greater magnitude relative sea-level rise), the Mowry transgression records the most southward extension of the Early Cretaceous boreal seaway.

Cretaceous strata. The D Sandstone in the Denver Basin and Dakota Sandstone near Grand Junction, Colorado mark the terminus of this transgression (Molenaar and Cobban, 1991). Although linkage of Boreal and Tethyan marine waters during upper Skull Creek Shale deposition suggests a greater magnitude sea-level rise, the Mowry Shale overlying the Muddy Sandstone comprises an equivalent thickness of marine strata, and its western onlap is positioned farther southward than the underlying Skull Creek Shale (Weimer, 1962; Fig. 14).

*Lakota Formation*

The Lakota Fm. forms an upward-fining succession of locally conglomeratic fluvial sandstones, nonmarine mudstone, coal, and lacustrine limestone corresponding to, in ascending stratigraphic order, the Chilson, Minnewaste, and Fuson Members (Gott and others, 1974). In the Black Hills, the Lakota Fm. thickens to the east and southeast (maximum thickness of 168 m near Angostura Reservoir, Mapel and Gott, 1959), with paleoflow to the north and northwest. These relations suggest a southeastern source area for at least sandstones comprising the Chilson Member.

The Lakota Fm. is thinnest (30 m) in the northern Black Hills, where conglomeratic fluvial sandstones locally erode and replace the underlying Morrison Fm (Mapel and Gott, 1959; Waage, 1959). Black chert pebble conglomerate and polished 16-cm long cobbles locally isolated in mudstones comprise the middle and upper part of the Lakota Formation in the northwestern and central Black Hills (Fig. 15). Similarities in clast composition with the Cloverly Formation and Pryor Conglomerate suggest this black chert pebble conglomerate was derived from the Rex Chert Member of the Phosphoria Formation in the Beartooth Mountains, northwestern Wyoming (Hooper, 1962a,b; Young, 1970).

Sandstone-rich successions of the lower Lakota in the southern Black Hills grade upward to ostracod-rich lacustrine deposits of the Minnewaste Limestone, and nonmarine mudstones of the Fuson Shale. The Fuson Shale and Minnewaste Limestone are lithostratigraphic units locally developed in the southwestern Black Hills (Waage, 1959; Gries, 1962). Waage (1959) correlates the upper part of the Lakota Formation, including black chert pebble conglomerates, in the north to these southern units.

Two major northwest-trending paleovalleys are inferred to confine thicker nested and amalgamated fluvial sandstone successions seen in the southern Black Hills near Hot Springs and Edgemont, South Dakota, in the central Black Hills near Newcastle,

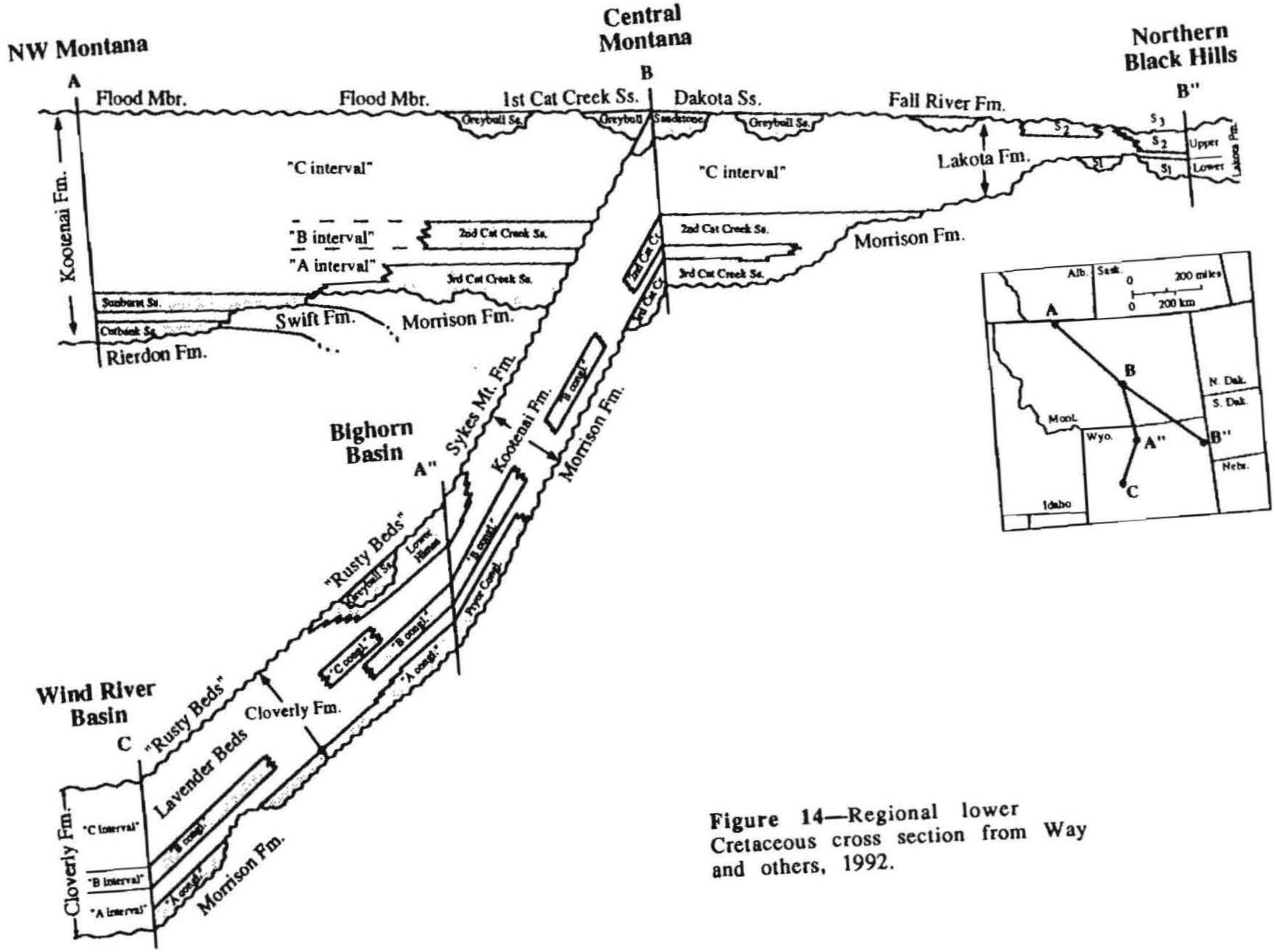



Figure 14—Regional lower Cretaceous cross section from Way and others, 1992.

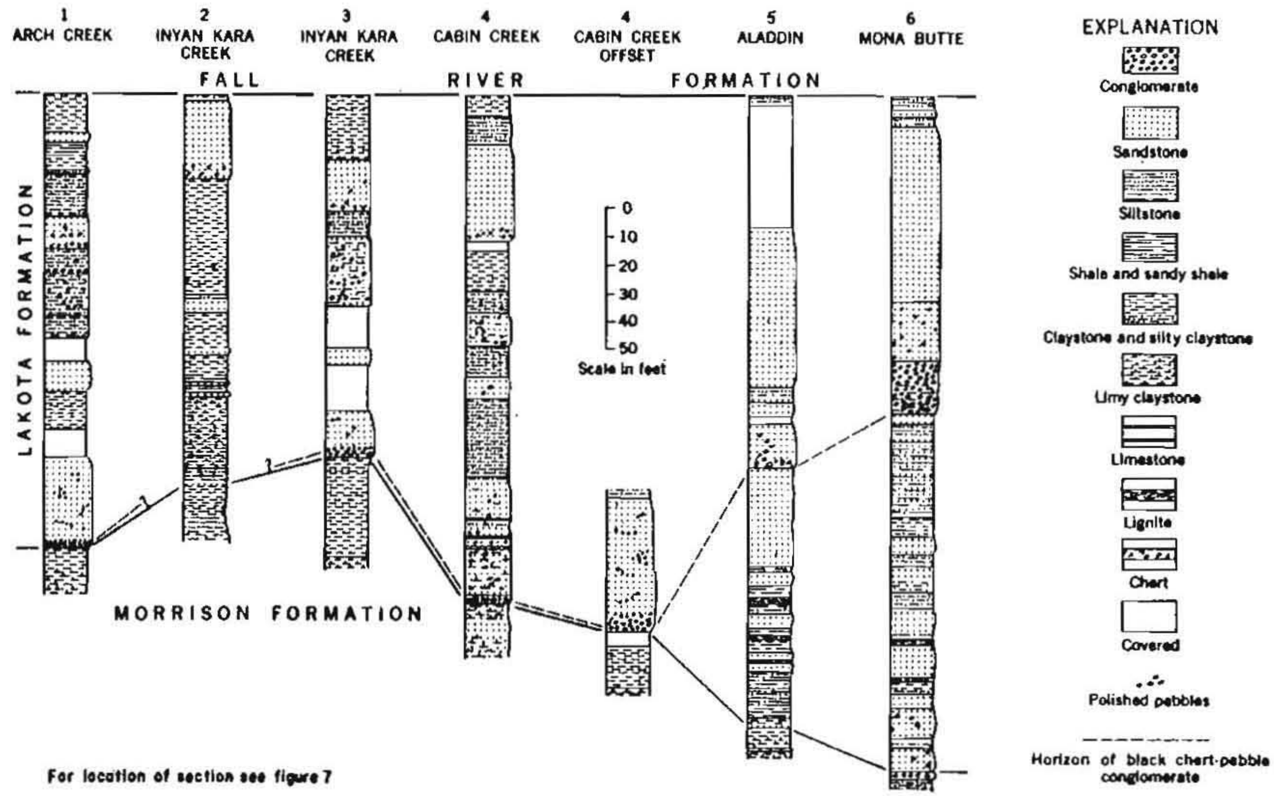



**Figure 15**– Stratigraphic cross section of the Lakota Formation across the northwestern Black Hills from Waage (1959). Sandstone lenses occur at three distinct stratigraphic horizons, with a distinctive black chert pebble conglomeratic sandstone separating the lower and upper sandstone horizons

Wyoming, and Rapid City, South Dakota, and in the northern Black Hills near Aladdin and Carlile, Wyoming. Sandstone bodies occur at four distinct stratigraphic horizons, with distinctive black chert pebble conglomeratic sandstone separating uppermost sandstone horizons. The distinctive black chert pebble conglomerate overlies an erosional surface that shows considerable relief and probably bounds a paleovalley. These sandstone horizons comprise 10- to 60-m thick upward-fining successions inferred to record short-term base-level cycles. Such successions consist of highly interconnected and amalgamated fluvial sandstone bodies that pass upward to variegated mudstone, lacustrine limestone, coal and carbonaceous mudstone.

In summary, the Lakota Fm. comprises at least four unconformity-bounded fluvial-dominated valley fills. Such sandstone-rich fluvial successions were deposited in valleys incised on a low relief alluvial plain at different stratigraphic levels. Locally developed lacustrine limestone and a flora of cycads, ferns, and conifers in coals and carbonaceous mudstones indicate a temperate to subtropical climate with vegetated floodplains locally separated by lakes and swamps. The upward increase in mudstone proportion in the Lakota may record base-level rise culminating in marine transgression at the Lakota - Fall River Formation boundary.

The transgressive disconformity at the top of the Lakota Fm may be correlative to a late-Aptian eustatic sea-level rise (Scott, 1988). This transgressive disconformity is commonly marked by a zone of iron-stained specks of spherulitic goethite-bearing sandstone often bioturbated and consisting of storm-dominated and wave-generated sedimentary structures. This sandstone is typically overlain by a dark gray to black laminated mudstones with pyrite and iron in a reduced state. Across the Black Hills, the upper Lakota Fm consists of variegated red, yellow, and white siltstone and carbonaceous mudstone, with the contact separating the two formations commonly marked by iron changing from an oxidized to reduced state. Thin carbonaceous shales and coal locally occur near the top of the Lakota Formation providing additional evidence of base-level rise immediately preceding transgression recorded at the base of the Fall River Fm.

### *Fall River Formation*

The Fall River Fm. is based by a transgressive disconformity across the Black Hills, and is conformably overlain by the Skull Creek Shale. The Fall River Fm. contains thin regionally extensive shallow-marine deposits that thicken to the southeast (110 to 165 ft). As deposits thicken, the proportion of marine deposits decrease. Shallow marine deposits are locally incised by paleovalleys where the Fall River is thickest, and proportion of valley-fill deposits increases southward.

The Fall River Formation was deposited in a low accommodation setting along the cratonic margin of the seaway (Fig 16). Low accommodation promoted development of unconformities during short-term base-level fall. Stratal architecture and heterogeneity styles in the Fall River Fm. are most effected by the position of erosionally based paleovalleys incised into shallow-marine deposits (Fig 17).

This Early Cretaceous seaway was narrow across much of north-central Wyoming (Haun and Barlow, 1962; Dolson and Muller, 1994) promoting tidal and wave processes (Fig 18). Shoreface deposits less than 11 m thick suggest the seaway was shallow. Near the southern terminus of this seaway in Wyoming, fresh water influx produced low sea-water salinities and brackish water conditions, a paucity of calcitic shells of marine macrofauna and microfauna, and abundant siderite/goethite (Sellers and Hawkins, 1992). Fresh to brackish water with low sulfate content may have promoted early siderite precipitation.

The Fall River Formation records the first intermediate-term base-level cycle following the maximum base-level fall of the long-term cycle. This intermediate-term stratigraphic sequence consists of six short-term stratigraphic cycles arranged in three seaward-stepping and three landward-stepping stacking pattern. The lower four short-term stratigraphic cycles are unconformity-bounded. Such unconformity-bounded cycles are chronostratigraphic units correlated across marine-shelf, shallow-marine, and valley-fill, and alluvial-plain deposits consisting of two to eight parasequences.

Intermediate-term base-level fall of the Fall River stratigraphic sequence produced a succession of three seaward-stepping cycles. Significantly, a major unconformity predicted to separate seaward- from landward-stepping cycles in comparable third-order composite sequences is absent. Instead, SC 3 records maximum intermediate-term base-level fall as a maximum basinward shift in proximal facies. In more proximal settings, SC 3 is thin and contains the highest proportion of alluvial-plain deposits containing more erosional surfaces, whereas in more distal settings, coeval shallow-marine deposits contain the highest sandstone-mudstone ratio (Keyhole Sandstone Member of Davis and Izett, 1958). The turnaround from intermediate-term base-level fall to rise in shallow-marine deposits is marked by a change from fluvial-tidal to mixed-energy/storm-dominated delta-front successions. Intermediate-term base-

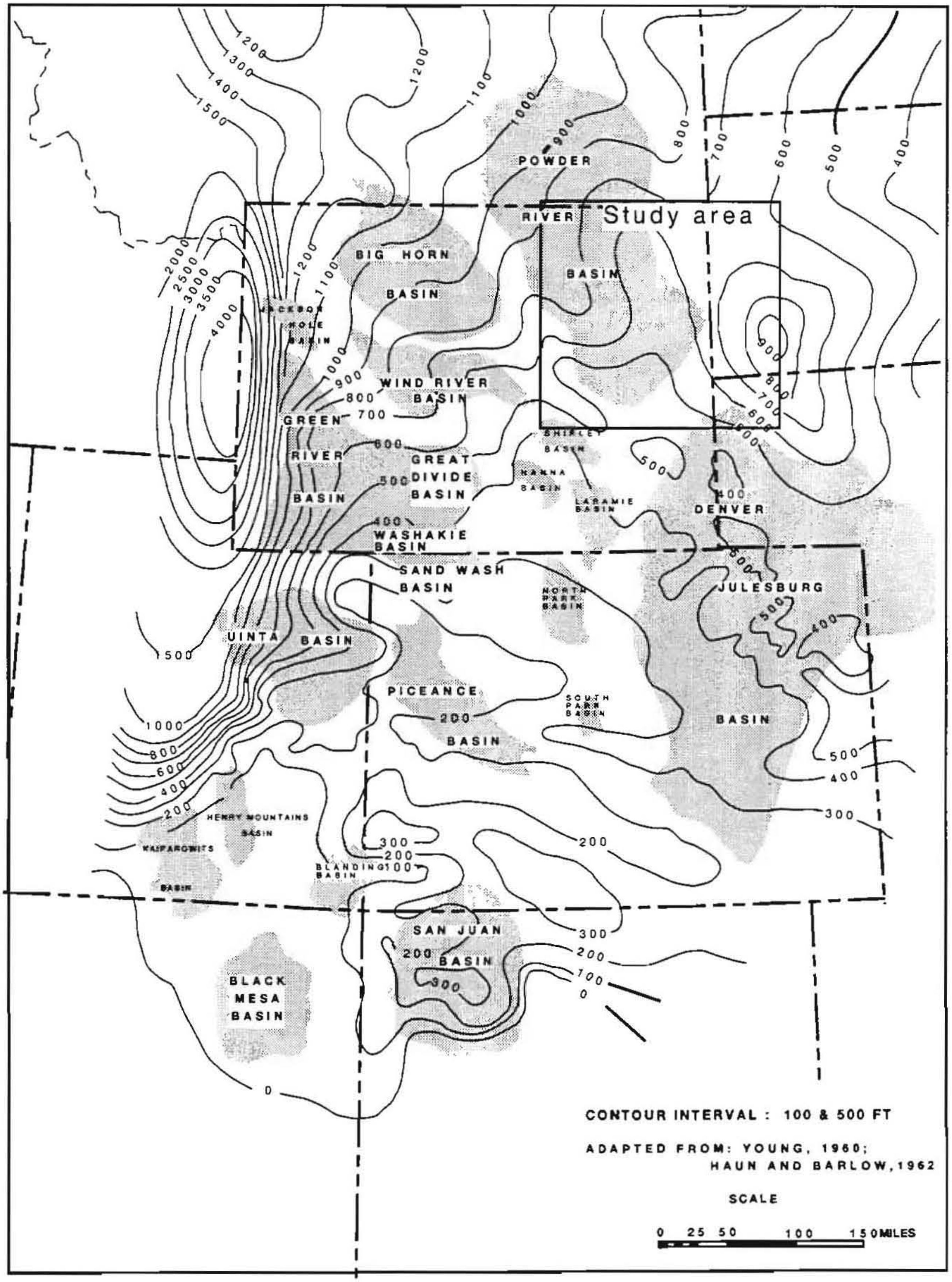



Figure 16—Isopach map of Lower Cretaceous in the Western Interior of North America (Adapted from Young, 1970)

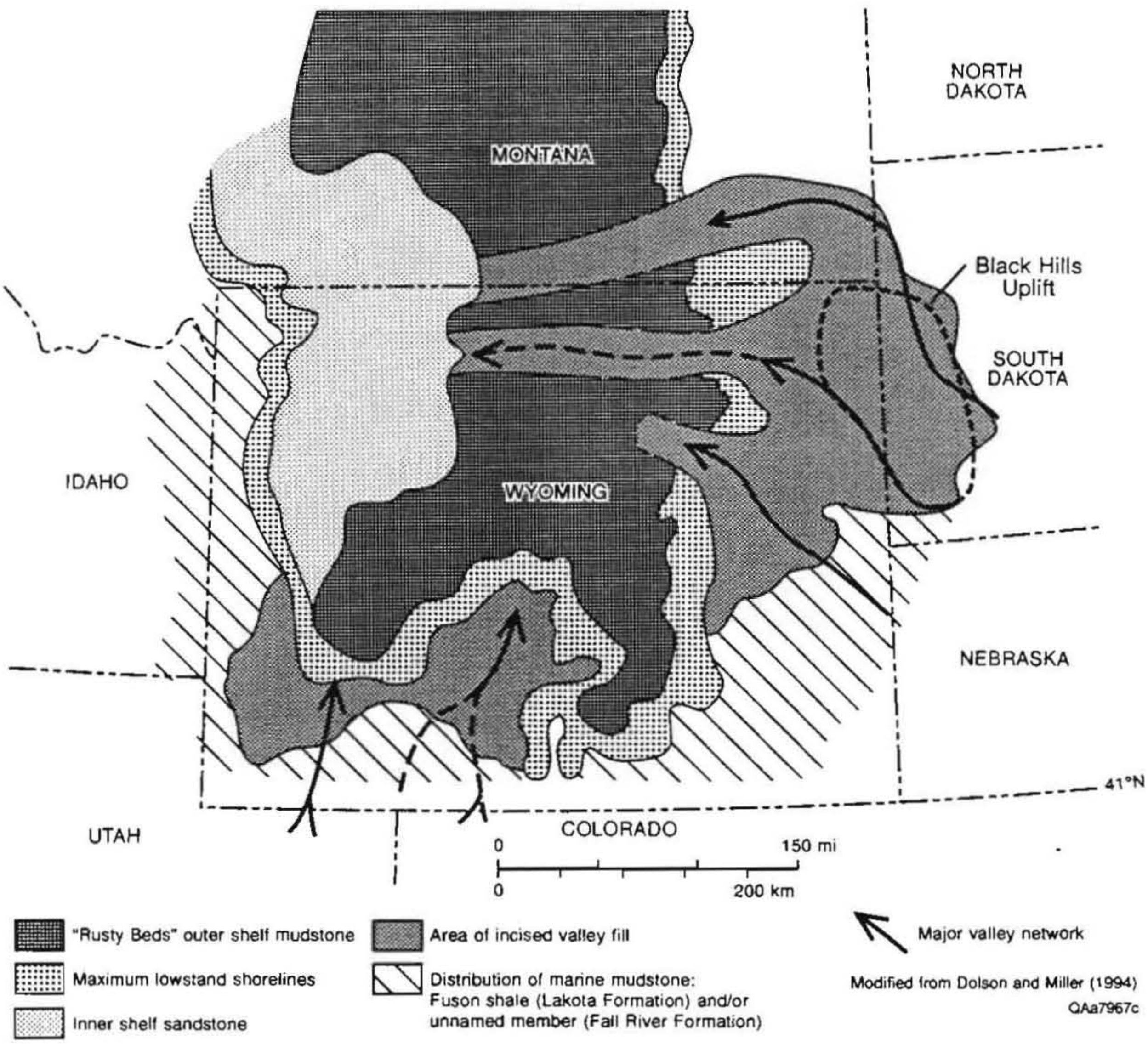
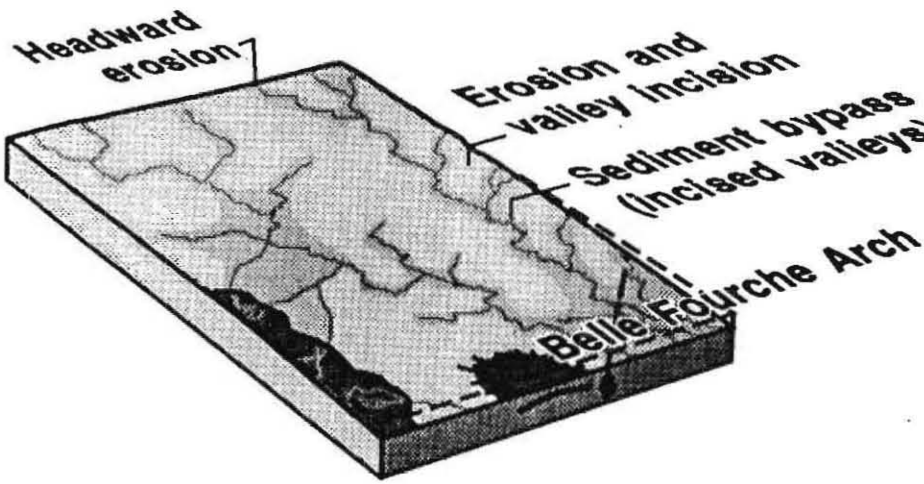
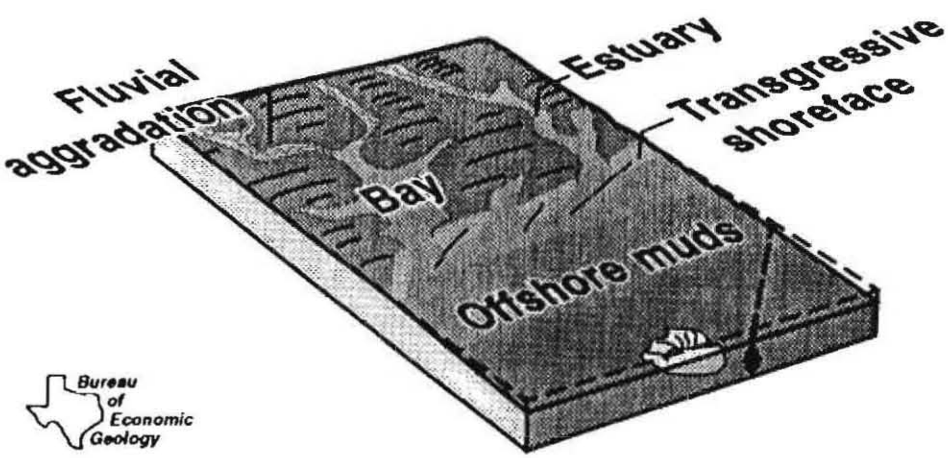



**Figure 17**—Paleogeographic map of Early Cretaceous seaway in Wyoming during Fall River deposition.

## Base-Level Fall Paleogeography




## Base-Level Rise Paleogeography

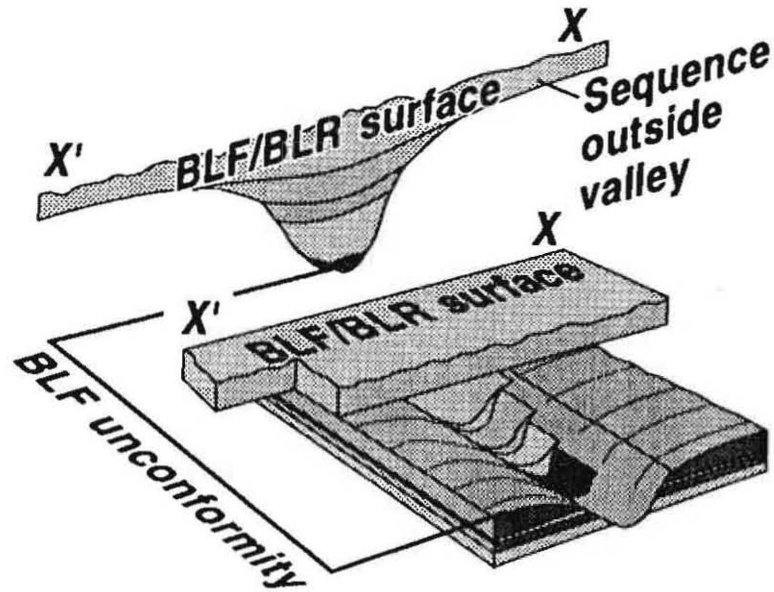



# FLUVIAL-ESTUARINE VALLEY-FILL DEPOSITIONAL SYSTEM

## FALL RIVER FORMATION, WYOMING

Adapted from Wheeler et al. (1988)

## Valley-Fill Stratal Architecture




Bureau of Economic Geology

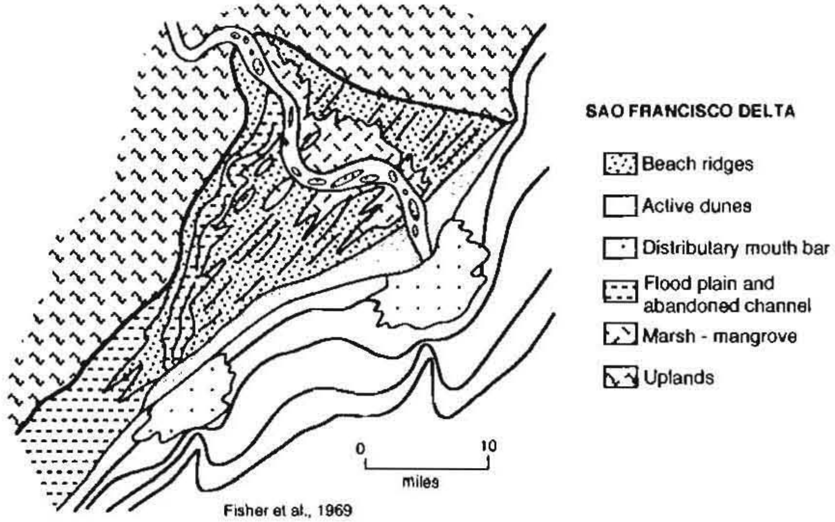
Figure 18–

level rise produced a succession of three landward-stepping short-term cycles, each recording progressively more southeastward deposition of shelf mudstones.

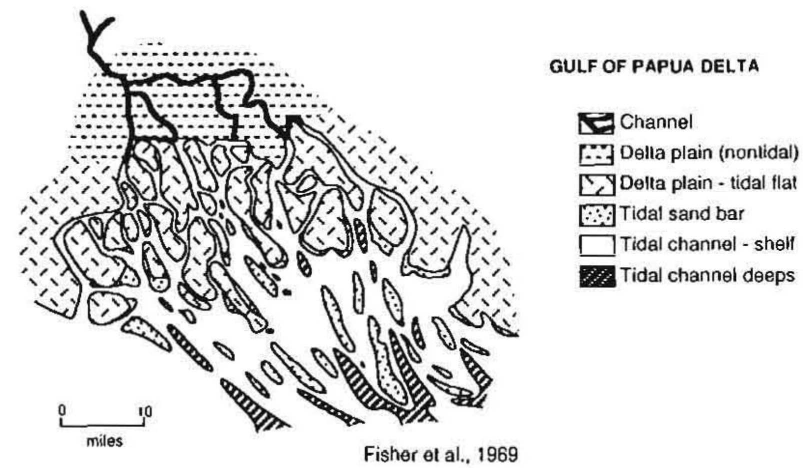
Shallow-marine deposits of short-term cycles change upward from tidal/fluvial- to storm-dominated (Fig 19). Tidal/fluvial-dominated shallow-marine deposits of seaward-stepping SC 1 and 2 are present across the Black Hills, with landward and seaward pinch-outs of marine sandstone absent in outcrop. Seaward-stepping SC 3 contains the most sandstone-rich shallow-marine deposits, with the most basinward shift in proximal facies indicated by the most basinward positioned landward pinch-out of marine sandstone in the central Black Hills, near Newcastle, Wyoming. This marine sandstone is capped by a regionally extensive and well-developed rooted and burrowed zone commonly overlain by a thin coal. Landward-stepping cycles record a progressive landward-shift in position of shallow-marine sandstones best developed in SC 4 near Newcastle, Wyoming, in SC 5 near Edgemont, South Dakota, and in SC 6 near Hot Springs, South Dakota (Fig. 20).

Valley-fill deposits of short-term cycles change upward from more fluvial to more estuarine. SC 1 and 2 valley-fill deposits consist of large sandstone-dominated channels. Fluvial-dominated valley fills are well exposed in SC 2 in the northern Black Hills, and in SC 1 and 2 across the southern Black Hills. These elongate, highly interconnected and multistory sandstone bodies are deeply incised into underlying strata (up to 30 m) and vary in width (0.8 to 2 mile wide). Internally, they consist of discrete erosive-based sandstone bodies (1.5 to 3 m in thickness and 300 to 900 m in length) that change upward from coarse to medium-grained and moderate to well-sorted. Primary stratification consists of structureless sandstone, and/or stacked sets (0.1 to 1 m thick) of broad unidirectional planar-tabular and trough cross-stratification. Foresets are straight and commonly show grain size separation resulting in alternating coarse and fine laminae. Wedge-shaped planar-tabular sets are commonly truncated by reactivation and accretion surfaces, may be oversteepened or overturned in a downcurrent direction, contain smaller superimposed sets of tabular cross strata, or contain toesets of counter current ripples. Intraformational goethite-coated-clay-pebble ripup clasts and rare extraformational chert pebbles form lag deposits lining basal contacts of sandstone bodies and internal bedsets. These sandstone bodies are inferred to represent alternate bars of a low-sinuosity, bedload-dominated fluvial system confined to deep and narrow paleovalleys.

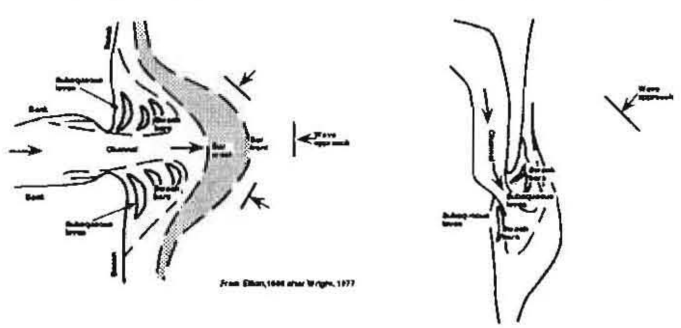
## Facies Association in Wave-Modified Deltas of Seaward-Stepping Short-term Cycle




## Facies Association in Tide-Dominated Deltas of Landward-Stepping Short-term Cycle




### WAVE-DOMINATED CHANNEL MOUTH BAR




### CHANNEL MOUTH BAR OF TIDE-DOMINATED DELTAS

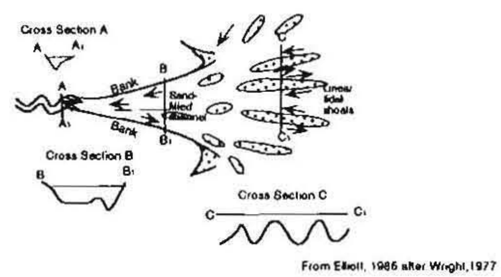



**Figure 19**

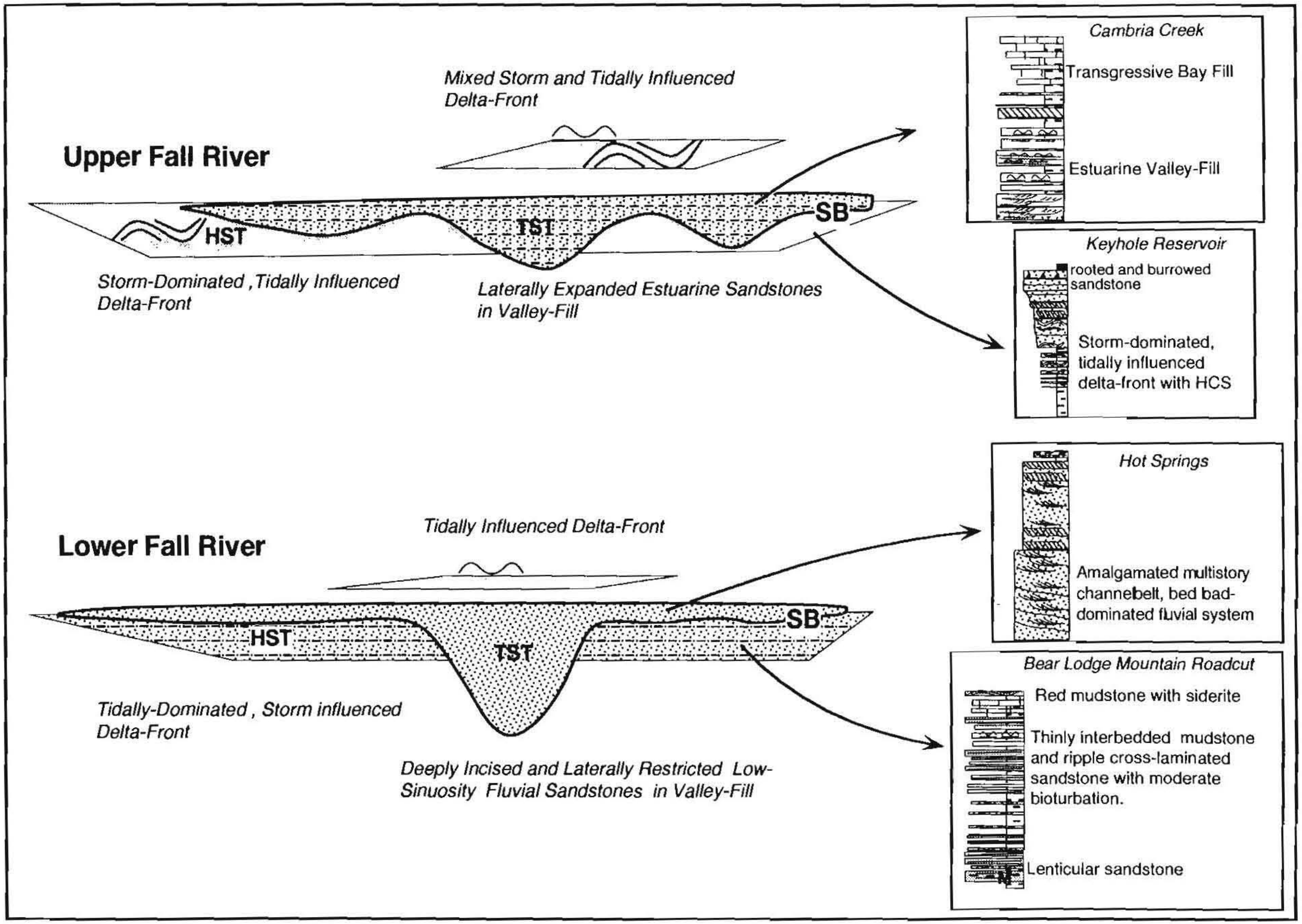



**Figure 20**—Facies Architecture of shallow-marine facies tracts in depositional sequences of the Fall River Formation.

In unnested valley fills, SC 3 and 4 valley-fill deposits are generally thinner but more laterally extensive (23 m thick and 3 to 10 km wide). These mixed fluvial-estuarine successions may contain previously described low-sinuosity sandstone bodies typically overlain by high-sinuosity sandstone bodies that more commonly comprise the entire valley-fill. In such cases, multi-storey and multi-lateral high-sinuosity sandstone bodies are moderately interconnected separated by abandoned channel-fill deposits, and are overlain by heterolithic estuarine deposits. Discrete high-sinuosity sandstone bodies (1.5 to 14 m thick and 100 to 200 m wide) are erosive-based and fine upward, show increased lithofacies diversity, lower sandstone-to-mudstone ratios, and a higher proportion of estuarine facies. Trace fossils are common, of low diversity and are preserved most commonly in the upper parts of the valley-fill. Primary stratification consists of stacked sets (0.1 to 1 m thick) of broad unidirectional planar-tabular and trough cross-stratification. Wedge-shaped planar-tabular sets form up to 2 m thick bedsets commonly truncated by lateral accretion surfaces dipping at 10°. Clay-pebble ripup clasts more frequently occur along set boundaries and lateral accretion surfaces, but goethite-coatings are less abundant. Interbedded estuarine mudstones and sandstones are best developed in the upper part of valley fills, but comprise higher proportions of the valley-fill in more proximal positions of the paleovalley. Such valley fills are well exposed in SC 3 in the Bear Lodge Mountains of the northern Black Hills, and in SC 3 and 4 in the southern Black Hills. Along the west flank of the south-central Black Hills, SC 4 valley-fill deposits are well exposed and show a 80 km long, southeast to northwest, down paleovalley facies change from estuarine near Red Canyon, to fluvial meanderbelt from Clifton to Oil Creek Canyons and farther northwest in the subsurface Donkey Creek-Miller Creek trend.

Low accommodation settings record lower preservational conditions producing more cannibalistic facies associations. Changes in facies associations from similar water-depth environments (e.g., from below to above wave base) may reflect how time is represented as either rock or stratigraphic surfaces of discontinuity (Gardner, 1993). Facies associations recording more time as surfaces of erosion and nondeposition contain a low diversity of lithofacies. Short-term stratigraphic cycles of the Fall River Formation are comparable in thickness, geometry, facies association, and parasequence stacking patterns to short-term stratigraphic cycles of the Ferron Sandstone, but Fall River short-term cycles appear to be an order of magnitude longer in duration (Fig. 21).

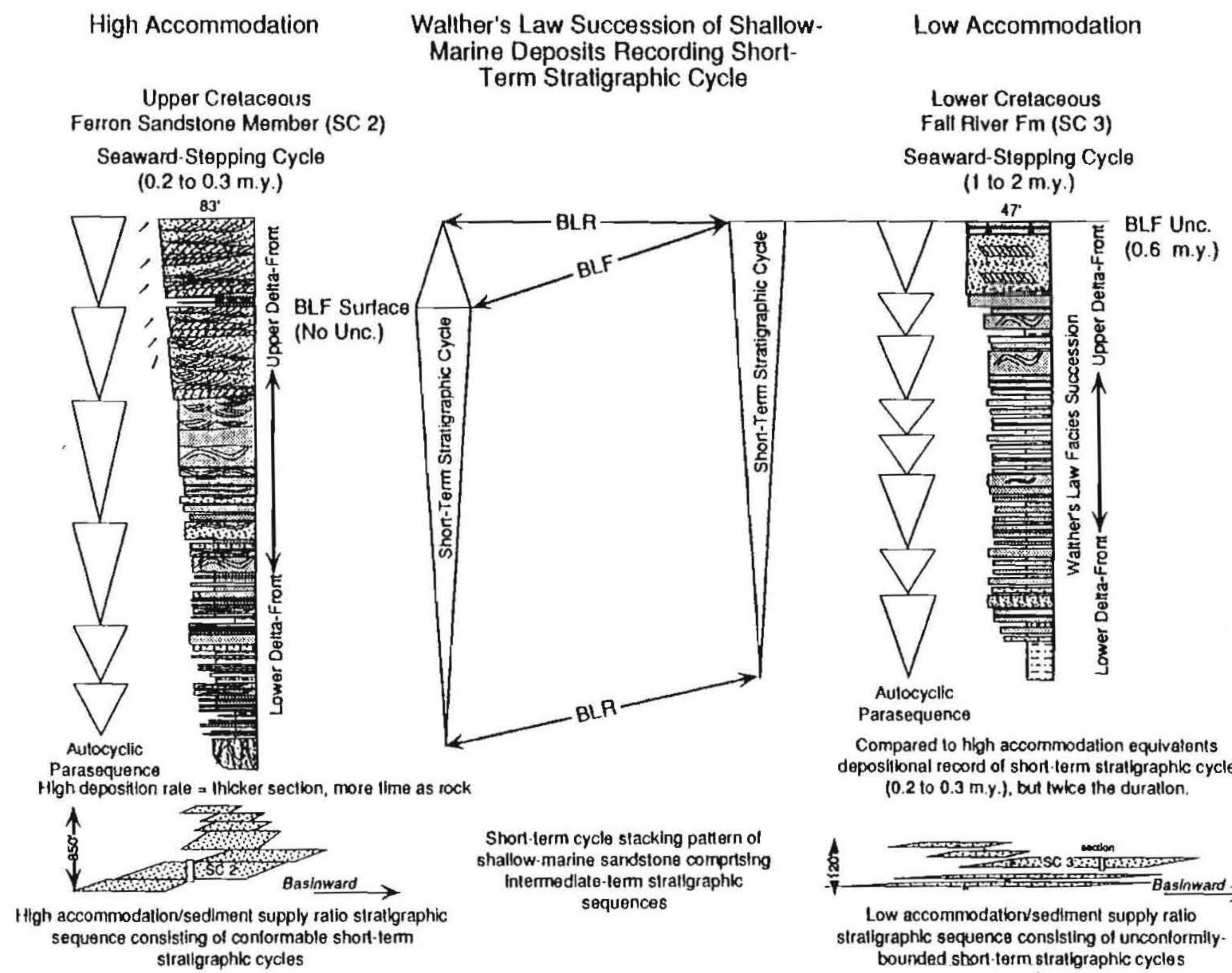



Figure 21—Accommodation and stratigraphic cycles architecture of shallow-marine deposits.

Hence, changing preservational conditions produces stratigraphic cycles of comparable thickness but of differing duration.

*Characteristics of low accommodation siliciclastic depositional systems*

Variations in tectonic subsidence, eustasy, and sediment supply produce changes in stratal architecture within chronostratigraphic units that require calibration. Chronostratigraphic units must also be calibrated to depositional system and sedimentary regime. For example, third-order depositional sequences are calibrated for shelf morphology, with shelf-slope and shelf-ramp profiles related to type I and II sequence boundaries, respectively (e.g., Posamentier and others, 1988). Facies succession comprising valley-fills are calibrated to sedimentary regime (e.g., Dalyrymple and others, 1993). There is, however, no such calibration to accommodation. Results from this study suggest that primary controls on valley fills are: (1) shelf physiography, (2) sedimentary regime, and (3) accommodation/sediment supply ratio.

Six short-term stratigraphic cycles, four with regionally extensive valley fills, are recognized across the 7,500 $mi^2$ area of the Black Hills suggesting the Fall River Formation records the same sea-level record. The thickness of the Fall River Fm., although increasing southeastward, is similar in the northern and southwestern Black Hills suggesting similar tectonic subsidence rates (the Fall River is thickest in the southeastern Black Hills, but valley fills are nested). In the northern Black Hills, successive short-term stratigraphic cycles consist of shallow-marine deposits locally replaced by discrete vertically and laterally isolated valley-fill deposits. By contrast, valley fills of successive short-term cycles in the southern Black Hills are highly interconnected and nested, with younger valley-fills erosively replacing older valley-fills producing pronounced lateral partitioning of shallow-marine and valley-fill deposits.

These changes in valley-fill architecture correspond to a southeastward progression to more landward paleoenvironments. Although shallow-marine deposits of short-term stratigraphic cycles in the northern Black Hills are commonly capped by paludal and nonmarine deposits, marine mudstones proportions increase northward, whereas the proportion of nonmarine deposits increase southward. Paleovalley trends and paleoflow indicators, however, suggest such proximal to distal facies changes are not within the same paleovalley. Instead two deltaic depocenters fed by trunk streams, and separated by a broad interdeltaic region in the central Black Hills are recognized. Higher proportions of marine mudstone in the northern Black Hills may reflect the outcrops position along the southern margin of the northern deltaic depocenter in southeastern Montana.

Across the Black Hills contributions from primary tectonic subsidence and eustatic controls to Fall River stratal architecture appear to be similar suggesting variations in sediment supply between discrete deltaic depocenters controlled observed along-strike changes from nested to unnested valley fills. This variation may reflect paleovalleys either under- or over-filled with sediment. Changes in sediment supply may occur along the same paleovalley, or between different paleovalleys recording the same record of base-level change.

Assuming along-strike changes in valley-fill architecture do not reflect only proximal to distal changes, and because the Fall River Fm. appears to record a similar sea level and tectonic subsidence history across the Black Hills, unnested valley-fills in the northern deltaic system may reflect increased sediment supply. Paleovalleys in the northern Black Hills appear to have completely filled during short-term cycles, while coeval paleovalleys to the south did not. Paleovalleys over-filled with sediment may have topographic expression producing unconfined fluvial systems that would achieve a gradient advantage by shifting position during the succeeding short-term cycle. Such paleovalleys would promote more frequent lateral shifting of fluvial channels producing laterally and vertically isolated valley fills. Hence, increased sediment supply rates in short-term cycles recording a low A/S ratio may be manifested as discrete unnested valley fills.

*Shallow-Marine Facies*

Conformable Fall River shallow-marine facies successions are arranged in autocyclic parasequences comprising short-term stratigraphic cycles. These resemble shallow-marine facies successions in the Ferron Sandstone, albeit thinner. To obviate a poor biostratigraphy, Fall River parasequence and short-term stratigraphic cycle durations were calibrated to comparable facies successions with better temporal resolution from the Ferron Sandstone (0.2 to 0.3 m.y. short-term stratigraphic cycles). This comparison suggests shallow-marine deposits of short-term stratigraphic cycles from both intervals record similar depositional records, but twice the temporal duration.

Biostratigraphic and isotopic age dates indicate the intermediate-term stratigraphic sequence comprising the Fall River Fm represents 4 million years, suggesting a 0.6 m.y. duration for each of the six short-term cycles. The longer temporal duration of Fall River short-term stratigraphic cycles could reflect either decreased sedimentation rates or a significant hiatus at capping subariel exposure surfaces. Similarities in depositional record suggest sediment supply changes required to account for such differences in temporal duration is implausible.

Despite low accommodation Fall River shallow-marine deposits contain a depositional record comparable to similar facies associations from the Ferron Sandstone (Fig. 21). Hence, sedimentological tendencies and trends in facies proportion, lithologic ratio, and sediment volume of successive short-term stratigraphic cycles may be anticipated from both units despite changes in accommodation. Shallow-marine deposits of successive Fall River short-term cycles change upward from tidal/fluvial-dominated to storm-dominated facies successions showing an upward increase in sandstone-mudstone ratio and decrease in facies proportion. Subariel exposure surfaces capping shallow-marine successions of short-term cycles are also wide-spread erosional surfaces locally flooring paleovalleys. Such surfaces mostly likely record significant periods of time and may account for the increased temporal duration of Fall River short-term cycles. Hence, low accommodation promotes unconformity development at a higher frequency than predicted from traditional sequence stratigraphic models.

The intermediate-term Fall River stratigraphic sequence is temporally and spatially comparable to a third-order depositional sequence (Vail and others, 1977). Unconformity-bounded third-order depositional sequences may be described by stacking patterns of higher frequency parasequences resembling Fall River short-term stratigraphic cycles (Van Wagoner and others, 1990). Short-term cycle stacking patterns in the Fall River resemble such depositional sequences, but higher frequency short-term cycles are unconformity-bounded. Third-order depositional sequences consisting of shorter-duration unconformity-bounded units are recognized as composite sequences, and high-frequency sequences, respectively (Mitchum and Van Wagoner, 1991). Because high-frequency sequences consist of parasequences, this stratigraphic hierarchy includes a chronostratigraphic unit (e.g. stratigraphic hierarchy consisting of composite sequence, high-frequency sequence, and parasequence) absent in unconformity-bounded short-term cycles (Fall River parasequences are local autocyclic units). Although stacking patterns of unconformity-bounded Fall River short-term cycles resemble parasequence sets of a third-order depositional sequence, an intermediate-term base-level fall unconformity is absent (third-order sequence boundary). These relations suggest tectonic subsidence may be a first-order control on accommodation, with low tectonic subsidence manifested in higher frequency unconformity development relative to comparable facies successions in areas with higher rates of tectonic subsidence (i.e., Ferron Sandstone). In this view, variations in initial, tectonically generated, accommodation are modulated by eustasy, with resultant accommodation filled by sediment at varying rates.

### *Valley-Fill and Fluvial Facies*

Distinguishing valley-fill from fluvial deposits is an important, but often equivocal criteria for calibrating to accommodation. Valley-fill interpretations span a broad spectrum of architectural styles, and existing facies models fail to describe such variability. Although changes in sedimentary regime of different valley-fill settings account for some facies variability, this also reflects the spectrum of fluvial responses to changing accommodation. Because both fluvial channel and valley-fill deposits are floored by an erosional surface that may or may not represent a stratigraphic unconformity, and because no consistent facies association distinguishes these deposits, sedimentological tendencies and preservational trends must be related to a record of base-level change.

Stratigraphic unconformities fundamentally represent a condition of no accommodation most likely to develop during base-level fall. Incised valley-fill deposits overlying such surfaces record base-level rise as an upward increase in marine influence, facies proportion, and lateral expansion of autocyclic sandstone bodies back-filling the paleovalley (Figs. 22). Erosive-based channel sandstone bodies are autocyclic units comprising both fluvial and valley-fill successions, but in valley fills erosive channel bases are confined within the major unconformity flooring paleovalleys. Major unconformity surfaces separate higher frequency erosive-based sandstone bodies from deposits they incise. On outcrop this is recognized by cross-cutting relationships, such that erosive channel bases do not cross basal valley unconformities.

Because unconformities flooring valley fills record significant periods of time, there is greater facies offset across such surfaces. For example, valley-fill facies successions in the Fall River of the Black Hills resemble coeval equivalents over 180 miles basinward in the Bighorn basin, where they are incise shelf strata and show westward sediment transport (Klave andVondra, 1993). Additionally, valley fills are generally an order of magnitude thicker than associated fluvial deposits in conformable Walther's law facies successions (Figs. 23 and 24).

By contrast, channel sandstone bodies interfinger with deposits they incise in conformable fluvial successions recording a comparable base-level cycle as first decreasing (base-level fall) and then increasing accommodation (base-level rise). Channel sandstone bodies rarely incises deposits of preceding stratigraphic cycles. This produces multi-storey and multi-lateral sandstone bodies recording a base-level fall to rise turnaround by lateral expansion of the channel-belt, decreased interconnectivity, and increased facies diversity reflecting a history of first decreasing and then increasing preservational trends in successive sandstone bodies. If base-level fall to rise turnarounds are not resolvable within such fluvial successions, then this base-level turnaround must occur at the basal erosional surface recording unconformity development during base-level fall (Fig. 25).

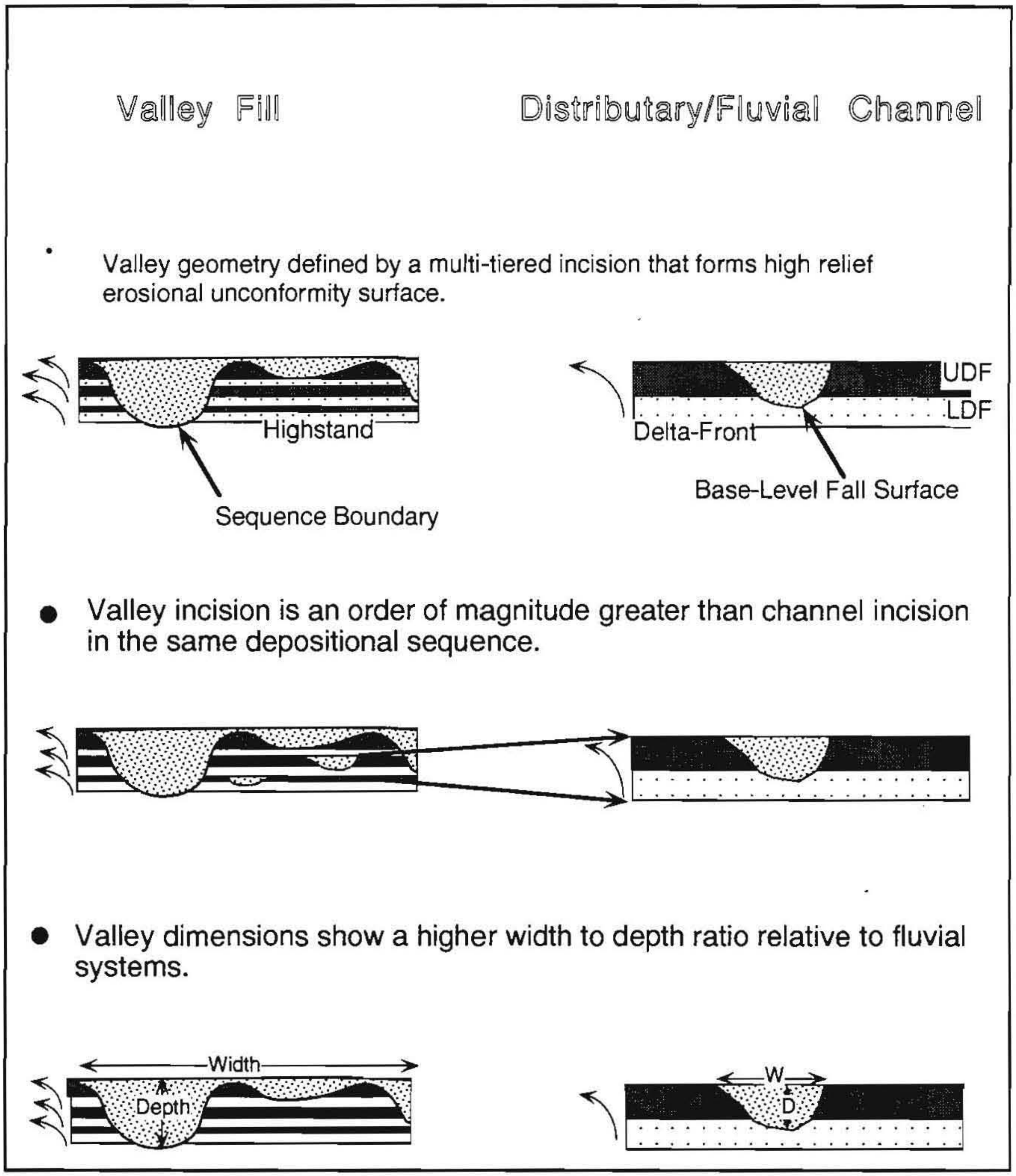



**Figure 22**—Objective criteria for distinguishing incised valley-fill deposits from distributary channel-belt deposits

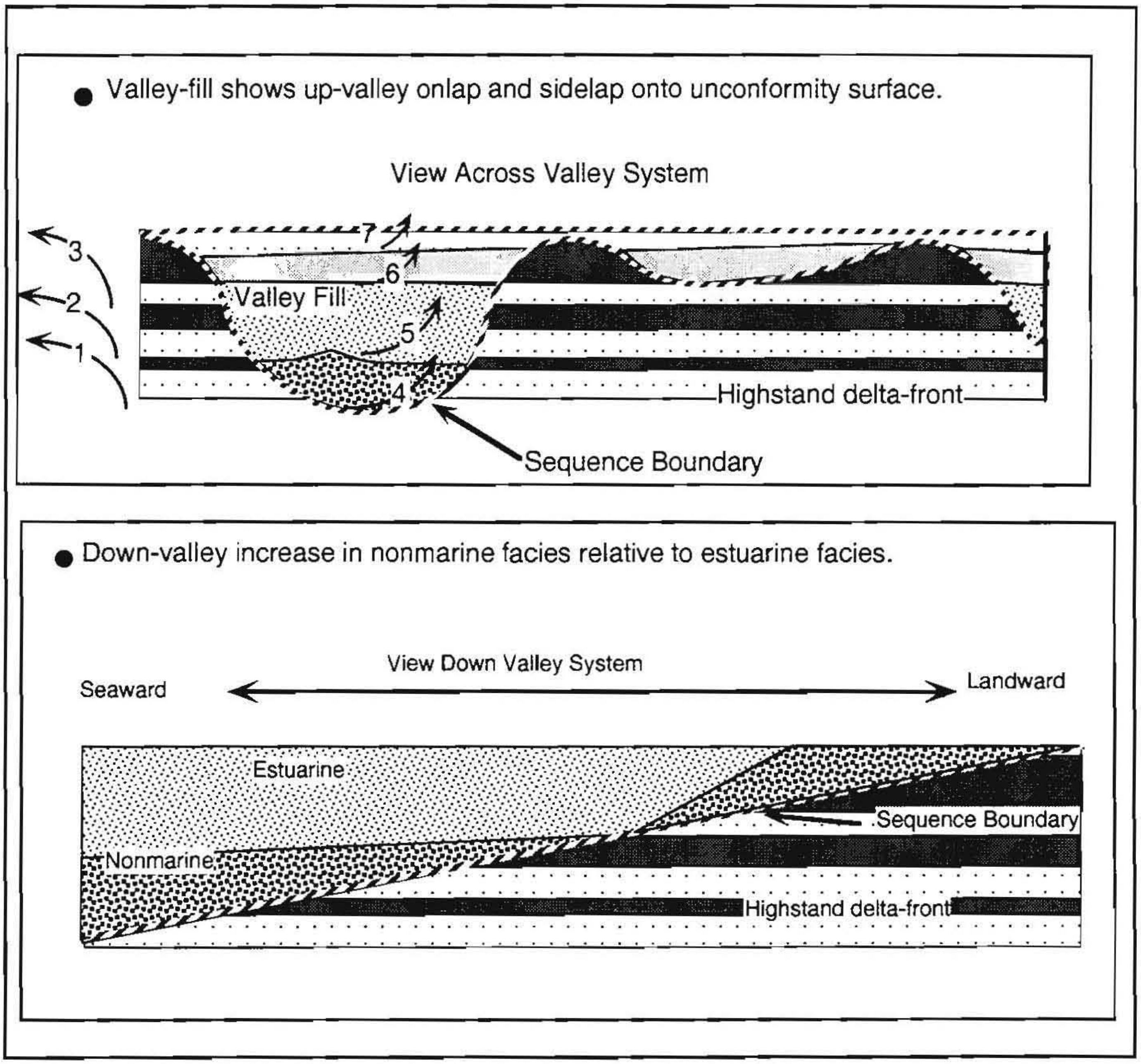



**Figure 23** —Objective criteria for distinguishing incised valley-fill deposits from distributary channelbelt deposits

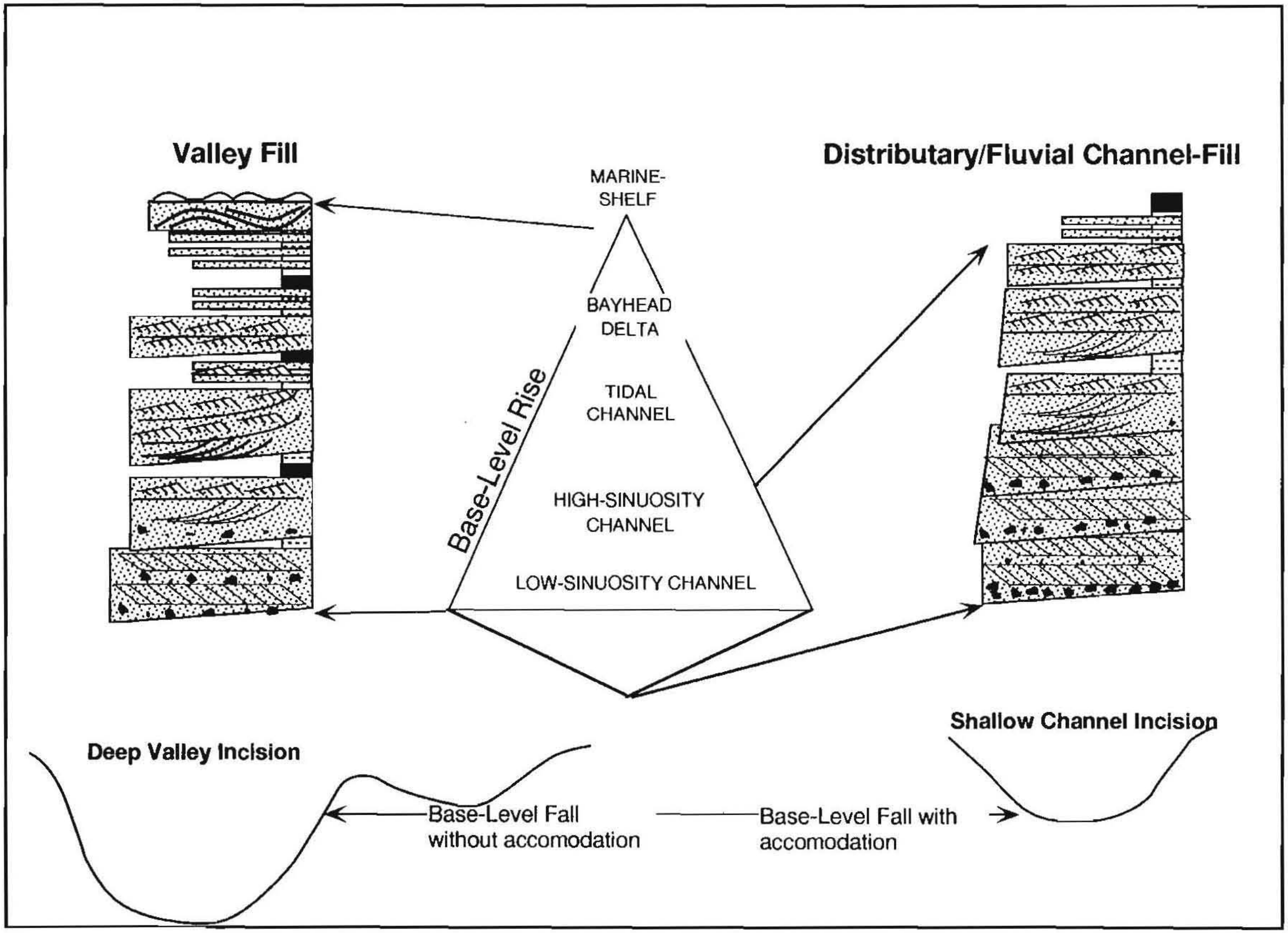



**Figure 24**—Diagram showing vertical facies successions from incised-valley-fill and distributary channel settings. Both settings record increasing accomodation; however incised-valley-fill deposits record a longer-term base level cycle that is embedded with short-term base-level cycle, which produces more orders of stratal cyclcity.

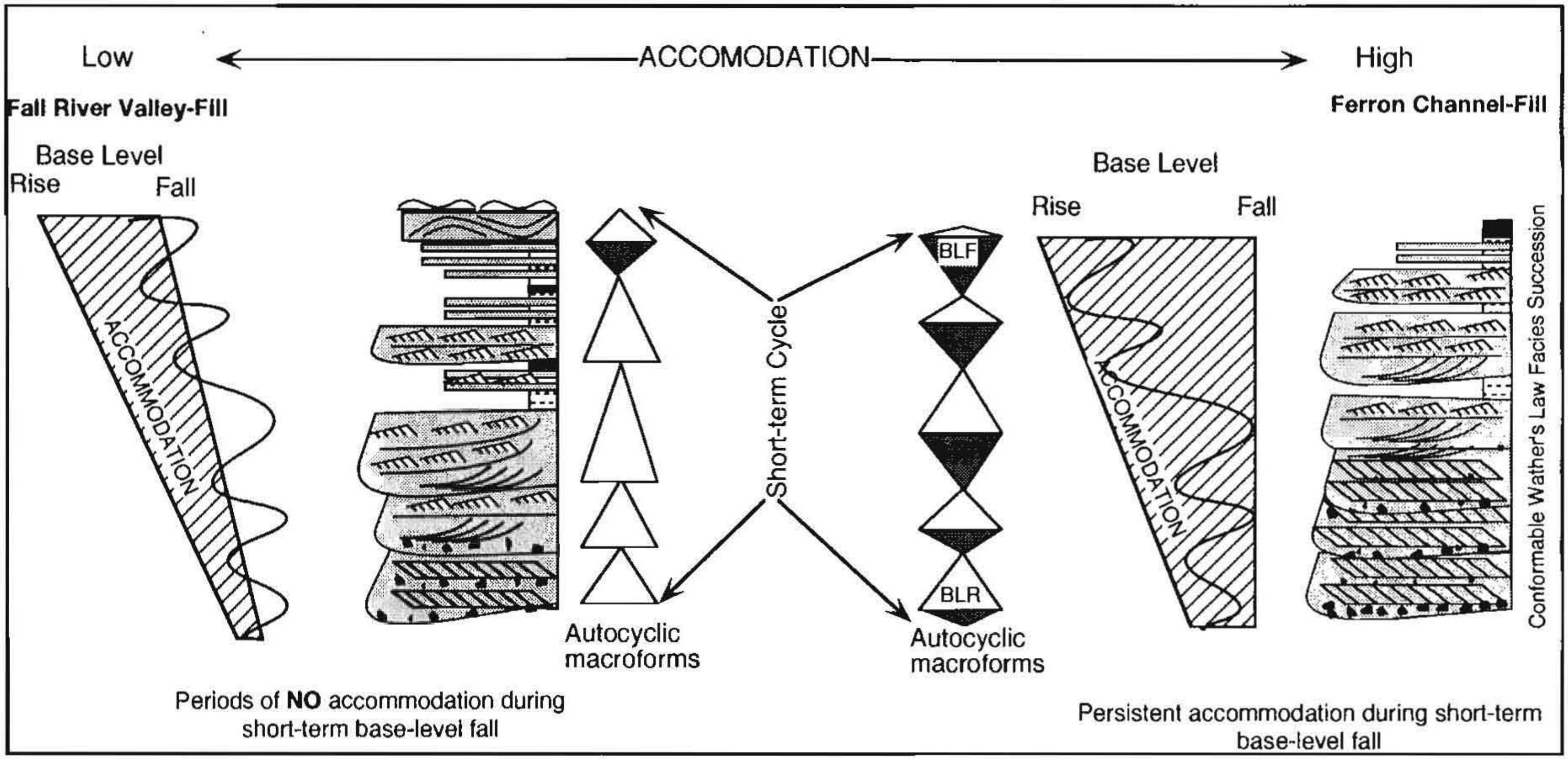



**Figure 25**—Schematic vertical profiles comparing facies successions from low and high accomodation settings. Autocyclicparasequences are superimposed on allocyclic short-term cycle recording base-level cycles of differeing periodicity. In a low accomodation setting periods of base-level fall occur under conditions of no accomodation. Thus, a comparable thickness of valley-fill strata records more time as surfaces relative to strata. These proportions change in deposit recording high accommodation, where facies successions are more fully preserved.

## Day One: Northern Black Hills

### *Discussion*

In the northern Black Hills, we will examine Fall River outcrops showing more distal facies deposited along the southern flank of the northern deltaic depocenter. The three stops here are generally arranged in a seaward to landward traverse of the northern depocenter (Figs. 26 and 27). Because valley fill successions of discrete short-term stratigraphic cycles are unnested and separated by marine mudstone tongues, they are more easily resolved.

The Fall River Formation in the northern Black Hills consists of three distinctive lithostratigraphic units: a lower sandstone-rich interval consisting of three laterally continuous sandstone benches, a middle slope-forming marine mudstone, and a thicker ridge-capping sandstone. The lower three benches comprise two seaward-stepping cycles locally replaced by deeply incised fluvial-dominated valley fills confined to narrow paleovalleys. The lower two benches consist of tidal/fluvial-dominated shallow-marine successions, each capped by a discontinuous rooted and goethite-rich horizon, whereas the uppermost bench consists of amalgamated hummocky cross stratified sandstones recording marine deepening and the initiation of a significant transgression that culminated in deposition of marine mudstones capping SC 2. The ridge capping sandstone comprises SC 3 and represents the most seaward-stepping short-term cycle containing the thickest and most basinward positioned shallow-marine sandstone exposed in the Black Hills. This storm-dominated shoreface sandstone is locally incised by wide and broad fluvial-to-estuarine valley fills (Fig. 28). Similar valley-fill deposits are incised into thin mudstone-rich shallow-marine sandstones of landward stepping SC 4. Shallow-marine deposits of SC 5 are locally present as thin shallow-marine successions best developed on the west side of the Bear Lodge Mountains, where the Fall River contains higher proportions of valley-fill and nonmarine deposits.

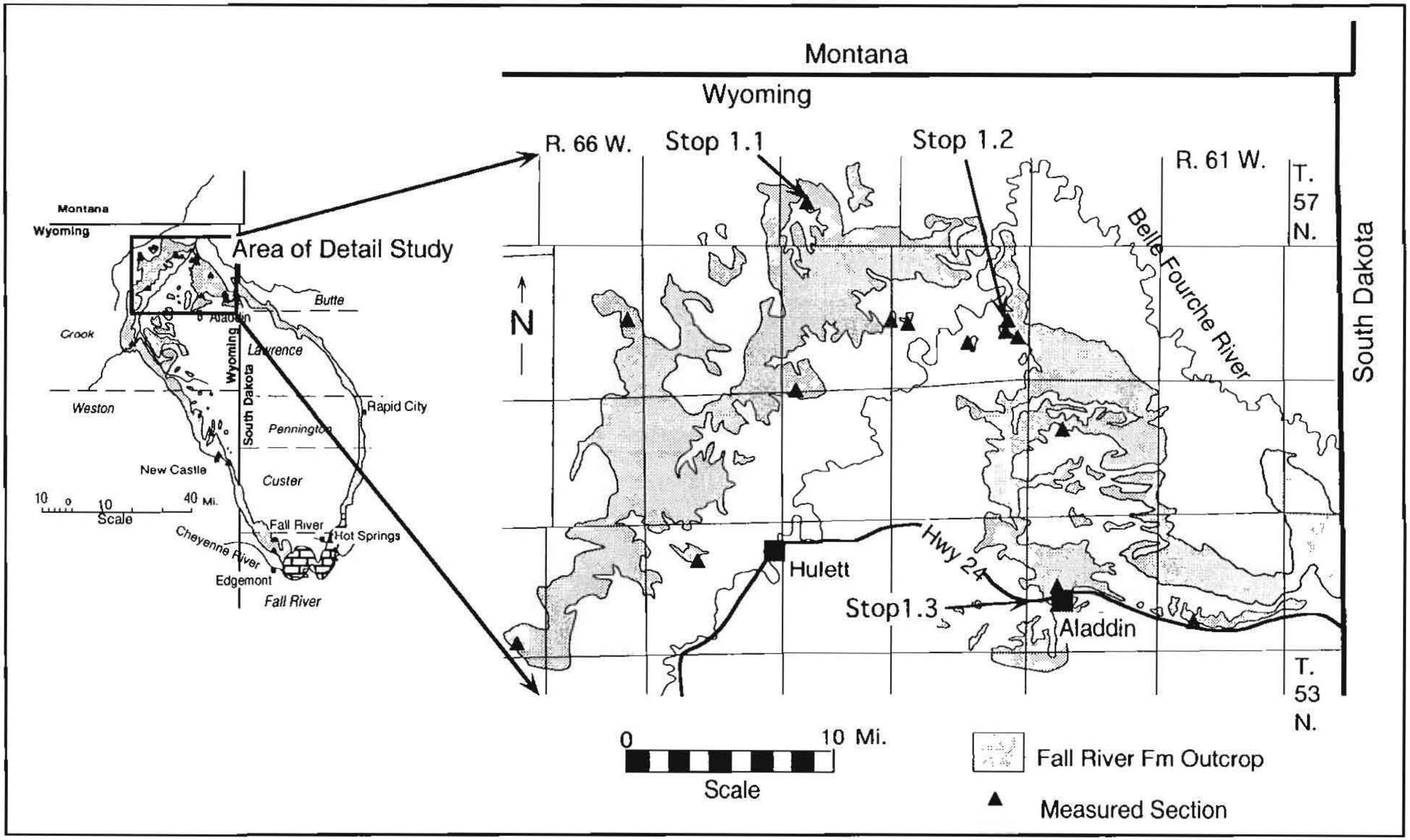



**Figure 26**—Location map for fieldtrip stops in the northern Black Hills.

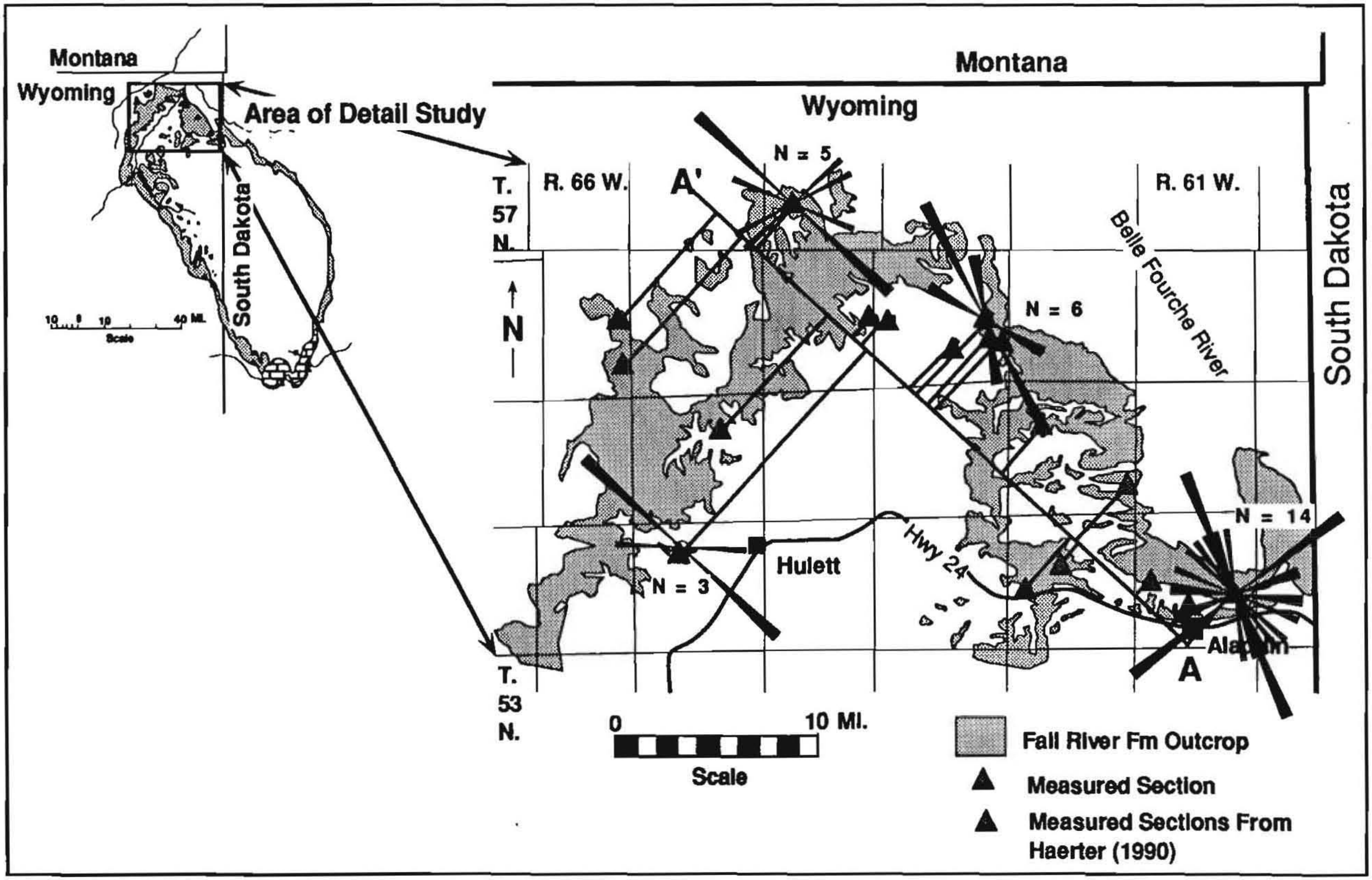



**Figure 27**—Map showing rose diagrams of symmetrical ripple crest orientations from shallow-marine sandstones of the Fall River Formation. The line of regional cross-section is oriented along depositional dip and perpendicular to the northeast shoreline trend.

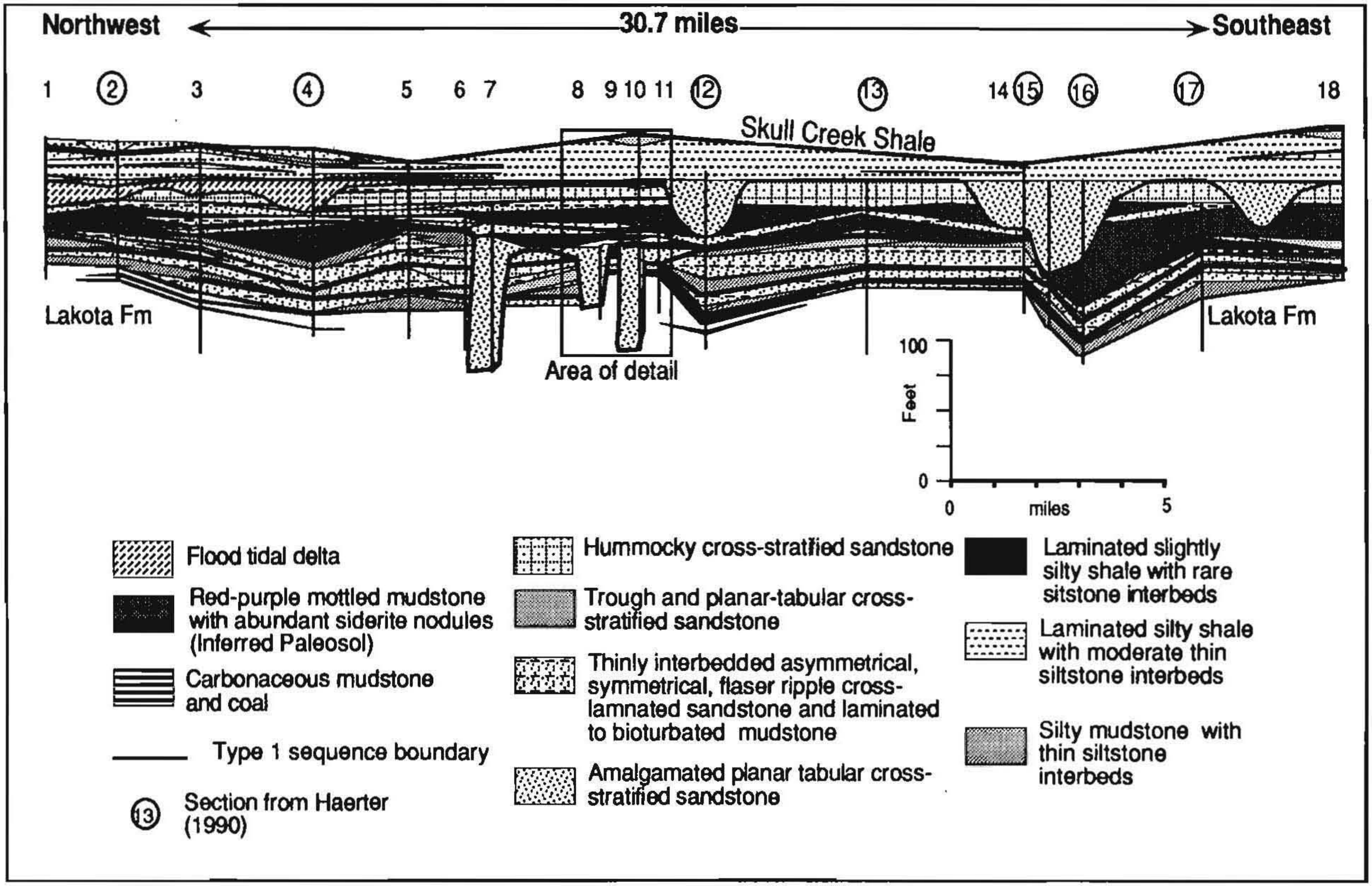



**Figure 28**—Stratigraphic cross-section along depositional-dip showing correlations and facies relations in stratigraphic cycles and depositional sequences of the Fall River Formation in the Northern Black Hills.

## Government Canyon

**Stop 1.1** Drive west 31 miles west on Interstate 90 from Spearfish, South Dakota to Sundance, Wyoming. Take the first exit (185) immediately west of Sundance, and turn right onto state highway 14. Drive 18.8 miles northwest to Devils Tower Junction. Turn right onto state highway 24 and drive 19.9 miles north to Hulett, Wyoming. Just before entering Hulett, turn left onto state highway 112 and drive 13.7 miles north. Just after the sign to Alzada, approximately 2 miles north of Seely, Wyoming turn left onto gravel road and drive north approximately 5.5 miles to Government Canyon locality. We will be driving across a private ranch, so please staying on roads if possible, do not make multiple tracks with vehicles, and shut all gates. Smoking is not permitted on private ranches.

**Objectives**

(1) Examine the Fall River and Lakota Formation contact.
(2) Contrast changes in shallow-marine facies associations of short-term stratigraphic cycles.
(3) Determine stacking pattern of short-term cycles comprising the intermediate-term Fall River stratigraphic sequence, and evidence for intermediate-term sequence boundary (?).

*Discussion*

The transgressive disconformity separating the Fall River Formation and Lakota Fms. is well exposed here (Fig 29). The upper part of the Lakota Formation consists of variegated red to yellow mudstones overlain by white siltstones containing upward-branching organic-lined traces of stem casts suggestive of an aggradational paleosol. Polished chert and quartzite pebbles are present in weathered slopes. Overlying the white siltstone are two thin carbonaceous mudstones beds that record a change from oxidizing to reducing conditions. The contact between the Lakota and Fall River Formations is placed at the base of overlying bioturbated and thinly bedded sandstone containing abundant goethite specks.

The three sandstone benches comprising the lower Fall River are sandstone-rich and well exposed here. The lower two sandstone benches consist of upward-shoaling shallow-marine successions grading up from marine mudstone to thinly interbedded sandstone and mudstone capped by a thicker, commonly erosive-based sandstone containing ripup clasts, transported carbonaceous material and amalgamated sets of unidirectional trough cross strata. Thinly bedded sandstones contain abundant goethite specks and nodules, low angle laminations, asymmetrical and symmetrical ripples, with crests commonly showing flow reversal. Trace fossils of low diversity include *Skolithos*, *Arenicolites*, and *Planolites* and increase in intensity upward, with up to 1 m long and 2 mm diameter vertical escape burrows (*Fugichnia* ?) commonly extending down from the top of capping

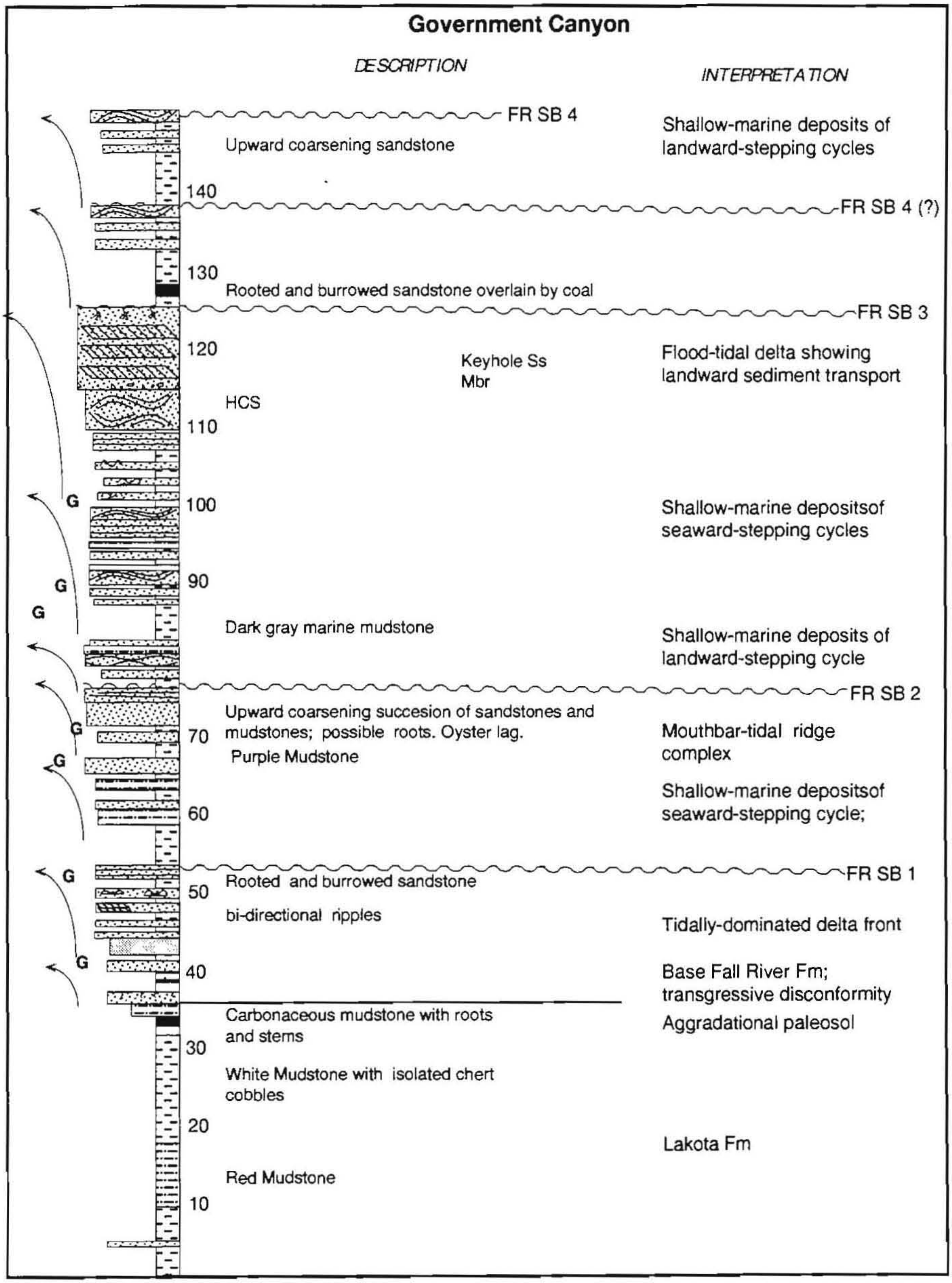
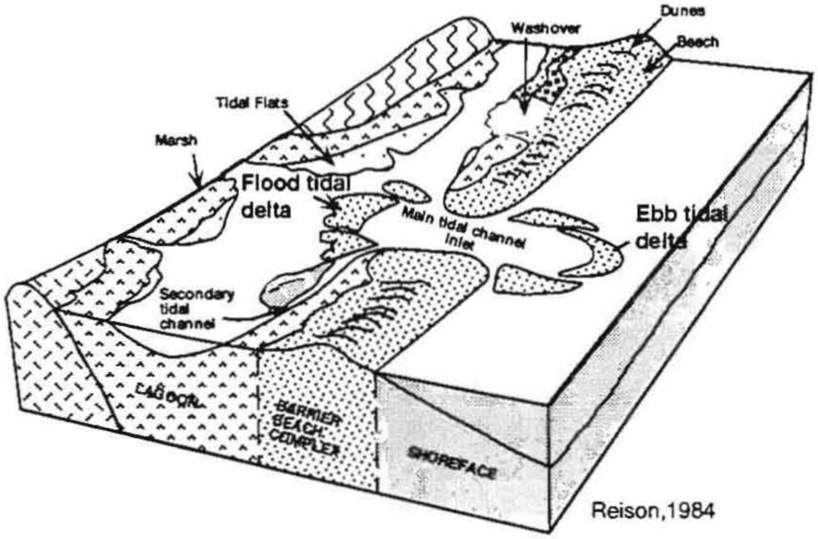



**Figure 29**—Vertical profile of the Fall River Formation at Government Canyon

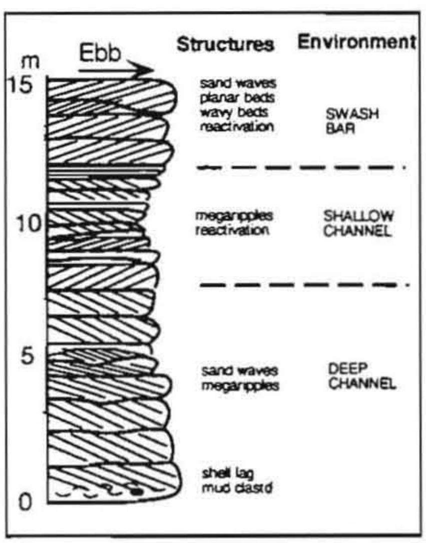
sandstone beds The SC 1 sequence boundary is placed at a thin rooted locally goethite-rich horizon capping the lowermost sandstone bench.. This vertical succession is inferred to represent an upward-shoaling tidally-dominated delta-front succession capped by tidal ridge-mouthbar deposits.

The second sandstone bench consists of two upward-shoaling parasequences containing a similar facies association, with the uppermost sandstone bench capped by well-developed goethite zone, locally rooted and interpreted to represent the SC 2 sequence boundary. The third sandstone bench in the lower Fall River shows a conspicuous increase in mudstone content, burrowing intensity, and contains the first hummocky cross stratified sandstone in the Fall River Fm. This upward-deepening facies succession is inferred to represent a landward-stepping parasequence recording SC 2 base-level rise and culminating in deposition of the thick marine mudstone separating lower and upper Fall River sandstones here.

SC 3 consists of three sandstone-rich, upward-shoaling, shallow-marine parasequences showing a conspicuous increase in proportion of hummocky cross-stratification. These cycles show a progressive increase in thickness, sandstone proportion, and shallower water facies. The cliff capping sandstone representing the uppermost parasequence is the Keyhole Sandstone Member (Davis and Izett, 1958) consists of hummocky cross-stratified sandstone erosionally overlain along a low-relief surface by amalgamated sets of unidirectional planar-tabular cross-strata showing landward (southwest) paleoflow. These planar-tabular sets stack to form 1 to 2 m thick bedsets separated by gently inclined, landward dipping surfaces. Such inclined surfaces apparently formed under the same hydraulic regime as smaller-scale bedsets recording and record punctuated landward sediment transport. This vertical facies succession showing landward directed sediment transport is consistent with deposition of a flood-tidal delta, possibly located at the mouth of a paleovalley (Fig. 30). The top of this sandstone is rooted, burrowed and overlain by a thin coal bed present throughout the northern Black Hills. The SC 3 sequence boundary recording both short- and intermediate-term base-level fall to rise turnarounds is placed at this rooted horizon, with the coal inferred to record base-level rise. This coal is overlain by landward-stepping SC 4 and 5, here consisting of progressively thinner and more mudstone-rich, upward-shoaling shallow-marine successions.




**Ebb-tidal Delta Sequence**
Hayes,1980




**Flood-tidal Delta Sequence**
Reison, 1984, after Hayes,1980

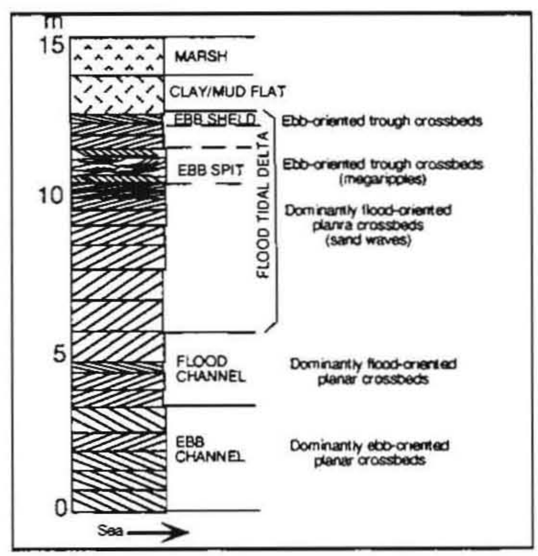



**Figure 30**–Wave-dominated shorezone and associated deposits.

## Buffalo Basin

**Stop 1.2** Retrace route back to Hulett, WY to intersection of Hwy. 112 and Hwy. 24. Turn left (east) onto state Hwy. 24 and proceed through Hulett and drive 8.4 miles to intersection with gravel road marked by sign to A. L. Ericsson Ranch. Turn Left (north) onto gravel road and drive about 23 miles to the lone abandoned building of the Mona townsite and Fish Ranch. Drive 0.8 mi east of the Fish ranchhouse to intersection with gravel road. Turn Left (north) onto gravel road and drive 1.2 mile to left turn through hayfield and gate onto track leading to the outcrop.

**Objectives:**

(1) Examine fluvial-dominated valley-fill of SC 2
(2) Examine rooted SC 3 sequence boundary capping the Keyhole Ss Mbr
(3) Examine SC 4 fluvial deposits

*Discussion*

This stop is about 11 miles to the southeast and landward of Government Canyon. The Lakota Formation is well exposed on Mona butte, across the valley to the west of here. At Mona Butte, the Lakota Formation consists of a thick fluvial succession containing black chert pebble conglomerate lenses. Here, the upper Lakota consists of red mudstone and sandstone sporadically exposed.

Fluvial-dominated valley-fill sandstones of SC 2 are well exposed here forming a massive cliff. This sandstone buttress is oriented along depositional dip of SC 2 valley-fill deposits, with a cross-sectional view of this paleovalley well exposed along north-south tending exposures to the east. Note the abrupt southward change from fluvial sandstone forming the massive cliff to bench-forming upward-shoaling shallow-marine sandstones of SC 1 and 2 (Fig. 31). SC 2 valley-fill deposits consist of highly interconnected, multistory, erosive-based sandstone bodies 10- to 15-ft thick. Such sandbodies commonly contain a goethite-bearing basal clay-pebble lag overlain by amalgamated sets of unidirectional planar-tabular cross strata, with some overturned and oversteepened sets and minor burrowing that increases upward. Planar tabular cross bed sets commonly are truncated by reactivation surfaces and generally decreasing in size upward. Discrete sandbodies contain inclined surfaces oriented at a low angle and/or parallel to internal cross strata and are inferred to represent downstream accretion surfaces of alternate bars.

SC 3 consists of a poorly exposed upward-shoaling shallow-marine succession capped by a rooted hummocky-cross-stratified sandstone. This rooted sandstone correlates to the rooted ridge-capping sandstone (flood-tidal delta) at Government Canyon and represents the SC 3 sequence boundary.

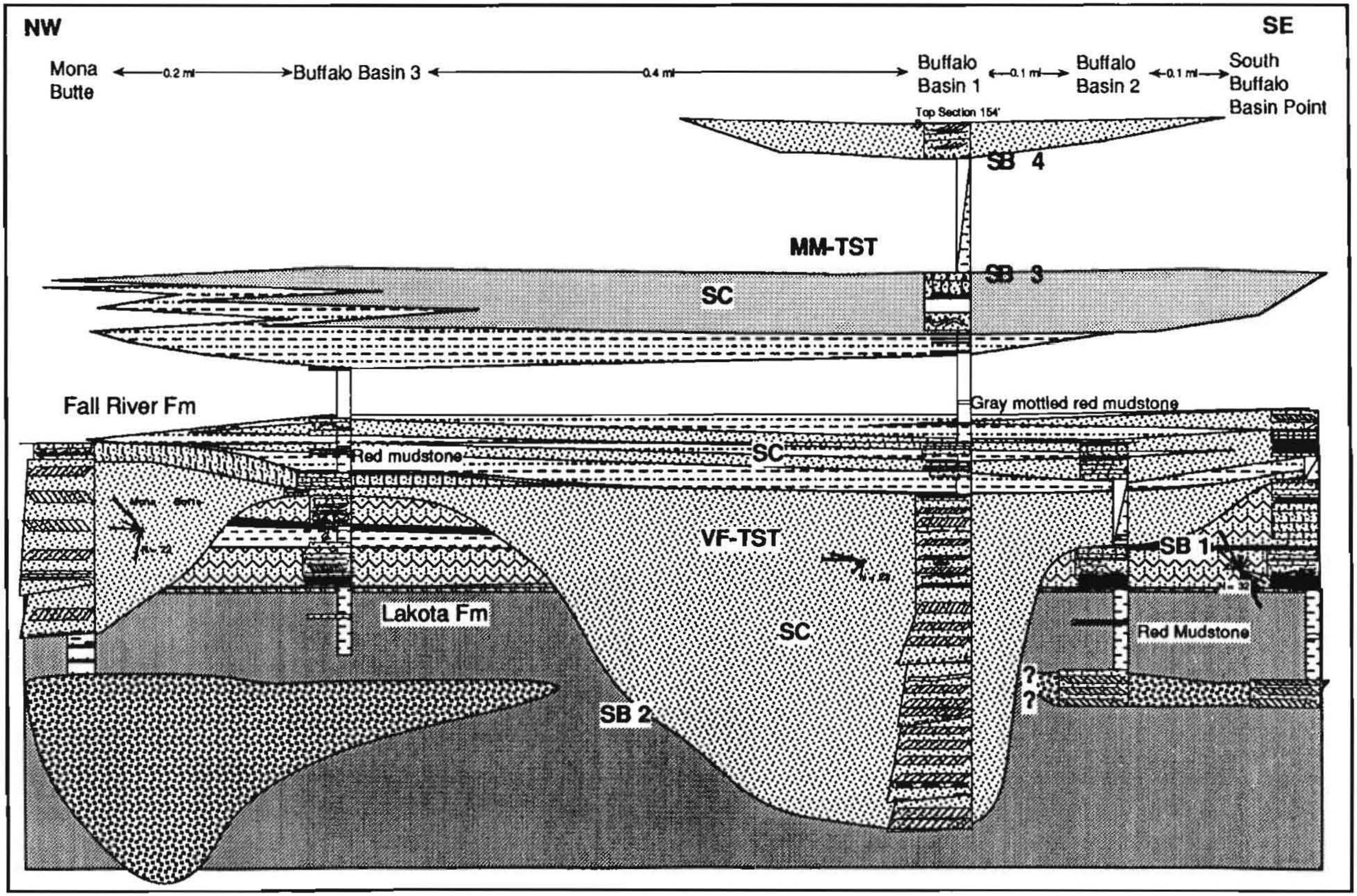



Figure 31—Stratigraphic cross-section oblique to depositional dip of Fall River Formation in the Buffalo basin region

SC 4 caps the ridge and consists of fluvial-tidal channel sandstone.

Unnested valley-fills of short-term cycles in the northern Black Hills consist of fluvial-dominated to mixed fluvial-estuarine facies successions. Such facies changes may record paleovalleys either under- or over-filled with sediment, with the effectiveness of valley filling recording accommodation changes of short-term stratigraphic cycles. Valley fills in seaward-stepping cycles are typically fluvial dominated. Increased fluvial facies proportions in downstream reaches of these paleovalley may record more efficient upstream fluvial bypass during short-term base-level fall, and a more pronounced basinward-shift in proximal fluvial facies resulting in fluvial aggradation in more downstream reaches. By contrast, valley-fills of landward-stepping cycles may record decreased efficiency of upstream bypass, minor basinward translation of fluvial facies resulting in increased estuarine facies proportions in downstream reaches of the valley. Such mixed fluvial-estuarine facies successions show an upward increase in estuarine facies proportions.

## Bearlodge Mountain Roadcut

**Stop 1.3** Retrace route to intersection with Ericcson road. Turn left (east) and proceed 0.3 mi to right turn (south) onto dirt track. Proceed 2.6 miles on private land through three farm gates to national forest access gate. At 5.5 miles take left fork onto forest service road 830. Continue on forest service road 830 17.1 miles to intersection with state highway 24. Turn right (west) onto highway 24 and drive 0.3 miles to Bearlodge Mountain roadcut. We will park near the top of the pass and walk down along the road. Watch out for logging trucks!

After stop, proceed 7 miles east on Highway 24 to intersection with State Highway 111, about 1 mile west of Aladdin, WY. Note valley-fill sandstones of SC 3 capping ridge on north side of road. Turn right (south) onto State Highway 111 and drive about 8 miles to intersection with Interstate 90. Turn right (west) and drive 12 miles to Sundance, WY.

**Objectives:**

(1) Contrast interdistributary tidal flat facies in SC 1 and 2 with Government Canyon facies successions
(2) Examine conformable equivalents to SC 1 and 2 sequence boundaries
(3) Examine mixed fluvial-estuarine valley-fill deposits of SC 3

*Discussion*

This stop is about 19 miles southeast and landward of Government Canyon, and about 8 miles southeast of the Buffalo Basin. Exposed near the base of the roadcut on the north side of road, the upper 6 m of Lakota Formation consists of a red mudstone overlain by a white slope-forming siltstone and thinly bedded sandstone (Fig. 32). The transgressive disconformity separating the Lakota and Fall River Fms is marked by an erosive-

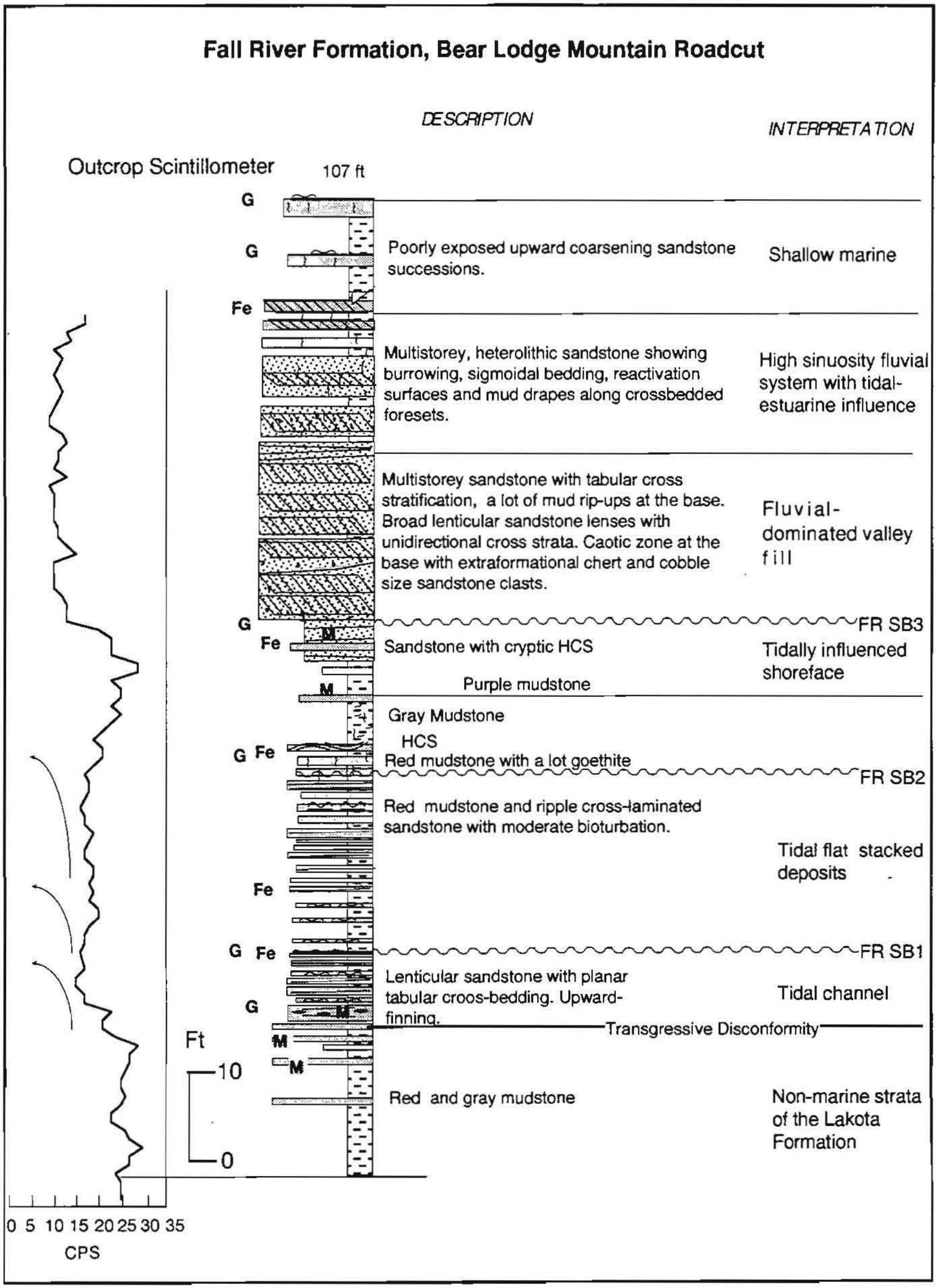



**Figure 32**—Vertical profile of the Fall River Formation with outcrop scintillometer data from the Bearlodge Mountain roadcut

based, upward-fining, dark tan sandstone (0.5 m thick) consisting of stacked sets of trough cross strata and rounded clay-pebble ripup clasts containing abundant hematite and goethite coatings.

Shallow-marine deposits in seaward-stepping short-term cycles consist of two main upward-shoaling successions: (1) heterolithic interdistributary bay deposits consisting of stacked tidal flat deposits, and (2) sandstone-rich delta-front deposits capped by lenticular distributary mouthbar sandstone bodies (100's of m wide and 1 to 2 m thick). Sandstone-rich distributary mouthbar sandstone successions characterize SC 1 and 2 at Government Canyon. Here, SC 1 and 2 comprise a heterolithic succession of interdistributary tidal flat deposits. These short-term cycles are thin (10 m thick) and mudstone-rich, consist of numerous 1 to 2 m thick upward-shoaling parasequences, and capping subariel exposure surfaces are absent, suggesting lower sedimentation rates and deeper water deposition. The three sandstone benches characterizing the lower Fall River across the northern Black Hills are less conspicuous here. Instead this roadcut provides a rare exposure of sandstone-poor covered intervals commonly separating sandstone benches.

The transgressive disconformity separating the Lakota and Fall River is overlain by an erosive-based upward-fining sandstone overlain by 2 tidal flat parasequences, each capped by thin marine mudstone. SC 1 tidal flat parasequences consist of tabular to broadly lenticular sandstone beds (up to 30 cm thick) that thicken upward, contain a diverse suite of asymmetrical, symmetrical, and flaser ripples, and sharp to slightly erosional bases, and ripple laminated tops showing *Planolites* and *Skolithos* trace fossils. SC 2 consists of 3 similar tidal flat parasequences, but the upper parasequence is capped by a red goethite-bearing and iron-stained mudstone recording oxidized conditions during maximum base-level fall. This mudstone is overlain by a hummocky cross stratified sandstone that grades upward to a dark gray bioturbated mudstone mottled red and purple in the middle and black to gray at top, and containing vertical 2 mm diameter sandstone-filled tubes, spreite-filled vertical tubes, and a crocodile tooth (*Teleorhinus*, identified by Chris Collom, pers. commun., 1993). A similar upward-deepening facies succession caps SC 2 forming the middle mudstone bench at Government Canyon and across the northern Black Hills.

SC 1 and 2 show increased resolution of thin upward-shoaling parasequence here. Enhanced resolution of such thin stratigraphic cycles may record lateral facies changes from more proximal and sandstone-rich delta-front deposits at Government Canyon to more mudstone-rich and sediment starved interdistributary deposits here. These changing depositional styles may also reflect along-strike facies changes along the southern margin of the northern deltaic depocenter.

The middle mudstone is overlain by a burrowed dark gray siltstone that coarsens up to a light tan sandstone displaying faint low-angle and hummocky cross-stratification and capped by a resistant iron-stained zone. This sandstone correlates to the SC 3 Keyhole Sandstone Member at the previous two stops and is thin here by erosion. Abundant goethite-bearing and iron-stained sandstone and mudstone ripup clasts, extraformational chert cobbles, and large chaotic sandstone blocks locally mark the irregular contact separating this shallow-marine sandstone from overlying valley-fill deposits.

Fluvial-estuarine valley-fill deposits of SC 3 are 11 m thick and cap the ridge for 13 km eastward toward Aladdin, Wyoming. Exposures of this valley fill here show 5 highly interconnected erosive-based sandstone bodies (2 to 4 m thick). The lower part of this valley-fill consists of fluvial sandstone bodies containing stacked sets of unidirectional planar-tabular cross strata decreasing in thickness upward. Clay-pebble rip-ups are common at set boundaries and at erosional bases of discrete sandstone bodies suggesting significant erosion and cannibalization. The upper 3 m of this valley fill shows an upward increase in burrowing and a change in bedding style to thinner sets of planar tabular and trough cross strata, and asymmetrical ripple-laminated sandstone beds interbedded with thin mudstones. Reactivation surfaces, mud drapes and sigmoidal bedding in heterolithic, lenticular and burrowed sandstones in the upper valley fill record increasing marine and tidal influence. Mudstone ripup clasts changing upward to mudstone interbeds may also reflect increasing preservation. Such distal estuarine deposits overlying more proximal fluvial deposits record progressive back-filling of a paleovalley.

## Day 2: West Central Black Hills

*Discussion*

Outcrops along the west flank of the Black Hills cross the two Fall River deltaic depocenters. Today we will examine traverse a broad interdeltaic region extending from Keyhole Reservoir in the northwest, to Osage, Wyoming in the southeast. Paleovalleys are absent across this region and the proportion of shallow-marine deposits is high. Stops are arranged from northwest to southeast and corresponds to a landward progression toward more proximal paleoenvironments in the southern deltaic depocenter (Fig 33).

Syndepositional movement along preexisting tectonic blocks and lineaments has been shown to control the position of fluvial systems producing paleovalleys (Bridge and Leeder, 1978; Weimer, 1984; Alexander and Leeder, 1989). Many workers have recognized the role of structural lineaments controlling the position of Early Cretaceous fluvial systems; Lakota and equivalents in the Wind River and Bighorn Basin (May and other, 1992, DeCelles, 1992, Klave, 1993, 1994, Dolson and Mueller, 1994); Fall River equivalents in the Bighorn basin (Klave, 1993); the Fall River in the Black Hills region (Gott, 1974; Slack, 1981, Way and others, 1994), and the Muddy Sandstone and equivalents across the central Western Interior (Weimer, 1978, Berman and others, 1980, Gardner and Gustason, 1987, Wheeler and Gustason, 1988; Dolson and Muller, 1994).

In the Black Hills region, the northeast-trending Belle Fourche Arch is recognized as an important paleotectonic element affecting the position of Early Cretaceous fluvial systems (Slack, 1981; Way and others, 1994; see Plate 3). The absence of paleovalley deposits along the western margin of Black Hills suggests the Belle Fourche Arch may have formed a paleohigh during Fall River deposition. More recent mapping along the east flank of the Black Hills, however, shows two north to northwest trending fluvial systems, flanking the margins of the Black Hills uplift, and crossing the inferred northeast-trending Belle Fourche Arch. Although the Belle Fourche Arch apparently deflected a northwest trending fluvial system exposed along the west flank of the Black Hills farther westward (i.e., Donkey Creek and Miller Creek subsurface trend west of Fall River outcrops), and controlled the position of deltaic depocenters in the northern and

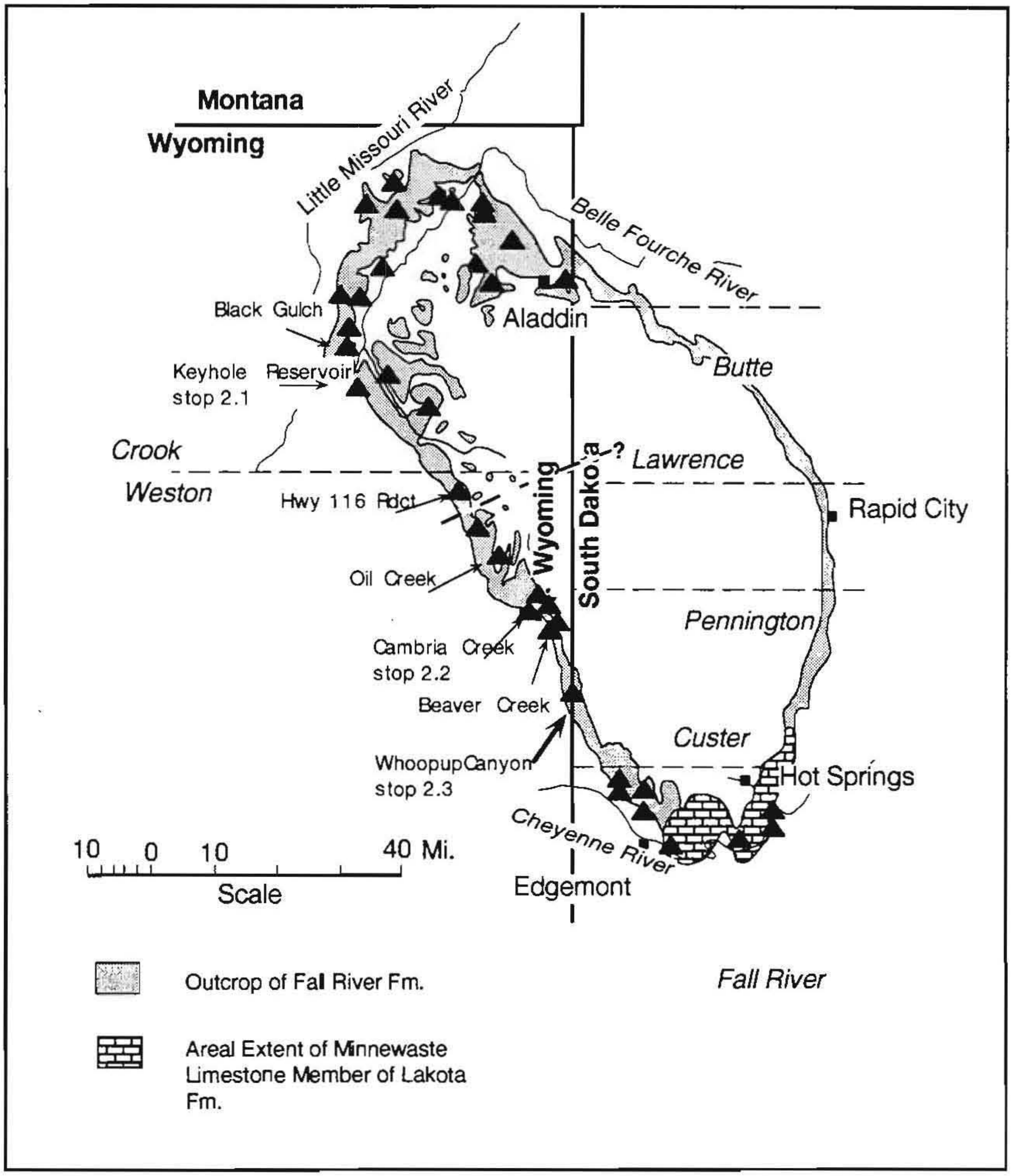



**Figure 33**—Location map showing field trip (day 2) stops in the Black Hills

southern Black Hills, it did not affect the general northward drainage of southeast sourced Fall River fluvial systems.

The first stop today at Keyhole Reservoir (stop 2.1) shows SC 3 exposures consisting of well developed storm-dominated shallow-marine facies. This stop is about 60 km along depositional strike from Buffalo Basin locality, stop 1.2, where this interval consists of a thin shallow-marine sandstone capped by roots. Southeast along the west Flank of the Black Hills, similar facies characterize the landward limit of SC 3 shallow-marine sandstone. Near Newcastle, Wyoming, (stop 2.2) SC 1 and 2 comprise nested valley fills. Here, SC 1 valley-fill deposits consist of fluvial-dominated valley fills resembling equivalents in the northern Black Hills. These are incised by SC 2 estuarine-dominated valley-fill deposits. This valley fill is correlative to the thick mudstone interval separating lower and upper sandstone horizons in the northern Black Hills and records the greatest marine influence. In the southern deltaic complex, SC 3 and 4 valley-fill deposits change upward from fluvial to estuarine and resemble coeval equivalents in the upper Fall River of the northern Black Hills. Cliff forming valley-fill sandstones of SC 4 comprise a fluvial meanderbelt confined to a broad and shallow paleovalley in this region.

## Black Gulch Overview

(Optional)

**Stop 2.1a** From Sundance, Wyoming drive west on state highway 14 18.8 miles northwest to Devils Tower Junction (intersection of Hwy. 24 and Hwy. 14). Proceed 1.8 miles past intersection (west) to left turnoff onto Kara Creek ranch road. Turnoff is 0.1 mi. east of Belle Fourche River bridge. Turn left (south) onto gravel road; at 3.8 miles road forks, bear right and drive 1.7 mi to Black Gulch overview.

**Objectives:** (1) Examine vertical succession of Fall River Formation

*Discussion*

In the Keyhole Reservoir area the Fall River consists of 2 sandstone-rich intervals separated by slope-forming mudstone (Fig. 34). The three sandstone benches of the lower Fall River resemble facies successions examined at Government Canyon. The lower two upward-shoaling successions consist of tidally-dominated delta-front sandstones capped by tidal sand ridge/mouthbar complexes rooted and goethite-rich. The uppermost sandstone bench of the lower Fall River consists of thin hummocky cross-stratified sandstone. Slope forming marine dark gray laminated silty shale separates the lower and upper sandstone benches. Ridge-capping sandstones of the Keyhole Sandstone Member are well developed here and consist of storm-dominated, tidally influenced delta-front facies locally incised by tidal channels. Note truncation surface descending from left to right across cliff top. SC 4 is locally preserved above the ridge-capping sandstone and resembles exposures at Government Canyon.

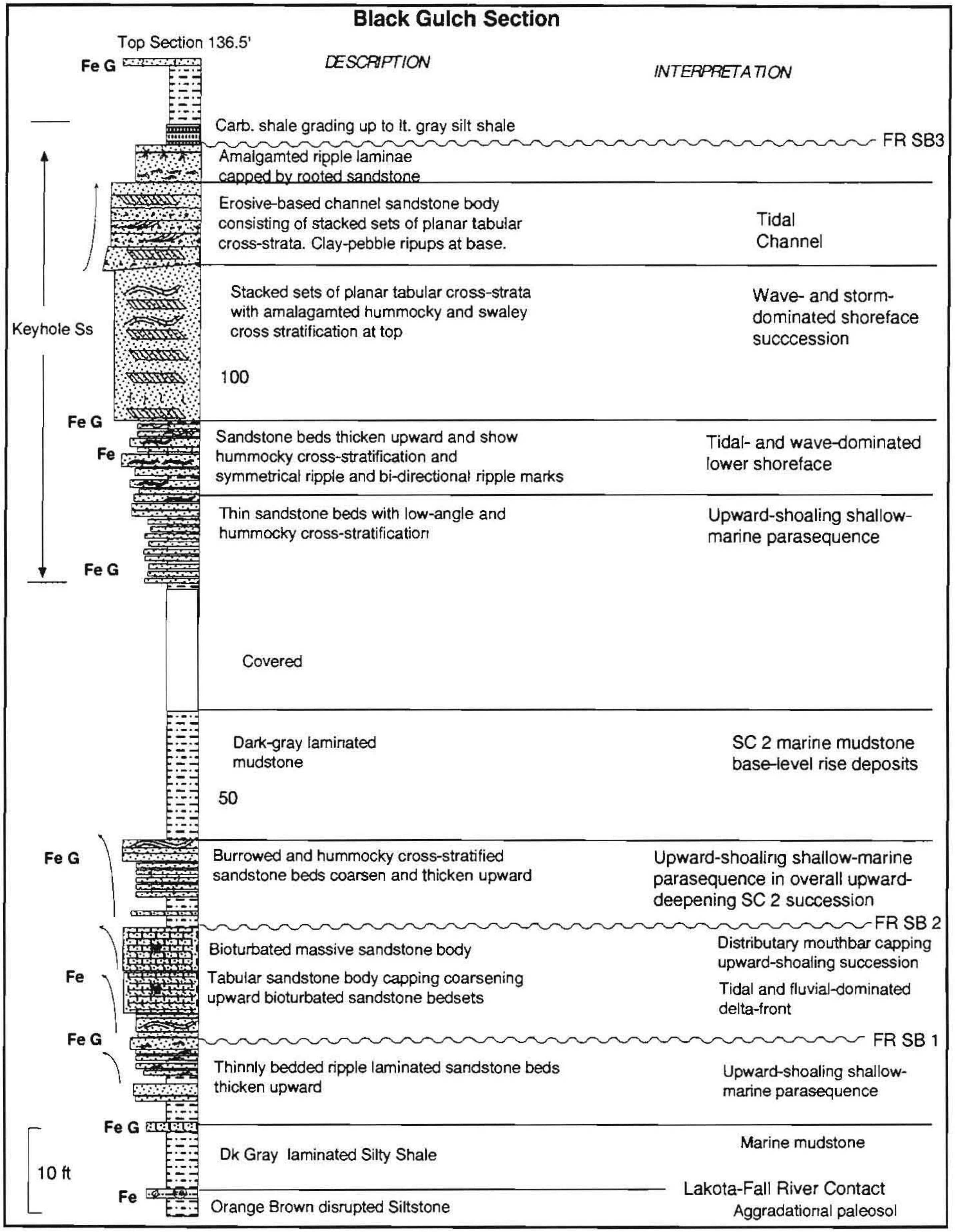



**Figure 34**—Vertical profile of Fall River Formation at Black Gulch.

## Keyhole Reservoir

**Stop 2.1** Continue 5.1 miles south on Kara Creek road driving through Fall River exposures (top at 3.7 miles), to right (west) turn to Keyhole Reservoir damsite. From right turn drive approximately 4.5 miles to stop below the dam along the east bank of the Belle Fourche River. Retrace route back to dam and examine lower Fall River on the west side of reservoir. Retrace route back to intersection with Kara Creek Road, turn right (south) and drive 2.0 miles past campground to right turn to Coulter bay on southeast side of reservoir.

**Objectives:**

(1) Contrast upward change from tidal- to storm-dominated facies in shallow marine deposits of the Fall River Formation
(2) Examine storm-dominated and tidally influenced delta-front facies of SC 3 and capping sequence boundary

### *Discussion*

Exposures of the upper Lakota Formation here consist of two highly interconnected sandstone bodies. Sandstone-matrix-supported black chert pebble conglomerates in the lower sandstone body are exposed at river level.

Overlying shallow-marine deposits of the Fall River are well developed here (Fig. 35). These deposits show the same consistent upward increase in storm-dominated facies that characterizes the lower Fall River in the northern Black Hills. SC 1 and 2 comprise the lower Fall River and are best exposed near the dam. These short-term stratigraphic cycles consist of four thin (up to 2.5-m-thick), upward-shoaling shallow-marine parasequences consisting of thinly interbedded mudstone and sandstone containing a diverse suite of asymmetrical, symmetrical, and flaser ripples. Trace fossils of *Planolites* and *Skolithos* show minor burrowing on sandstone bedding planes. Hummock cross-stratified sandstone of the uppermost lower Fall River sandstone bench is overlain by slope-forming mudstone of the middle Fall River. Ridge capping sandstone of the Keyhole Sandstone Member consists of 2 upward-shoaling parasequences forming upward-coarsening and sandstone bed-thickening successions (up to 1.5-m-thick). Thinly interbedded mudstone and hummocky cross-stratified sandstone capped by symmetrical ripples change upward to amalgamated hummocky cross-stratified sandstone overlain by trough to planar-tabular cross strata showing diverse, multi-directional paleoflow. These sandstones are overlain by low-angle seaward-dipping laminations rooted and burrowed at top, and overlain by a thin coal also present at Government Canyon. This facies succession is inferred to record shoaling from below storm wave-base to foreshore in a storm-dominated and tidally influenced setting. Near

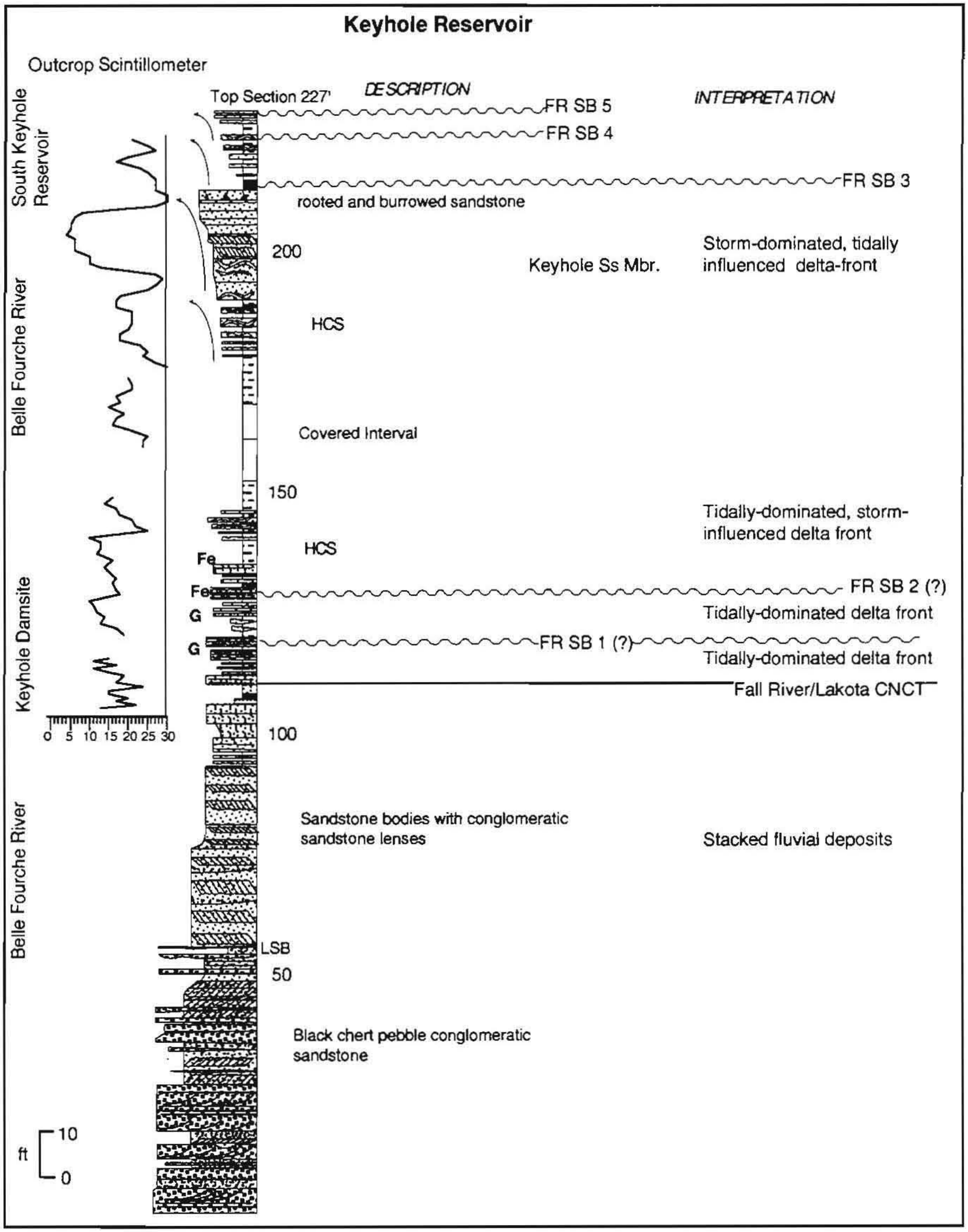



**Figure 35**—Vertical profile with outcrop scintillometer data of the Fall River Formation at Keyhole Reservoir

Coulter Bay, the coal is overlain by two thin upward-shoaling shallow-marine successions that decrease in thickness and increase in mudstone proportion upward, and consist of hummocky cross-stratified sandstone with asymmetrical ripple caps. These distal shelf deposits are inferred to represent landward-stepping SC 4 and 5 and record the intermediate-term base-level fall to rise turnaround of the Fall River stratigraphic sequence (top SC 3). This turnaround recording minimum accommodation is characterized by the most basinward positioned and sandstone-rich shallow-marine facies, the most extensive rooted horizon, and the change from seaward- to landward-stepping stacking patterns.

## Dry Creek Overview

(Optional)

**Stop 2.1b** Retrace route from Pine haven to intersection with Coulter bay and Kara Creek road. Turn right at intersection and proceed south about 3 miles to intersection with Interstate 90. Turn left onto Interstate 90 and drive east about 9 miles to Inyan Kara Creek exit. Take exit and turn right onto gravel road (Arch Creek Road) and drive 8.1 miles to Y intersection, bear right and continue 4.0 miles south to intersection with state highway 116. At intersection, turn left onto Hwy. 116 and drive east 5.6 miles to Fall River Roadcut and overview stop/or turn right to Upton and intersection with state highway 16. Turn right (southwest) and drive 5.4 miles from right turn on state highway 116 to Upton, Wyoming.

**Objectives:** (1) Examine shallow-marine dominated facies successions of the Fall River Formation.

*Discussion*

The upper Fall River is exposed in two roadcuts on north side of road. Valley deposits are absent and four Fall River short-term cycles exposed here are each capped by roots. These exposures do not warrant extensive investigation but are representative of the Fall River Formation across the region of the inferred Bell Fourche Arch (Fig. 36).

Natural exposures 150 m east of the roadcut show the Lakota/Fall River contact, with SC 1 and 2 form sandstone benches overlying red mudstones of the upper Lakota. These consist of tidally-dominated delta-front facies successions capped by rooted and goethite-rich zones. SC 2 forms the thickest sandstone bench here, and is overlain by a thin hummocky cross-stratified sandstone overlain by slope-forming dark gray laminated silty shale.

The roadcut exposes the upper part of the Fall River Formation, here consisting of two to three shallow-marine parasequences containing storm-dominated and tidally influenced facies of the Keyhole Sandstone Member. The ridge-capping sandstone locally consists of thin erosive-based sandstone bodies (up to 2 m) containing stacked sets of unidirectional planar tabular cross strata showing landward (eastward) paleoflow. Such sandstone bodies are inferred to represent tidal channels and mark the turnaround from intermediate-term base-level fall to rise of the Fall River stratigraphic sequence. Overlying SC 4 is poorly exposed capping the easternmost roadcut and consists of thinly bedded bioturbated sandstone and mudstone rooted at top.

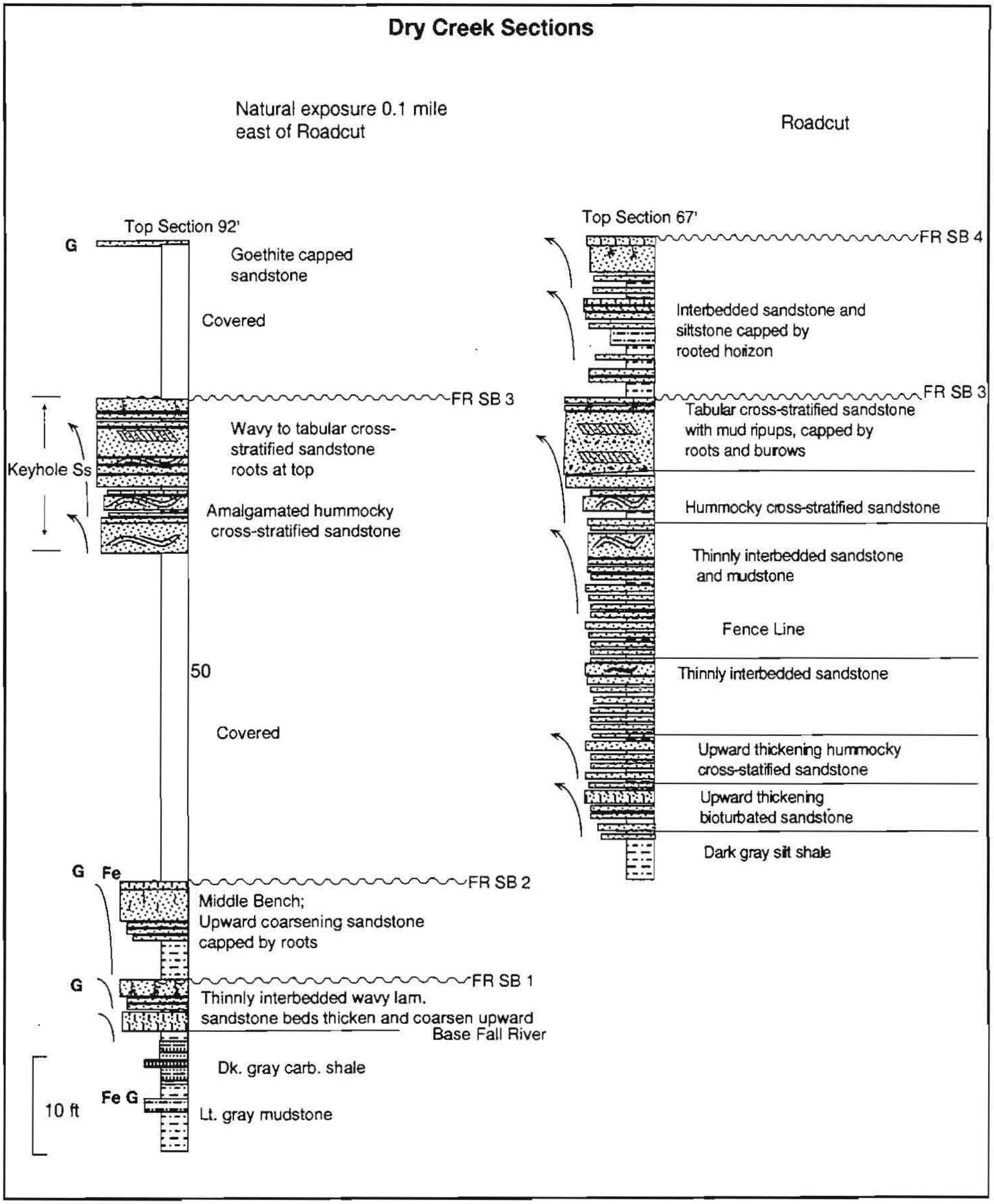



**Figure 36**—Vertical Profile of the Fall River Formation at Dry Creek, Hwy.116.

## Oil Creek Overview

(Optional)

**Stop 2.1c** From intersection of state highways 16 and 116 in Upton, Wyoming, turn left (east) and drive 14 miles to Osage, Wyoming. From Osage, Wyoming continue east 8.3 miles on Hwy. 16 to intersection with Oil Creek Road. Oil Creek road is first gravel road past airport on north side of Hwy. 16. Turn Left (north) cross railroad tracks and follow gravel road 2.5 miles to overview.

**Objectives:** Examine short-term cycles of the Fall River Fm. and ridge capping SC 4 valley-fill deposits.

*Discussion*

At this stop, we will examine from afar exposures typical of the Fall River Formation in the west-central Black Hills (Fig. 37 ). This locality is south of the inferred Belle Fourche Arch and marks the first occurrence of valley-fill deposits in the southern deltaic depocenter. At the canyon mouth, SC 4 valley-fill sandstones cap ridge on west side of road.

The Lakota Formation forms massive cliffs at road level and consists of locally conglomeratic fluvial sandstone. Chert pebble conglomerate sandstone lenses present in the uppermost sandstone body are overlain by thin mudstones forming the covered slope separating Lakota and Fall River sandstones.

The Fall River here resembles exposures to the south at Cambria Creek, near Newcastle, Wyoming. From here southward, the SC 2 mudstone tongue separating lower and upper Fall River sandstones is replaced by heterolithic estuarine-dominated valley-fill deposits. Thin SC 3 shallow-marine sandstones of the Keyhole Sandstone here become progressively thinner southward toward their landward pinch out. Ridge capping sandstones of SC 4 (15-m thick) consist of highly interconnected, multistory erosive-based channel sandstone bodies (up to 3 m thick) containing stacked sets of amalgamated unidirectional trough cross strata showing westward sediment transport. An upward increase in marine influence in SC 4 valley-fill deposits is indicated by an upward increase in both burrowing intensity and the proportion of thinly interbedded mudstone and sandstone containing asymmetrical ripples. This valley fill is thin at Cambria Creek, but forms the most conspicuous sandstone capping the Fall River hogback in this area.

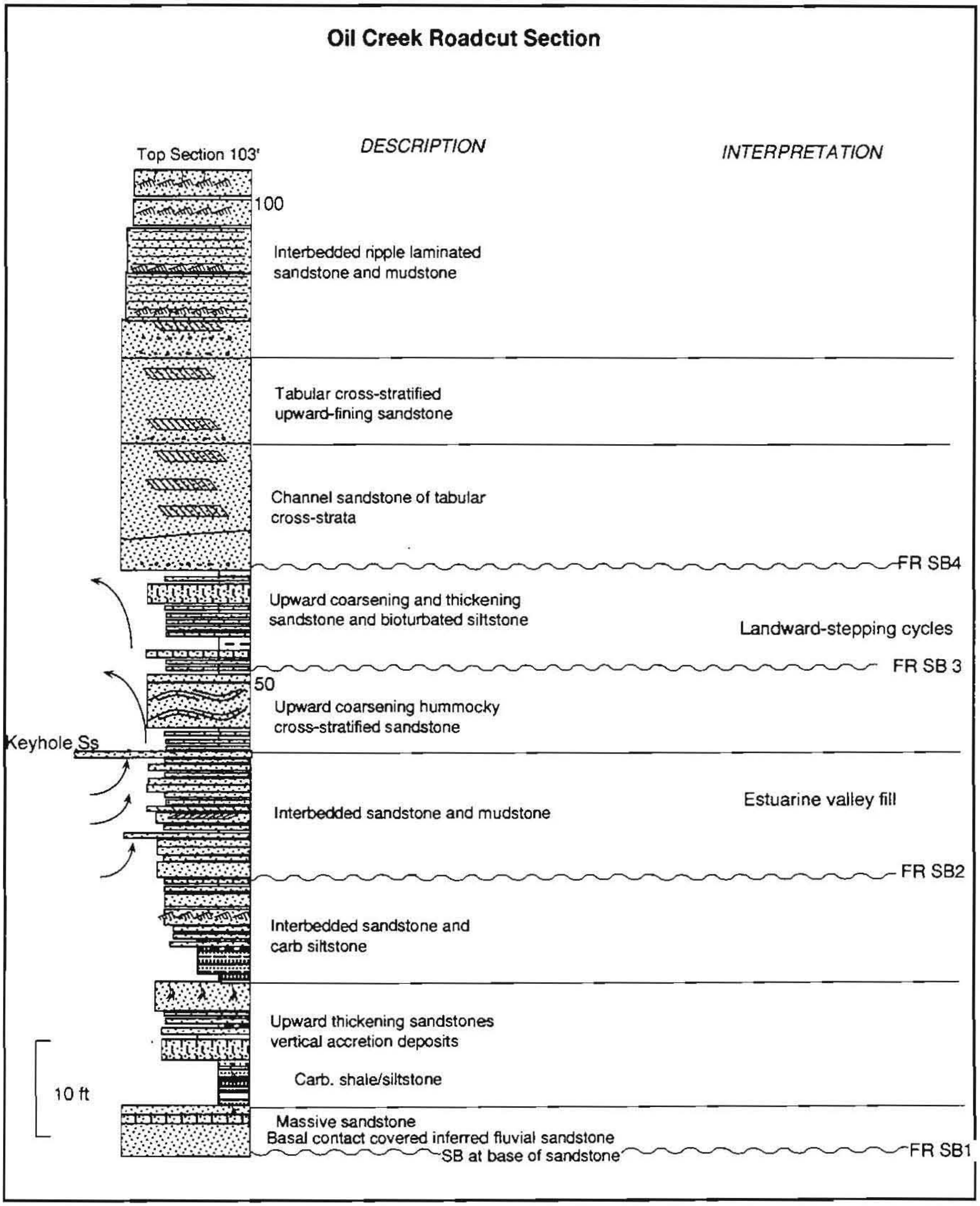



**Figure 37**—Vertical profile of the Fall River Formation at Oil Creek.

## Cambria Creek

**Stop 2.2** Retrace route to intersection and turn left (east) onto Highway 16. Drive 5.2 miles to Newcastle Bypass, bear right and continue east about 2 miles to left turn (north) onto old highway 16 (turnoff is across from Pizza Hut). Turn left and drive about 1 mile northwest through town, past the Weston County courthouse to dirt road leading to Newcastle dog pound along Cambria Creek.

**Objectives:** (1) Examine nested and amalgamated valley-fill deposits of SC 1 and 2.
(2) Examine shallow-mariner deposits and stacking pattern of SC 3 and 4.

### *Discussion*

Cambria Creek obliquely cuts Fall River sandstone hogbacks dipping 11° to the southwest. Sporadic exposures along stream cuts complicate cross canyon correlations. The Lakota Formation is exposed in a gully on the west side of the creek about 0.5 miles to the north (Fig. 38). The upper Lakota Formation at the base of the gully consists of a 50-ft-thick cliff-forming multistory fluvial sandstone. This cliff contains 7 erosive-based sandstone bodies (1.5 to 3 m thick) consisting of stacked sets of unidirectional planar-tabular and trough-cross-strata showing southward sediment transport. These fluvial sandstones are overlain by poorly exposed variegated mudstones (10 m thick) containing carbonaceous interbeds with cycad seed pods. On the southeast side of Cambria Creek, these mudstones are incised by lower Fall River sandstone poorly exposed here, but well exposed along the road and west side of creek.

The Lakota-Fall River contact is not exposed, but overlying SC 1 consists of multistory fluvial-dominated valley-fill sandstones. Highly interconnected, erosive-based sandstone bodies, based by small clay-pebble rip-up lags, consist of stacked sets of amalgamated, unidirectional, planar-tabular cross-strata showing north to northwest sediment transport. On the west canyon wall, these sandstones are overlain by thinly bedded sandstone and mudstone capped by coal. On the east canyon wall, these deposits are eroded forming a lag deposit with meter-wide coal clasts overlain by heterolithic valley-fill deposits of SC 2 (up to 13 m). This estuarine-dominated valley fill overlies a high relief erosional surface and contrasts sharply with underlying SC 1 deposits. These heterolithic deposits contain thin meter-scale, erosive-based upward-fining successions consisting of thin sets of unidirectional planar-tabular cross stratified sandstone overlain by thinly interbedded ripple cross-laminated sandstone and mudstone. Such tabular to broadly lenticular sandstone beds contain a diverse suite of asymmetrical, symmetrical and flaser ripples showing diverse, commonly bi-directional, sediment transport. Trace fossils are low diversity but common on bedding planes and consist of feeding and resting tracks and trails of *Planolites* and *Arenicolites* and vertical escape burrows of *Skolithos*.

On the west canyon wall, SC 2 is sharply overlain by a thin upward-shoaling shallow-marine succession of thin to medium bedded hummocky cross stratified sandstone of the Keyhole Sandstone Member of SC 3. A basal granule lag is present here and at Oil Creek and Beaver Creek sections. This hummocky cross stratified sandstone is truncated by thin erosive-based sandstone bodies containing clay pebble ripup clasts and thin sets of trough cross-strata. This sandstone in interpreted to represent a tidal channel deposit capping the ridge on the west and near the mouth of the canyon on the eastern wall. This sandstone is rooted and overlain by a thin carbonaceous mudstone. These small channel-fill deposits are inferred to represent the scale of channels sourcing progradational shoreline successions.

Two shallow-marine parasequences overlie SC 3 channel sandstone on the eastern canyon wall near the gate. The second parasequence is truncated by a 3-m thick erosive-based fluvial sandstone body rooted and capped by a thin coal bed. This fluvial sandstone correlates to thicker SC 4 valley-fill sandstones exposed at Oil Creek, Salt Creek, and at Whoopup and Clifton Canyons, where we will examine them. The coal capping SC 4 fluvial sandstone is overlain by several shallow-marine parasequences that thin and show increasing mudstone proportion upward. Tabular sandstone beds comprising these parasequences thicken and coarsen upward consisting of hummocky cross-stratification capped by asymmetrical, symmetrical, and flaser ripples. Burrowing is moderate with *Planolites* and *Skolithos* the most common trace fossils. An anomalously coarse conglomerate containing pebble- to cobble-size sandstone clasts caps one of these parasequences and appears to represent a transgressive deposit overlying a ravinement surface. This lag deposit is also present south of Clifton Canyon and may mark the SC 5 sequence boundary, with the coarse fraction transported during base-level fall, but reworked during subsequent base-level rise. The Dakota Silt marker forms a thin upward-shoaling shallow-marine succession capping a thick succession of marine mudstones exposed near the dog pound.

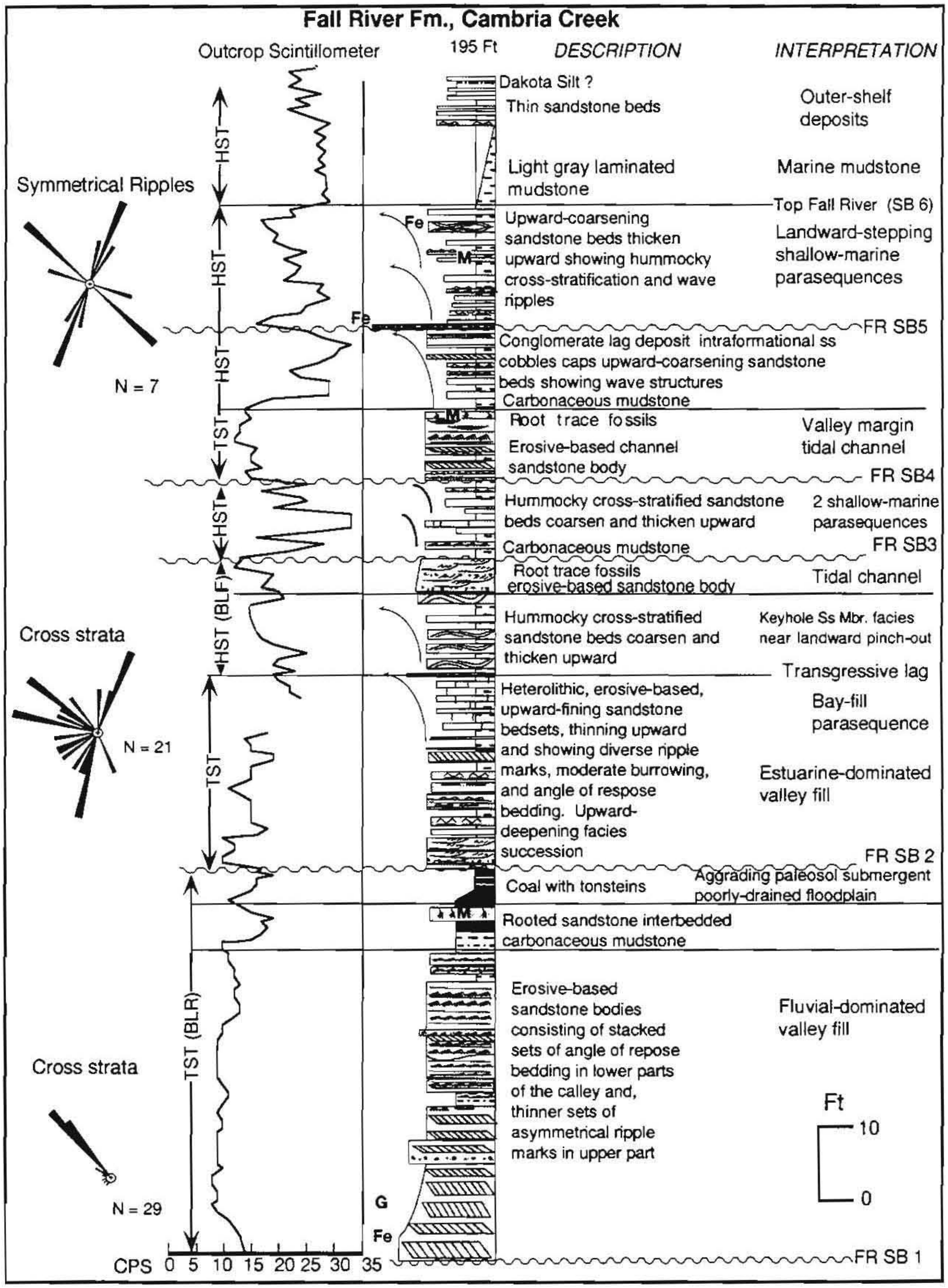



**Figure 38**—Vertical profile of Fall River Formation at Cambria Creek.

## Stockade Beaver Creek

(Optional)

**Stop 2.2b** Retrace route through town to Newcastle Bypass and intersection with Hwy. 16. Turn left onto Hwy. 16 and drive about 1 mile to intersection with Hwy. 85. Proceed through intersection on Hwy. 16 and drive 4.8 miles east to intersection with Beaver Creek farm road. Turn left onto Beaver Creek Road and park.

**Objectives:** (1) Examine valley margin deposits of the Fall River.

### *Discussion*

The Fall River Formation forms a prominent hogback on the west flank of the Black Hills near Newcastle, WY. The steep dip obscures lateral facies relations but serves to illustrate along-strike changes between valley-margin deposits present here (Fig. 39), and valley-fill deposits 7.5 miles to the northwest at Cambria Creek.

The Lakota Formation at the LAK reservoir is about 67 m and consists of four discrete sandstone-to-mudstone cycles High net-to-gross multistory fluvial sandstone bodies comprise the lower part of the Lakota (41 m). A thick laterally persistent carbonaceous mudstone caps matrix-supported black, red, and gray chert pebble conglomerate 25 m above the base. The upper part of the Lakota (25 m) is covered but contains sporadic exposures of green mudstones resembling the Lakota Formation to the south.

The lower part of the Fall River here resembles exposures at Oil Creek and Cambria Creek. The basal Fall River contact is not exposed, but overlying strata consist of moderately burrowed, structureless sandstone rooted at top and inferred to represent fluvial valley-fill deposits of SC 1. If true, this sandstone is correlative to planar-tabular cross-bedded sandstone at Cambria Creek. This sandstone is erosively overlain by heterolithic estuarine-dominated valley-fill deposits of SC 2. These estuarine deposits resemble thicker SC 2 valley-fill deposits at Cambria Creek and Oil Creek. A well developed granule lag deposit bases overlying hummocky cross-stratified sandstone inferred to represent the SC 3 Keyhole Sandstone Member near its landward pinch out.

The Keyhole Sandstone is overlain by a dark gray mudstone overlain by SC 4 here consisting of a thin erosive-based fluvial sandstone body rooted and capped by a thin coal bed. This fluvial sandstone correlates to 20-m thick valley-fill sandstones at Oil Creek, Salt Creek and Whoopup Canyon, and thin fluvial sandstone bodies at Cambria Creek.

Above the channel, the upper portion of the Fall River Formation contains four shallow-marine parasequences. The lower parasequence consists of an upward-shoaling succession rooted at top and overlain by mudstone grading up to a thin carbonaceous shale. Overlying shallow-marine parasequences are progressively thinner and more mudstone-rich upward recording an overall landward-stepping stacking pattern of bayhead deltas.

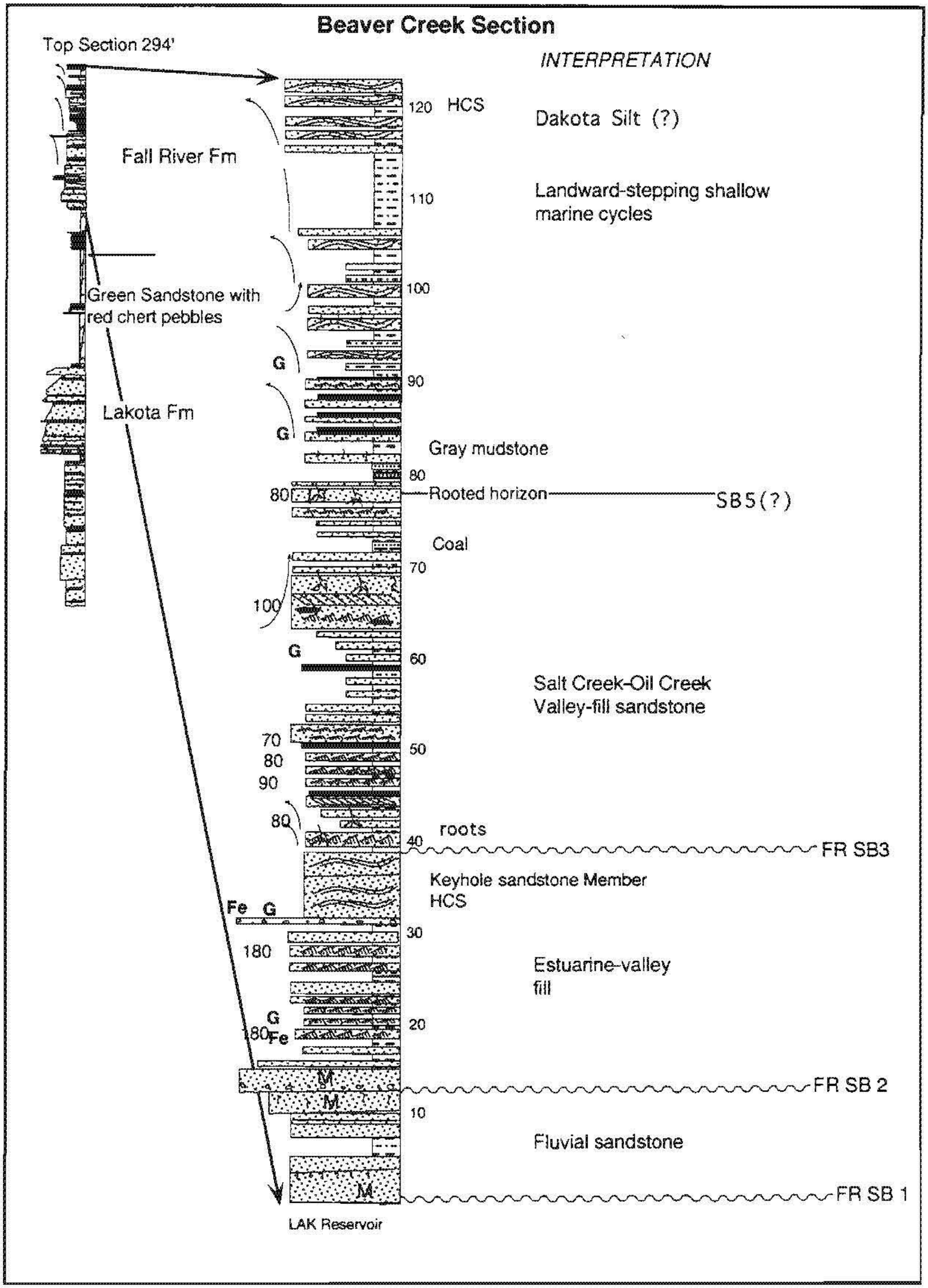



**Figure 39**—Vertical profile of the Fall River Formation at the Beaver Creek.

## Whoopup Canyon

**Stop 2.3** Retrace route through town to Newcastle Bypass and intersection with Hwy. 16. Turn left (east) onto Hwy. 16 and drive about 1 mile to intersection with Hwy. 85. Turn right (south) and drive 3.3 miles south to intersection with Old Highway 85 and left turn (east) at sign to Newcastle solid waste facility. Turn left and head east 0.5 miles to Y junction, bear right heading south. Proceed south on gravel road about 9 miles to left turn through gate and onto track on LAK ranch. Head east about 1 mile past abandoned building to left fork, and head north about 2 miles to Whoopup Canyon mouth

**Objectives:**

(1) Examine SC 2 estuarine-dominated valley-fill.
(2) Examine SC 3 meanderbelt confined to broad and wide paleovalley
(3) Examine SC 4 fluvially-dominated valley-fill

### *Discussion*

Whoopup creek dissects a low amplitude, north-south plunging anticline flanking the Fanny Peak monocline to the west and forming Whoopup canyon here. The canyon is floored by the upper part of the Lakota Formation, with overlying Fall River sandstones exposed on flanking canyon walls. Excellent exposures of sandstone-rich valley-fill deposits in the overlying Muddy Sandstone are also present here, forming buff-colored sandstone cliffs to the east. Whoopup Canyon exposes Fall River valley-fill facies (Fig. 40) transitional to Cambria Creek to the north and Clifton Canyon to the south. As we enter the canyon from the south, the upper part of the Fall River (SC 4) forms a massive cliff containing an impressive display of rock art dated at 12,000 BP. This canyon contains the highest concentration of rock art of this age in North America, and access to this area is restricted. Please do not touch any of the rock art and stay at least 5 m from the cliffs. The base of the Fall River is exposed farther north along Whoopup creek.

The upper Lakota is well exposed along the east flank of the anticline and contains a slope-forming paleosol consisting of reddish-brown rooted mudstone grading up to a carbonaceous mudstone and coal. This succession resembles the upper Lakota at Cambria creek. The Fall River/Lakota contact is placed at the top of this coal. The coal is sharply overlain by an upward-coarsening succession of dark-gray silty shale grading up to light-gray structureless siltstone. This upward-coarsening succession is inferred to represent erosional remnants of SC 1 shallow-marine deposits. Fluvial-dominated valley-fill sandstones of SC 1 exposed at Cambria creek are absent here. SC 2 valley-fill deposits erosionally overlie SC 1 siltstones and represent the

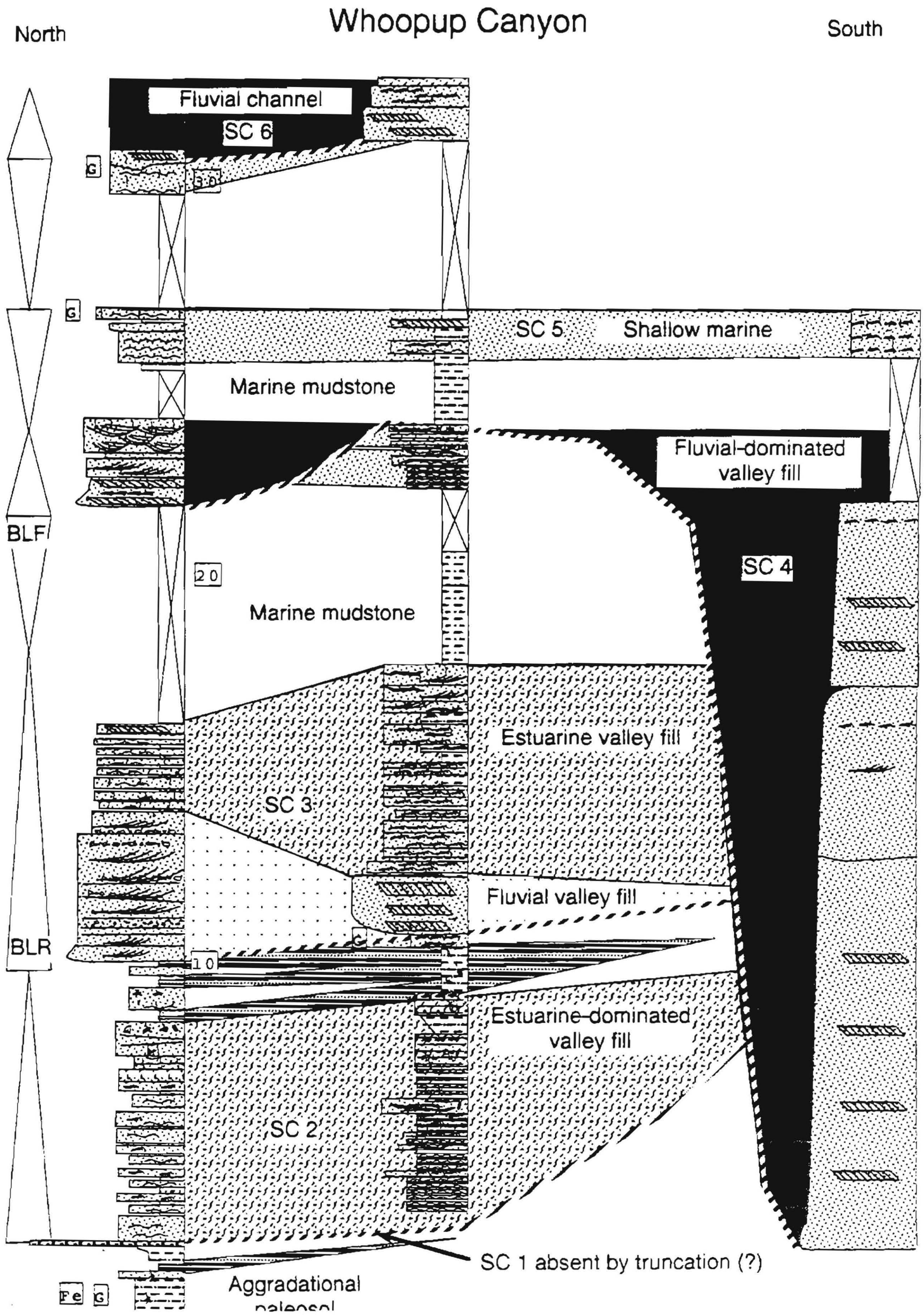



**Figure 40**—Stratigraphic cross section from Whoopup Canyon.

southernmost exposure of these estuarine-dominated valley-fill facies. These are replaced by facies change to the south by fluvial-dominated valley-fill sandstones at Clifton canyon. The erosional basal contact is marked by a lag deposit containing rip-up clasts of underlying SC 1 deposits and extraformational chert and quartzite pebbles. This lag deposit is overlain by heterolithic interbedded sandstone and mudstone consisting of meter-scale upward-fining successions previously described at Cambria creek. These estuarine-dominated valley-fill deposits are correlative to the thick marine mudstone tongue separating the Fall River in the northern Black Hills. These deposits may record higher amplitude short-term sea-level rise. Rates of relative sea-level rise exceeding sedimentation rates during SC 2 deposition resulted in rapid drowning of the paleovalley, decreased basinward deposition, and a landward shift in deeper-water marine mudstones.

SC 2 estuarine deposits are rooted at top and capped by a carbonaceous mudstone. This carbonaceous mudstone is locally truncated by an erosive-based upward-fining sandstone body (6 m thick) that thickens to 20 m northward and thins to less than 2 m southward. Here, it consists of stacked sets of trough cross strata that change upward to thinly interbedded sandstone and mudstone showing moderate burrowing by *Planolites* and *Skolithos* trace fossils. This fluvial to estuarine facies succession is inferred to represent valley-fill deposits of SC 3. The intermediate-term base-level fall to rise turnaround of the Fall River stratigraphic sequence is placed at the base of these valley-fill deposits. SC 3 deposits are overlain by light-gray marine mudstone grading up to an upward-shoaling shallow-marine succession capped by hummocky cross-stratified sandstone of SC 4. This hummocky cross-stratified sandstone is rooted and replaced to the south by thick fluvial sandstones forming the massive cliff at the mouth of the canyon. This cliff contains 4 multistory erosive-based sandstone bodies, each consisting of stacked sets of trough and planar tabular cross strata showing northwest sediment transport.

Fall River short-term cycles at Whoopup canyon consist of successive valley-fill deposits (SC 2 to 4) showing an upward increase in sediment volume inferred to record a landward shift in accommodation and increased sediment storage in paleovalleys. Increased sediment storage in successive valley-fills here is manifested in the landward-stepping stacking pattern of shallow-marine deposits observed 70 miles basinward at Keyhole reservoir. Southward of Whoopup Canyon, Fall River short-term cycles are dominated by nested valley-fill deposits showing a progressive upward increase in marine influence indicated by upward increasing proportions of estuarine facies.

## Day 3: Clifton Canyon

**Stop 2.3** From the Fountain Inn, drive 3.3 miles south to intersection with Old Highway 85. At the turnoff, there is a sign to the Newcastle solid waste facility. Turn right and head east 0.5 miles to Y junction and bear right heading south. Proceed south on gravel road 15.6 miles to left turn (east) onto farm road. Drive 1.2 miles past abandoned farm road to gate and railroad crossing. Cross railroad tracks and through another gate to right turn on track and head south 1.1 miles through another gate to intersection with forest service road 818. Turn left (east) and proceed about 0.2 miles to right fork (south) and continue on track for about 0.5 miles to mouth of Clifton Canyon.

**Objectives:**

(1) Contrast facies architecture of four nested fluvial-dominated valley fills.
(2) Examine valley margin facies relationships
(3) Examine facies architecture of point bar sandstone bodies comprising SC 4 valley-fill

### *Discussion*

Clifton Canyon is one of two canyons, or outcrop windows, documenting the internal architecture of nested valley fills. Exposures here are 9 km south of more distal valley fills examined at Whoopup Canyon, and 38 km northwest of more proximal valley-fill deposits at Red Canyon. Clifton Canyon contains a 2 km wide oblique cross sectional view of nested, fluvial-dominated valley-fill deposits incised into shallow-marine deposits. This fault-controlled dip-slope canyon exposes the eastern paleovalley margin. Northeast-southwest trending canyon walls show northeastward expansion of successive valley fill deposits (comprising four short-term cycles) that progressively overlap of the eastern paleovalley margin. Valley-fill deposits of SC 4 comprise the entire cliff to the northeast (Fig. 41). The Fall River-Lakota contact is well exposed from the valley margin northward, where it underlies shallow marine deposits of SC 1. The upper part of the Fall River is absent by modern erosion, and SC 1 through 4 valley-fill sandstones form canyon walls here.

Short-term cycle boundaries of nested valley fills are recognized as high-relief erosional surfaces recognized by grain size change and/or lag deposits (up to 3 m thick). Lag deposits are sandstone matrix-supported conglomerate containing intraformational sandstone and mudstone clasts (up to 1 m in diameter). These major erosional surface cross cut erosive-based fluvial sandstone bodies and bound discrete valley fills. It is difficult to trace major erosional surfaces

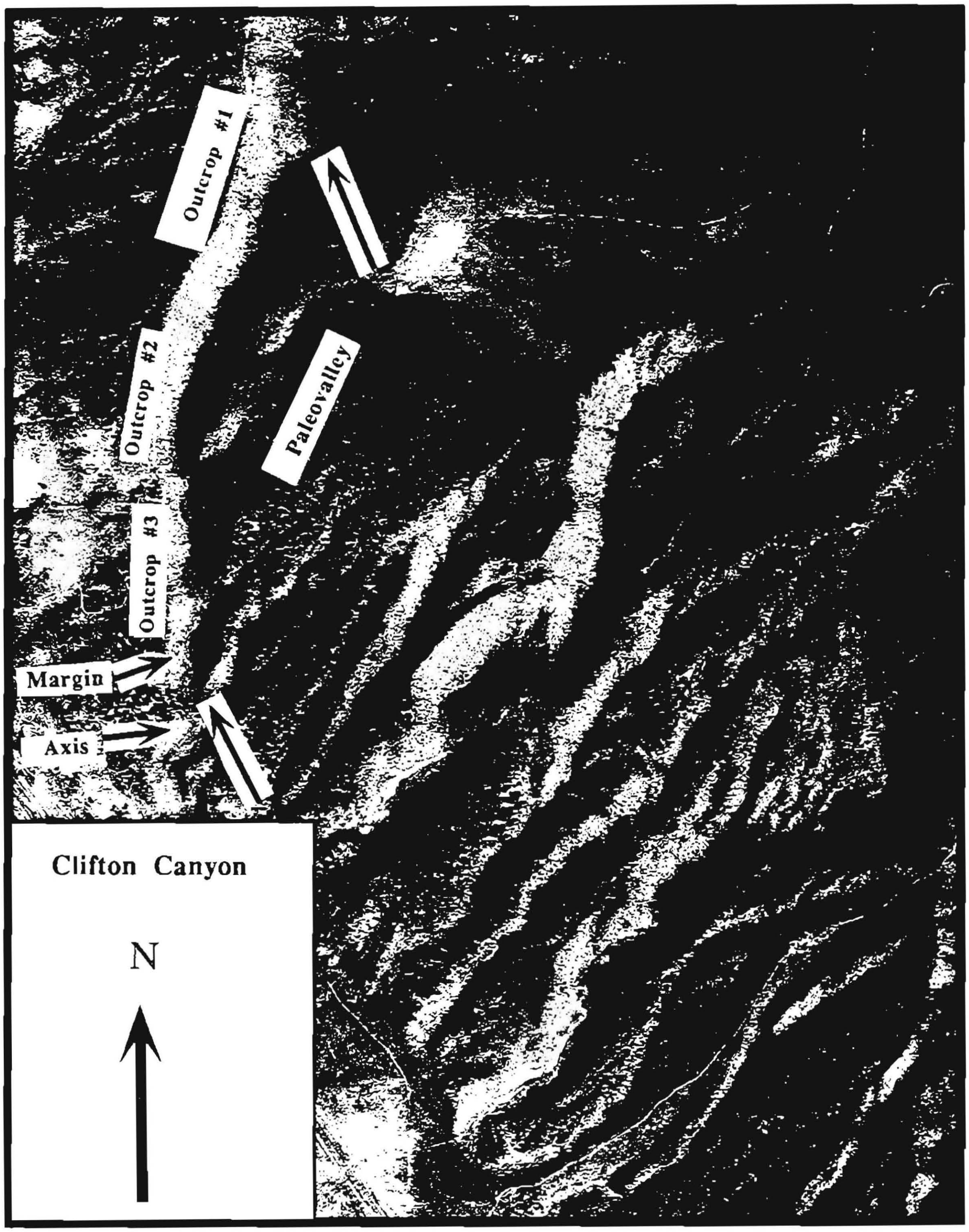



**Figure 41**—Areal photo of Clifton Canyon

across the canyon, because of covered intervals and abrupt lateral changes in lag thicknesses, and soft sediment deformation (Fig. 42). These major erosion surfaces are inferred to record short-term base-level fall.

Sandstone-rich, fluvial-dominated facies successions are representative of nested valley-fill deposits of the southern deltaic complex. Heterogeneity in such sandstone-rich valley fills is primarily related to lag deposits overlying major erosional surfaces and the juxtaposition reservoir and nonreservoir strata having up to 5 orders of magnitude difference in permeability. Valley-fill successions (up to 20 m thick) consist of a basal lag deposit (up to 3 m thick) overlain by stacked erosive-based sandstone bodies (up to 10 m thick) internally partitioned into bedsets by laterally-continuous, inclined accretion surfaces (up to 100 m across). Bedsets (1 to 2 m thick) and defined by systematic organization of grain size and primary structures. High proportions of structureless sandstone with scattered clay pebble rip-ups are seen in basal portions of valley fills (up to 5 m thick). These are replaced upward by a more diverse assemblage of planar tabular and trough cross strata and asymmetrical ripple cross-laminations that show a progressive increase in burrowing and mudstone interbeds. This upward increase in the diversity of primary structures comprising successive valley fills reflects increased preservation in upper parts of the valley fill.

Twenty nine vertical profiles spaced from 15 to 61 m laterally are tied to continuous photomosaics to document vertical and lateral variations in facies architecture of the four nested valley fills (Fig. 43). Two scales of valley-fill architecture are documented. At the large-scale, the changing architecture of successive valley fills, and at the small-scale, detailed facies analysis of internal sandstone bodies comprising the upper part of the SC 4 valley-fill (Fig. 44). Sandstone bodies are particularly well preserved in SC 4 and paleochannel dimensions can be reconstructed. In addition, vertical and lateral permeability profiles were collected from two SC 4 sandstone bodies (Figs.45,.46). An additional vertical profile (Fig.47) was taken through the entire valley-fill and a horizontal profile (Fig.48) was taken through the massive sandstone of SC 3 (Fig.49). Proximal to distal changes in valley-fill architecture between here and Red Canyon are contrasted. These southwest-northeast oriented cliff faces show lateral facies changes from the valley center to valley margin. Todays stops will follow this traverse.

*Center of stacked valley fills*

Although the basal contact of the Fall River Formation is not exposed at the canyon mouth, exposures of a thick lag deposit on the south side of the canyon are inferred to occur near the base of nested paleovalley sandstone. This is the thickest lag deposit (3 m thick) consisting of a poorly sorted, sandstone-matrix supported conglomerate containing intraformational lithified sandstone, mudstone, and interbedded sandstone and mudstone clasts up to 1 m in diameter. Some sandstone clasts internally contain mudstone rip-ups, whereas interbedded sandstone and mudstone clasts are derived from underlying shallow-marine deposits.

Structureless sandstone is the dominant facies on the south-facing canyon wall at the canyon mouth. Such structureless sandstones contain dark brown, goethite-coated concretions (up to 1 meter in diameter), and relict laminae deformed and randomly dipping at high angles suggesting dewatering and complex soft sediment deformation. Concretions are commonly goethite-coated mudstone ripup clasts. The lower three valley fills have high proportions of structureless sandstone in basal parts, and stacking of successive valleys make this the dominant facies here. Prominent lag deposits overlie laterally continuous, high-relief, irregular erosional surfaces basing the lowest three short-term cycles. These lag deposits change laterally from discrete zones containing high concentrations of mudstone rip-up clasts to more diffuse intervals with mudstone rip-up clasts more widely disseminated vertically. This lateral change in the thickness and character of basal lag deposits may also reflect abundant soft sediment deformation in valley center deposits. Significantly, such lateral changes in lag deposits decrease their integrity and continuity as potential fluid-flow barriers, but may add to reservoir heterogeneity by disseminating low permeability mudstone clasts vertically producing wider vertical flow baffles. The uppermost lag deposit basing SC 4 valley-fill deposits is marked a change in bedding style to stacked sets of planar tabular cross strata separated by northeast-dipping accretion surfaces.

*Margin of stacked valley fills*

Along the paleovalley margin, successive valley-fill deposits show a serrated stepwise overlap, with successive valley-fill margins displaced laterally. Such valley fills are extremely thin along the valley margin and are defined by an upward change from fluvial to estuarine facies over successions less than 1 m thick. These thin valley-fill deposits may contain up to 1 m long vertical *Skolithos* escape burrows. Valley-fill deposits of SC 1 erode and replace underlying shallow-marine deposits here, with a thin dark gray mudstone laterally separating these

Section 3-E Clifton Canyon

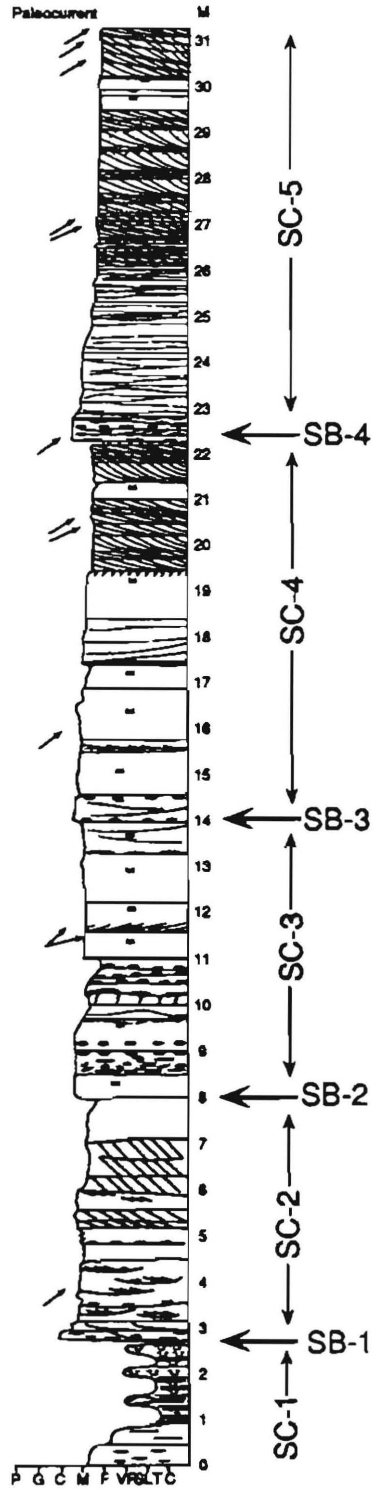



**Figure 42**—Vertical profile from Clifton Canyon

NESTED VALLEY-FILL ARCHITECTURE OF THE FALL RIVER FORMATION AT CLIFTON CANYON

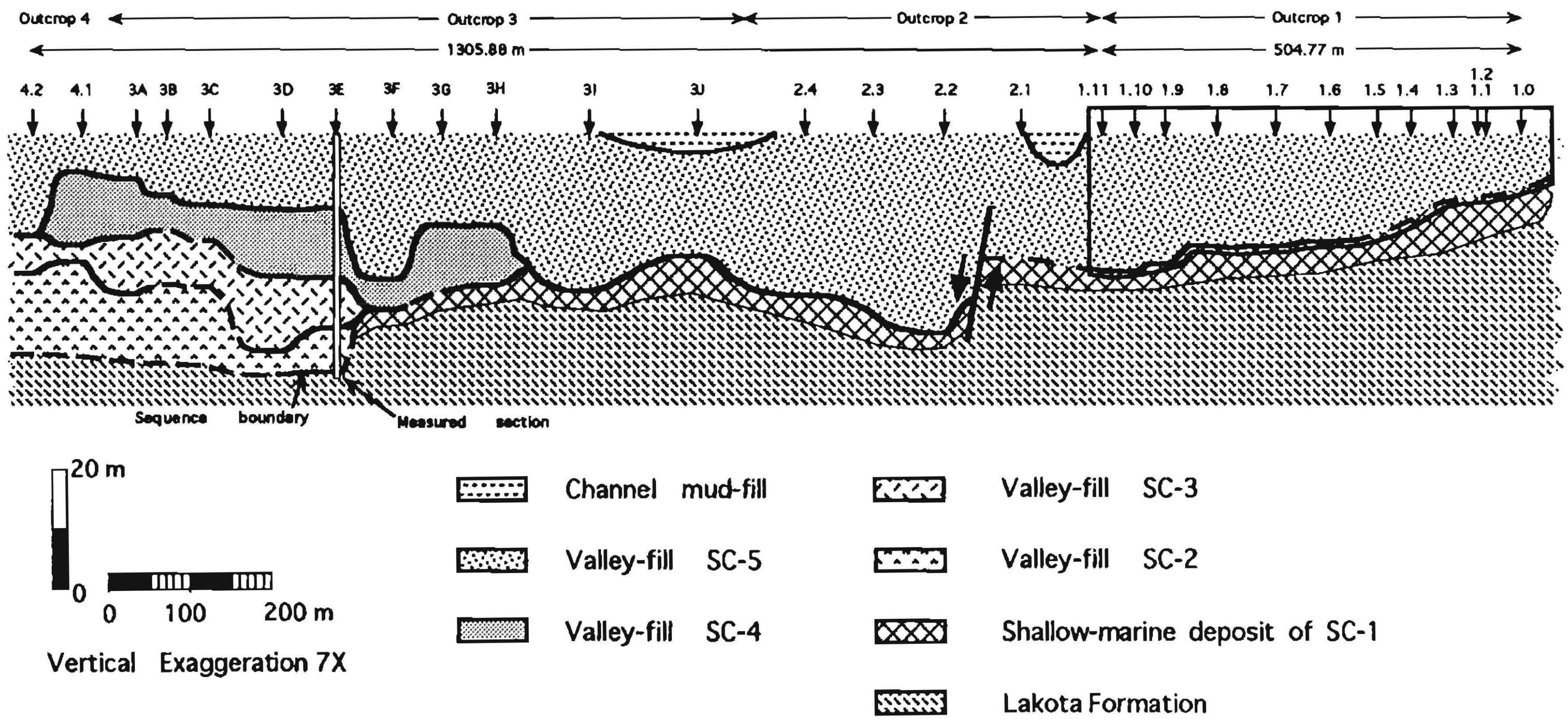



**Figure 43**—Cross section across Clifton Canyon

# VALLEY-FILL ARCHITECTURE OF SC-4 AT OUTCROP 1, CLIFTON CANYON

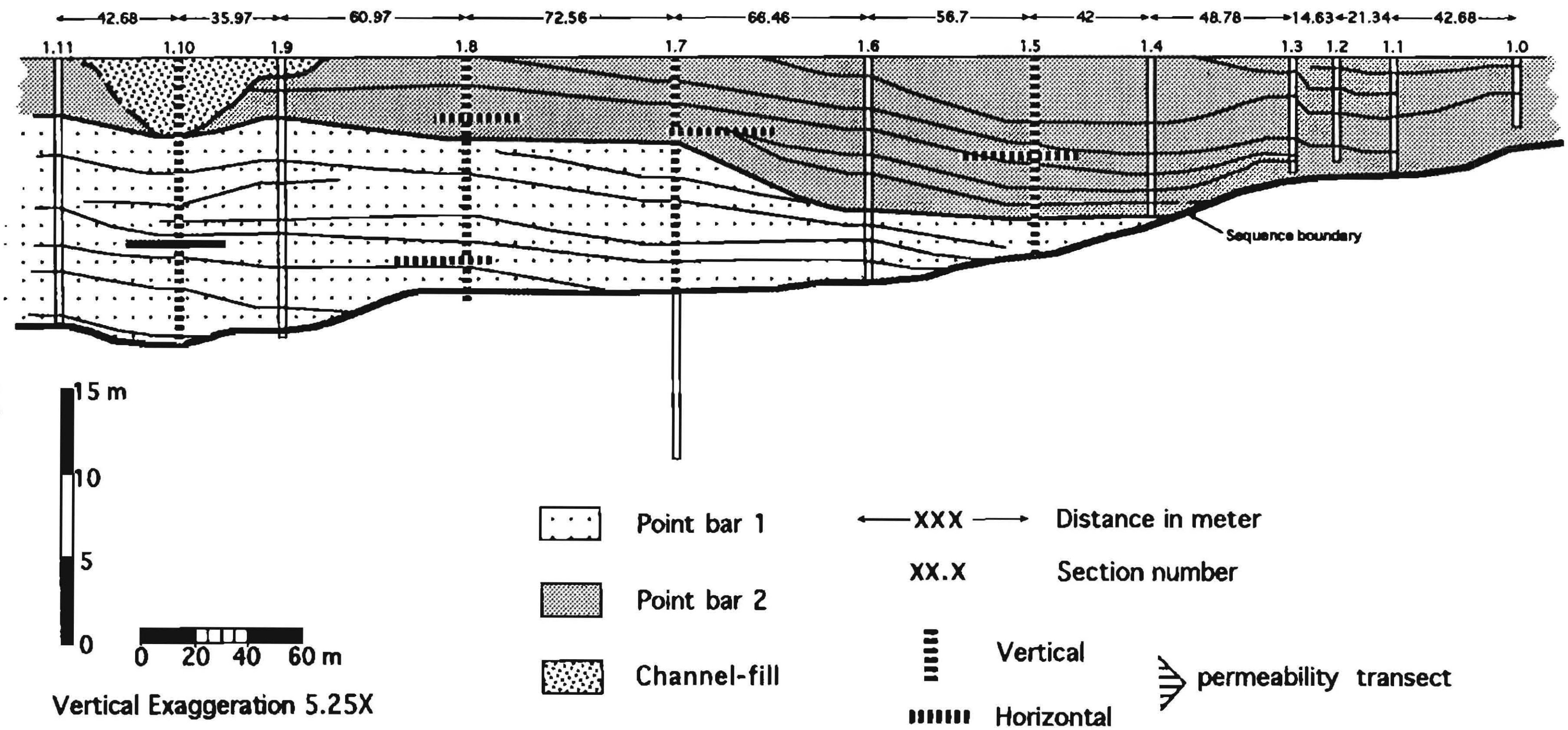



Figure 44— Cross section of SC 4 sandstone bodies at Clifton Canyon

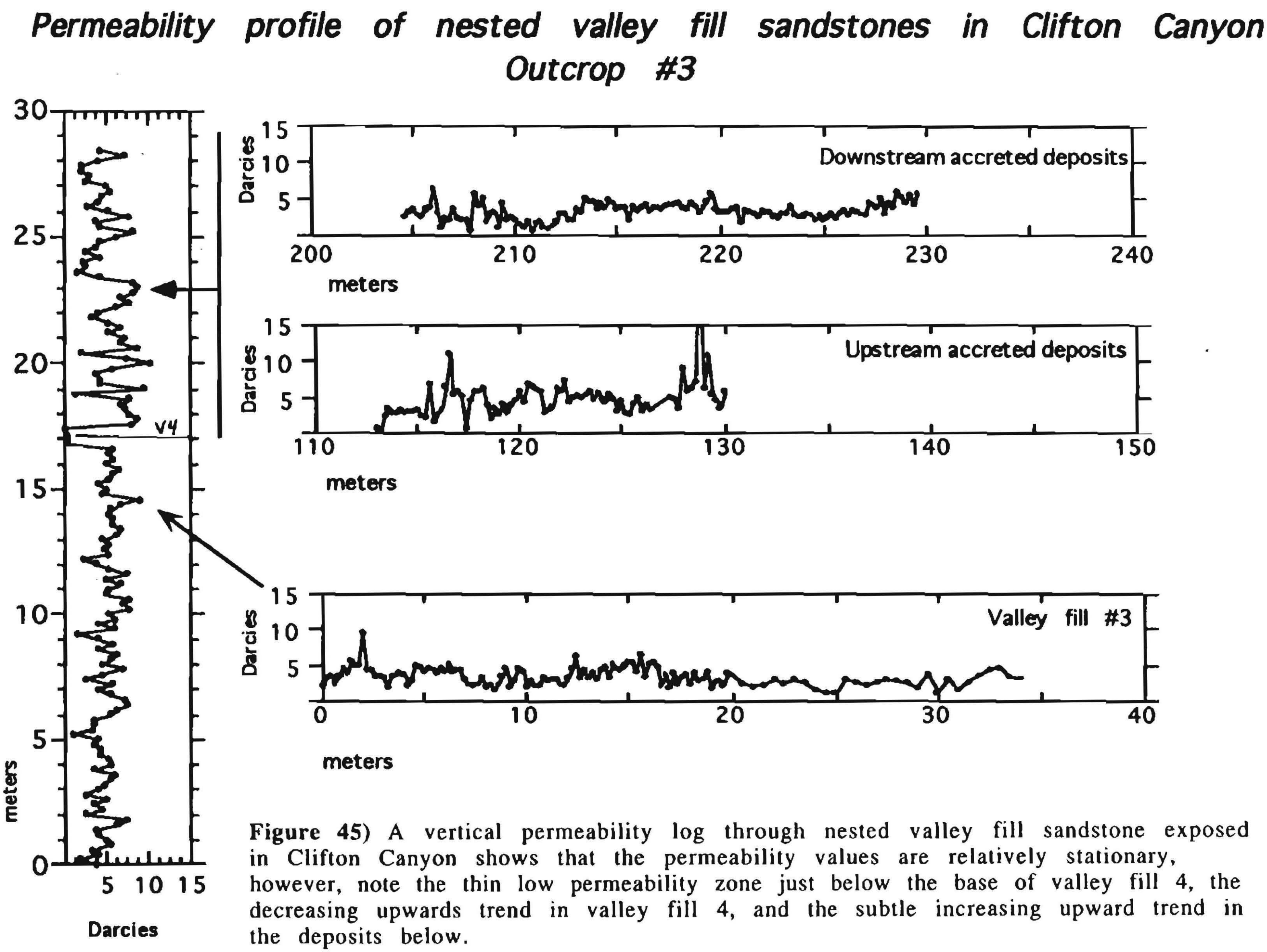
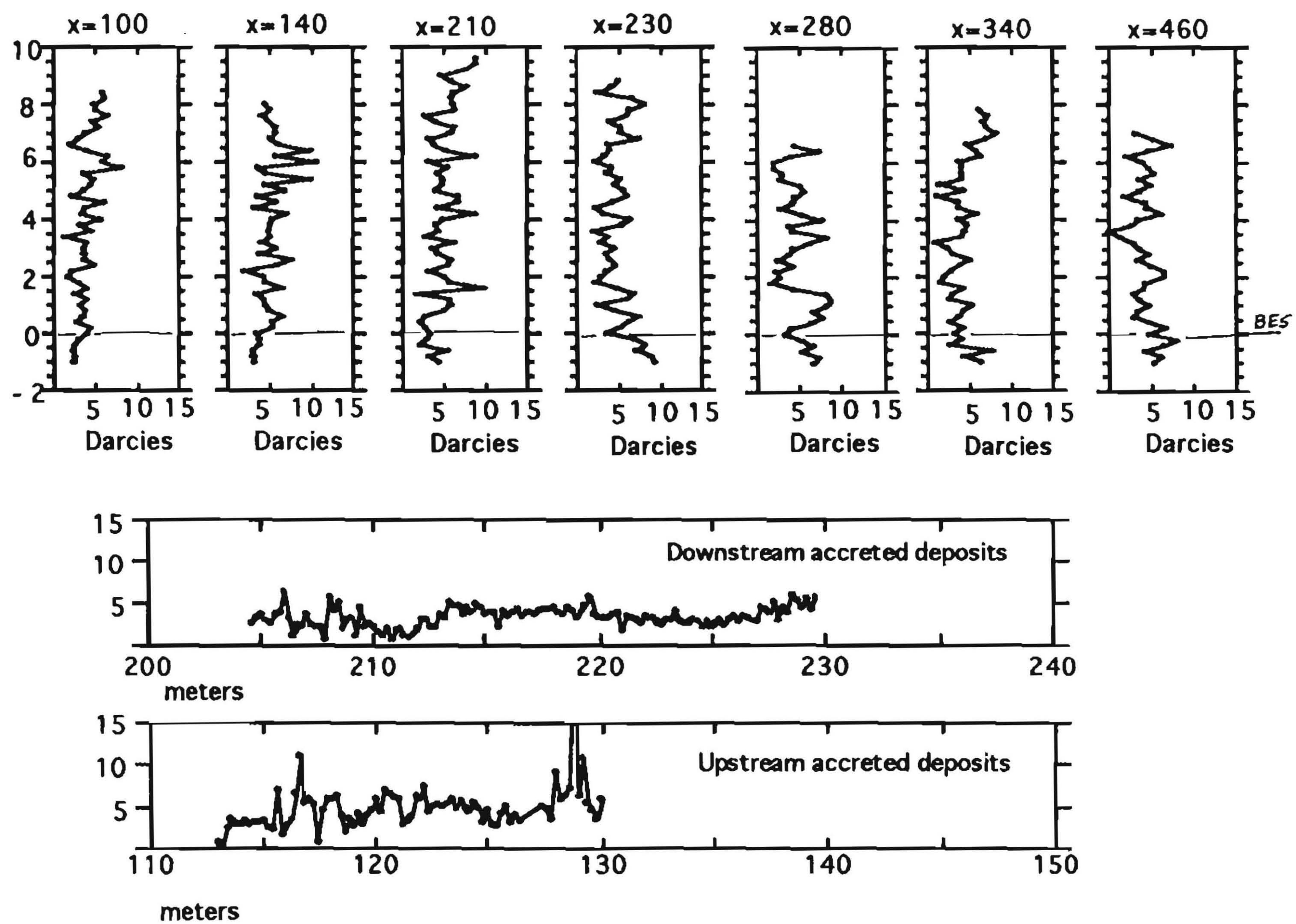



**Figure 45)** A vertical permeability log through nested valley fill sandstone exposed in Clifton Canyon shows that the permeability values are relatively stationary, however, note the thin low permeability zone just below the base of valley fill 4, the decreasing upwards trend in valley fill 4, and the subtle increasing upward trend in the deposits below.

**Figure 46)** Valley fill 4 deposits in outcrop 3 of Clifton Canyon are exposed nearly paleoflow parallel. The sandstone body is composed of a convex upwards set of beds, that dip upstream to the south and downstream to the north. In the center of this convex form, beds dip solely down stream. These beds are interpreted as a channel bar deposit. It appears that the bar initially migrated down stream as it grew, but then become stationary and grew in place preserving both upstream and down-stream parts of the bar form. Permeabilities increase upwards in the upstream end of these deposits and generally fine upwards in the down-stream end. These permeability trends match grainsize trends predicted for a point bar deposit of this genesis. Large cross-strata sets capping deposits just down stream of the bar deposit center have higher Permeabilities, which deviates from the general trend just described (e.g., see vertical log at x=340). These deposits may be scroll "bars" preserved on the inside bank of the channel bar, but minimal along outcrop paleocurrent variations suggest a very low sinuosity channel. Permeability means and variances appear to be slightly greater in upstream relative to down-stream accreted deposits.

*Bar deposits, Clifton Canyon, Valley fill #4, outcrop #3*



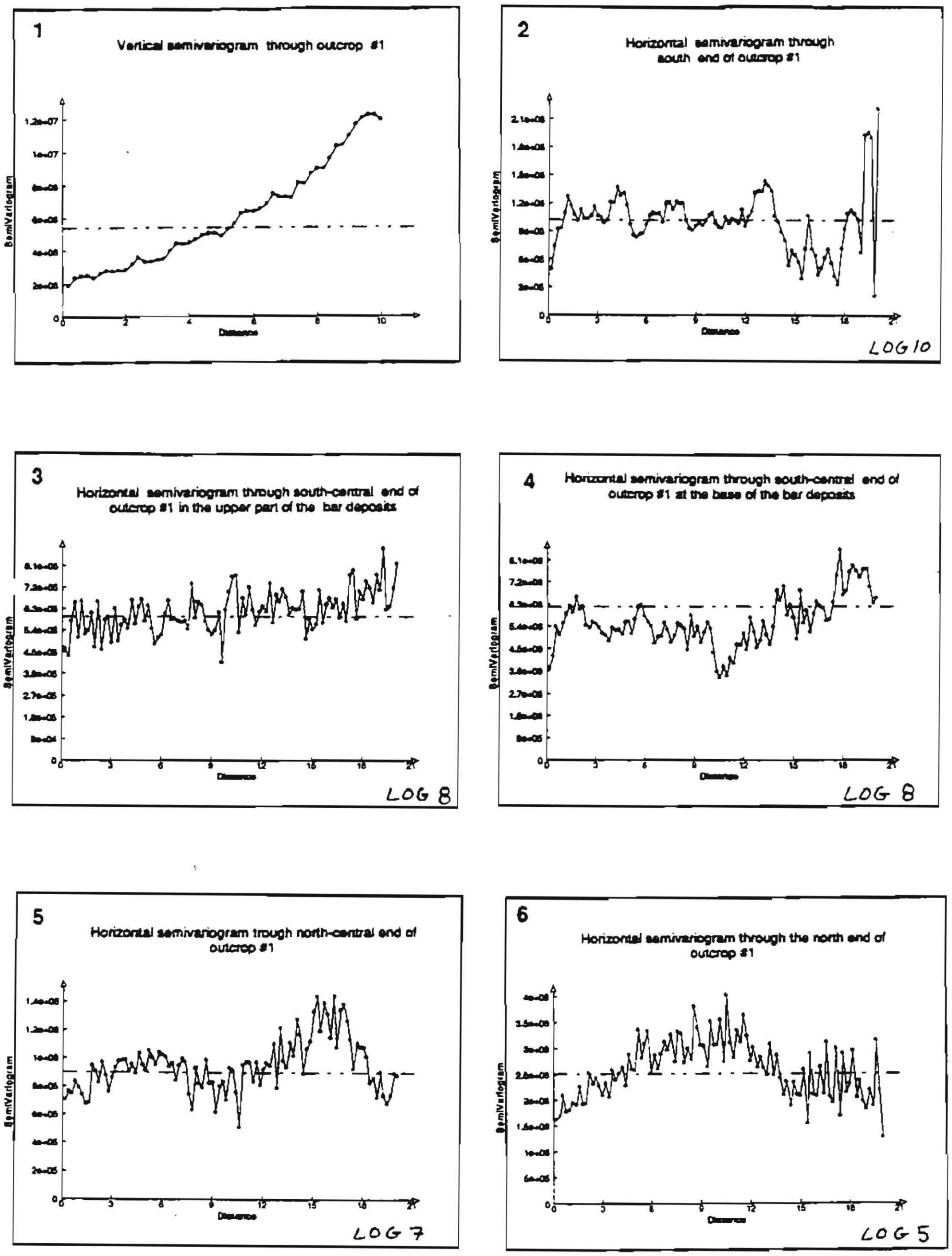
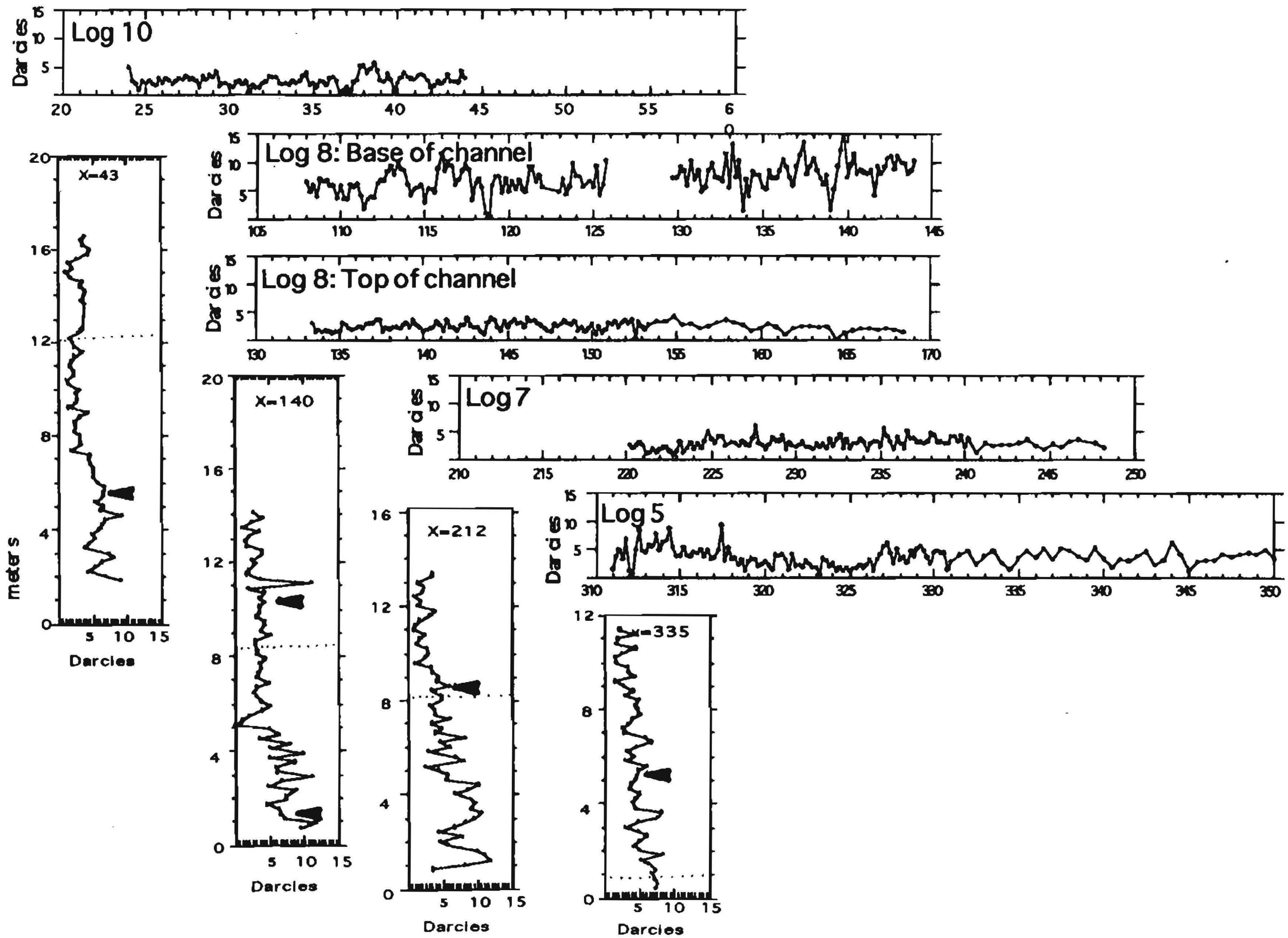



**Figure 47)** Semivariograms of data presented in Figures 51 and 52.

**Figure 48)** Valley fill 4 exposed in outcrop 1 of Clifton Canyon is a 16m thick sandstone composed of inclined beds that dip northward. The sandstone thins northward to 12m thick. An erosion surface, dipping in the same direction as the inclined beds, divides the beds into two sets. The outcrop exposes these bar deposits along a cross-section oriented about 30 degrees oblique to paleoflow. Inclined beds all dip in the down-stream direction. Each set of beds is interpreted as deposits of a migrating channel bar. Preservation of only down-stream dipping beds indicates both bars migrated down stream as they grew. The down stream set truncates the upstream set, indicating the bar deposits were superimposed by channel switching. This pattern of bar stacking tends to remove channel filling deposits, and none separate these two bar deposits.

Four vertical and five horizontal permeability logs where measured along this set of inclined beds. Permeability means and variances decrease upwards in this inclined set, but this trend is more subtle where the sandstone body becomes thinner to the north. The erosion surface dividing the two sets of inclined beds is not associated with a striking change in permeability (position of this surface is marked by dotted lines on vertical logs). Systematic changes in permeability along the set of inclined beds were not noted, but permeability changes across individual inclined beds have yet to be examined in detail.

# *Bar Deposits in Clifton Canyon, Valley fill #4, Outcrop #1*



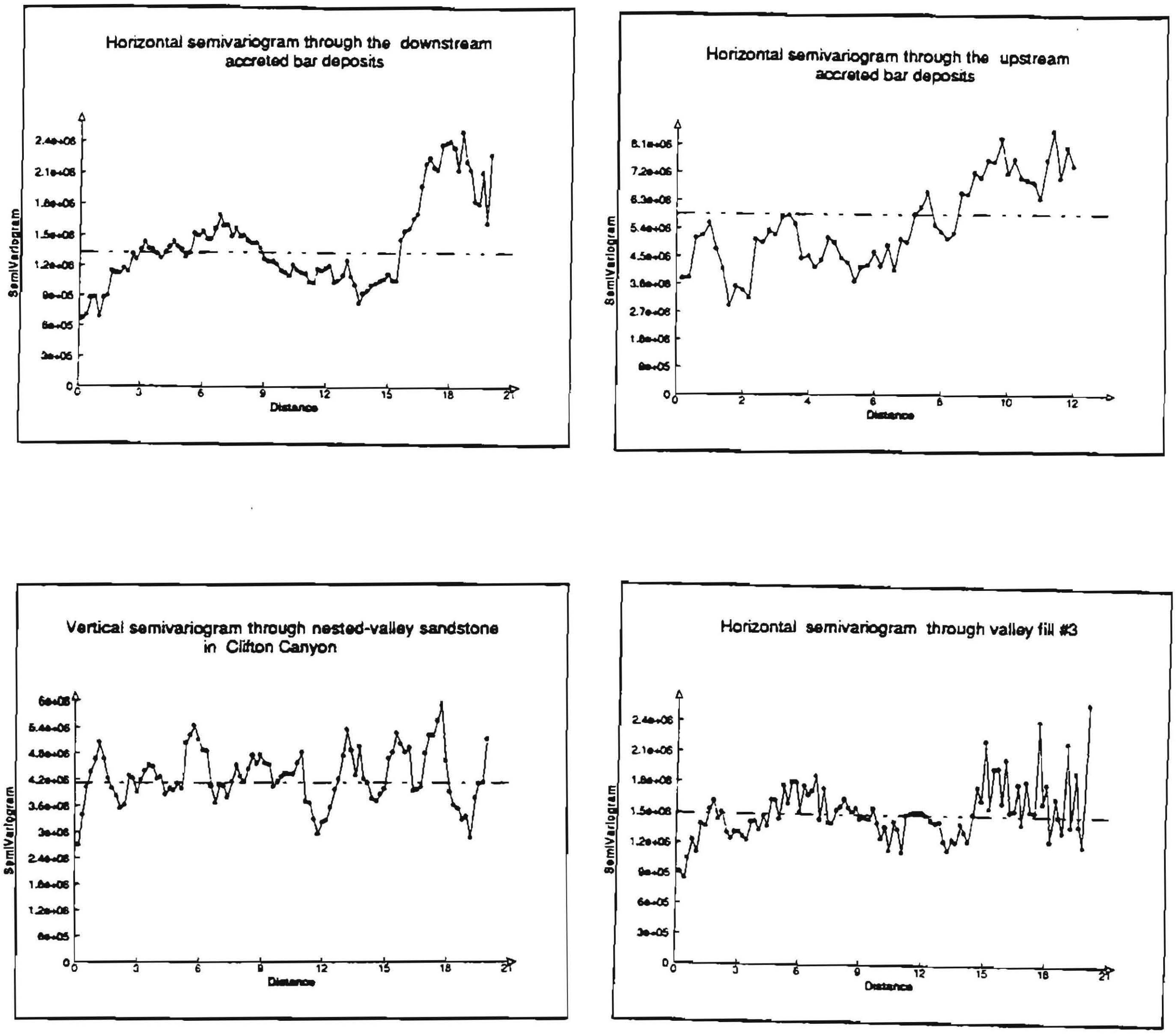



**Figure 49)** Semivariograms of permeability data collected in bar deposits exposed in outcrop 1 in Clifton Canyon (associated with data presented in Fig. 4). The semivariogram of vertical permeability logs shows upwards decreasing permeabilities (note drift). The permeability variance in the horizontal logs appears to depend more on the vertical position than on the lateral position in the set. One semivariogram shows a clear range to 12m, but the others show little horizontal spatial correlation.

deposits from adjacent shallow-marine sandstones. Hence, there is no master surface defining the margin of the nested valley-fill deposits. Instead each valley fill contains a discrete valley margin. This overlap pattern of discrete valley-fills is also observed at Red Canyon. A prominent erosional surface at base of SC 4 valley fill cuts down section toward this valley margin eroding successively older valley-fill deposits to the north.

Convex-down linear sandstone veins 1 to 2 cm wide and encased by convex upward mudstone form 5 cm wide polygonal-shaped sandstone veins showing an interlocking pattern with positive relief in bedding planes. Such structures are desiccation crack fills formed in mudstone but filled with sandstone. These features are typically overlain by a fluvial lag deposit, occur along the valley margin, and record subariel exposure during base-level fall.

### *Characteristics of Clifton Canyon Valley fills*

SC 1 and 2 valley fills contain the thickest lag deposits, the highest proportion of structureless sandstone, the lowest burrowing intensity, and lowest preservation of discrete erosive-based sandstone bodies. SC 3 valley-fill deposits are thicker, show increased preservation of discrete channel sandstone bodies with lateral accretion surfaces, and an increased diversity of lithofacies. SC 4 valley-fill deposits comprise the thickest and most heterolithic valley fill showing increased burrowing, suggesting a marine influence. The lower part of this valley fill contains heterolithic cut-and-fill sandstone bodies, based by well developed lag deposits containing the highest proportion of mudstone rip-up clasts. There is also an increased diversity of lithofacies, more mudstone interbeds, and increased preservation of sandstone bodies, particularly in the upper part of the succession. This trend of upward increasing preservation of sandstone bodies in valley fills may record increasing accommodation and storage of sediment volumes in successively younger valley fills. This trend is consistent with the change from a seaward-to landward-stepping stacking pattern of associated shallow-marine deposits.

In contrast to more proximal valley-fill deposits at Red Canyon, there is less relief on basal valley erosional surfaces, valley fills are overall more sandstone-rich, and there is a high proportions of fluvial facies, and structureless sandstone recording soft sediment deformation.

*Facies Architecture of SC 4 Sandstone Bodies*

SC 4 is the dominant valley fill in this canyon, and is exposed to the north through Whoopup, Salt Creek, and Oil Creek Canyons. North of Oil Creek, this northwest-trending paleovalley projects into the subsurface, where these valley-fill sandstones form the main reservoir in the Miller Creek-Donkey Creek trend. Across this region, SC 4 valley-fill deposits are characterized by moderately interconnected, multi-lateral point bar sandstone bodies. Clifton Canyon was chosen, in part, because of excellent exposures of these fully preserved channel sandstone bodies.

Coarse- to fine-grained sandstone bodies (120 to 180 m long and up to 16 m thick) fine upward, consisting of stacked sets of wedge-shaped planar tabular cross strata (up to 1 m thick) that show complex wedge-shaped geometries that generally thin upward. Planar tabular sets are bundled in 1 to 2 m thick bedsets extending laterally for 100s of meters, each bounded by laterally continuous inclined erosion surfaces. The outcrop exposes these northeast dipping (5°) surfaces oblique to paleoflow. The basal erosion surface of bedsets is typically overlain by a thin lag deposit that marks a grain-size change. Stacked sets of planar tabular cross strata do not cross inclined bedset boundaries. Sandstone bodies contain a low diversity of primary stratification types with planar-tabular sets dominant. Foresets are straight and commonly show an alternation of coarse and fine laminae. Planar-tabular sets are commonly truncated by reactivation and accretion surfaces, may be oversteepened or overturned in a downcurrent direction, contain smaller superimposed sets of tabular cross strata, or contain toesets of counter current ripples. Intraformational goethite-coated-clay-pebble ripup clasts form lag deposits lining basal contacts of sandstone bodies and internal bedsets.

Tangential foreset-bottomset contacts and normally graded foresets record laterally extensive avalanching over a large slipface (Hunter, 1985). Uniformity of internal primary stratification comprising these medium to fine sandstone bodies suggests lower flow regime deposition. Foresets are strongly unidirectional and vary only about 20° across a sandstone body. Similarly, there is little change in foresets comprising the four capping SC 4 sandstone bodies (from north to south across these sandstone bodies paleoflow indicators vary from N 60 E to N 35 E). The low variance in foreset orientations across sandstone bodies is suggestive of deposition in a low-sinuosity channel.

Sandbodies comprising the upper part of the SC 4 valley fill are interpreted as a fossilized train of low-sinuosity pointbar deposits. Inclined surfaces partitioning sandstone bodies represent accretion surfaces recording both lateral and downstream migration of these barforms. Thin mudstone interbeds lining lateral accretion surfaces record a change to lower energy suspension fallout deposition, and pauses in bar migration. Subsequent erosion of the bar surface, indicated by mudstone rip-up clasts, record reactivation, migration and increasing flow strength. These erosional surfaces formed during rising flood stages and increased flow strength. Because accretion surfaces extend across the entire sandstone body, are associated with low permeability mudstones, and are oriented systematically across the sandstone body, they impart a textural grain that may affect fluid movement in reservoirs.

From north to south across Clifton Canyon and up the SC 4 paleovalley, there are systematic changes in the internal architecture of four capping sandstone bodies. The northernmost sandstone bodies are highly interconnected, with a major reactivation surface separating two superimposed sandstone bodies. These sandstone bodies contain accretion surfaces oriented at a low angle to internal primary stratification suggesting preservation of only the downstream portion of the migrating barform. By contrast, the southernmost sandstone body contains accretion surfaces dipping upstream and lower angle downstream-dipping accretion surfaces suggesting this sandstone body records aggradation and lateral expansion of the barform in both upstream and downstream directions. Within a sandstone body, there is an upward increase in burrowing intensity, mudstone interbeds, proportion of mudstone rip-up clasts, and diversity of primary stratification types. These attributes increase southward in sandstone bodies occupying successively more upstream positions in the paleovalley. These relationships may reflect increased preservation of successively more landward positioned sandstone bodies and may record base-level rise in the paleovalley.

Across Clifton Canyon, the four sandstone bodies are laterally separated by two mudstone-rich covered slopes. These mudstone-rich intervals are inferred to represent channel-fill deposits. Distances between these mudstone channel-fills record barform wavelengths (120 to 200 m), and vertical and lateral dimensions of internal accretion surfaces record channel widths and depths (i.e., 90 m wide and about 15 m deep).

## Day 4: Red Canyon

*From Hot Springs (SD) go 20.5 miles west on state highway 18 to the entrance of Red Canyon Road (note the historical marker just before the turn, if you arrive in Edgemont SD. you have gone several miles to far). Continue 3 miles north on Red Canyon Road. A succession of outcrops along the mouth of Red Canyon together provide a complete section through the Fall River Formation. During this stop we will start at the base of the Formation and progress stratigraphicly upwards. Note the mild structural dip here (2-3° SW), and beware of several normal faults with displacements of several meters. We will drive between some of these outcrops as they are up to a kilometer apart.*

### *Discussion*

Red Canyon exposes an oblique cut through a 3.5 km wide, northwest trending sandstone body incised into mudstone-rich, shallow-marine deposits (Fig.50). Five short-term stratigraphic cycles are recognized in marine deposits exposed in southern Red Canyon. Exposure surfaces capping the lower four of these marine stratigraphic cycles correlate laterally to major erosion surfaces in the sandstone body. In the sandstone body, each of these erosion surfaces show tens of meters of relief. The fifth stratigraphic cycle extends across Red Canyon and caps the sandstone body to the north. As in Clifton Canyon viewed yesterday, the thick sandstone body is interpreted as deposits of four nested valley fills. Here, however, valley fill successions are interpreted to be in a more proximal position of the basin and show a greater influence of tide and particularly wave currents on deposition relative to the fluvial dominated sandstones of Clifton Canyon.

In the area of Red Canyon we have: (1) mapped short-term stratigraphic cycle boundaries from marine deposits through the nested valley sandstone; (2) documented sedimentologic variations within progradational shoreline successions and within each valley fill; (3) documented permeability variations though the marine and valley deposits of the Fall River Fm., and at a finer scale along depositional strata within different facies comprising the valley fills (plates 2 and 3). This allows the four nested valleys to be compared in terms of their dimensions, internal stratal geometries, facies, and the magnitude of permeability variations.

The trip today will include four stops in Red Canyon (Fig. 50). At the first stop, a series of outcrops together expose a complete vertical traverse though the marine deposits comprising stratigraphic cycles at the southern mouth of Red Canyon. At the second stop, a large outcrop near the axis of the sandstone body exposes four nested valley fills.

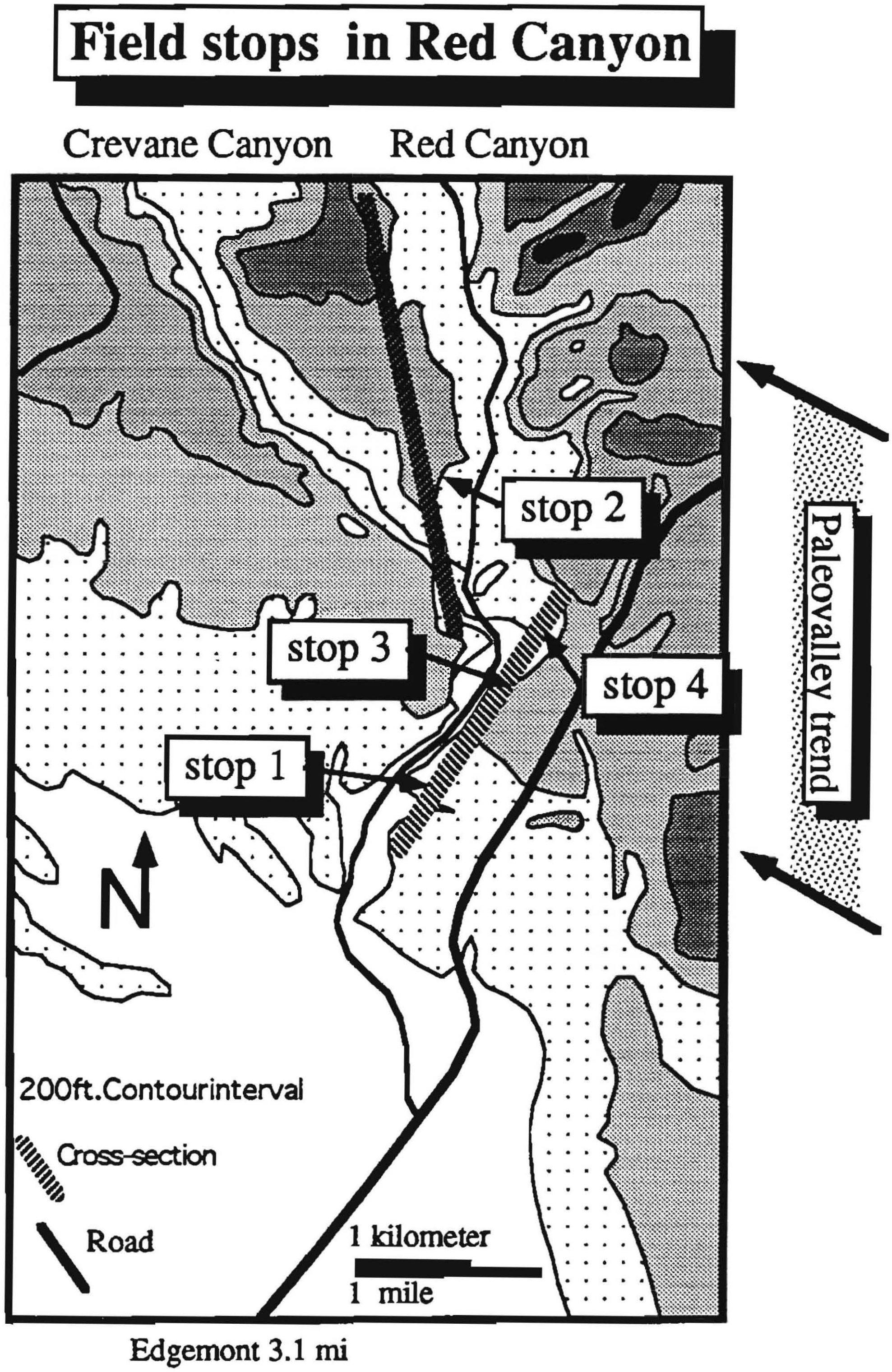



**Figure 50)** Map of Red Canyon field trip stops.

Because each valley cuts downward into those below, the deposits preserved here are generally those deposited lower within individual valley fills. After viewing the outcrop from a distance, we will inspect the deposits during a two-three hour hike across the top and base of this outcrop. The third stop is another large outcrop that exposes the sandstone body near it's southern margin. A shorter hike along the base of this outcrop shows strata that were deposited generally higher within individual valley fills. The final stop will be at the top of this same outcrop. Here lateral changes in valley fill 4 and a panorama of Red Canyon outcrops can be viewed.

### *Stop 4.1: Shallow Marine Stratigraphic cycles*

**Objectives:** Examine the five short-term stratigraphic cycles that comprise marine deposits of the Fall River Formation at the mouth of Red Canyon.

The lower three stratigraphic cycles consist of tide- and fluvial-dominated delta front facies, each capped by shallow distributary channels, mouth bars and/or a rooted horizon. The fourth stratigraphic cycle is composed of disrupted mudstones, capped by an interval with red hues and oxidized mottles interpreted to be a paleosol. A half kilometer wide distributary channel cuts downwards from this paleosol in one location. The fifth stratigraphic cycle consists of tide-dominated delta front deposits capped by wave reworked delta front sandstones. The upper most sandstone bed of the fifth stratigraphic cycle caps the ridges for nearly the length of Red Canyon, and thus it was used as a datum.

Outcrop 1:

The first outcrop exposes the Lakota-Fall River contact and the first stratigraphic cycle of the Fall River Fm. (Fig.51). A change from disrupted, light gray mudstones containing siderite/goethite nodules to laminated dark-gray mudstone marks the base of the Fall River Fm. This contact has been interpreted to record a major transgressive disconformity. The first Fall River stratigraphic cycle (SC 1) consists of thinly interbedded sandstones and mudstones that can be subdivided into two smaller-scale successions (parasequences). Each parasequence increases in sandstone proportion and bed thickness upwards, and then fine more abruptly to a mudstone-dominated interval. In the lower succession, beds appear horizontal. The upper succession contains even smaller-scale coarsening-upwards bedsets, with some beds dipping at a very low angle to the south. These deposits contain opposing current ripple cross-lamination and wave ripple marks. The stratigraphic cycle is interpreted as two shoaling upwards

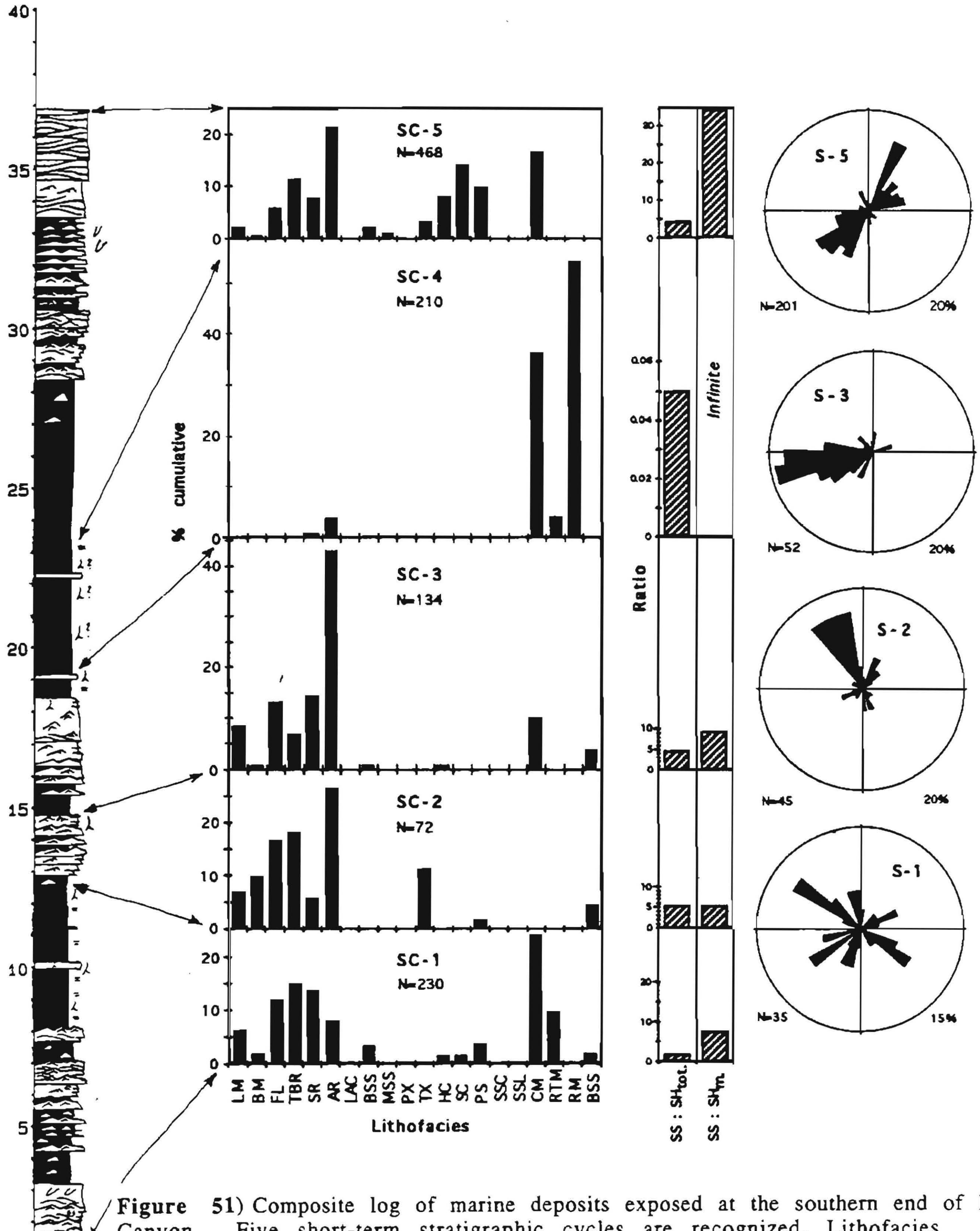



**Figure 51)** Composite log of marine deposits exposed at the southern end of Red Canyon. Five short-term stratigraphic cycles are recognized. Lithofacies proportions, lithology ratios, and mean paleocurrent orientations for each stratigraphic cycle are show.

successions recording an episodically prograding shoreface. The dark gray disrupted mudstone that caps SC 1 contains root trace fossils and records subarial exposure.

Outcrop 2:

A section through stratigraphic cycles 2-5 is exposed here (Fig. 51). The paleosol capping SC 1 is at the outcrop base. In both SC2 and SC3 sandstone proportion and bed thickness increases upwards, and each stratigraphic cycle is capped locally by shallow channel sandstone bodies that cut into the underlying deposits. Coarsening upwards parts have wave and opposing current ripple cross-lamination. Channel bodies are coarser-grained and locally contain large-scale cross strata. Root traces are seen capping both stratigraphic cycles. Permeability values increase upwards across each stratigraphic cycle, and are highest in capping distributary channel deposits (Fig.52). Each stratigraphic cycle records marine transgression, shoreface progradation, and finally subarial exposure and erosion by minor distributary channels.

The fourth stratigraphic cycle (SC4) consists of reddish-gray mudstone with oxidized mottles. Mudstones become more disrupted upwards, but near the top of the stratigraphic cycle mudstone beds again become laminated. Laterally along the cliff face extending towards the road, this paleosol correlates with the basal erosion surface of a 9m thick channel that incises into the SC4 deposits. On the east side, this channel has a complex fill that contains multiple smaller channel fills within. To the west, the channel is composed of a single set of inclined beds dipping westward, nearly perpendicular to paleoflow. Internally these beds are large-scale cross-stratified. permeabilities in this set decrease upwards and in the direction the beds dip (Fig.53).

The upper most Fall River stratigraphic cycle becomes more sandstone-rich upwards, but local smaller-scale coarsening upwards parasequences can be recognized within, each separated by thin mudstone-dominated intervals. Lower the deposits are wavy-lenticular bedded, but the 3m thick capping sandstone is hummocky/swally cross-stratifed. This stratigraphic cycle can be viewed closer up at the next stop.

Outcrop 3:

The prograding shoreface deposits of SC5 are well exposed at this stop (Fig. 51). These deposits can be divided into two smaller scale parasequences. The lowest parasequence is based by a granule lag, inferred to represent erosion during maximum base-level rise and marine transgression. Both parasequences coarsen and beds thicken upwards. In both parasequences beds dip at a low angle southward. Asymmetrical ripple cross-lamination

## permeability of marine sequences

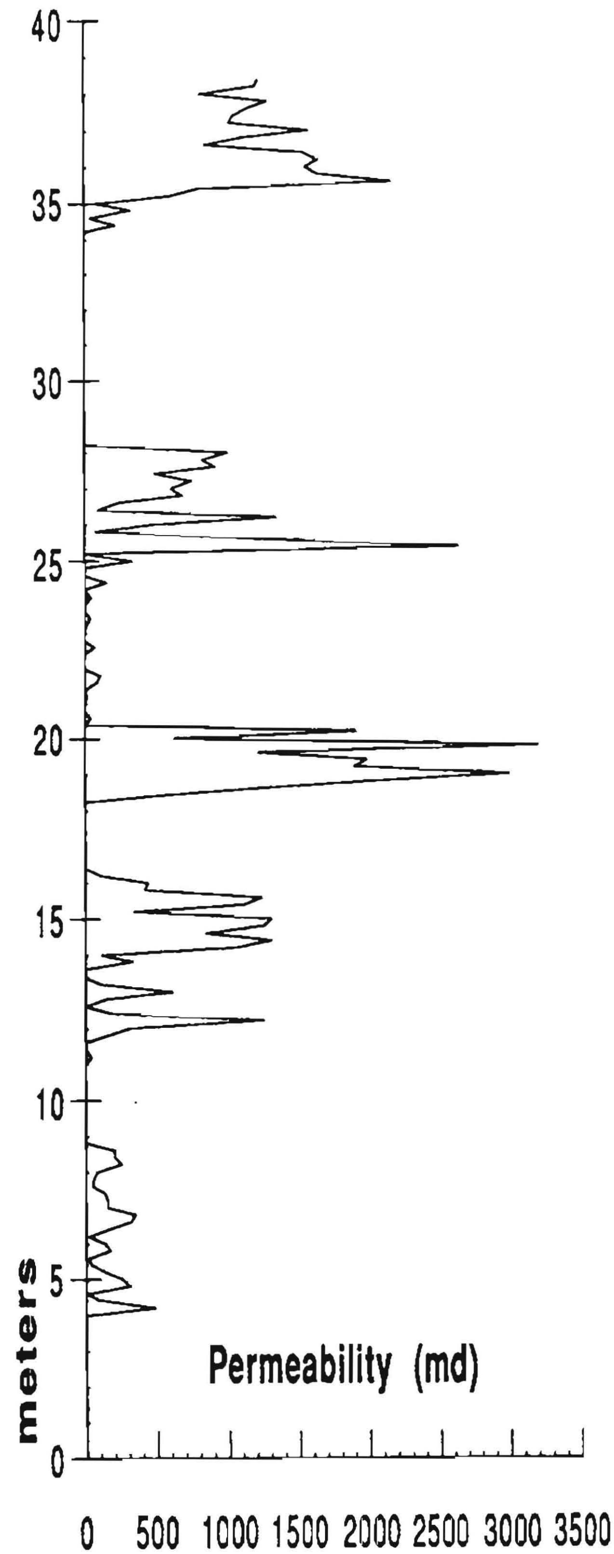



**Figure 52**) Permeability variations upwards through marine deposits exposed in the southern end of Red Canyon. Generally the marine stratigraphic cycles coarsen and increase in permeability upwards. In this permeability profile, SC1 consists of two parasequences. SC4 is wholly mudstone here, so it has no coarse grained cap (in contrast to the other stratigraphic cycles). Laterally, however, a 9m thick channel cuts down from the top of stratigraphic cycle 4.

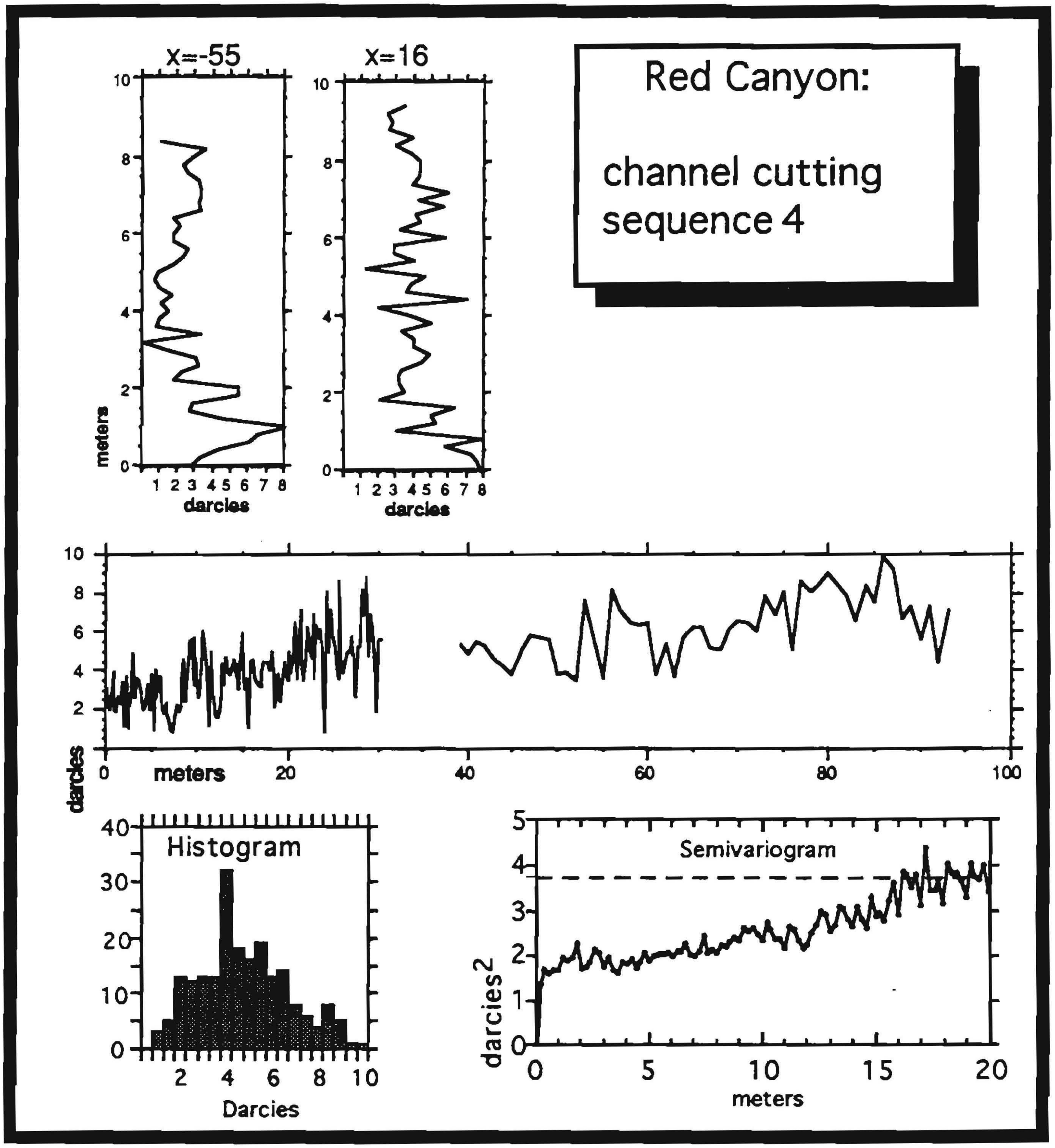



**Figure 53**) Permeability variations within a thick, isolated channel body that cuts into the top of stratigraphic cycle 4 at the southern end of Red Canyon. The channel is about half a kilometer wide and up to 10m thick. The deposits sampled are from a single set of lateral accretion deposits dipping to the west (i.e., towards lower positions on the horizontal permeability profile). Permeability values decrease upwards within the inclined set and in the direction the beds tip. These trends record a progression towards the channel filling margin of the sandstone body (note drift in semivariogram). Smaller scale cycles in the closely spaced horizontal permeability data (meters 0-30) record decreasing permeability upwards trends across individual inclined beds.

(oriented both NE and SW), parallel lamination, and rare wave ripple marks occur in these beds. Moderate bioturbation consists of *Planolites, Thalassinoides and Skolithos* burrows. Channel-shaped sandstone beds occur locally, and are generally less than a meter thick and a few tens of meters wide. Inclined beds of the second parasequence are capped by a 2.5 m-thick, amalgamated swally cross-stratified sandstone bed. The capping bed has a erosional base that clearly truncates underlying strata. Deposits of SC5 record episodic shoreface progradation and parasequences within may record individual mouth bars. The swally cross-stratified cap records reworking of shallow-water sands by strong wave currents. This bed is overlain by thinly interbedded sandstone and mudstones containing hummocky cross-strata, which are in turn overlain by the Skull Creek Shale.

*Stop 4.2: Center of stacked valley fills*

*Continue 1.3 mile north on Red Canyon Road to a side road leading up hill to a small gravel quarry. The large cliff on the opposite (west) side of the canyon is the subject of this stop. After viewing the outcrop here, we will continue 0.5 miles down Red Canyon Road. From here we will walk an abandoned mining road to the top of the cliff, progress down the cliff face viewing features from above, then back across the base of the cliff viewing features from below. This process will occupy several hours.*

**Objectives**: Examine the geometry and internal character of nested valley fills near the paleovalley axis. During a traverse along this outcrop, contrast stratal geometries, facies, and the magnitude of deposit heterogeneity with that seen yesterday in Clifton Canyon. Examine sites where permeability samples were collected.

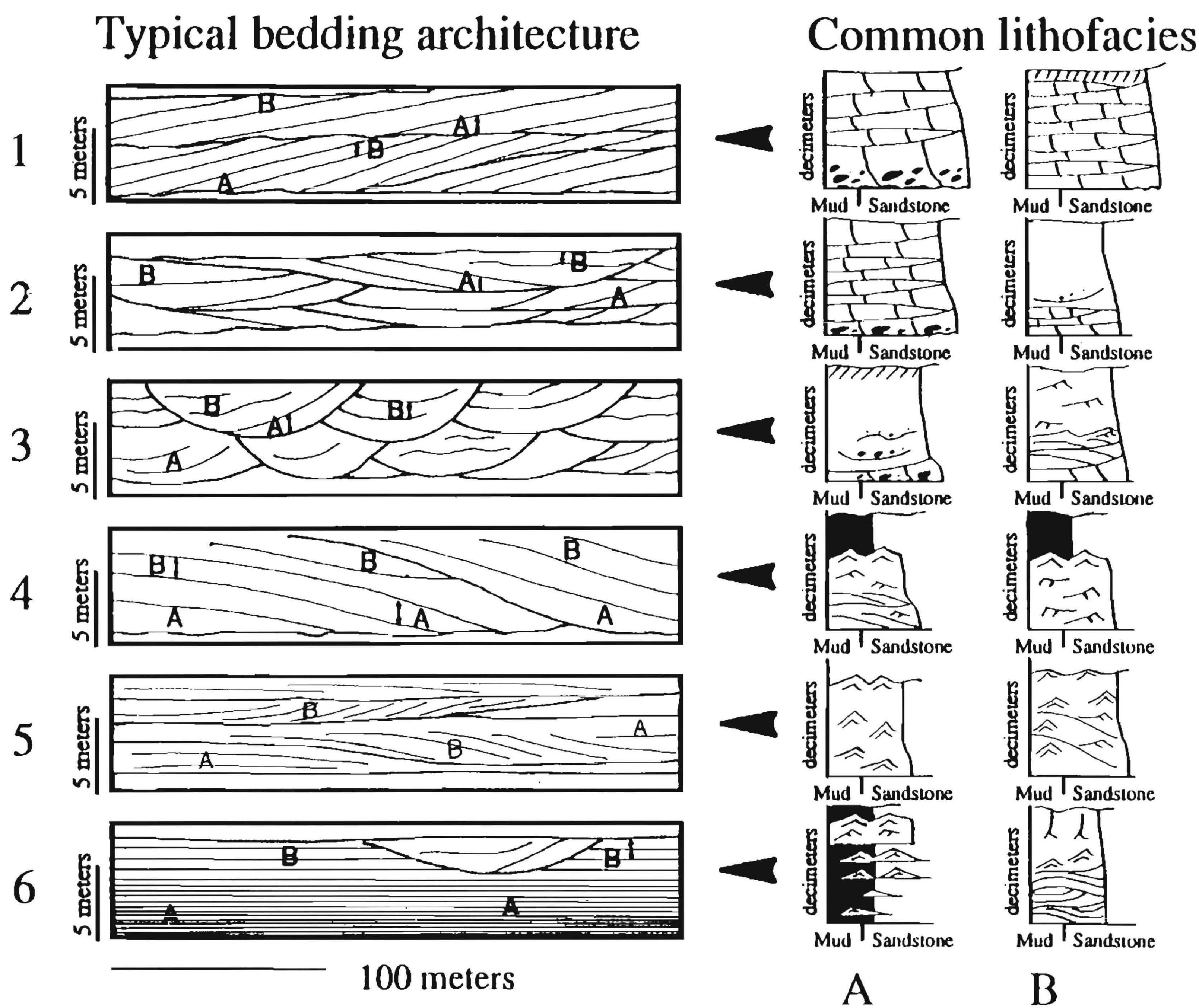
This outcrop is documented by a large photo mosaic, a bedding diagram overlay and sets of vertical sedimentological and permeability logs (plate 2; Figs. 54, 55, 56, 57, 58, 59, 60). The Lakota Fm. is exposed below the base of the main cliff to the left side (south) and locally further to the right (north). The pedogeneticly disrupted erosion surface that caps the Lakota Formation is overlain by a short succession of Fall River shoreface deposits in one location near the center of the outcrop (sheet 1, log K). Elsewhere the lowest Fall River valley fill cuts downward into the Lakota Formation and this transition in not preserved.

The Fall River Fm. is the large sandstone body forming the main cliff face capping the ridge. On the right side of the cliff face, this sandstone is clearly divisible into three parts, each bounded below by a major erosion surface. Each of the parts are composed of multiple channel deposits stacked both vertically and laterally, and each is interpreted to record deposition within a different valley fill. Near the middle of the outcrop, a fourth major erosion surface cuts

**Figure 54) Generalized lithofacies types observed in valley fill sandstones of Red Canyon.**

1) ***Coarse-grained fluvial:*** Individual channel bodies extend for several hundred meters but are normally only a few meters thick due to vertical truncation by overlying deposits. Internally beds of composed completely of large-scale cross-strata. Beds have very high permeabilities (commonly between 10 and 30 darcies) and almost never have laterally continuous shale drapes. 2) ***Fluvial:*** Similar to (1) but finer grained (very fine to fine) and lower overall permeabilities. Length of individual channel bodies may be slightly less on average, so there may be a lower proportion of lateral accretion "bar" depositions relative to channel filling deposits (however this is hard to estimate due to their highly cannibalized nature). As in (1) channel deposit thicknesses are low due to vertical truncation by overlying deposits. Deposits are dominated by large-scale cross-strata, but local ripple cross-laminated caps occur. 3) ***Concave-upwards estuarine channels***: Concave upwards channel bodies are arranged in a highly complex, interconnected stacking pattern. Individual channel bodies normally continue for less than 100m. Large-scale cross-strata can be common, and cross-strata dips can be less than the angle of repose, suggesting dunes did not build to full vortex stage before current reversal. The deposits lack abundant reactivation surfaces within cross sets or evidence of tidal bundles, suggesting weak tides and a highly ebb-dominated system. Wave and current ripple cross-lamination is also common. In some cases current ripple cross-sets dip in opposing directions, indicating current reversal. Mud chip lags are common, particularly at the base of scoop shaped channel deposits, but laterally continuous shales are rare. 4) ***Laterally accreted eustuarine channels***: Laterally continuous sets of inclined hetrolithic beds are seen only at the top of valley fill 4 in Red Canyon. In the west wall of Red Canyon two inclined sets cut oblique to paleo-flow suggest a channel width of about 50m, and a bar/channel bend wavelength of about 300m. Individual inclined beds dip at up to 12 degrees and fine to mudstone. Large-scale cross-stratification is rare, and is restricted to the base of the inclined beds. Most deposits show current ripple cross-strata with opposing dip directions (indicating flow reversal), but many beds have thick caps that are wave ripple cross-stratified. These rocks have the lowest permeabilities of those in the valley fill, and continuous shale drapes capping inclined beds would preclude horizontal movement of fluids. 5) ***Wave deposited channels or sheets:*** These deposits occur only in the upper part of valley fills, and their geometries are best expressed at the top of valley fill 3 exposed at the third stop. Some of these bodies gradually thicken laterally, and appear to have very broad channel-form shapes (i.e., meters thick and hundreds of meters wide). Where sheets are thinner, they can be separated by cm-thick shale drapes. Where thicker shale drapes are absent and bases appear to be erosional. Internally most sheets contain horizontal beds of planar and wave ripple cross-laminated sandstone. Less commonly internal beds can dip at near the angle-of-repose. These deposits are interpreted to record wave driven estuarine bars that locally developed steep slip faces as they migrated. ***6) Mudstone-dominated progradational lobes:*** These rocks cap valley fills and comprise the adjacent out of valley deposits. Deposits are meters-thick coarsening-upwards successions capped locally by small shallow fine-grained channel sandstones or a thick bed of hummocky cross-stratified sandstone. Beds in coarsening upwards deposits appear horizontal or can have low angle dips southward. Lower deposits are wavy-lenticular bedded, with wave and opposingly directed current ripples. Higher, thicker sandstone beds are hummoky cross-stratified with ripple marked caps. Shallow channel bodies capping stratigraphic cycles are generally

wave and current rippled, but locally deposits can be planar stratified and large-scale cross-stratified. The deposits record shoaling and progradation of the shoreface. Sets of inclined beds may record individual mouth bars. Hummocky cross-stratified beds record reworking of the shoreface by strong wave currents. Capping channel sandstones record minor distributaries.


Typical bedding architecture
Common lithofacies
1
2
3
4
5
6
5 meters
A
B
A1
B1
decimeters
Mud
Sandstone
100 meters
A
B

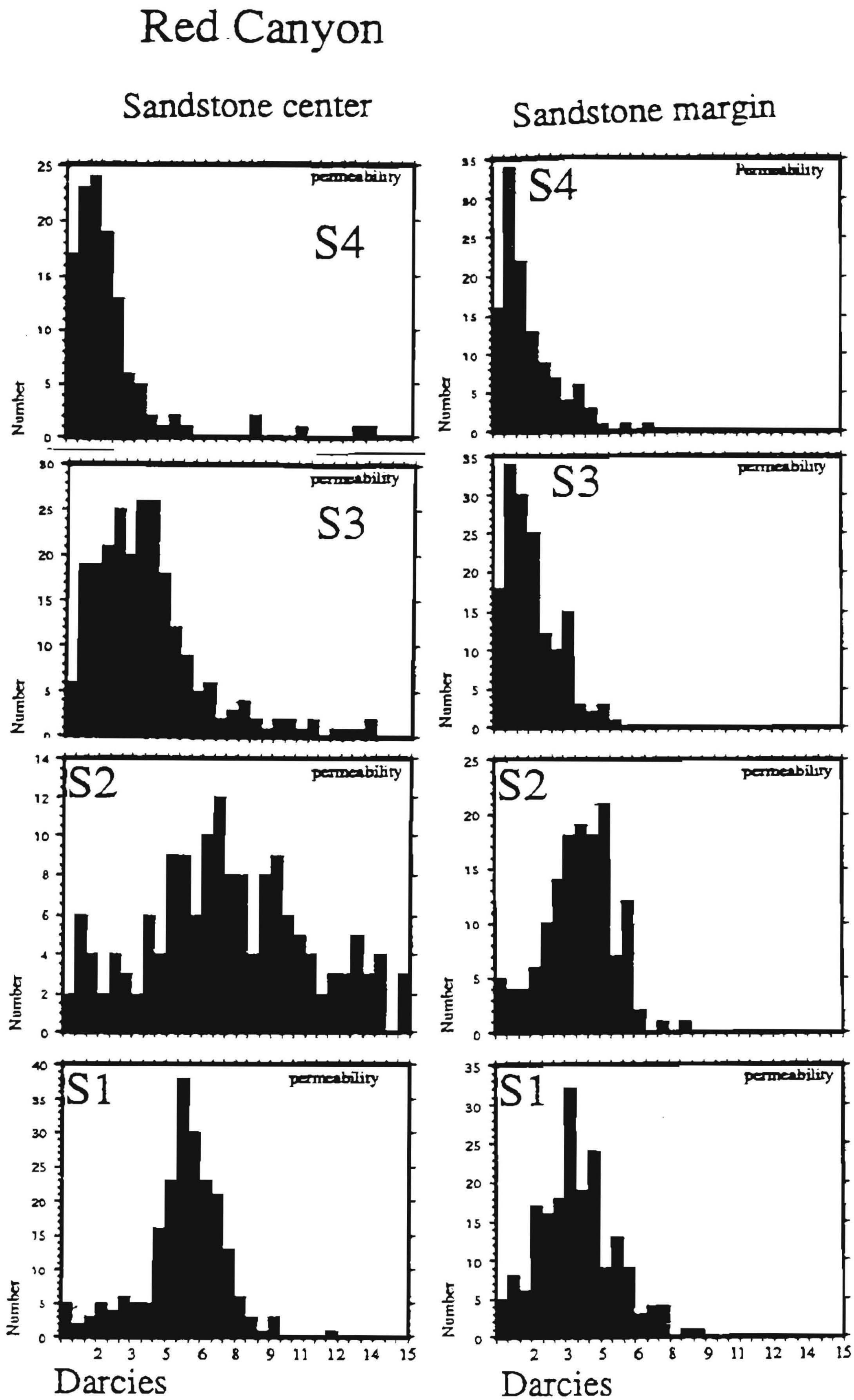



**Figure 55**) Distribution of permeability values within the valley fill deposits that comprise the large sandstone body exposed in Red Canyon. The second valley fill is on average coarser and more permeable than the first. The third and fourth valley fills are progressively finer and less permeable than the second. All valley fills are on average more permeable near the center relative to the margin of the sandstone.

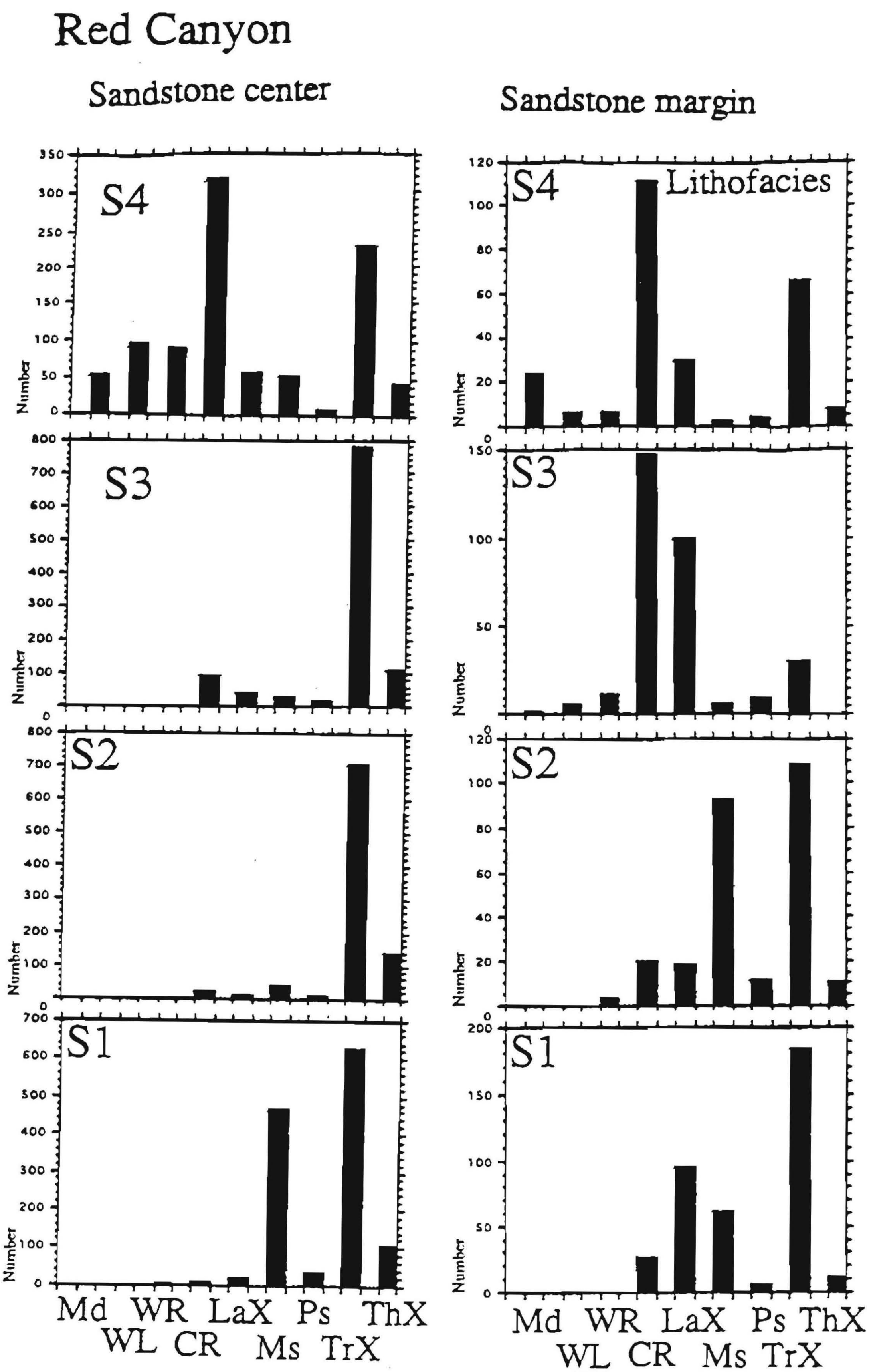
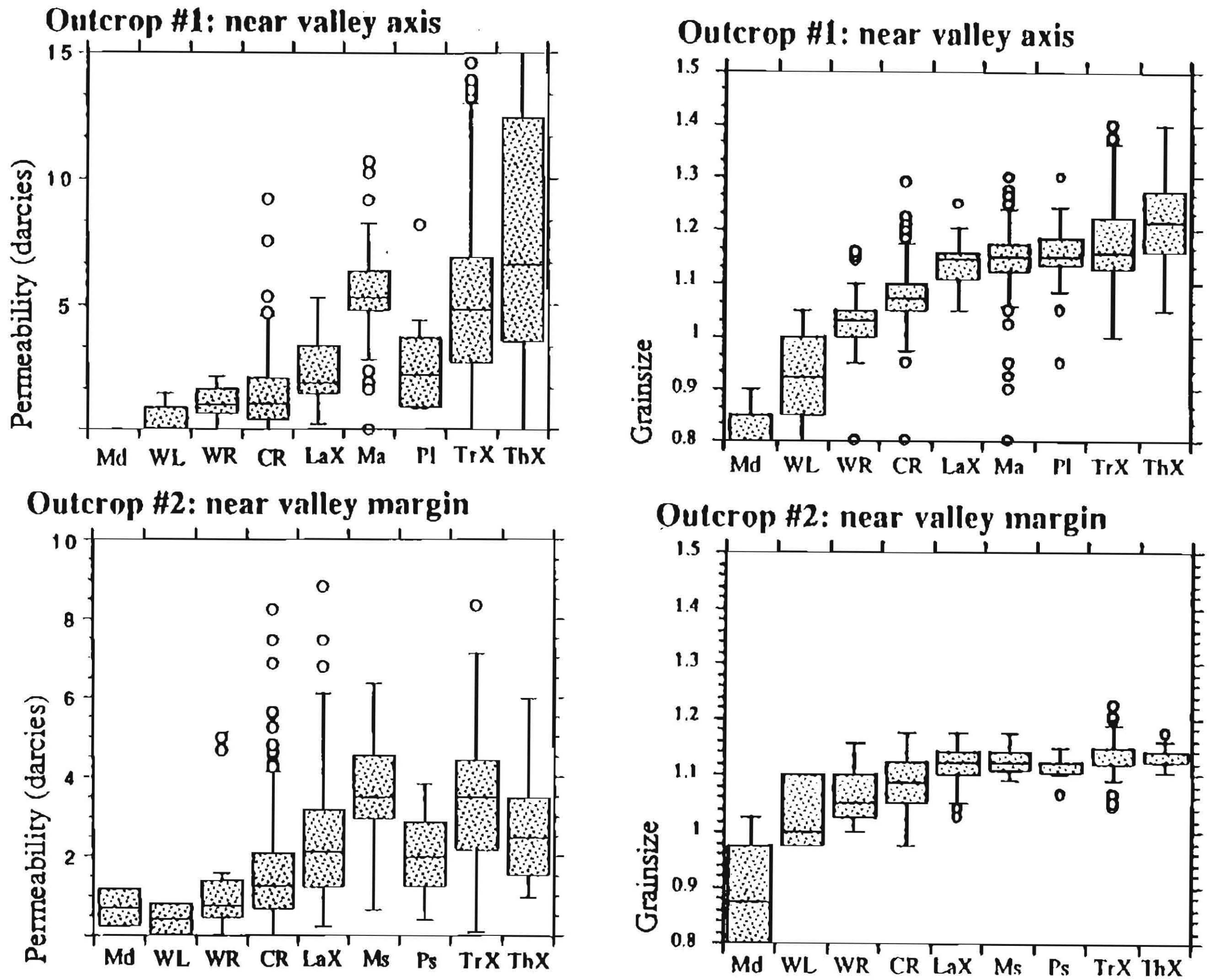



**Figure 56)** Lithofacies proportions within each valley fill deposit comprising the thick sandstone body exposed in Red Canyon (see Fig.57 for code to lithofacies). All valley fill deposits contain mostly large-scale cross-stratification, except for valley fill 4). Towards valley fill margins deposits generally have finer grain sizes, more wave and current ripple cross-lamination, and more planar strata. From valley fill 2-4 there is a progressive increase in the amount of ripple cross-lamination and mudstone beds, interpreted to reflect progressively more estuarine conditions.




Md = mudstone and disrupted sandstone
WL = wavy-lenticular bedding
WR = wave ripple cross-lamination
CR = current ripple cross-lamination
LaX = Low angle cross-strata
Ms = massive sandstone
Ps = planar strata
TrX = trough cross-strata
ThX = Thick-sets (>.4m) of cross-strata

**Figure 57)** Covariance between lithofacies, grain size and permeability within valley fill deposits of Red Canyon. Generally beds with high flow sedimentary structures (i.e., large-scale cross strata, planar strata) and coarser grain sizes have higher permeabilities than finer grained beds with low flow structures (i.e., wave and current ripples).

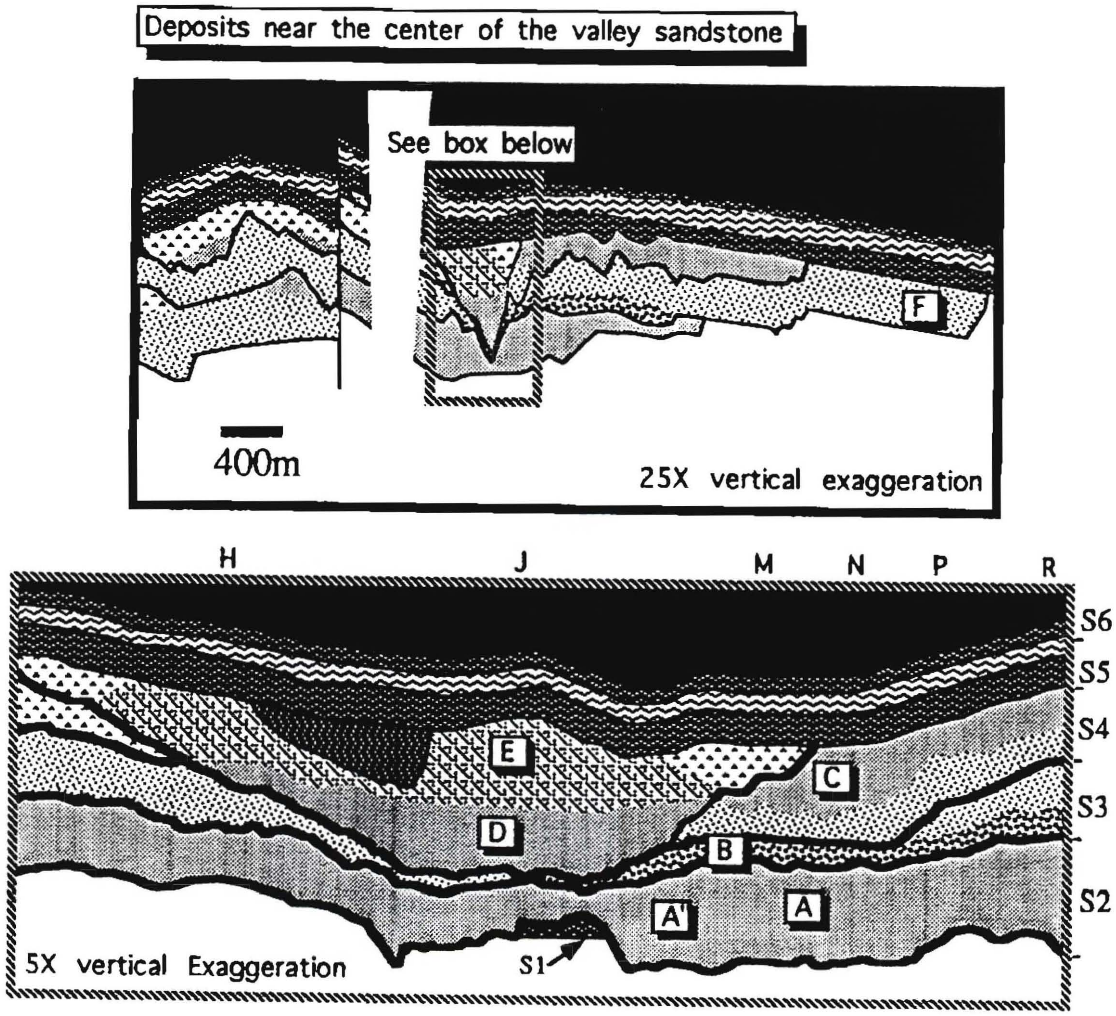



**Figure 58**) Simplified facies diagram showing variations at stop #2, near the center of the valley sandstone. Four valley fills are recognized. Valley fill 2 as the coarsest grain sizes, highest permeabilities, and the greatest cross-sectional area. Valley fills 3 and 4 have progressively finer mean grain size, lower mean permeabilities, are increasingly hetrolithic, and have progressively smaller cross-sectional extent. Letters on top of the lower box show positions of permeability logs in Fig. 11. Lettered boxes show positions of horizontal permeability profiles and detailed permeability measurements thought specific depositional strata (Fig. 61-67). See handout sheet #1 for more details, including an outcrop photo and more detailed positions of sedimentologic and vertical permeability logs.

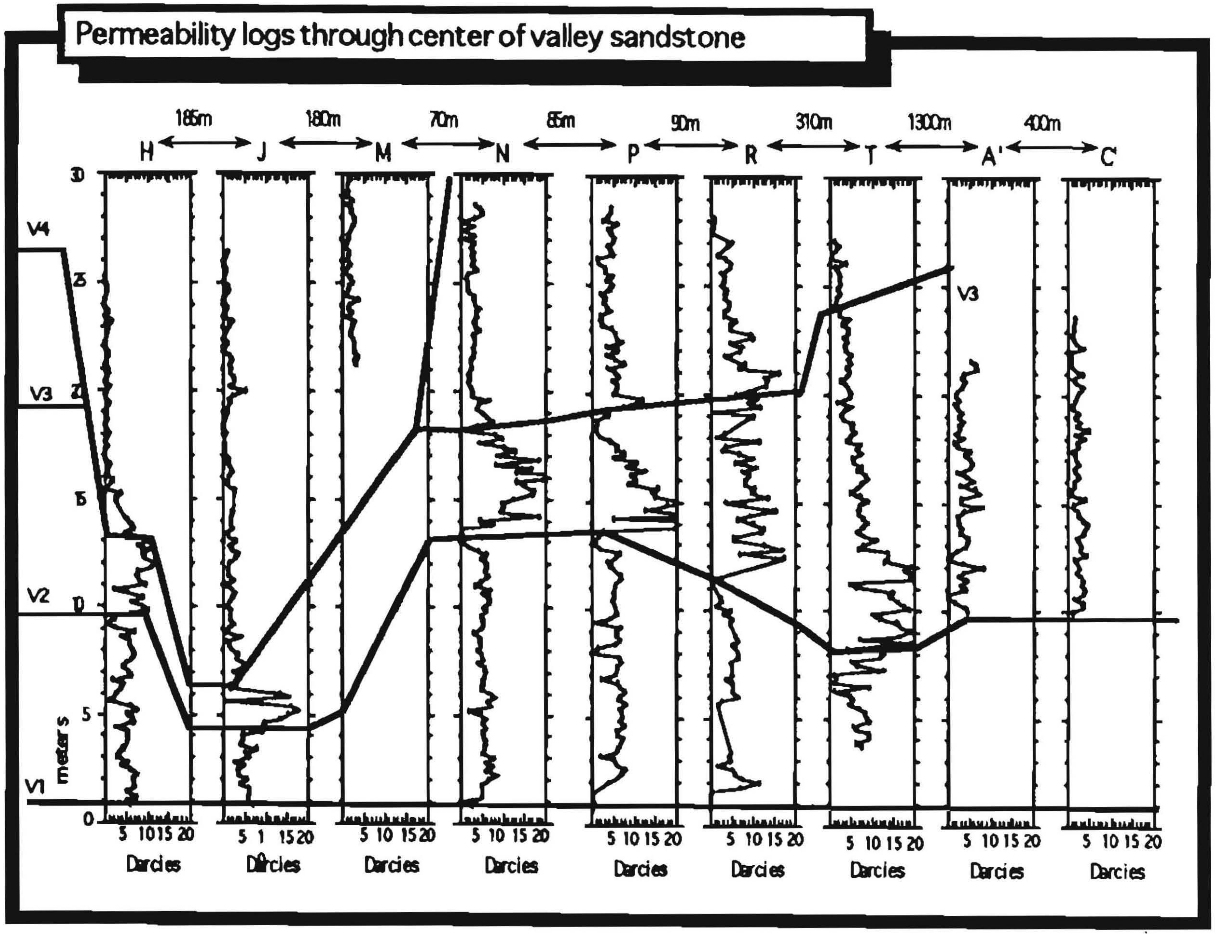



**Figure 59)** Permeability logs measured along the outcrop viewed at stop 2. Note decreasing upwards permeability trends across valleys 2-4, very high permeability values along the base of valley fill 2, and very low permeability values in valley fill 4 (see positions of logs in Fig. 58)

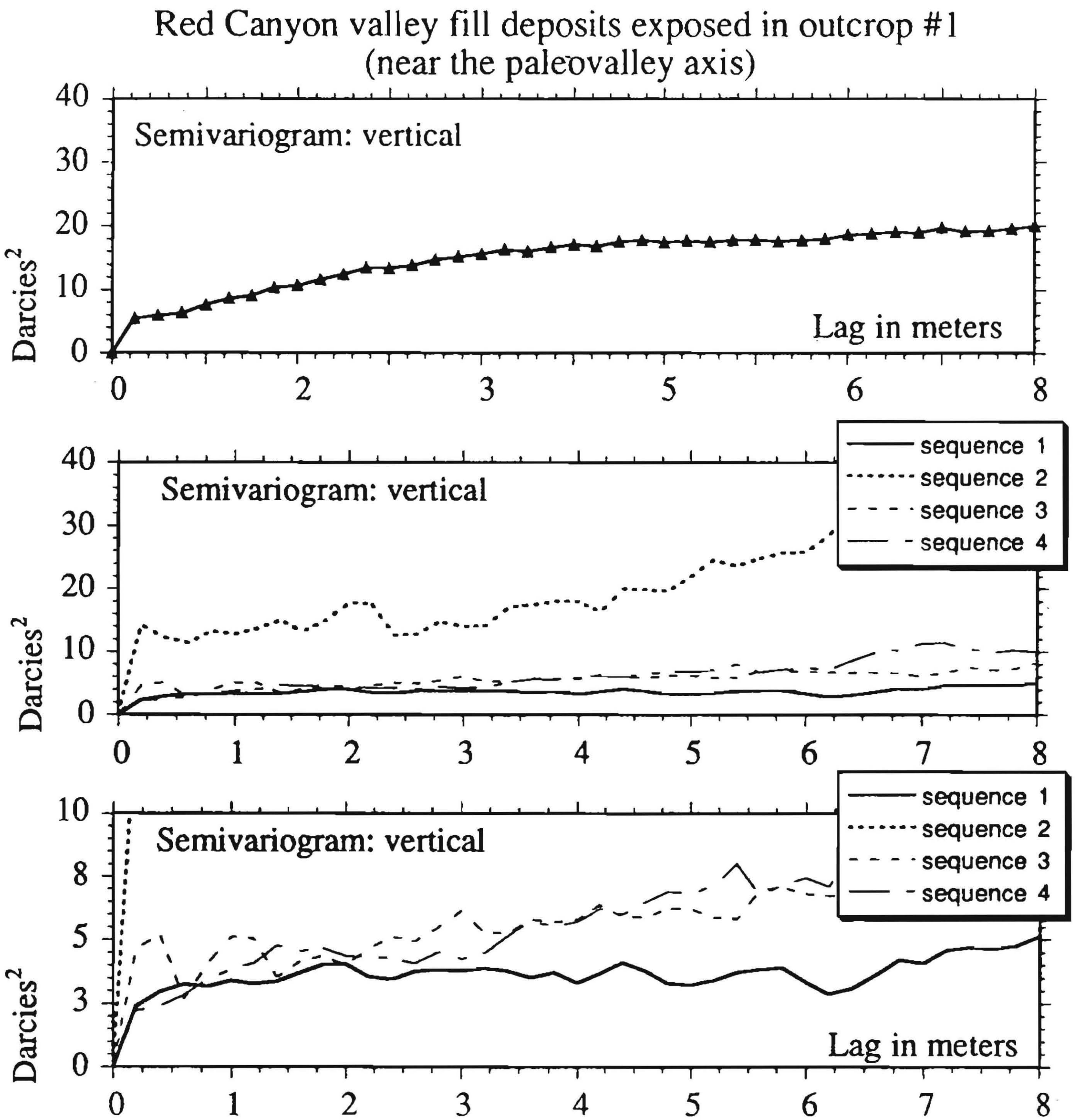



**Figure 60**) Vertical semivariogram of permeability data shown in Fig. 59. The five meter range of the whole sandstone variogram reflects the similarity of within valley fill deposits relative to deposits in adjacent valley fills. The short range of all within valley variograms reflects the highly vertically truncated nature of sediment bodies. The drift towards increasing variance with lag distance of within valley variograms reflects fining upwards tendencies in each fill and across the sandstone as a whole.

downward to the left, at it's lowest point removing all but thin sections of the lowest two valley fills. Deposits above this surface are finer grained, hetrolithic, and include large sets of inclined beds dipping to the right. These deposits comprise a fourth valley fill succession. Further to the left, towards the southern end of the outcrop, the erosion surface at the base of this fourth valley fill rises and deposits of the lower three valley fills are again exposed. A coarsening upwards marine stratigraphic cycle can be seen capping the fourth valley fill to the left, and these beds continue across exposures in Red Canyon.

Sandstones within the lowest valley fill (SC 1) are uniformly fine grained. Internally, a complicated array of concave upwards surfaces define a complex lateral stacking of channel bodies. Individual channel bodies extend for only tens of meters to a few hundred meters and all contain a low proportion of laterally accreted relative to channel filling beds. In most channel deposits a few laterally accreted beds dip away from one margin, and beds gradually decrease in dip and can become concave upwards the channel fill. Many channel deposits have concentrations of mud-chip clasts along their basal erosion surface, but in most places such clasts are suspended in a matrix of fine-grained sandstone. Sedimentary structures are difficult to see and many parts of the cliff face appear massive, however, angle-of-repose, large-scale cross-stratification is clearly the most common structure. Where this valley fill is most completely preserved, a thin bed of wave rippled cross-strata disrupted by *skolithos* burrows caps the fill. Decimeter-thick layers containing iron cements are common in deposits at and just below basal surfaces of individual channel deposits, particularly higher within the valley fill. Less commonly, similar layers are observed along individual inclined beds within channel deposits, or associated with individual cross-sets. Most of these cemented layers continue laterally for less than tens of meters; however, they are nearly continuously developed at the boundary with the overlying valley fill.

Permeabilities average 5.2 darcies in this part of valley fill 1 and show a standard deviation of about 1.8 darcies. Permeabilities decrease subtly upwards across depositional beds and across some individual channel deposits from the laterally accreted to the channel filling margin. However, many channel deposits show little systematic lateral change in permeability. Mud chip layers at channel basal lags do not seem to be associated with major permeability changes, however, iron cemented layers have substantially lower permeabilities than uncemented beds. Iron cements appear to have developed quite late, probably during uplift and outcrop exposure (S.

Dutton), and thus it is assumed that this change can not be transported directly to subsurface analogs. However, other types of cements may form preferentially at abrupt grainsize changes, in a similar way as iron cements here. A set of vertical logs spaced a few tens of meters apart, and a horizontal profile across the upper part of this valley fill shows permeability changes across several concave upwards channel bodies (Fig.61, 62, 63).

Sandstones within the second valley fill are coarse to medium grained initially (lowest 10m), sediments clearly because finer grained upwards where the valley fill is more completely preserved. Channel deposits in this fill are more laterally continuous and contain a greater proportion of laterally accreted beds relative to channel-fill deposits than those in the underlying valley fill (sheet 1, c.f., Fig. (Fig.64, 65, 66, 67). Thus individual channel bodies have a more sheet-like geometry, 1-5m thick and several 100m wide. Given the dimensions of complete channel bodies seen elsewhere, it appears that only a small fraction of the thickness of individual channel deposits are preserved here. Because each channel body is highly cannibalized by those above, the geometry of individual bodies is controlled more by preservational controls than by original depositional geometries. Angle-of-repose, large-scale cross-stratification dominates completely.

Deposits within the lowest 10m of this valley fill (SC 2) have substantially higher permeabilities than others exposed in this outcrop (Fig. (Fig.68, 69, 70). Closely spaced lithologic and permeability logs show variations across one channel deposit at the base of this fill (Fig. 68-70, the mean is over 10 darcies). A horizontal permeability log shows lateral variations across this same channel deposit along a 50m traverse 1.5m above the basal erosion surface (Fig. 68). This body contains a single lateral accretion set, with beds dipping south (left) at up to 5 degrees within the plane of the outcrop. It shows little systematic lateral trend in permeability values. The basal surface of the valley does not appear to have distinct permeability values, although clearly it marks an abrupt increase in permeability.

The third valley fill (SC3) is seen only at the outcrop margins, as it is truncated by valley fill SC4 in the center of the outcrop. Like the other valley fills it is composed of a complex stack of interconnected channel deposits. Lower deposits are like those in valley fill 2, with relatively laterally continuous but vertically truncated channel bodies dominated completely by large-scale, angle-of-repose cross-strata. Higher in this valley fill channel bodies have concave upwards geometries, are less truncated vertically, but show complex

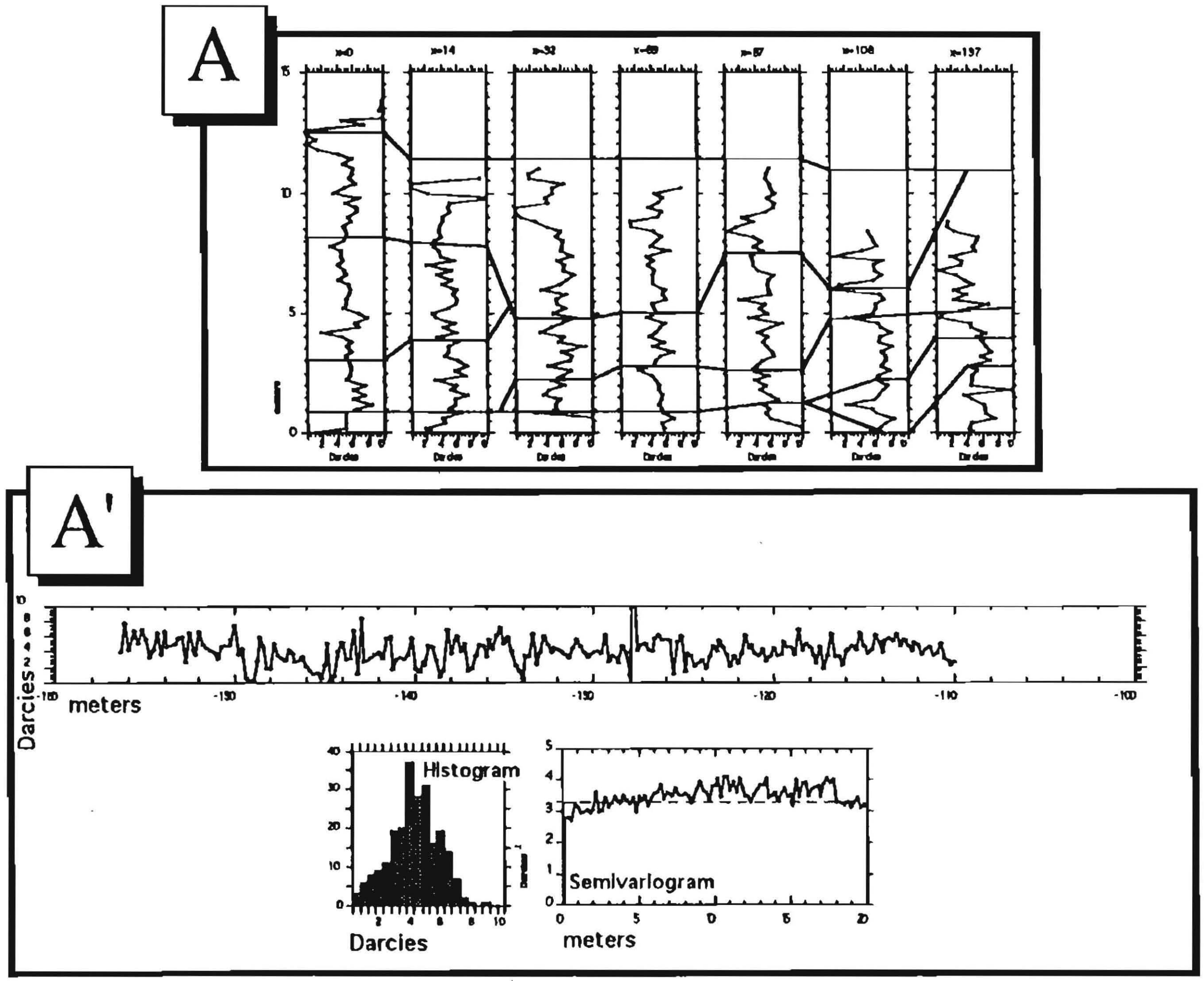



**Figure 61**) Closely spaced vertical permeability logs (A) and a 50m long horizontal permeability log (A') showing variations across interconnected, concave upwards channel bodies (see Fig. 58). Some bodies show decreasing permeability values towards one margin (e.g., horizontal profile (A'), meters -165 to -155). However, many bodies are so cannibalize that it is difficult to document lateral trends. On the semivariogram a subtle range to 10m suggests individual channel bodies are continuous for about 10m, in general agreement with outcrop observation.

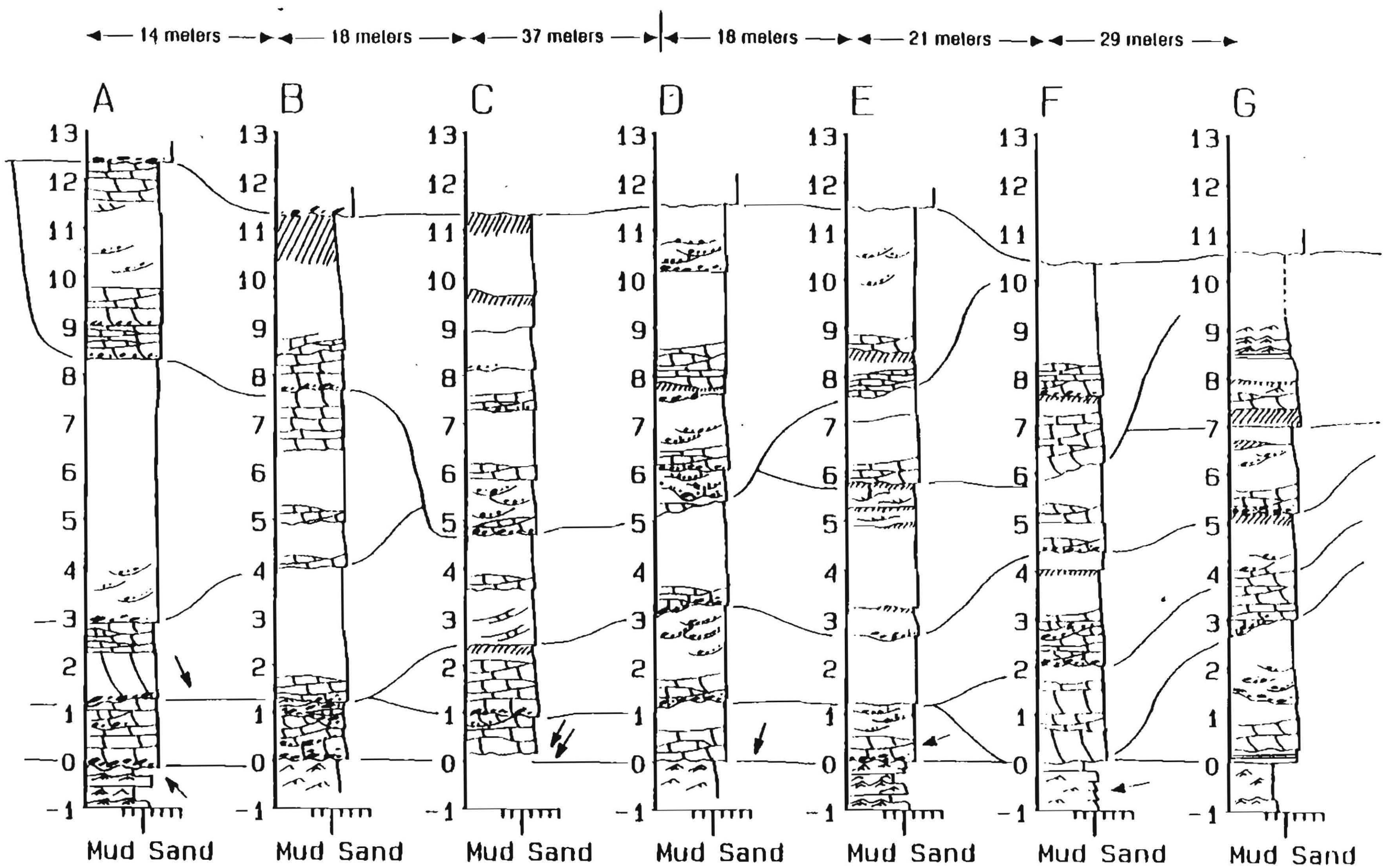



**Figure 62)** Sedimentologic logs associated with the permeability logs in Fig. 61 .

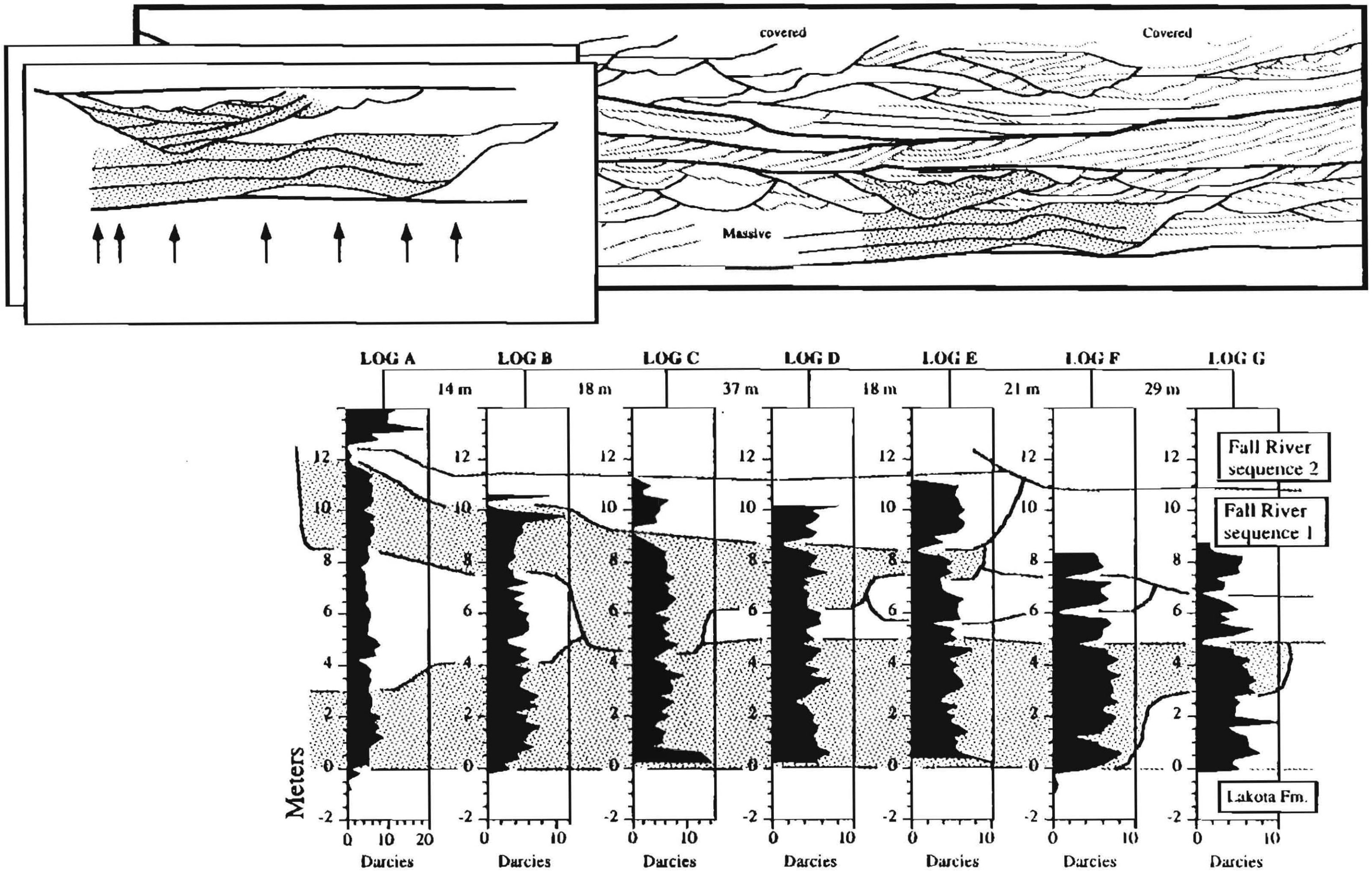



**Figure 63)** Diagram showing the architectural context of the sediment body documented in Fig. 61 and 62.

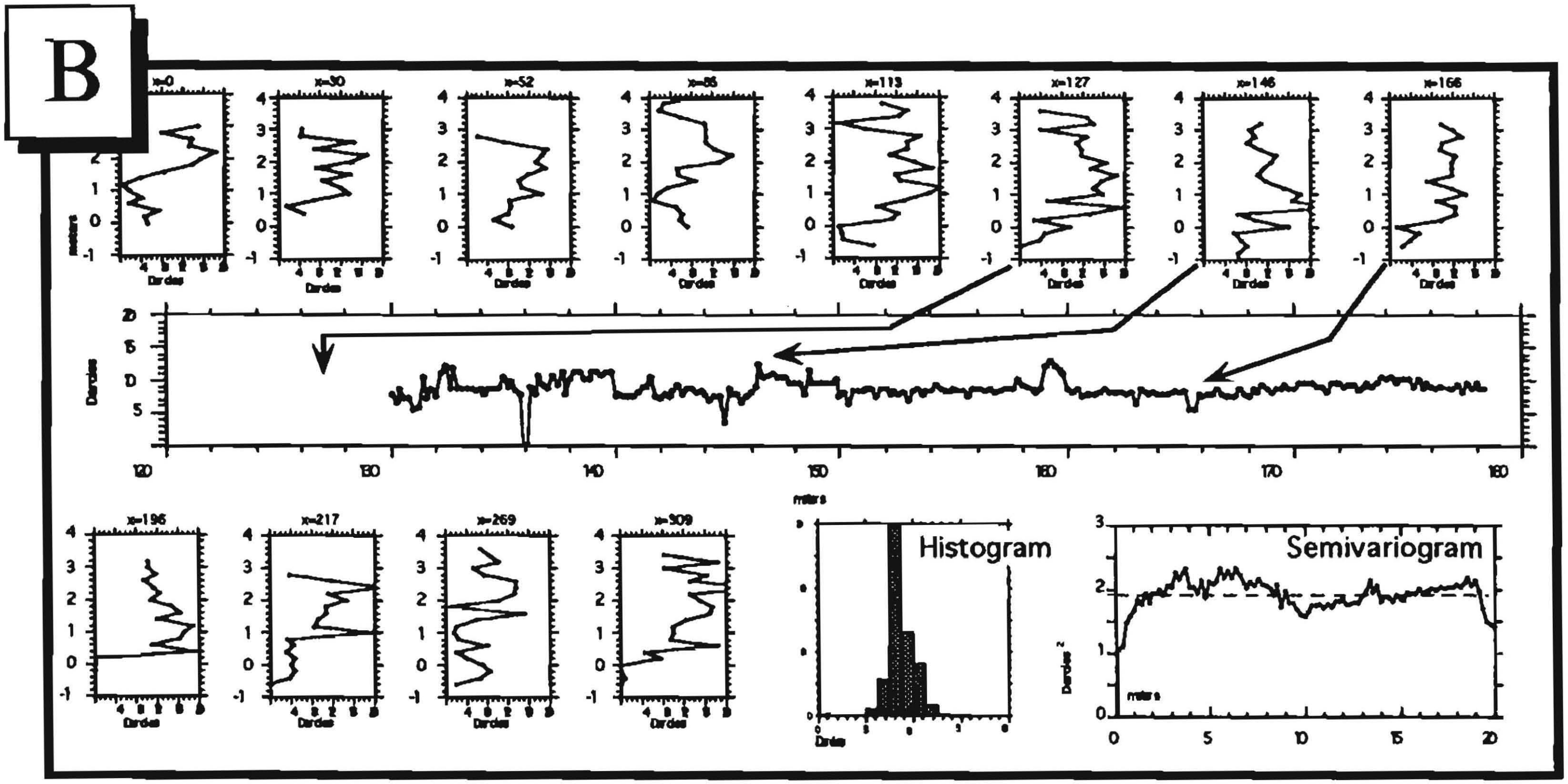



**Figure 64)** A set of closely spaced vertical permeability logs and a 50m horizontal permeability log sampling an individual lateral accretion set that comprises a channel deposit at the base of valley fill 2 (see position in Fig. **58**. These deposits have the highest mean permeability values of any seen in Red Canyon. The horizontal semivariogram shows a range of 4m and a sill at about 2 darcies$^2$. The range must reflect variations across individual laterally accreted beds.

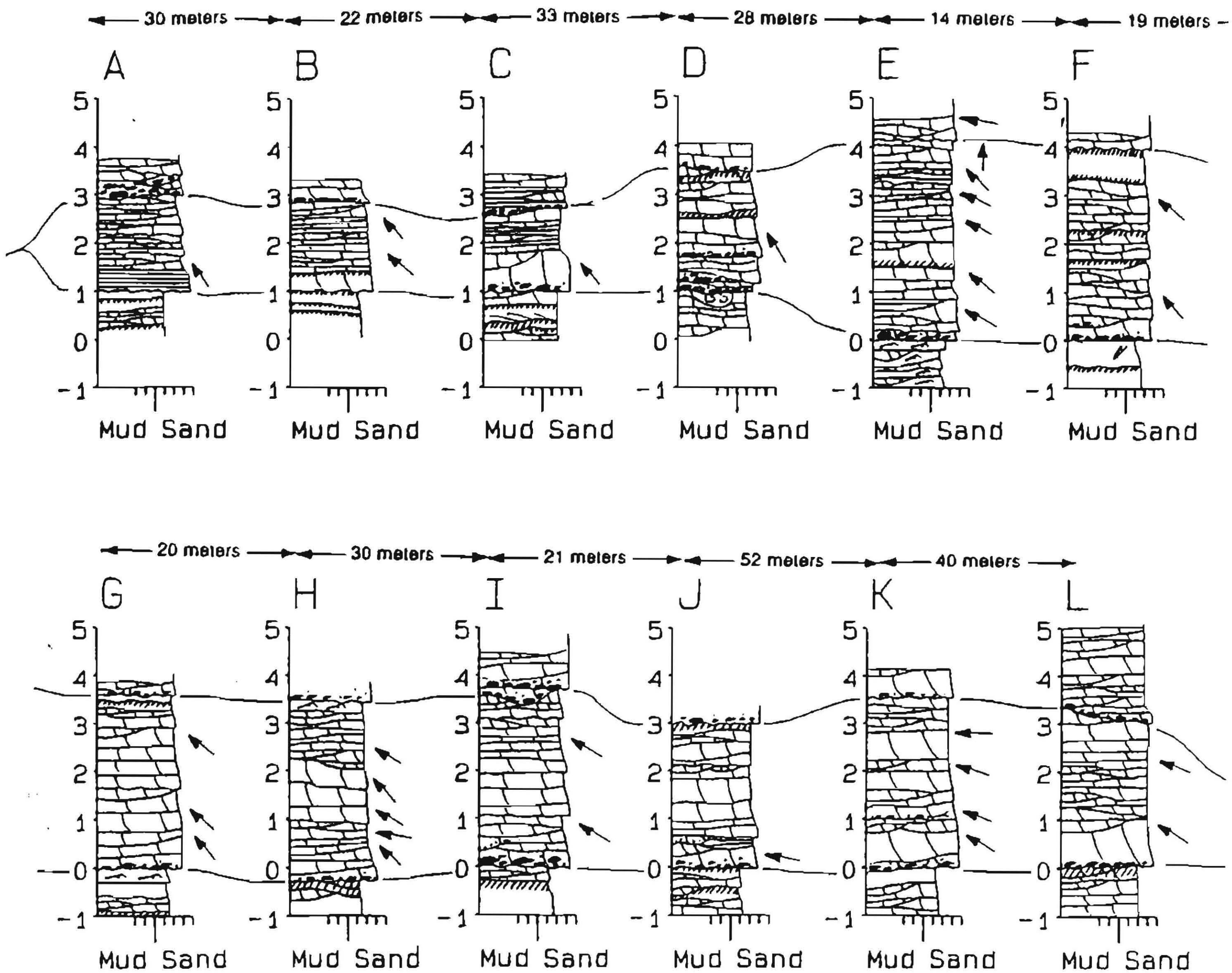



**Figure 65)** Sedimentologic logs associated with the permeability logs in Fig. **64**.

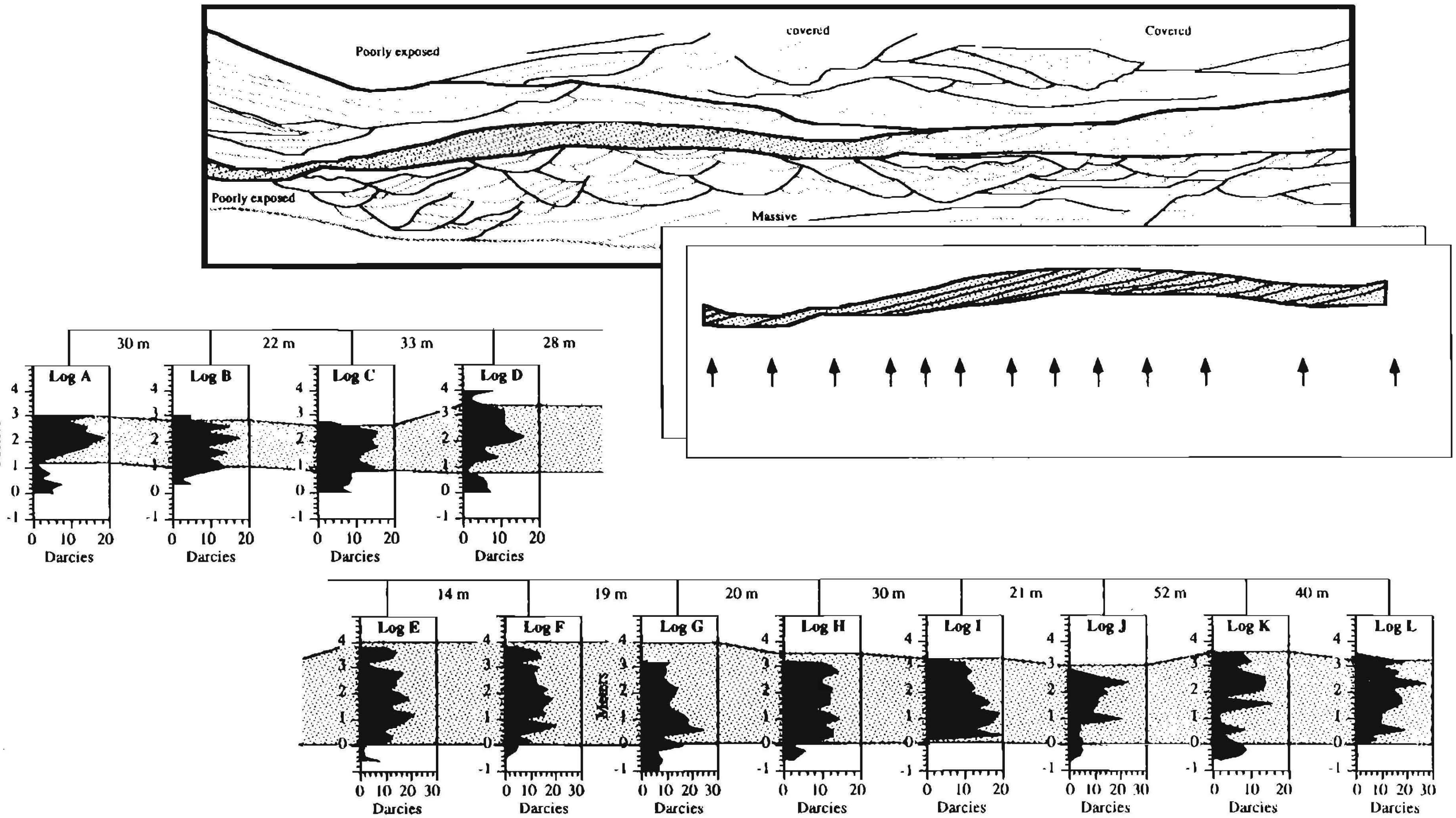



**Figure 66)** Diagram showing the architectural context of the sediment body documented in Fig. 64 and 65.

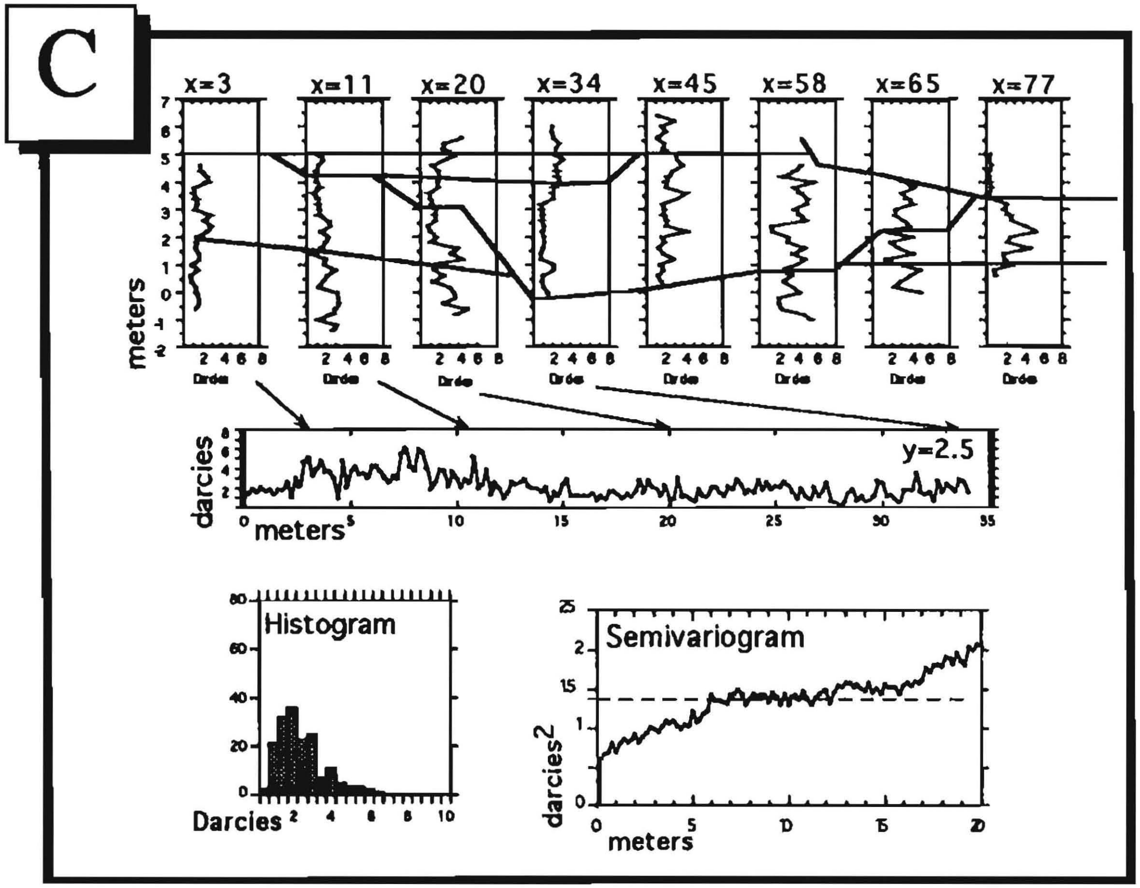



**Figure 67**) Permeability variations associated with concave upwards channel bodies near the top of valley fill 3 (see position in Fig.58; sheet 1). Concave upwards channel bodies are more completely preserved than those in valley fill 1 (c.f., Fig. 63). Mean permeabilities clearly decrease towards the channel filling margin of each body (see vertical logs and clear range to 7m shown by horizontal semivariogram).

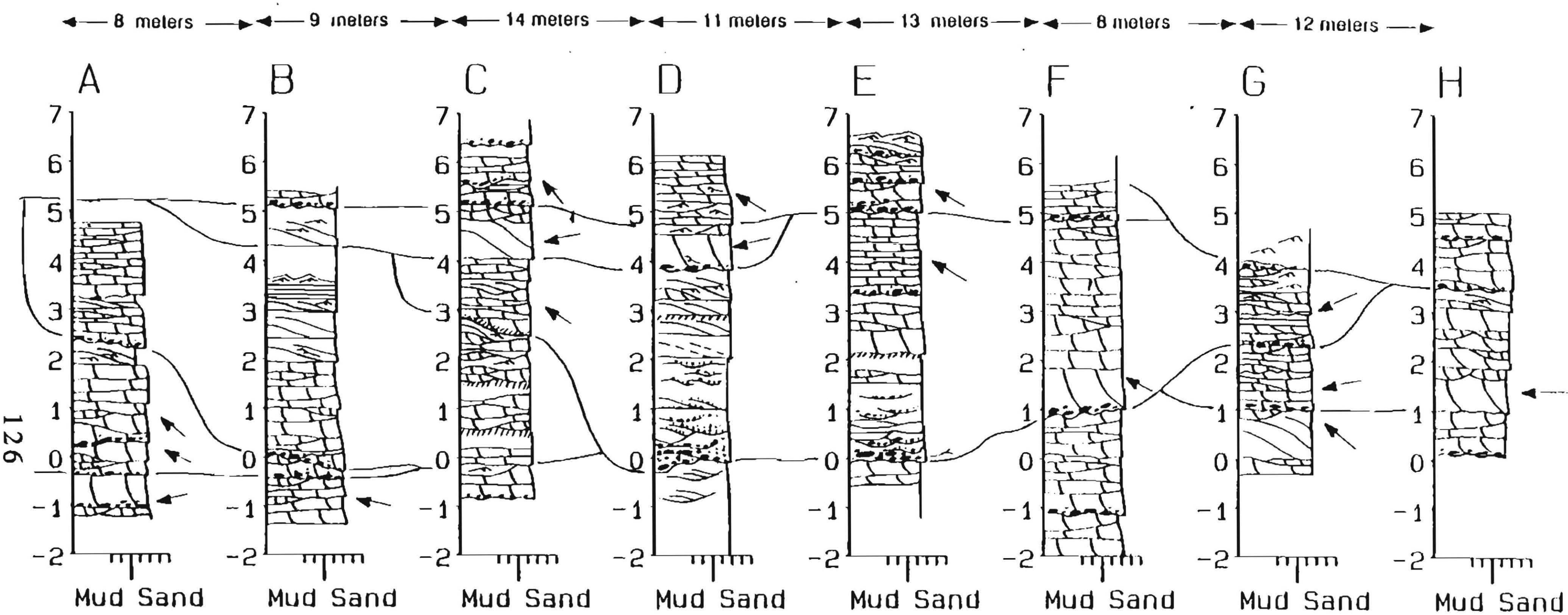



**Figure 68)** Sedimentologic logs associated with the permeability logs in Fig. 67.

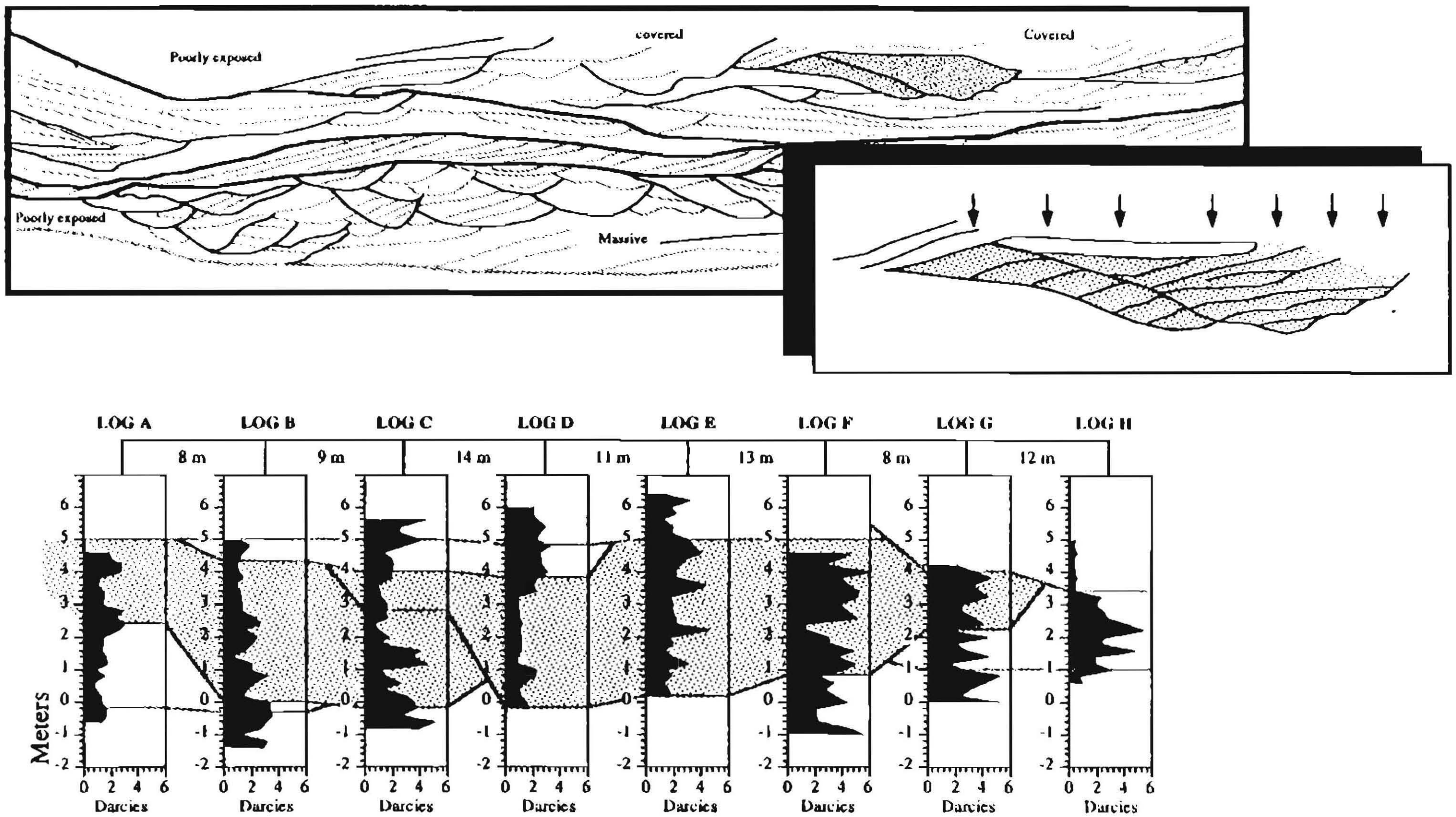



**Figure 69)** Diagram showing the architectural context of the sediment body documented in Fig. **67** and **68**.

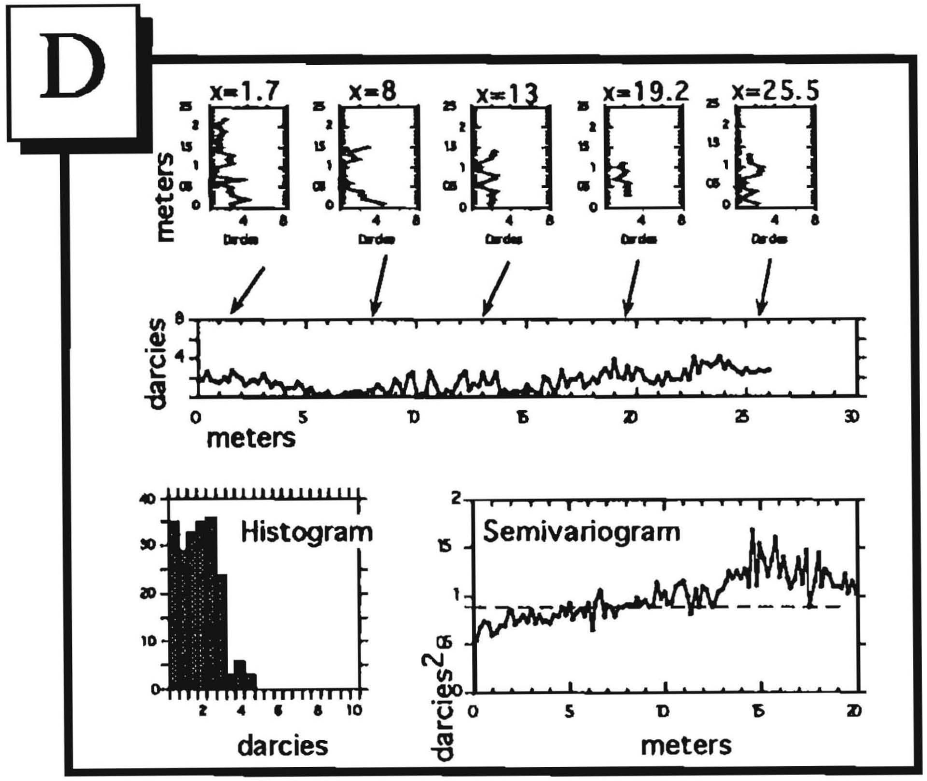



**Figure 70)** Short vertical permeability logs and a 25m horizontal permeability log document variations across a single channel deposit in the basal part of valley fill 4. Only a 2m sliver of a much larger channel deposit is pressured here. The drift in the horizontal semivarigram shows gradual changes across this channel deposit.

intertruncation laterally Laterally accreted beds comprise half the channel deposit in some bodies, but many are dominated be channel filling beds. These channel bodies can be dominated by low-angle large-scale cross-strata with superimposed wave ripple marks and oppositly directed small-scale cross-strata (suggesting an influence of wave and tidal currents on deposition). Evidence for a wave/tidal influence on deposition increases higher and towards the margins of the valley fill.

Permeability values in valley fill 3 average 3.6 darcies (sd=2.6 darcies), but values gradually decrease upwards. Closely spaced lithologic and permeability logs, and a horizontal permeability profile show variations across two laterally interconnected channel bodies in the upper part of valley fill 3 (Fig.71, 72, 73). As in valley fill 1, permeabilities vary subtly across different concave upwards channel bodies.

The fourth valley fill is relatively narrow, and it is exposed only in the left and center part of the outcrop. Although narrow, this valley locally truncates nearly all of the other valley fills where it cuts deepest. The lag at the base of the valley is weakly developed. Deposits near the valley fill base are thin, concave upwards bodies that are highly intertruncated laterally. As in the other valley fills, geometries of these bodies reflect small cannibalized segments of channel deposits, rather than the depositional geometries of bars and channels. Large-scale cross strata is common, and abundant wave and current ripple cross-strata, and mud drapes suggest estuarine conditions. At the top of this valley fill, two large sets of inclined hetrolithic beds define nearly completely preserved channel bar deposits. Beds within these sets can be large-scale cross-stratified lower down, but higher up wave and current ripple cross-strata dominate. Reversing paleocurrents are indicated by ripple cross-sets, and wave ripples with mud drapes commonly cap individual inclined beds. Mud drapes can be continuous for the full length of inclined beds. The two bar deposits are separated by a covered interval, composed completely of mudstone where trenched. This interval is assumed to the a mud-filled channel that records the latest stage valley fill. Valley fill 4 has substantially lower permeabilities than the others (Fig.74, 75): mean 2.3 darcies, sd=3.1). Permeability barriers such as shale and mud-chip layers are common. Shale drapes on the inclined beds at the top of the valley fill and the mud filled channel would inhibit all horizontal movement of fluids.

It is clear from this outcrop study that two elements will dominated the permeably structure in the central part of this sandstone body: 1) the coarse-

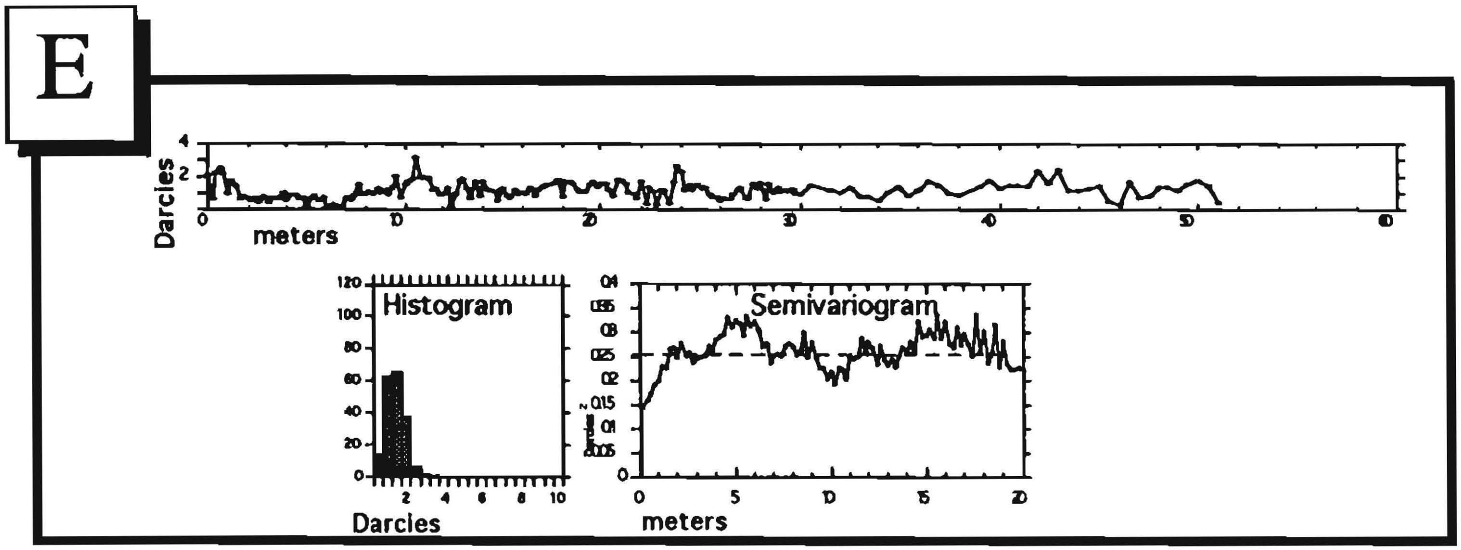



**Figure 71)** Horizontal permeability log though a set of inclined hetrolithic beds capping valley fill 4. A clear range of 5m reflects fining within individual inclined beds (note, inclined beds are less than a meter thick, but the horizontal traverse is highly oblique to a bedding plain orthogonal).

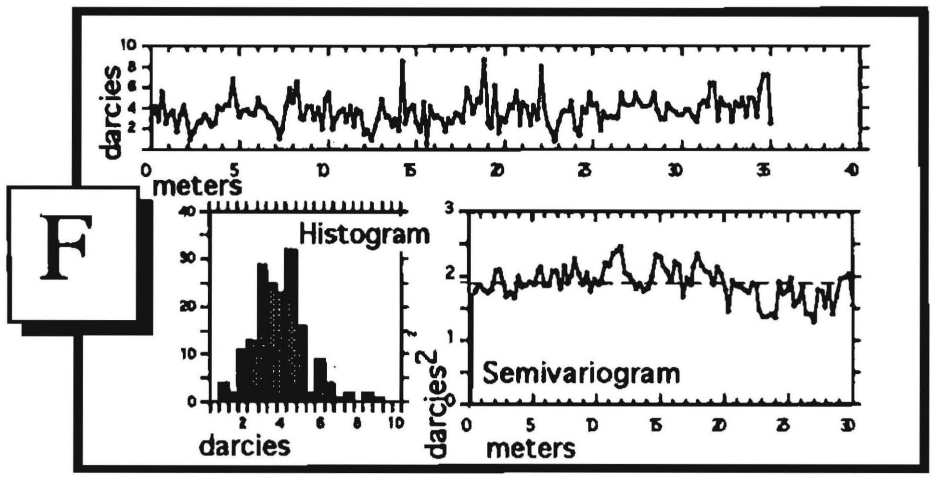



**Figure 72)** A horizontal permeability log through large-scale cross-stratified sandstones near the far northern margin of valley fill 2.

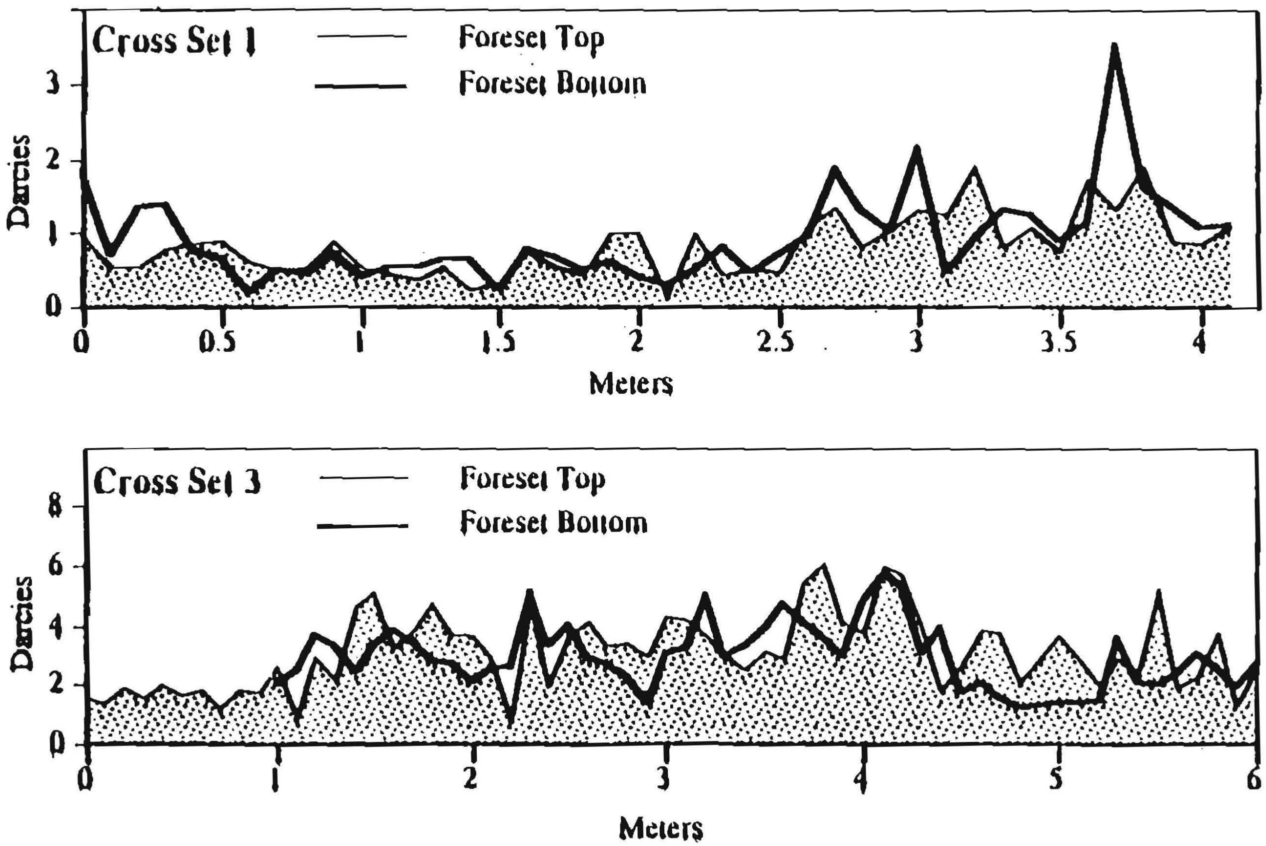



**Figure 73)** Horizontal permeability logs measured across the base and the top of two different cross-sets, one in valley fill 2 and one in valley fill 3. There is little difference in permeability means or variances for the top and base of each cross-set. This suggests that dune scale cross strata does not constitute an important scale of heterogeneity in these deposits.

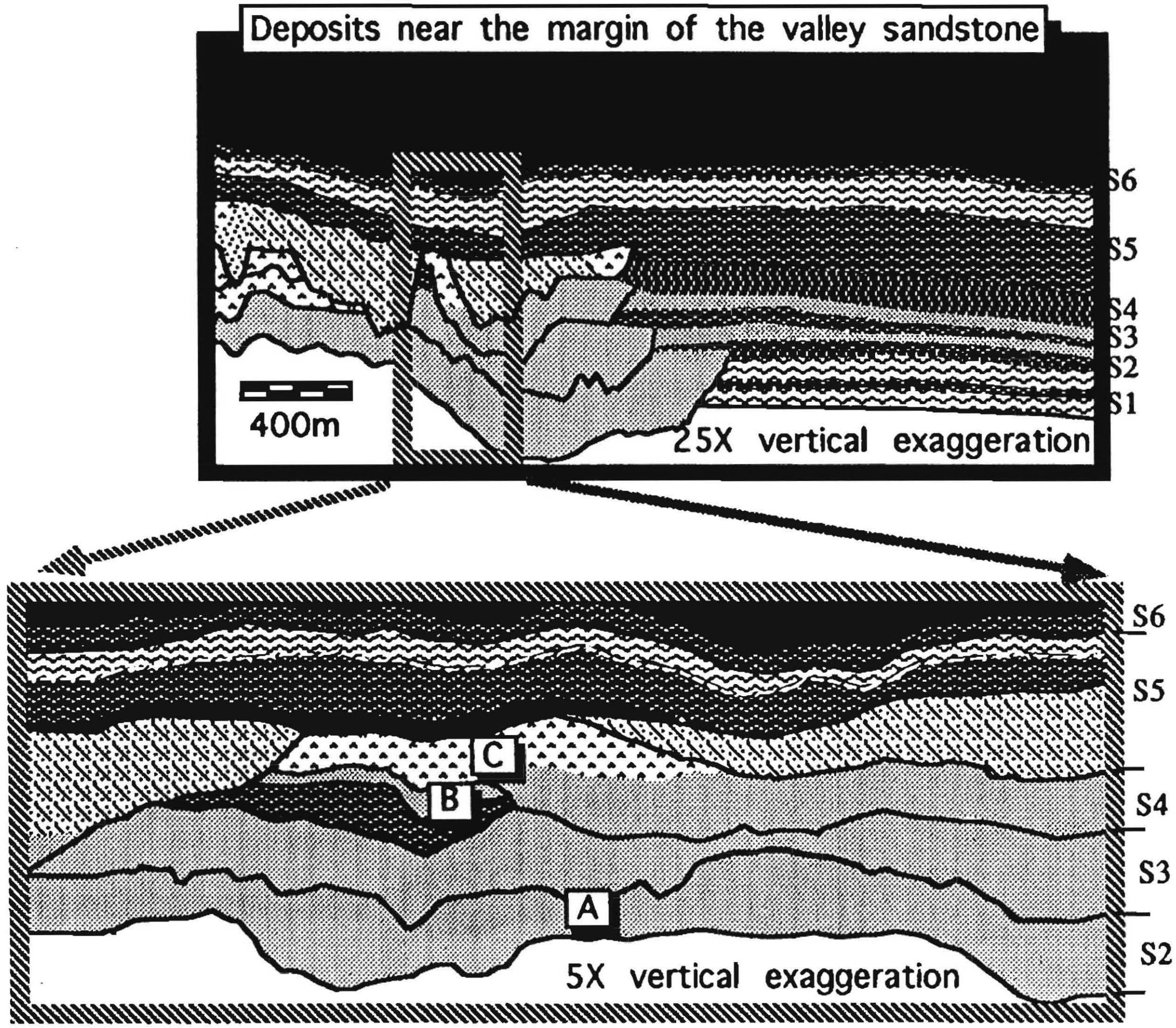



**Figure 74)** Simplified facies diagram showing variations at stop #3, near the center of the valley sandstone. Here valley fill 4 locally rises and ends exposing the upper parts of valley fills 2 and 3. Letters on top of the lower box show permeability logs in Fig. 75. Lettered boxes show positions of horizontal permeability profiles and detailed permeability measurements thought specific depositional strata (Fig. 61-66). See handout sheet #2 for more details, including a photo and the positions of sedimentologic and vertical permeability logs.

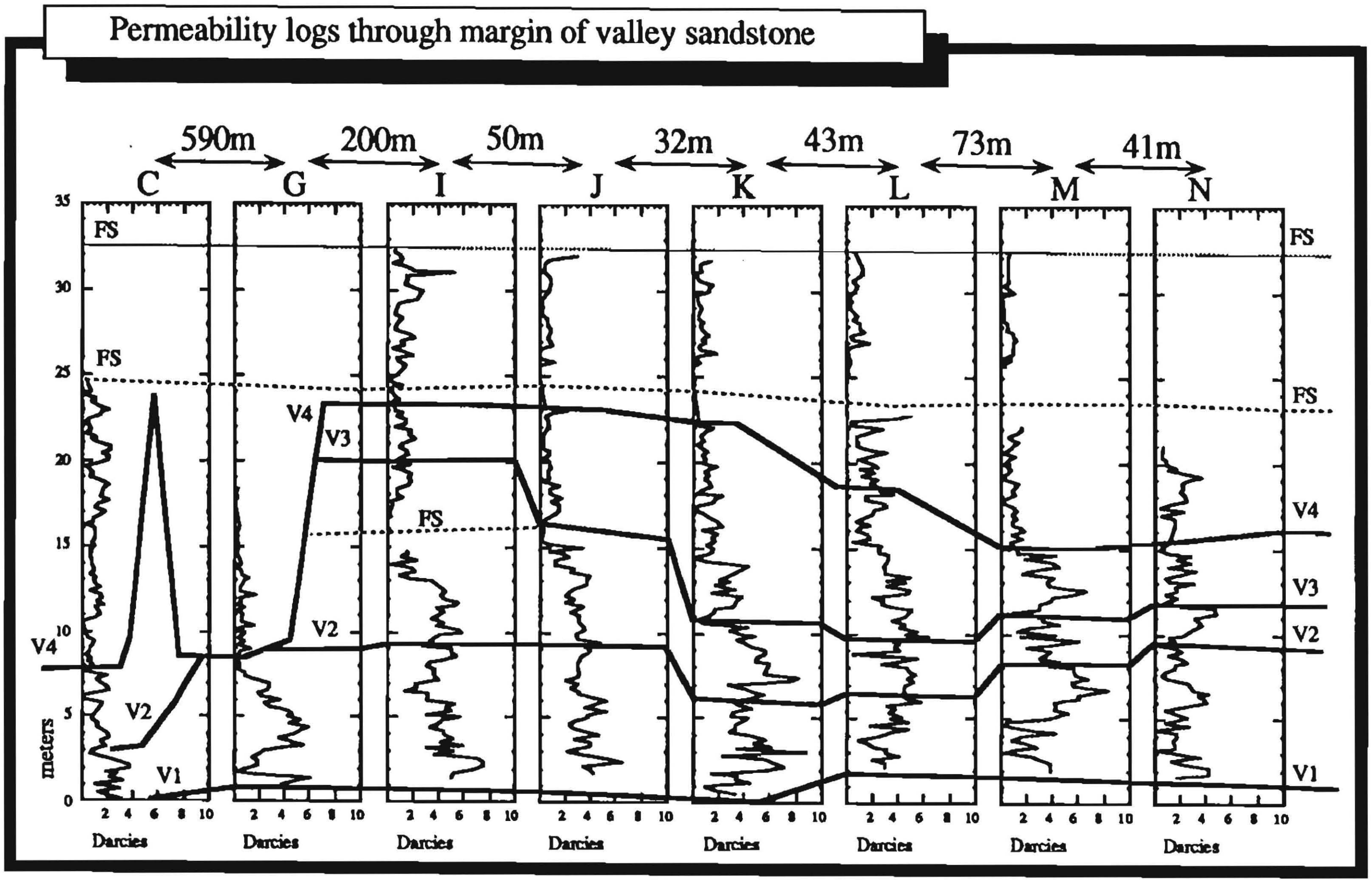



**Figure 75)** Permeability logs measured along the outcrop viewed at stop 3. Note decreasing upwards trend across the sandstone body as a whole, and the very low values that characterize valley fill 4 (see positions of logs in Fig. 74).

grained, high permeability basal valley 2 deposits, and 2) The fine grained, low permeability deposits of valley fill 4. Decreasing upwards permeability trends across valley fills 2-4, and distinct contracts of means and variances of permeabilities within each valley fill are also important. Variations across individual channel bodies, and across individual cross-sets within, are more subtle, except for the shale draped estuarine deposits capping valley fill 3 and dominating valley fill 4.

*Stop 4.3: Margin of stacked valley fills*

*Drive about 0.5 miles back towards the mouth of Red Canyon, just past the small cabin and chicken coop. The large outcrop on the east side of Red Canyon is the subject of this stop. After viewing the outcrop from the far side of the field, hike to the base of the outcrop along the abandoned mining road. After viewing valley fill 1 and 2 here, climb though the woods to the north to gain access to the margin of valley fill 3 and the coarsening upwards marine stratigraphic cycle above. Finally contour along the middle of the hill slope to see the hetrolithic deposits of valley fill 4 cutting into deposits of valley fill 1.*

**Objectives**: Examine the geometry and internal character of nested valley fill deposits near the margin of the sandstone body.

This outcrop is also documented by a large photo mosaic, a bedding diagram overlay and sets of vertical sedimentological and permeability logs (handout sheet 3: Fig. (Fig.76, 77, 78, 79, 80). The best exposed part of the cliff face consists of a 20m vertical sandstone wall with an overhanging top, and the following description of this outcrop will center on this wall. The Lakota Formation is not exposed at the base here, but it is exposed about 5m stratigraphically lower a few hundred meters to the north (left). The lower half of this cliff face can be divided into two parts separated by a laterally continuous erosion surface and lag that remains relatively horizontal to the left but climbs to the right Both these stratigraphic cycles (SC1 and SC2) are 5-10m thick, contain smaller channel-form bodies within, and are interpreted to be different valley fills. A surface passing through the middle of the wall (faint from a distance) defines the base of a concave upwards sandstone unit that is interpreted to be SC3 valley fill. Nearly horizontal beds within this fill progressively onlap the rising valley margin. To the north (left), this valley fill thins and ends exposing heterolithic deposits that coarsen upwards from wavy bedded thin sandstones and mudstones to amalgamated, shallow channel sandstone bodies. An erosion surface capping the sandstone cliff descends both to the north and south. To the south (right) a set of inclined hetrolithic beds occur above this descending erosion surface, to the north (left) deposits are poorly exposed hetrolithic channel deposits. These

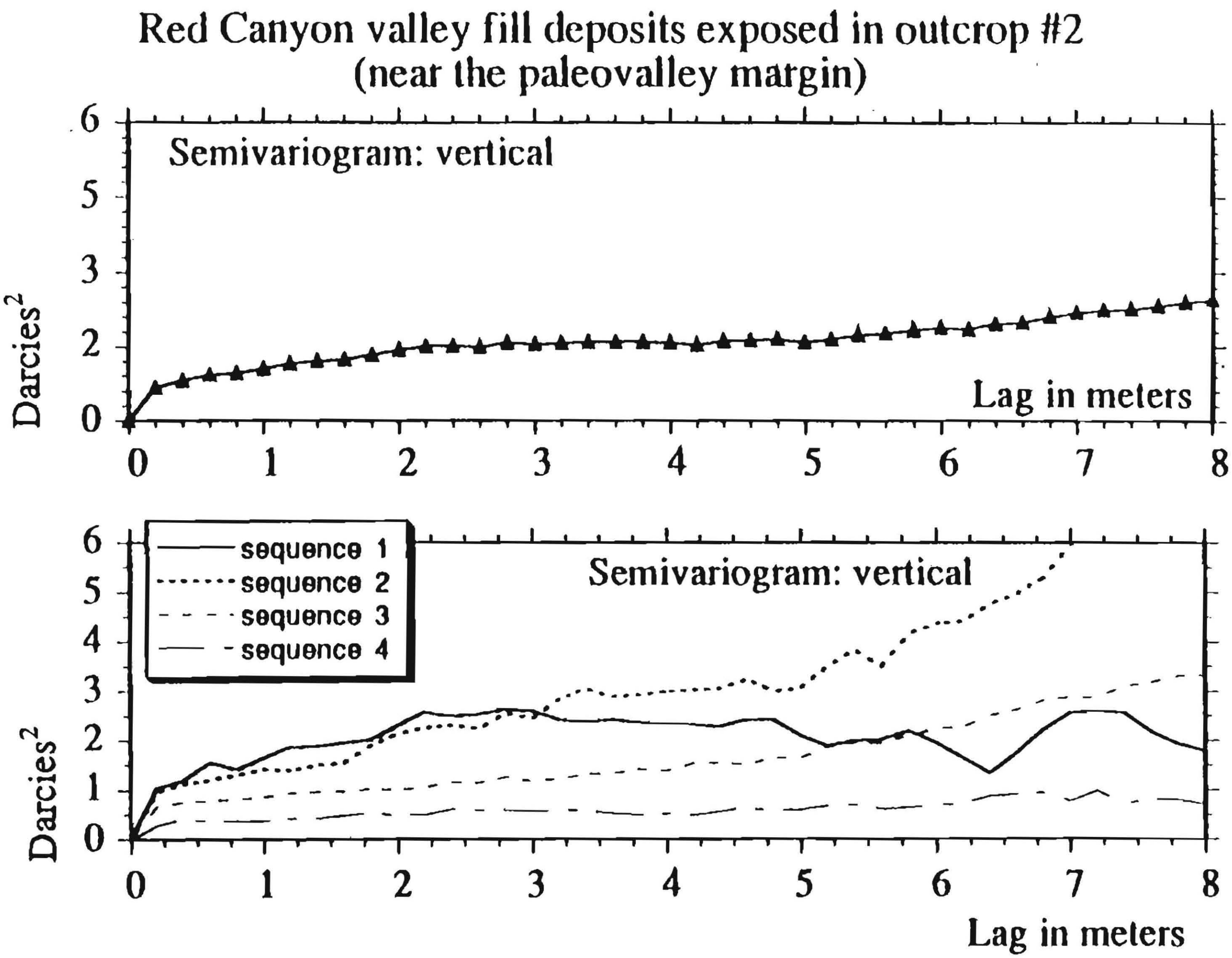



Figure 76) Vertical semivariogram of permeability data shown in Fig. 75.

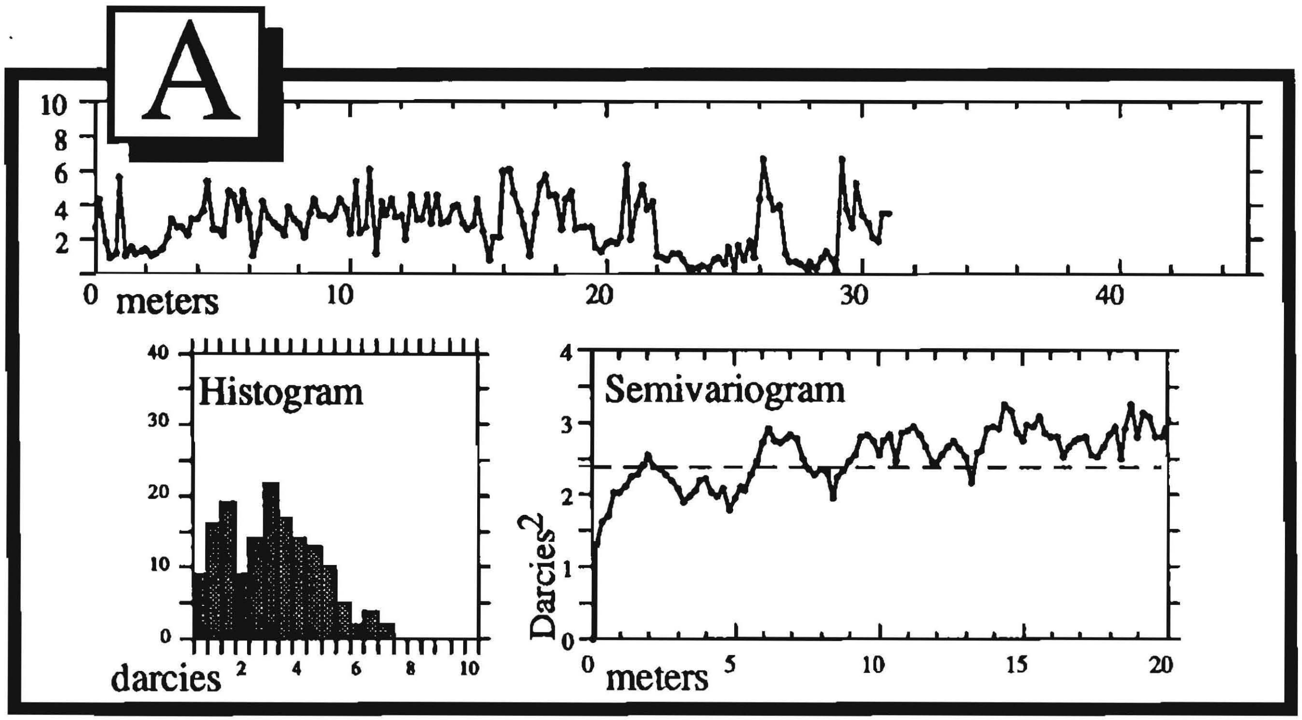



**Figure 77)** Horizontal permeability log showing variations near the margin of valley fill 1 (stop 3). Abrupt changes in permeability values occur at some channel deposit boundaries. The short range and nested appearance of the sill reflects the transverse through many different amalgamated, concave-upwards, channel deposits. Low values are generally in flaser wave or current rippled sandstones, whereas higher values are in large-scale cross-stratified sandstones.

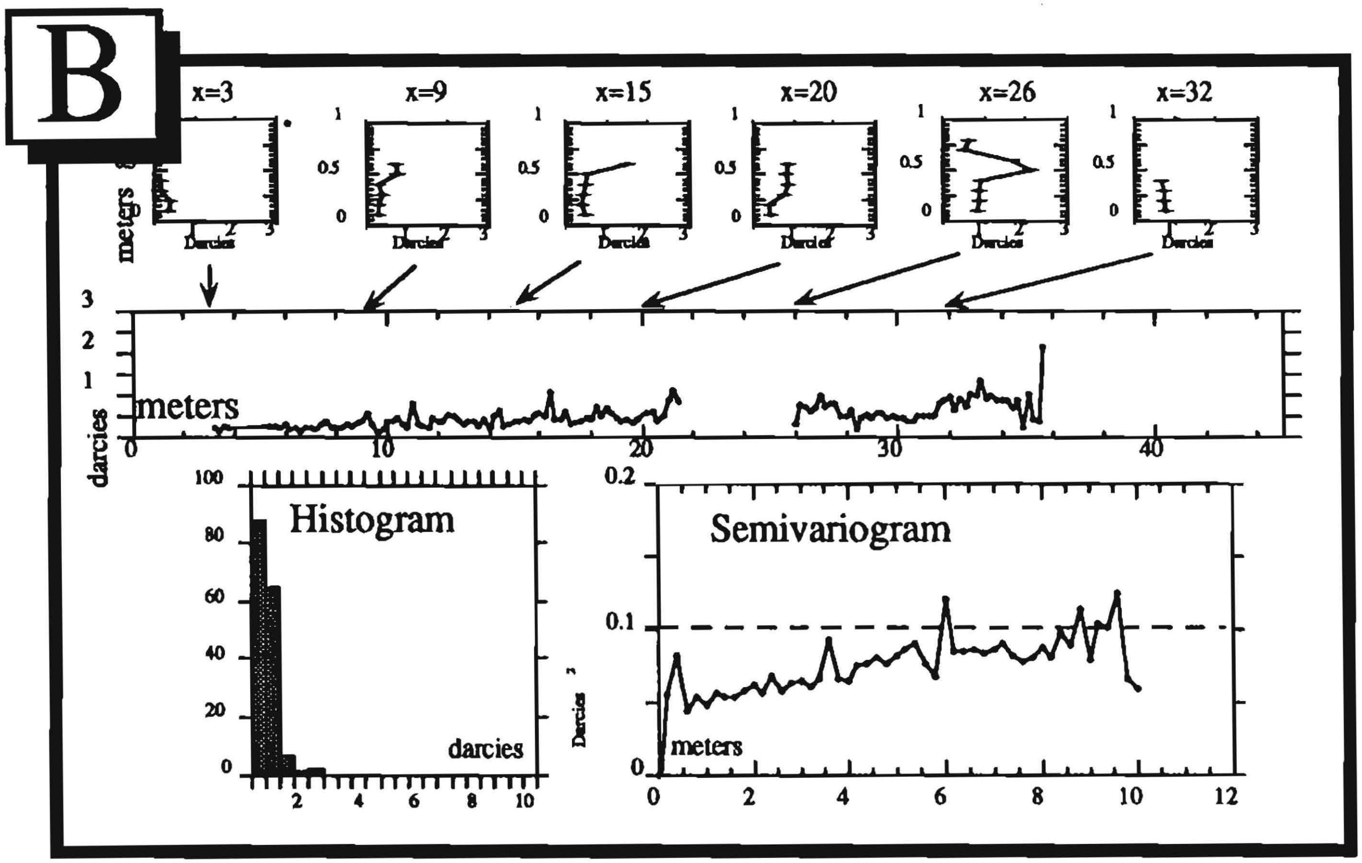



**Figure 78)** Short vertical and a horizontal permeability log through a thin, wave influenced distributary channel exposed over valley fill 2. Log follows a single channel deposit within an amalgamated set. The body is dominated by planar and ripple cross-lamination. Drift to increasing variance with lag distance in horizontal semivariogram records a gradual increase in permeability along the channel deposit.

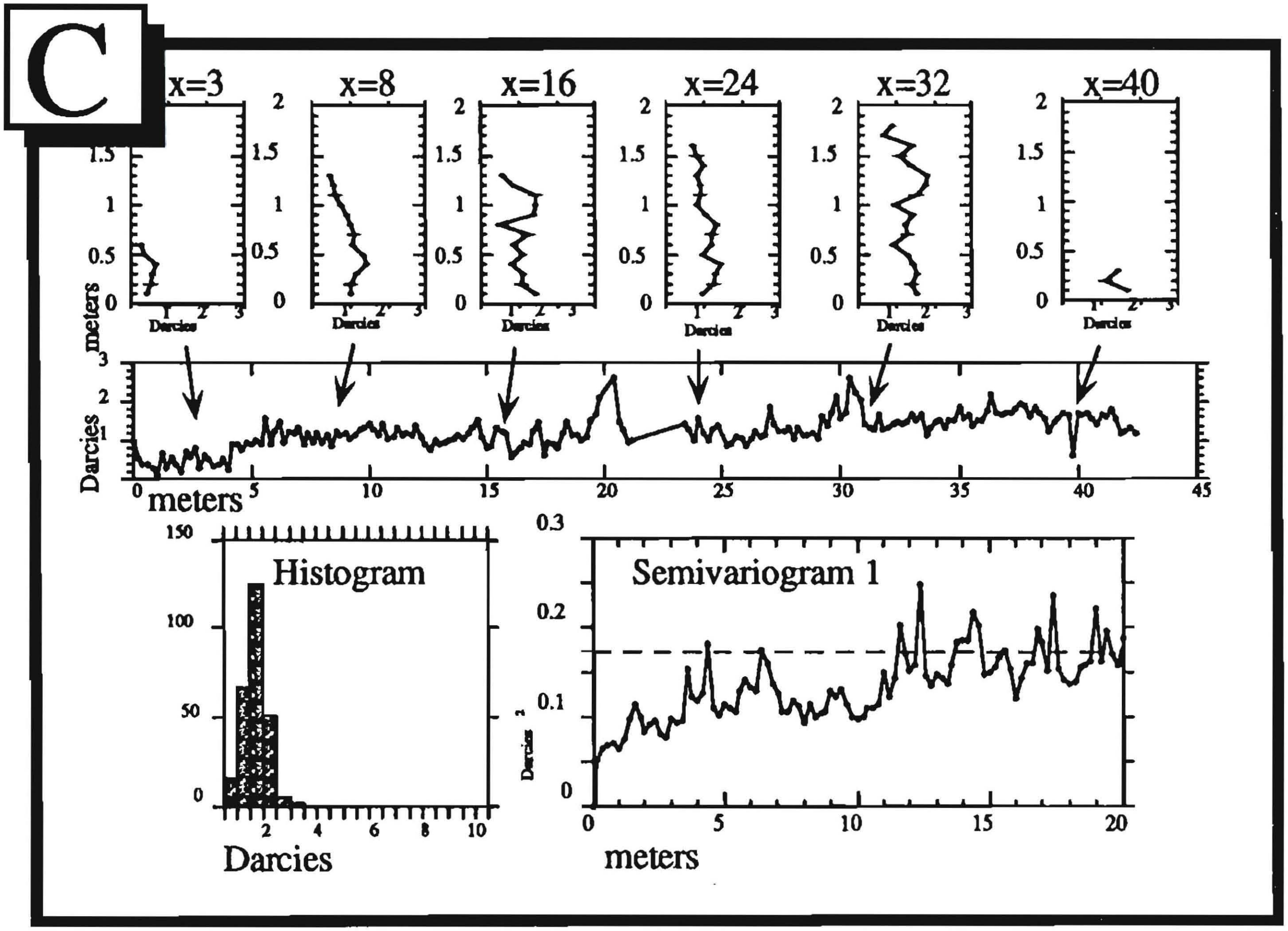



**Figure 79)** Short vertical logs and a horizontal log through a wave deposited sheet sandstone capping valley fill 3. Note the progressive permeability increase in the direction the strata thicken (towards the center of the valley fill.

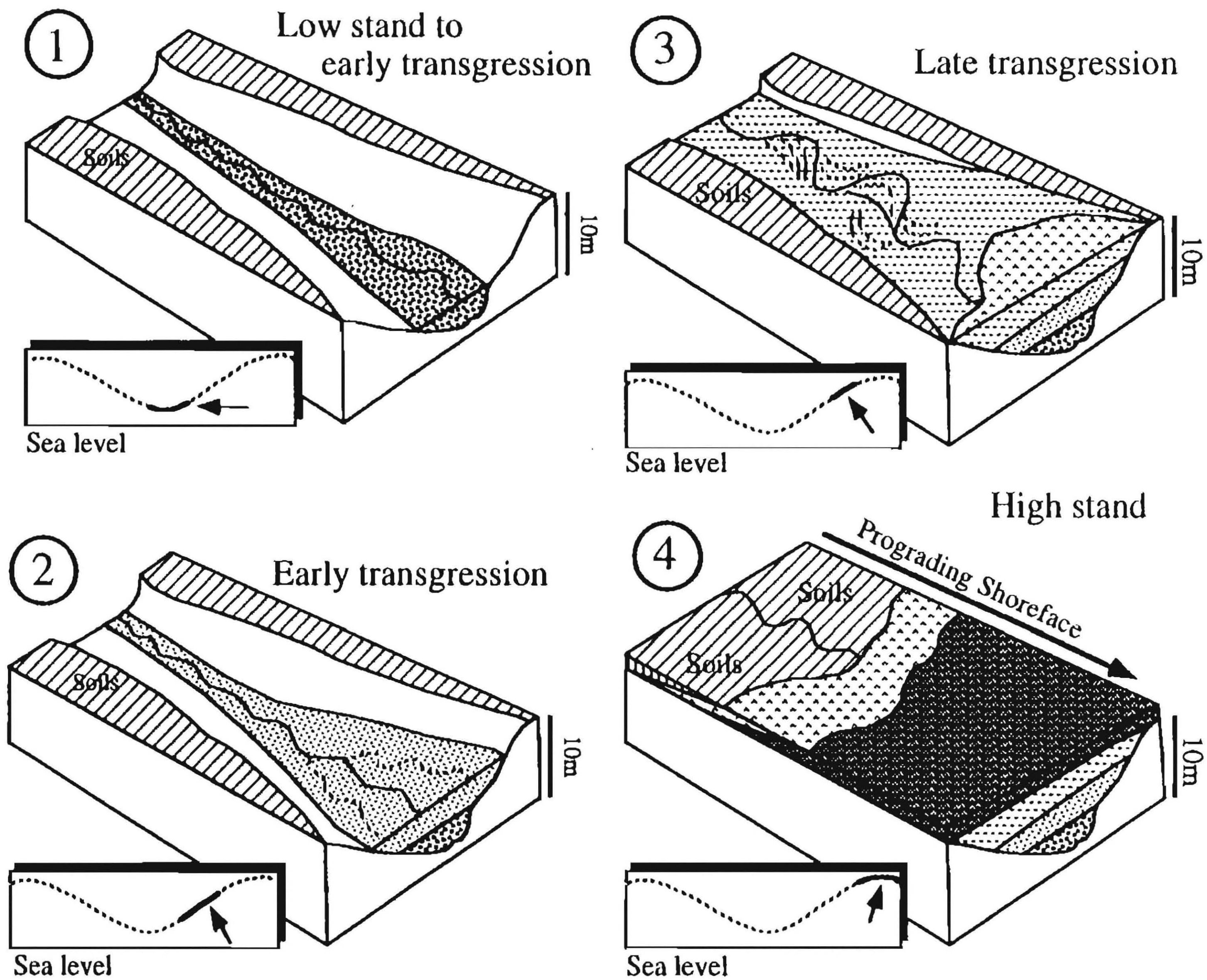



**Figure 80** – Genesis of valley-filling deposits.

hetrolithic deposits comprise SC4 valley fill. As at the last stop, a coarsening upwards marine stratigraphic cycle (SC5) caps the outcrop.

At the base of the main cliff face, valley fills SC1 and SC2 are well exposed. It is difficult to trace individual channel deposits within these two valley fills because sandstones are all fine grained and boundaries of individual channel deposits are clear only locally where lags of mud-chip clasts occur. However, channel deposits in valley fill SC1 appear to be concave upwards bodies that extend for only a few tens of meters laterally. Low-angle large-scale cross strata with superimposed current and wave ripple marks suggest a stronger influence of tide/wave currents during deposition relative to large-scale cross-strata dominated SC1 valley deposits further north (i.e., toward the valley axis).

Mean permeability values of valley fill SC1 and SC2 are similar here (3.5 and 3.7 darcies, respectively), which contrasts markedly with the large permeability increase from deposits of valley fill 1 to 2 at the last stop. Permeabilities in both valley fills are lower here than along the valley axis (Fig. 55). A horizontal permeability profile through the lower part of valley fill 1 shows marked changes in mean permeabilities over 30m (Fig. 78). In several cases, marked changes in this permeability profile record progression across individual channel bodies and a lateral change from large-scale cross-strata to ripple cross-strata (e.g., Fig. 78, two bodies are crossed between meters 20 and 30).

Mudstones capped by shallow fine-grained channel deposits record marine deposition over the fill of valley 2 (i.e., marine SC3 deposits exposed beneath valley fill 3 on the left side of the cliff face). Lower down these deposits are mudstones with thin wave ripple marked sandstone beds. The shallow channel sandstones capping these mudstones contain mostly planar strata, wave and current ripple cross-lamination, and *Skolithos* burrowed beds. These deposits record a shallowing upwards succession, and the channel-form sandstones may record shallow, wave influenced distributary channels. Permeability values of the capping channel-form sandstones are low, but can gradually increase along the length of the body (Fig. 79).

The lower part of valley fill SC3 is similar to that of valley fills SC1 and SC2 below, but the upper part is composed of meter-thick horizontal bodies that onlap the rising valley margin. These wave rippled sandstone bodies fine upwards to cm-thick beds of mudstone near the valley margin, but gradually thicken and become amalgamated where the valley fill thickens. Most beds in these sandstone bodies appear horizontal, but locally they can dip at nearly the angle of repose. Thus, the upper part of valley 3 appears to have filled with wave driven sand sheets that locally developed steep forward slip faces as they prograded. The sheets of valley fill 3 have low permeabilities relative to the channel deposits below, and thin mudstone layers separating sheets will provide barriers to vertical fluid flow near the valley margin.

The heterolithic channel deposits in valley fill 4 are comparable to those at the last stop, and similarly record a strong influence of wave and tide currents on deposition. Where the valley erosion surface cuts lower, basal deposits are less heterolithic but contain abundant mudclasts. Higher up the fill contains large sets of inclined hetrolithic beds. All these deposits have relatively low permeabilities, and the abundance of shale drapes on beds suggest this fill would be a barrier/baffle to fluid flow.

The 8m-thick, coarsening-upward succession capping valley fill 4 is wavy bedded lower down and a 3m thick bed of swally cross-stratified sandstone higher up. Completely bioturbated mudstones at the base of this succession record hiatus. A thin lag less than a meter above in the wavey bedded deposits may record maximum transgression. The overall coarsening upwards succession records gradual shoaling. We examined these beds at the mouth of the canyon this morning, and here they similarly contain evidence for deposition by both wave and tidal currents. These beds are bioturbated by vertical *skolithis*, and horizontal *planolites* and *meniscinities* burrows. These deposits have low permeabilities though out, but values increase upwards into the swaley cross-stratified sandstone cap.

*Stop 4.3: Lateral changes in valley fill 4*

*and a view from above.*

*Drive south out of the mouth of Red Canyon back to Highway 18, and turn east back towards Hot Springs. Drive 2.5 miles and turn on to a forest road (just before a bridge on highway 18). Enter two gates in short succession and drive along the top of the cliff face (avoid side turns that pass back under highway 18). Proceed to the cliff face directly over the farm house (walk from the forest road, or drive a convolute path through the woods just a little further to the north).*

**Objectives**: Examine lateral changes in valley fill 4 and see a panorama view of the outcrops visited earlier today. Valley fill 4 bifurcates here, and the side valley is sand-rich in contrast to the hetrolithic channel deposits preserved along the main axis of this valley.

From this vantage point, the outcrops visited during stops 2 and 3 can be viewed. Valley fill 4 cuts though the center of both these outcrops, forming a low permeability, heterolithic plug within a generally higher permeability sandstone body. South on the east canyon wall, valley fill 4 cuts downwards truncating all of valley fills 2 and 3 (i.e., at the location we visited during the last stop). Further northward towards this stop, the basal erosion surface of valley 4 rises, and valley fills 2 and 3 are again exposed. Valley fills 1 and 2 are more fluvial, and are dominated by large-scale cross-strata, whereas valley fill 3 is more estuarine and dominated by wave and current ripple cross-lamination with local mudstone drapes. In the ravine just to the east of this stop, the base of valley fill 4 again drops cutting valleys 2 and 3. These deposits comprise a smaller side branch of valley fill 4. Valley fill 4 is dominated by sandstone in this side valley, in contrast to the hetrolithic deposits filling the main axis of valley 4. Where the valley base first cuts down here, deposits are dominated by large-scale cross-strata, and several vertically stacked channel bodies can be recognized. But the base of valley fill 4 rises again northward towards the outcrop nose over the farm house, and deposits fine to sheets of current and wave rippled sandstones separated by thin shale drapes.

## Day 5: Southern Black Hills

*Discussion*

Outcrops of the Fall River Formation in the southern Black Hills contain the highest proportion of nonmarine and valley-fill deposits reflecting the southeastward progression to more landward paleoenvironments. These exposures demonstrate the regional distribution of short-term stratigraphic cycles comprising the Fall River stratigraphic sequence, document laterally extensive development of paleosols characterizing sequence boundaries outside of paleovalleys, and establish the southwest-to-northeast drainage pattern of fluvial systems. Hence, valley-fill deposits to the north were derived from fluvial systems originating here. Stops are arranged from south to north along the east flank of the Black Hills (Fig 81).

Well developed alluvial-plain deposits cap predominately estuarine valley-fills. The type section of the Fall River, near Hot Springs, shows SC 1 fluvial-dominated, valley-fill sandstones resembling basal valley-fill deposits at Cambria Creek. These valley-fill sandstones are replaced laterally to the south at Angostura reservoir by fluvial-dominated delta-front sandstones. This lateral facies change is similar to the traverse from the Cambria Creek (valley fill) to Beaver Creek (valley margin) in the central Black Hills. Shallow-marine sandstones at Angostura Reservoir are the thickest and best developed here.

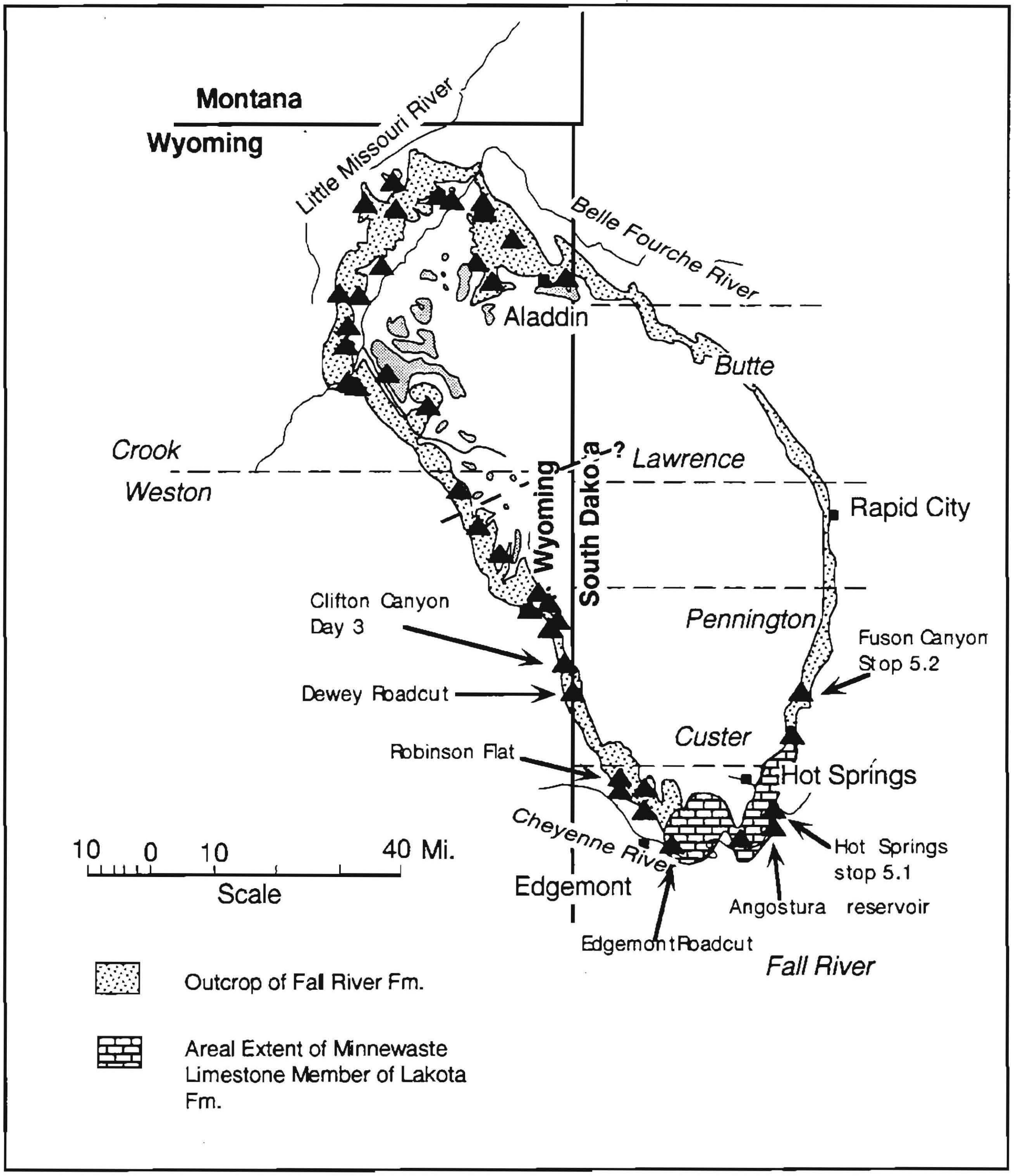



**Figure 81**—Location map showing day 5 field trip stops in the Black Hills

## Dewey Roadcut

(Optional)

**Stop 4.1** From the Fountain Inn, drive 3.3 miles south to intersection with Old Highway 85. At the turnoff, there is a sign to the Newcastle solid waste facility. Turn right and head east 0.5 miles to Y junction and bear right heading south. Proceed south on gravel road 26.5 miles to the town of Dewey, South Dakota. On east side of Dewey turn left at intersection of Fall River 6463 and farm road 769. Drive 3 miles east on 769 to roadcut.

**Objectives:** (1) Examine lower Fall River sequences of the southern deltaic complex

*Discussion*

The Dewey roadcut contains exposures of SC 1 and 2 (Fig. 82). The basal contact of the Fall River Formation is not exposed. SC 1 consists of thinly bedded, moderately burrowed sandstone beds showing symmetrical and asymmetrical ripple sets and rooted at top. This rooted sandstone is inferred to represent the SC 1 sequence boundary, and is overlain by silty shale and carbonaceous mudstone that caps SC 1 at Cambria Creek to the north and Edgemont to the south.

This mudstone is overlain by an erosional surface showing several meters of relief and overlain by a heterolithic estuarine valley fill of SC 2. Erosive-based, lenticular sandstone bodies comprise an upward-fining sandstone succession with thin mudstone interbeds. Sandstone beds thin upward and consist of stacked sets of unidirectional trough cross strata (0.5- to 2-ft thick) showing mud drapes along foresets, sigmoidal bedding, and reactivation surfaces suggestive of a tidal influence. Clay pebble ripups are common at bedset boundaries. Burrowing is moderate to intense, with vertical *Skolithos* burrows extending up to 1 m through discrete sandstone beds.

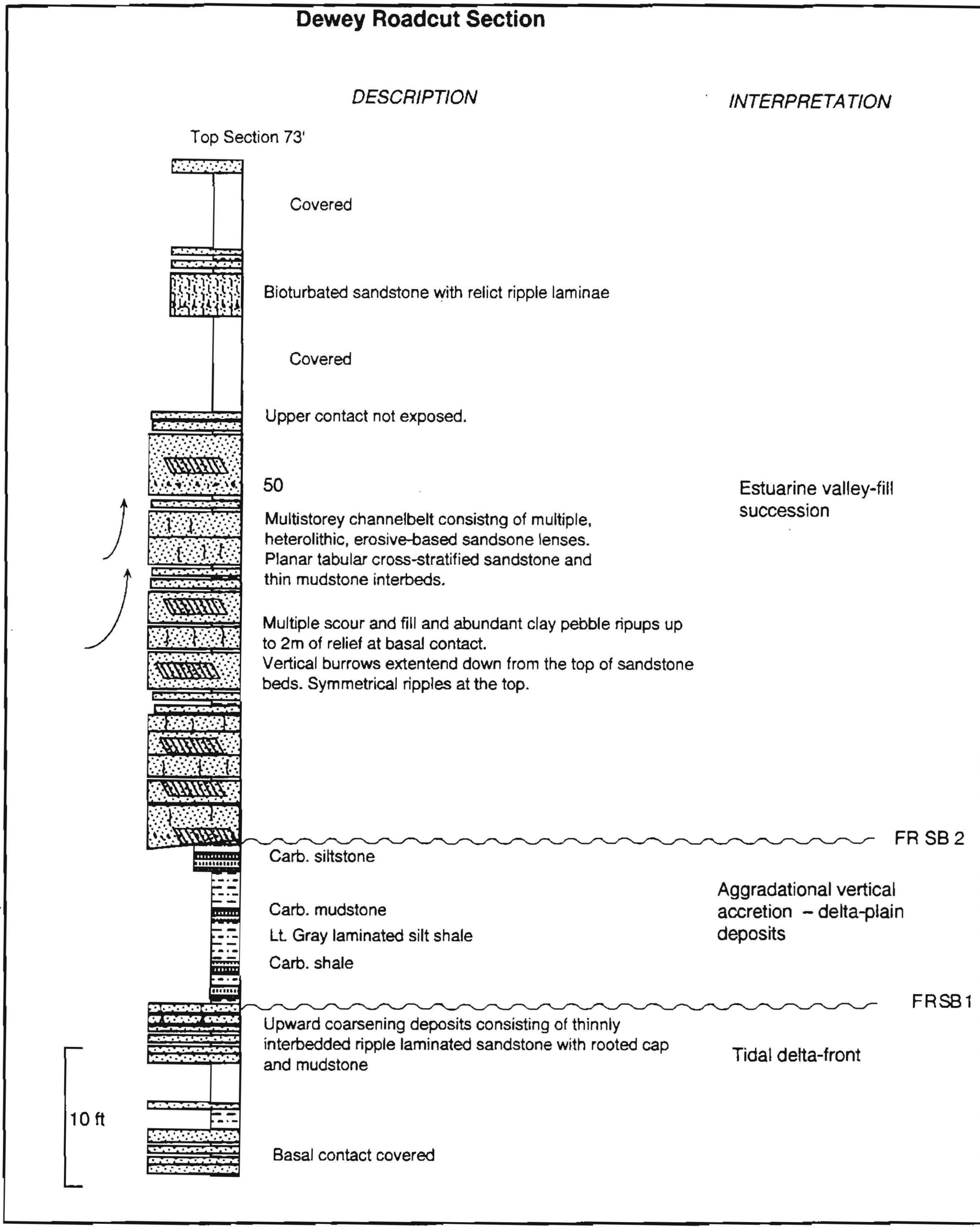



**Figure 82**—Vertical profile of the Fall River Formation at Dewey Roadcut.

## Robinson Flat

(Optional)

**Stop 4.2** Retrace route to the town of Dewey. At intersection turn left onto Dewey Road (Fall River 6463) and drive south 17 miles to junction with farm road 318. Turn left and drive north 5.7 miles to first stop. Continue north on gravel road for 2.5 miles to second stop at Robinson Flats.

**Objectives:** (1) Examine the distal estuarine valley-fill facies
(2) Examine SC 2 boundary and characteristics of storm-wave dominated deposits.

### *Discussion*

The transgressive disconformity separating the Lakota and Fall River Fms is well exposed at the first stop (Fig. 83). This transgressive disconformity overlies Lakota fluvial sandstone, and is overlain by a thin bioturbated sandstone containing abundant iron staining and goethite concretions. This sandstone is overlain by 10 m thick succession of dark-gray silty shale containing thinly bedded sandstone interbeds organized into meter thick shallow-marine parasequences. At the top of the roadcut, an erosive-based channel sandstone body marks the SC 1 sequence boundary. About 2.5 miles north of this locality, at Robinson Flats, basal marine mudstones here are replaced by stacked valley fills.

Robinson Flats exposes heterolithic valley-fill deposits containing higher mudstone proportions than more proximal equivalents at Red Canyon. This proximal to distal facies change within the paleovalley is similar to the downvalley facies changes observed at Buck Draw. If true, exposures at Robinson Flat may be representative of the type of downvalley facies change forming intra-valley seals (Fig. 84 ).

At Robinson Flats, the upper Lakota Fm consists of a 30 m thick slope-forming succession of green gray mudstone and fluvial sandstones are absent. This contrasts with upper Lakota exposures at Red and Craven canyons, where there is thick section of fluvial sandstone. Green gray mudstones here represent interfluve mudstones either laterally equivalent to Lakota channelbelts.

The Fall River Formation consists of four short-term cycles containing inclined sandstone beds dipping eastward 2-3°. Thin remnants of laterally discontinuous SC 1 sandstones consist of stacked sets of trough cross-strata that fill erosional topography and show SW-NE sediment transport (Fig. 85). Overlying SC 2 sandstones consist of stacked sets of amalgamated trough cross strata, and subhorizontal to wavy laminated sandstone truncated and rooted at top

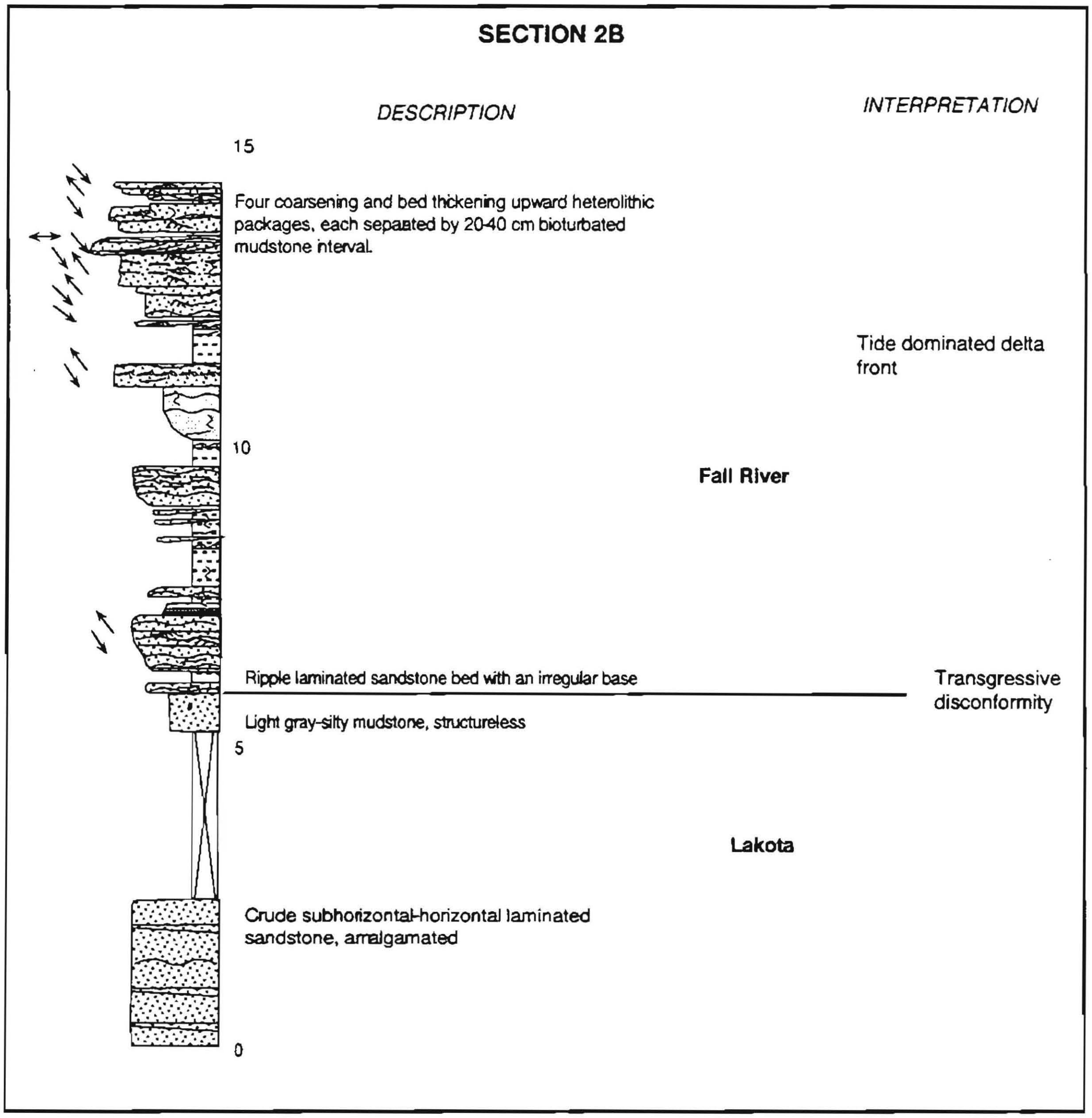



Figure 83 –Stratigraphic section at location 2B showing four distinct cycles within the first Fall River Sequence

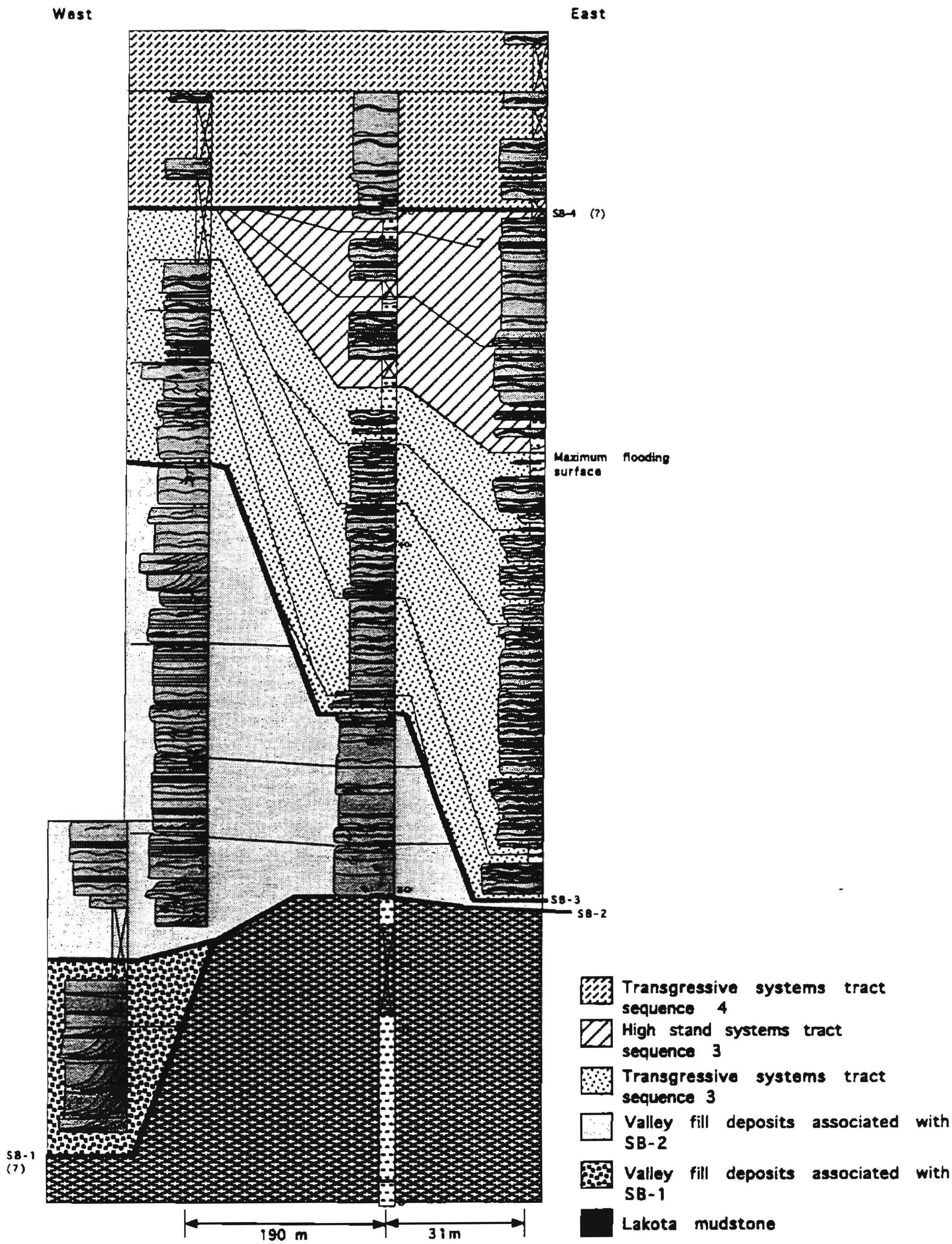



Figure 84: Stratigraphic cross-section at Crevane Canyon showing correlation of Fall River sequences.

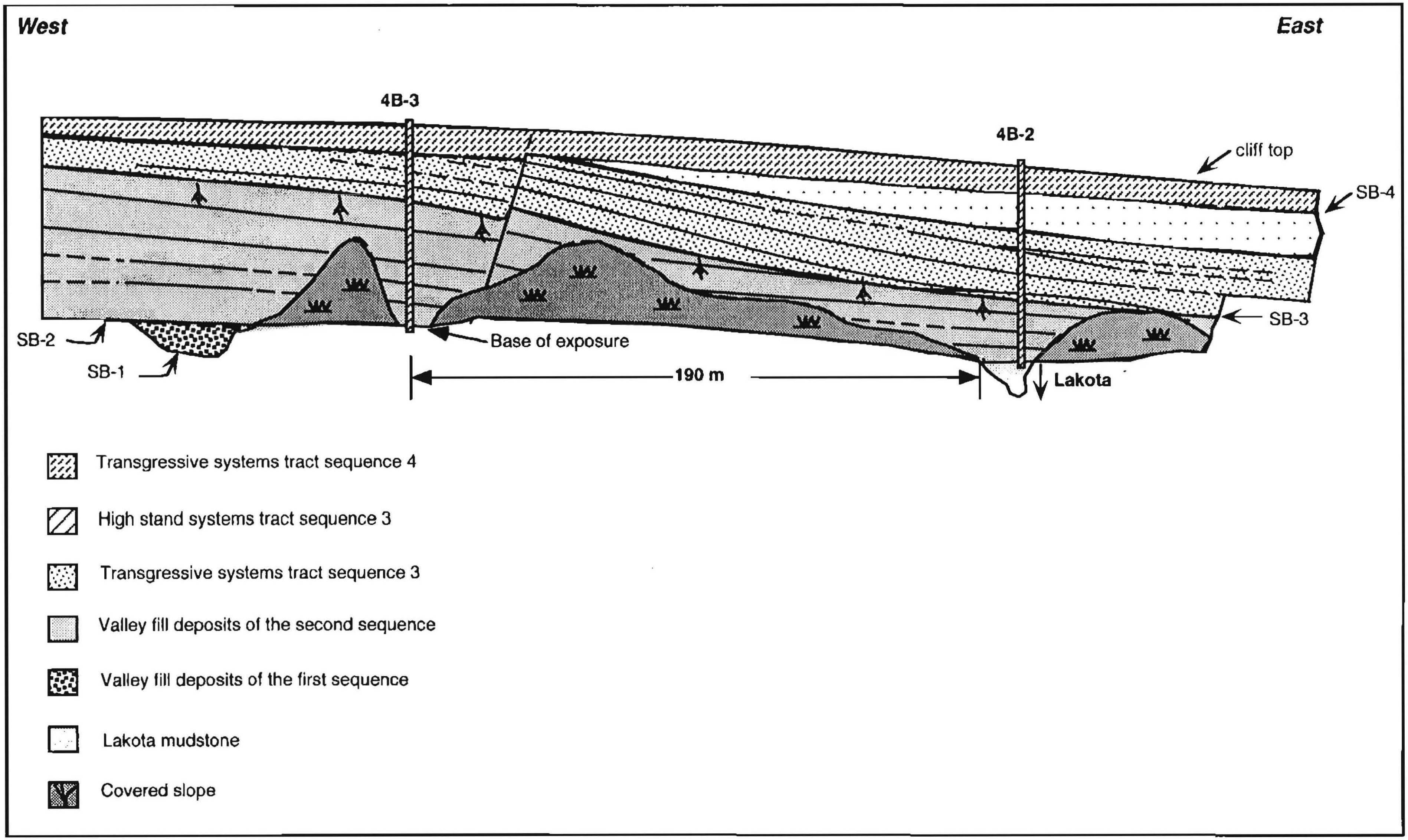



**Figure 85** –Photomosaic trace of surfaces showing correlation of Fall River sequences at Robinson Flat

(roots traced laterally from 4B-1 to 4B-2). SC 3 consists of sandstone beds that thin upward and show hummocky cross stratification, wave ripples, and subordinate unidirectional ripples. Symmetrical ripple crests show north-south and subordinate NW-SE paleoflow. Dark gray laminated mudstone (20 to 30 cm thick) caps SC 3 and records base-level rise. This mudstone is overlain by amalgamated HCS sandstones erosionally truncated by thicker amalgamated HCS-swaley cross stratified sandstone beds. This truncation surface juxtaposes sandstones inclined at different angles and represents the SC 4 sequence boundary.

## Edgemont Roadcut

(Optional)

**Stop 4.3** Retrace route back to fork with Dewey Road and continue south for 3.1 miles to the town of Edgemont, SD. At stop sign turn right (south) and then take an immediate left (east) onto old Highway 18s. Follow paved road 3.7 miles to roadcut east of the town of Edgemont.

**Objectives:** (1) Examine the facies architecture of Fall River sequences of the southern deltaic complex
(2) Examine facies of nested valley-fill deposits of the second and third Fall River sequences and their relationship to the sequence boundaries.

*Discussion*

The Edgemont roadcut exposes a nearly complete Fall River section (Fig. 86), but the basal contact is covered. SC 1 consists of three upward-shoaling shallow-marine parasequences containing thinly bedded, moderately burrowed sandstone beds showing symmetrical and asymmetrical ripples, wavy laminations, and abundant goethite coatings. The capping sandstone bed is rooted and overlain by an interbedded silty shale and carbonaceous mudstone correlative to coal horizons at Dewey. This carbonaceous mudstone is erosionally overlain by stacked valley-fills of SC 2 and 3. The SC 2 sequence boundary marks the base of this valley-fill complex and consists of erosive-based sandstone bodies (1 to 2 m thick) containing thin to medium sets of unidirectional planar tabular cross-strata based by rounded clay pebble rip-up clasts. An irregular erosional surface marks the SC 3 sequence boundary and separates sandstones containing stacked sets of planar tabular cross strata from overlying more heterolithic interbedded sandstones and mudstones capping the roadcut. Two upward-shoaling shallow-marine successions consisting of hummocky

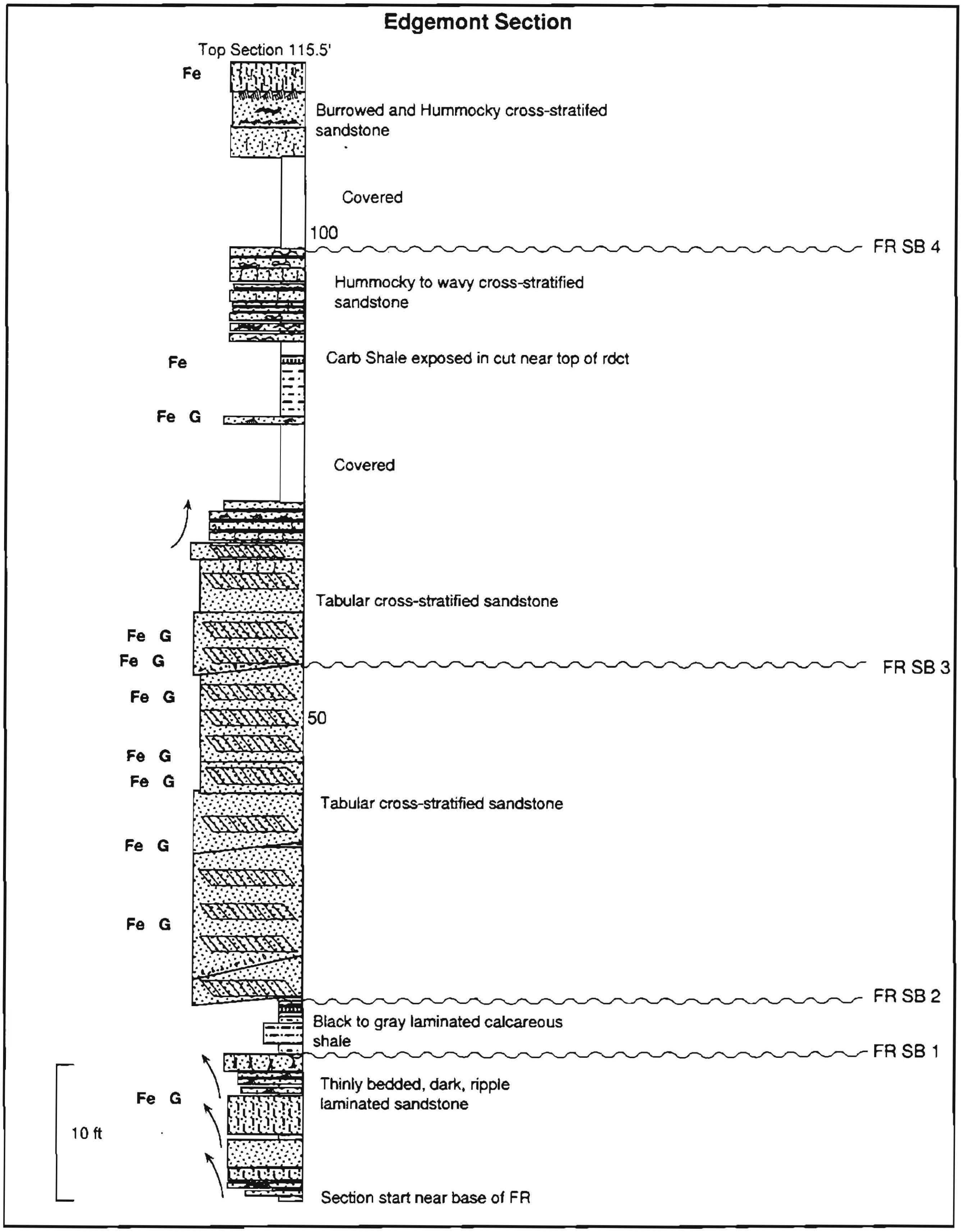



**Figure 86**—Vertical profile of the Fall River Formation at Edgemont Roadcut.

cross-stratified sandstone form laterally continuous benches overlying the uppermost valley fill. SC 4 comprises the lower upward-shoaling shallow-marine succession and is overlain by a poorly developed paleosol (?) forming sequence boundary. The ridge capping sandstone of SC 5 also caps the Fall River at Red Canyon.

## Hot Springs

**Stop 5.1** Take Hot Springs bypass road to intersection of Hwy. 385 and Hwy. 18. Turn right (southeast) onto State Highway 385 and drive 3.7 miles to St. Johns Lutheran church parking lot. The type section of the Fall River Fm is exposed on the north side of the road.

**Objectives:** (1) Contrast valley-fill deposits of successive Fall River valley-fill deposits in proximal setting.

### *Discussion*

This is the type section of the Fall River Formation (Fig. 87). The massive sandstone at the base of the roadcut was originally mapped by Darton (1901) as the Dakota Formation. Russell (1927) included overlying strata below the Graneros Shale in the Fall River Formation, thereby inadvertently giving this lithostratigraphic unit chronostratigraphic significance as a rock body bounded by marine flooding surfaces.

The transgressive disconformity separating Lakota and Fall River Fms is exposed at the base of a massive, cliff-forming, salmon-colored sandstone (50-ft-thick), locally termed the "quarry sandstone" and representing SC 1 valley fill. This fluvial-dominated valley fill consists of upward-fining, well sorted, fine-grained sandstone containing structureless to stacked sets of unidirectional trough cross-strata (6- to 8-in sets) grading up to planar-tabular cross strata at top showing west-southwest sediment transport. The conspicuous absence of mudstone interbeds makes resolution of discrete channel sandstone bodies difficult, but they may be marked by an abrupt change to horizontal laminations. The upper part of this sandstone contains hematite-staining and goethite-coated nodules sharply overlain by variegated yellow, tan, and red and rooted nonmarine mudstones (3 m thick). This sandstone body abruptly thins to the north and south, where it is laterally replaced by shallow-marine deposits (i.e., Angostura Reservoir section). Sandstone bodies comprising this valley fill are interpreted as stacked alternate bars deposited in a low-sinuosity, bedload-dominated channel confined to a paleovalley.

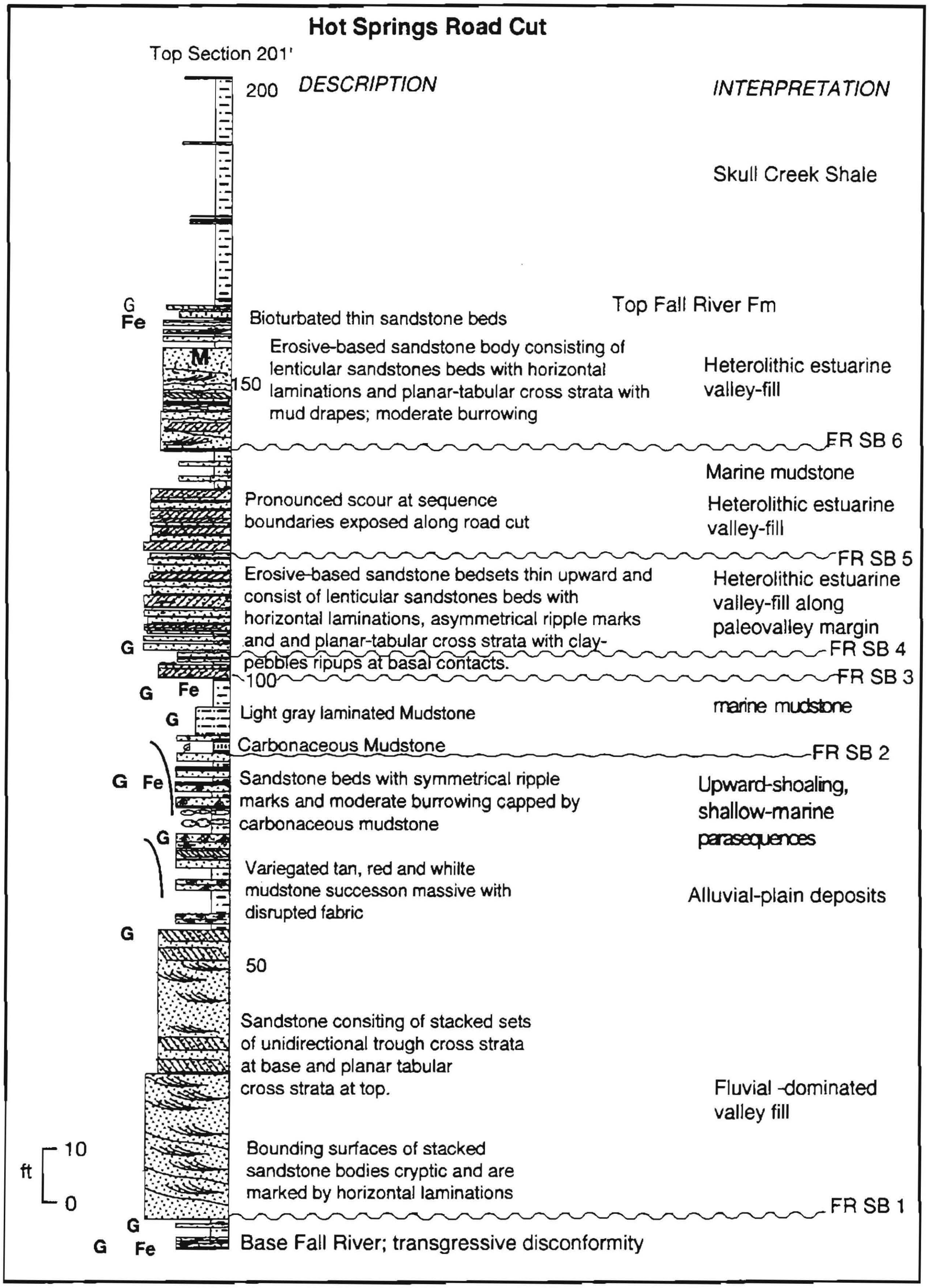



**Figure 87**—Vertical profile of the Fall River Formation at Hot Springs, South Dakota

Nonmarine mudstones are overlain by light gray mudstone grading up to two thin upward-shoaling shallow-marine parasequences of SC 2. Sandstone beds thicken upward and show wavy laminations and thin asymmetrical, symmetrical, and flaser ripple cosets. Tracks and trails of *Skolithos* and *Planolites* are present on sandstone bedding planes. The upper shallow-marine sandstone is capped by a goethite-rich layer overlain by carbonaceous mudstone grading up to light-gray silty shale mottled purple. Across the Black Hills, SC 2 records a major marine transgression reflected by thick marine mudstones in the northern Black Hills, estuarine-dominated valley-fills in the central Black Hills (i.e, Cambria Creek), and aggradational fluvial sandstones at Red Canyon. Here, this marine transgression is manifested in deposition of marine mudstone capping shallow-marine sandstones.

SC 2 mudstones are truncated by SC 3 valley-fill deposits comprising a heterolithic interbedded sandstone and mudstone succession. This estuarine-dominated valley fill forms the cliff on the south side of the highway along the Fall River. Internally, tabular to lenticular sandstones beds consist of planar tabular and trough cross strata (1 cm to 50 cm thick) arranged in meter-scale upward-bed-thinning successions, based by mudstone rip-ups and capped by flaser and asymmetrical ripples. Burrowing intensity increases upward. Road cut exposures show two major erosional surfaces with several meters of relief cross cutting these deposits. These major erosional surfaces may represent SC 4 and 5 (?) sequence boundaries formed during short-term base-level fall. Because these stratigraphic cycles are recognized in sections adjacent to here, and because these major erosional surfaces truncate smaller-scale sediment bodies recording autocyclic deposition in the estuarine fill, these surfaces are the most likely candidates for short-term base-level fall within this succession. Nesting of estuarine valley fills reflects the more proximal paleogeographic setting here, whereas estuarine facies reflect the stratigraphic position of these strata in landward-stepping cycles recording intermediate-term base-level rise.

Estuarine deposits of SC 4 and 5 are overlain by gray bioturbated mudstone (8-ft-thick) containing thin burrowed sandstone interbeds inferred to record base-level rise and marine transgression. With respect to marine mudstones capping SC 2, SC 5 marine mudstones record increased marine influence, and increased burrowing intensity reflecting decreased sedimentation rates associated with increasing accommodation and sediment storage in more proximal environments of landward-stepping short-term cycles recording intermediate-term base-level rise.

SC 5 marine mudstones are truncated by estuarine-dominated valley fill of SC 6. Lenticular to wedge-shaped sandstone beds thin and fine upward and show wavy bedding, asymmetrical ripples, and trough and tabular cross strata (25-ft-thick). Burrowing intensity is greater than in underlying estuarine deposits. This sandstone interval is capped by a thinly bedded burrowed sandstone marking the terminal Fall River transgression resulting in deposition of the Skull Creek (Graneros) Shale.

## Angostura Reservoir

(Optional)

**Stop 5.1b** From church parking lot drive 0.5 miles east on Hwy. 385 to intersection with Hwy. 79. Turn right (south) onto Hwy. 385 and drive 2.9 miles south to turnoff to Angostura Reservoir. Turn right (west) and follow road about 2 miles to Angostura State Park entrance. Take first right past entrance (west) and drive 0.9 miles west to pagoda near damsite.

**Objectives:**

(1) Examine delta-front facies in lower Fall River
(2) Examine Fall River sequence boundaries and basal transgressive disconformity
(3) Document valley-fill deposits in proximal setting.

### *Discussion*

Angostura Reservoir contains exposures of the most proximal facies in the Fall River Fm. in the Black Hills (Fig. 88). The transgressive disconformity separating Lakota and Fall River Fms. is well exposed and marked by a bioturbated sandstone and coarse lag deposit containing mudstone rip-up clasts from the upper Lakota. Fluvial-dominated valley-fill deposits of SC 1 at Hot Springs are replaced here by two upward-shoaling, fluvially-dominated shallow-marine parasequences (10- to 20-ft-thick). Thin to medium sandstone beds consist of low-angle to hummocky-cross-stratification, are commonly burrowed to bioturbated and are capped by asymmetrical, symmetrical, and flaser ripples. Sandstone bases show load and ball and pillow structures penetrating downward into underlying mudstones. These upward-shoaling successions are capped by thin tabular to broadly lenticular, sharp-based sandstone bodies consisting of thin sets of low-angle to trough cross strata. These sandstone bodies may represent distributary mouthbar sandstones. Distributary mouthbar sandstones are locally incised by thin heterolithic channel-fill deposits that show the size of the channels feeding deltas in conformable Walther's Law facies successions in the Fall River. The uppermost parasequence is rooted at top, and overlain by a thin carbonaceous mudstone and thinly bedded, ripple-laminated and rooted sandstone.

Overlying SC 2 deposits comprise a fluvial-dominated valley fill succession (9 m thick) consisting of four stacked channel sandstone bodies (1- to 3-m-thick). Channel sandstone bodies are based by abundant clay-pebble rip-ups and large logs and consist of stacked sets of unidirectional trough and planar-tabular cross strata (up to 1 m thick). Abundant logs and completely preserved trees are exposed on bedding surfaces along the lake. The upper part of the valley fill contains thinly bedded ripple-laminated sandstone showing moderate to intense burrowing by *Planolites* and *Skolithos*.

SC 2 valley-fill sandstones are overlain by light gray mudstone grading up to poorly exposed red and purple alluvial-plain mudstones that are extensively rooted and showing a disrupted fabric typical of paleosols. This paleosol marks the base of merged SC 3 and 4 and is overlain by an upward-shoaling shallow-marine sandstone succession consisting of thin to medium bedded sandstone of SC 4. Sandstones are intensely burrowed and contain 1 to 2 in thick asymmetrical ripple cosets. This paleosol marks the intermediate-term base-level fall to rise turnaround of the Fall River stratigraphic sequence. Overlying SC 5 deposits consist of a thin lenticular channel sandstone body containing stacked sets of planar-tabular cross strata showing *Skolithos* and *Planolites* burrows on bedding planes. This sandstone caps the cliff near the pagoda and the upper part of the Fall River is exposed along the reservoir to the south, where two upward shoaling shallow-marine sandstones may represent SC 5 and 6. SC 6 contains the thickest shallow-marine succession and overlain by marine mudstones of the Skull Creek Shale.

The Fall River here shows a progressive increase marine increase above the intermediate-term turnaround of SC 3 capped by the most proximal deposits and describes an overall symmetrical stratigraphic cycle. SC 1 and 2 deposits comprise seaward-stepping cycles showing increased fluvial influence, whereas SC 4, 5 and 6 are arranged in a landward-stepping stacking pattern and contain shallow-marine deposits showing increasing wave influence. Marginal marine facies of these cycles are commonly capped by alluvial plain deposits that reflect the proximal setting here.

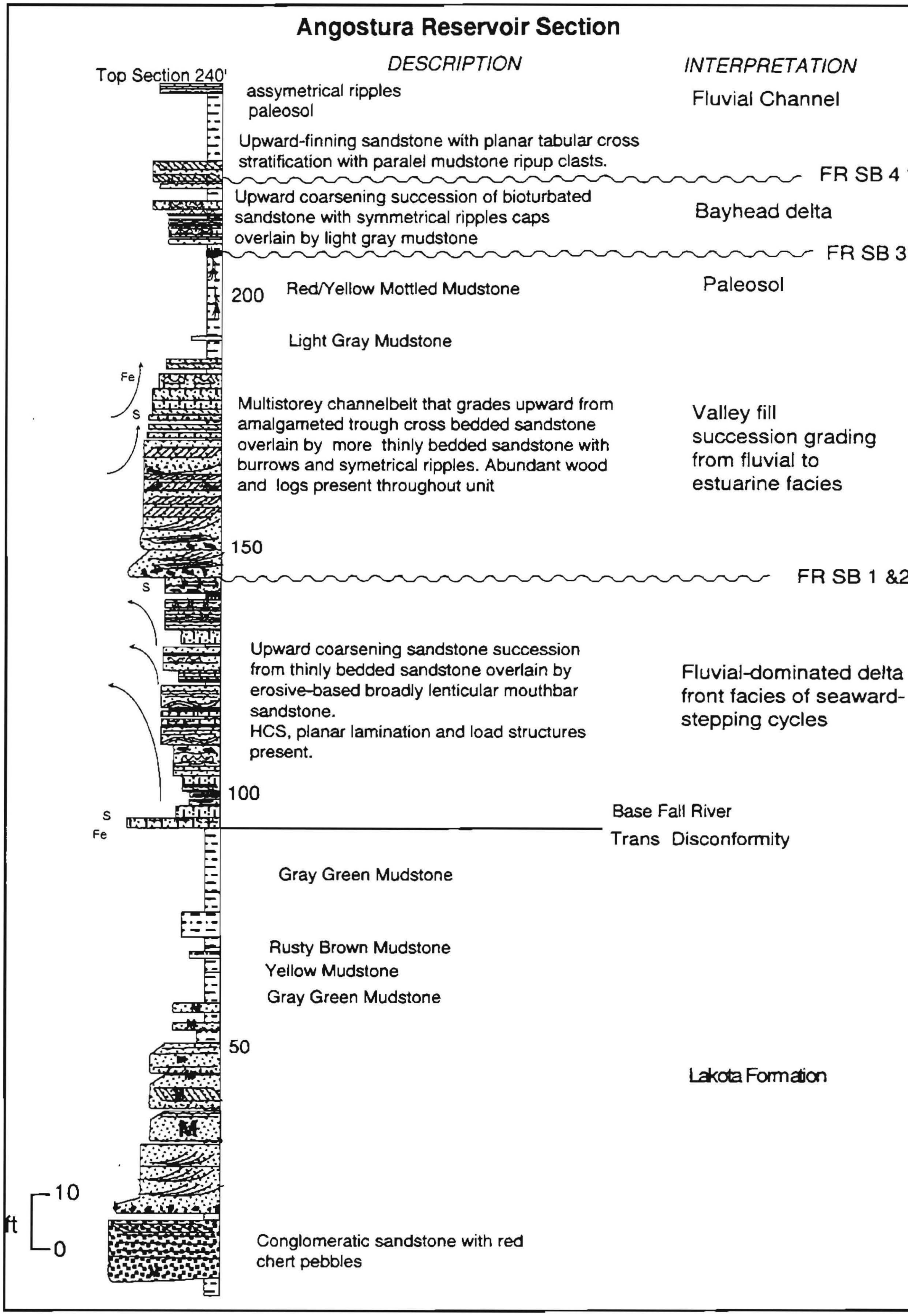



**Figure 88**—Vertical Profile of the Fall River Formation at the Angostura Reservoir.

## Fuson Canyon

**Stop 5.2** From church parking lot drive 0.5 miles east on Hwy. 385 to intersection with Hwy. 79. Turn left (north) onto Hwy. 385 and drive 9 miles north to Buffalo Gap. Turn left (west) and follow road about 2 miles to right turn (north) onto. Drive past Streeter Ranch to right turn (east) onto track leading to Fuson Canyon.

**Objectives:**

(1) Examine delta-front facies in lower Fall River
(2) Examine Fall River sequence boundaries and basal transgressive disconformity
(3) Document valley-fill deposits in proximal setting.

### *Discussion*

This is the type section of the Fuson Member of the Lakota Formation (Fig. 89). The overlying Fall River Fm. is well exposed and consists of stacked valley fills recording a major fluvial system here. These valley fills thin southward and contain increased proportions of estuarine facies at Hot Springs reflecting a lateral facies change toward valley margins. The transgressive disconformity separating Lakota and Fall River Fms. is marked by an undulatory erosional surface overlain by a massive, poorly-sorted, coarse sandstone containing quartzite cobbles and mudstone rip-up clasts from the upper Lakota (Fuson Member). Fluvial-estuarine valley-fill deposits of SC 1 (5 m thick) locally incise the transgressive lag deposit and consist of stacked sets of planar-tabular cross strata showing northwest sediment transport. Foresets are normally graded with granules and pebbles on bedding surfaces. Fluvial sandstones are sharply overlain by thinly bedded sandstones showing increased burrowing intensity upward.

The SC 1 top is rooted and overlain by 3 estuarine valley fill units in SC 2 showing eastward downlap onto the underlying rooted horizon and SC 2 sequence boundary. Each SC 2 estuarine unit contains progressively deeper water facies upward. Sandstone beds comprising estuarine units thicken upward and consist of low-angle to wavy laminations and asymmetrical, symmetrical, and flaser ripples. Burrowing intensity increases upward and the top is rooted.

A major erosional surface truncates the rooted SC 2 top and floors SC 3 fluvial-dominated valley-fill deposits (6 m thick) consisting of stacked sets of planar tabular cross strata showing northwest sediment transport. This valley fill is also truncated by a major erosional surface showing 10 m of relief and overlain by a massive lag deposit containing rounded clay-pebble rip-up clasts. SC 4

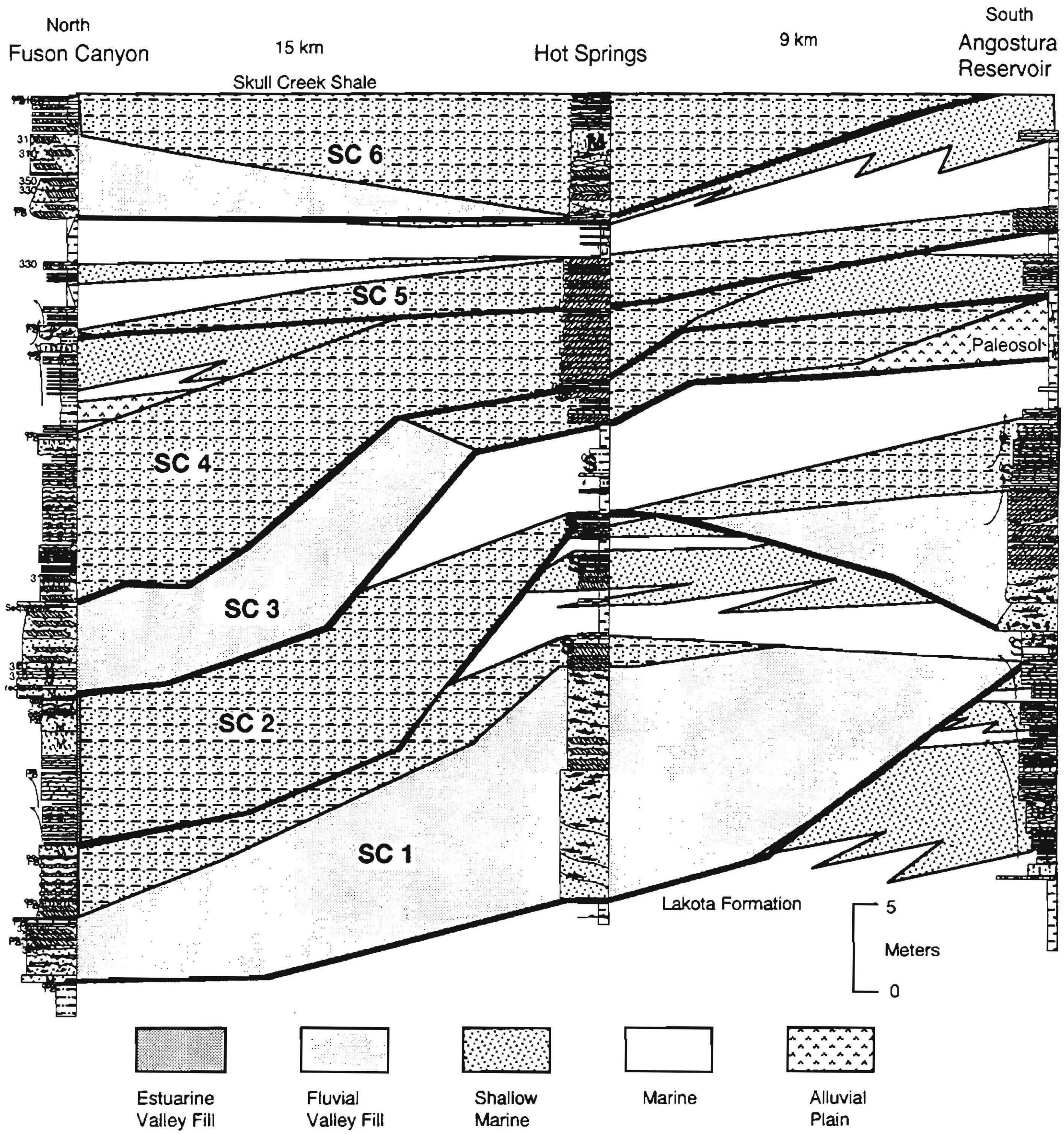



**Figure 89**—Vertical profile of the Fall River Formation at Fuson Canyon, South Dakota.

sandstones above this lag deposit show an abrupt change in bedding style to more heterolithic sandstone bodies (2 to 3 m thick) of this fluvial-estuarine valley fill. Sandstones contain stacked sets of unidirectional trough and planar-tabular cross strata (0.5- to 2-ft-thick) changing upward to thinly bedded ripple-laminated sandstone showing moderate to intense burrowing by *Planolites* and *Skolithos*. This sandstone is overlain by slope-forming orange-brown mudstone grading up red mudstone sharply overlain by an upward-shoaling shallow-marine succession consisting of thin to medium sandstone beds that thicken upward and contain asymmetrical ripple cosets. These shallow-marine deposits are incised by a thin lenticular channel sandstone body containing stacked sets of planar-tabular cross strata showing *Skolithos* and *Planolites* burrows on bedding planes.

Light-gray mudstones overlying this shallow-marine sandstone are sharply overlain by another upward-shoaling shallow-marine succession containing symmetrical ripple crests showing a N 30 E shoreline trend. Overlying light-gray mudstones are incised by SC 6 valley-fill sandstones capping the hogback and consisting of 3 highly interconnected fluvial channel sandstone bodies. Sandstone bodies contain stacked sets of planar tabular cross strata showing northwest sediment transport and grading up to thinly bedded asymmetrical ripple cross-laminated sandstone.

The Fall River here records the intermediate-term base-level fall to rise turnaround (minimum accommodation) of SC 3, by a rooted horizon incised by SC 3 fluvial-dominated valley fill. Deposits above this succession show a progressive increase in the proportion of marine mudstone and facies, and decreased sandstone-mudstone ratio. SC 4 consisting of fluvial-dominated valley-fill deposits at Clifton Canyon are more estuarine here reflecting increased marine influence up the paleovalley.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←Marine-Shelf Facies Tract→ ←Shallow-Marine Facies Tract→ ←Valley-Fill Facies Tract→

# EXPLANATION

## Facies

Coal

Organic-rich mudstones, carbonaceous shale and coal. Present in both lower and upper delta-plain facies associations

Upward-fining sandstone succession forming erosive-based sandstone lens with trough and tabular cross strata, with structureless sandstone &abundant clay-pebble ripup lags. Alternate bars of bedload dominated, low sinuosity fluvial system.

Sandstone consisting of sandwaves, heterolithic cross strata, sigmoidal cross strata mud drapes, complex and compound cross strata, moderate bioturbation. Mudstone interbeds. Tidal channel, tidal inlet and tidal sandbar deposits of estuarine valley-fill

Upward-coarsening sandstone succession consisting of hummocky and swaley cross stratafication with symmetrical ripple tops and and moderate bioturbation. Multidirectional trough cross strata of upper shoreface and/or amalgamated trough cross strafication of distributary mouthbar deposits, foreshore deposits. Storm-dominated lower and upper delta-front deposits; > 80 % sandstone

Interbedded heterlithioc mudstone and sandstone with moderate to intense burrowing; thin carbonaceous mudstone beds, a variety of asymmetrical ripple types & brackish water fauna. Tidally-domianted delta-front succession; < 50% sandstone

Siltstone and structureless to graded sandstone beds; sand-poor upward-coarsening succession of marine-shelf

Laminated mudstone with thin siltstone and structureless to graded sandstone interbeds; marine-shelf deposits

Bioturbated muddy sandstone forming condensed section facies, hiatal surfaces or "pause"planes" of nodeposition

## Correlations

Time boundary of short-term stratigraphic cycle

Time boundary of intermediate-term depositional sequence

Volcanic ash bed

## Sedimentary Structures

Multidirectional trough cross stratification

Trough cross stratification

Planar tabular cross stratification

Sigmoidal bedding

Climbing ripple lamination

Asymmetrical ripple lamination

Starved ripple lamination

Symmetrical ripple lamination

Hummocky cross stratification

Wavy bedding

Horizontal Lamination

Soft sediment deformation

Ball and pillow structure

Load structure

Lag deposit

Wood

Root

Plant debris

## Trace Fossils

Ophiomorpha

Skolithos

Planolites

Rhizocorallium

Shell debris

Arenicolites

Diplocraterion

Thalassinoides

Ammonite collection

Inoceramid or other fossil collection

## Clastic Grain Size