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Middle Shoreface Intervals: Evidence of Barred Nearshore Systems in he Stratigraphic Record

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MIDDLE SHOREFACE INTERVALS:
EVIDENCE OF BARRED NEARSHORE SYSTEMS
IN THE STRATIGRAPHIC RECORD

by

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ABSTRACT

MIDDLE SHOREFACE INTERVALS: EVIDENCE OF BARRED NEARSHORE SYSTEMS IN THE STRATIGRAPHIC RECORD

James V. Gravette
Old Dominion University, 1997
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An interpretation for middle shoreface (MSF) intervals was developed by comparing MSF intervals from the Upper Cretaceous (Campanian) Blackhawk Formation, east-central Utah, with conceptual models proposed for modern nearshore areas. Specifically, MSF intervals identified within the Sunnyside Member were compared with MSF intervals identified within the Spring Canyon (Kamola and Van Wagoner, 1995) and the Aberdeen (Kamola, unpublished data) members.

A comparison of MSF interval data revealed that MSF intervals occur stratigraphically between upper and lower shoreface deposits, disrupting the standard vertical succession for nearshore marine deposits (consisting of offshore, lower shoreface, upper shoreface, and foreshore deposits). Nearly all MSF intervals consist of alternating planar bedded-to-burrowed beds of varying thicknesses. Only one MSF interval consists entirely of planar beds. The total thickness of MSF intervals varied from 1.5 to 9.5 meters.

Based upon conceptual models proposed for modern nearshore areas, MSF intervals were interpreted as ancient seaward slope deposits. In other words, MSF intervals are evidence of barred nearshore systems preserved in the stratigraphic record. While preservation of seaward slope

deposits had already been predicted (Shipp, 1984), this is the first time that these deposits have been interpreted in the stratigraphic record.

This thesis is dedicated to my wonderful wife, Julie, for her endless support and unquestionable confidence throughout the writing of this paper.

ACKNOWLEDGMENTS

Appreciation is extended to the faculty and staff in the Geology Department at Old Dominion University for their technical and financial assistance. Thanks are expressed to Dr. Diane Kamola, Dr. Randall Spencer, and Dr. Dennis Darby for helpful discussions, instruction, and constructive criticism during the course of this study.

I would also like to thank Julie Gravette, Pete and Liz Henderson, Dan Thibodeau, Aimee and Manny Kokotakis, Duke and Susan Heinz, Kim Smith, Rob Fraley, Pablo Luchetti, and my parents, all of who were there every step of the way.

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INTRODUCTION

Sedimentologic studies (Howard and Reineck, 1979; Hunter et al., 1979; McCubbin, 1981; Reinson, 1984; Shipp, 1984; Taylor and Lovell, 1992; O'Byrne and Flint, 1995; Kamola and Van Wagoner, 1995; Van Wagoner, 1995) indicate that the majority of wave-dominated nearshore deposits typically display some or all of the standard vertical succession (SVS) consisting of offshore, lower shoreface, upper shoreface, and foreshore deposits. However, some deposits deviate from this succession by displaying an additional middle shoreface (MSF) interval. While conceptual models proposed for modern nearshore areas adequately explain the SVS (Howard and Reineck, 1979; Hunter et al., 1979), they do not account for the addition of a MSF interval within it. The purpose of this study is to determine whether or not MSF intervals represent evidence of nearshore bars in the stratigraphic record. This study is important because, to date, there is very little evidence to allow for the recognition of barred nearshore systems in the stratigraphic record.

The objectives of this study are three-fold. The first objective is to identify MSF intervals consisting of parallel-to-burrowed sandstone within the marine portions of the Sunnyside Member of the Upper Cretaceous (Campanian) Blackhawk Formation, east-central Utah. This member was chosen for analysis because it was the last of the six Blackhawk

Formation members to be studied in detail. In addition, MSF intervals have already been identified within other members of the Blackhawk Formation. The second objective is to document MSF interval variability by comparing any MSF intervals identified within the Sunnyside Member with MSF intervals previously identified within other members of the Blackhawk Formation. The third and final objective is to interpret MSF intervals based upon conceptual models proposed for modern wave-dominated nearshore areas.

METHODOLOGY

A field study was conducted to document MSF intervals within the marine portions of the Sunnyside Member. Thirteen stratigraphic sections were measured, recording at the meter scale, lithology, grain size, and physical and biogenic sedimentary structures. Based upon these criteria and, particularly, their vertical succession, each section was compared to the SVS. MSF intervals were recognized as being distinctly different from all other intervals associated with the SVS and, as their name implies, occur stratigraphically between upper and lower shoreface deposits.

After MSF interval data had been collected from the Sunnyside Member, it was compared with previously collected MSF interval data from the Spring Canyon (Kamola and Van Wagoner, 1995) and the Aberdeen (Kamola, unpublished data) members of the Blackhawk Formation. Comparisons were based upon the stratigraphic location of these intervals with respect to the deposits associated with the SVS, the thicknesses of these intervals, and the thicknesses and types of physical and biogenic sedimentary structures within these intervals. The purpose of comparing these intervals was to document interval variability within MSF deposits. Finally, MSF intervals were interpreted using conceptual models proposed for modern wave-dominated nearshore areas. An interpretation for the MSF interval was based upon a "best fit" scenario. In other words, MSF intervals were interpreted based upon sedimentologic analysis of modern non-barred and barred wave-dominated nearshore deposits. The "best fit" modern nearshore deposit was evaluated in terms of how it formed, and under what conditions it could be preserved in the stratigraphic record.

STANDARD VERTICAL SUCCESSION (SVS)

The standard vertical succession (SVS) for wave-dominated nearshore deposits consists of offshore, lower shoreface, upper shoreface and foreshore deposits (Howard and Reineck, 1979; Hunter et al., 1979; McCubbin, 1981; Shipp, 1984; Taylor and Lovell, 1992; O'Byrne and Flint, 1995; Kamola and Van Wagoner, 1995; Van Wagoner, 1995. This vertical succession of deposits formed as a result of shoreface progradation (Howard and Reineck, 1979; Hunter et al., 1979) (Figure 1). It is generally assumed that the deposits associated with the SVS from top to bottom approximate the lateral sequence of deposits observed on modern profiles from beach to offshore (McCubbin, 1981).

Deposits associated with the SVS are defined in terms of lithology, grain size, and physical and biogenic sedimentary structures, and are interpreted in terms of wave energy (Howard and Reineck, 1979; Hunter et al., 1979; Taylor and Lovell, 1992; O'Byrne and Flint, 1995; Kamola and Van Wagoner, 1995; Van Wagoner, 1995). The following is a brief description and interpretation of these deposits, and is summarized from the literature cited above.

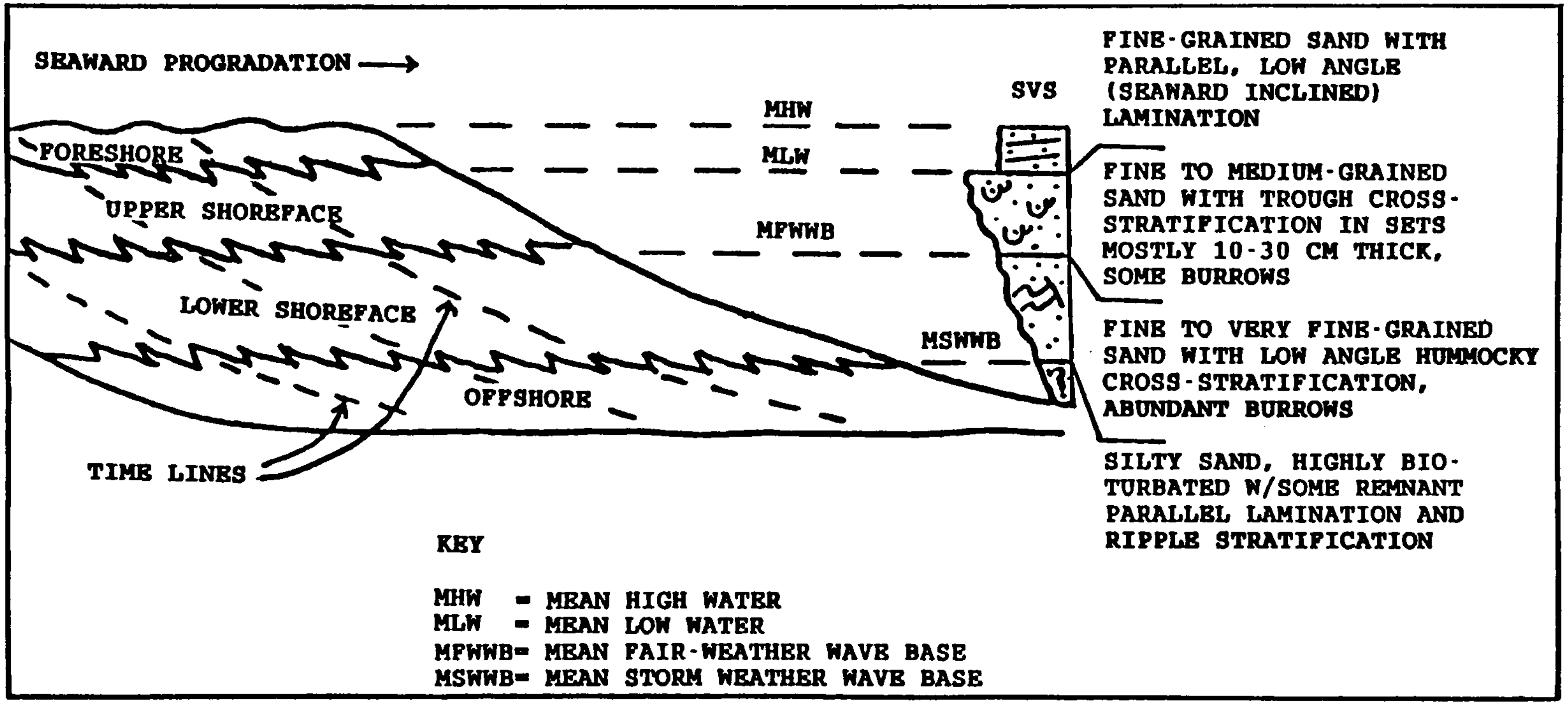


Figure 1. Seaward progradation of the shoreline results in a basinward migration of foreshore, upper shoreface, lower shoreface, and offshore deposits, producing the vertical succession of sub-environments shown as the standard vertical succession (SVS) (modified from McCubbin, 1981).

OFFSHORE DEPOSITS

Offshore deposits consist predominantly of muds and silts, and are commonly bioturbated (Howard and Reineck, 1979). These deposits are characterized by organic detritus and remnant ripple and parallel laminae (Frey, 1990). The Cruziana ichnofacies is most characteristic of these deposits (Frey and Howard, 1990).

Offshore deposits are interpreted as distal shelf deposits (Howard and Reineck, 1979). These deposits were produced seaward of mean storm-weather wave base (Clifton et al., 1971) (see Figure 1). They formed as sediment slowly rained out of suspension in water deep enough to be unaffected even by storms waves (Clifton et al., 1971). These low-energy deposits are associated with relatively stable environmental parameters (temperature, salinity and sedimentation rates) which explains why biogenic structures are abundant, diverse (representing dwelling, resting, crawling, feeding and escape responses) and, as opposed to many other environments, preservable (Frey and Howard, 1990).

LOWER SHOREFACE DEPOSITS

Lower shoreface deposits are typically coarser than offshore deposits, consisting of very fine lower to fine lower sands (Howard and Reineck, 1979). These deposits are characterized by hummocky cross-stratified (HCS) beds (Figure 2) that are commonly interbedded with variably bioturbated beds (Harms et al., 1982). Individual HCS beds become increasingly amalgamated upwards through the lower shoreface (Howard and Reineck, 1979). A mixed Skolithos-Cruziana ichnofacies is most characteristic of these deposits (Frey and Pemberton, 1984).

Lower shoreface deposits are interpreted as storm deposits (Harms et al., 1982). These deposits were produced between mean storm-weather wave base and mean fair-weather wave base (Howard and Reineck, 1979; Harms et al., 1982; Walker, 1984) (see Figure 1). Many studies (Walker, 1984; Duke, 1987; Southard et al., 1990) suggest that HCS beds were formed as a result of storm-enhanced wave action between mean fair-weather and storm-weather wave base. Bioturbated beds were formed as the result of burrowing that occurred between storm events (Black, 1988). Amalgamated HCS beds were formed when all evidence of burrowing was completely reworked during the next storm event (Howard and Reineck, 1979; Walker, 1984; Duke et al., 1991). Typically, HCS beds become increasingly amalgamated upwards through the lower shoreface deposits as the depth of sediment reactivation increases with decreasing water depth. The mixed Skolithos-Cruziana ichnofacies resulted from hydrodynamic energy fluctuations associated with passing storm events (Howard and Frey, 1975). The diverse Cruziana ichnofacies is representative of a stable benthic

FIELD NOTEBOOK

SCALE

0 1 METER

Figure 2. Photograph of hummocky cross-stratified lower shoreface deposits, field notebook for scale.

community that dominated between storm events, while the Skolithos ichnofacies is representative of a community of opportunistic filter feeders that dominated during storm events (Frey and Pemberton, 1984).

UPPER SHOREFACE DEPOSITS

Upper shoreface deposits (Figure 3) are typically coarser than lower shoreface deposits, ranging from fine upper to medium lower sands (Howard and Reineck, 1979). These deposits are characterized by trough cross-beds, in sets approximately 10-30 centimeters thick (Howard and Reineck, 1979). The Skolithos ichnofacies is most characteristic of these deposits (Howard, 1972, 1975).

Upper shoreface deposits are interpreted as high-energy surf zone deposits that are dominated by wave surges and wave generated currents (Howard and Reineck, 1979). These deposits were produced between mean fair-weather wave base and mean low water level (see Figure 1) and were the product of bi-directional shore-normal oscillatory motion and uni-directional longshore rip-currents (Clifton et al., 1971). Trough cross-sets associated with these deposits were formed as a result of megaripple migration, and were preserved as bar-trough couplets that were buried by the landward migration of bars (Howard and Reineck, 1979).

HAMMER

SCALE

0 1 METER

Figure 3. Photograph of trough cross-stratified upper shoreface deposits, overlain by planar stratified foreshore deposits, hammer for scale.

FORESHORE DEPOSITS

Foreshore deposits (see Figure 3) are typically finer than upper shoreface deposits, consisting of fine upper sands (Howard and Reineck, 1979). These deposits are characterized by parallel to sub-parallel horizontal plane beds, which dip basinward at about 3 degrees (McKee, 1957). Individual bedsets are generally 1-to-15 centimeters thick (McKee, 1957). The Skolithos ichnofacies is most characteristic of these deposits (Howard, 1972; 1975).

Foreshore deposits are interpreted as intertidal wave swash and backwash deposits. These deposits were produced between mean low water level and mean high water level (Clifton et al., 1971) (see Figure 1). The thickness of foreshore deposits may be directly related to paleo-tide range (Clifton et al., 1971). The angle of dip of each individual bed set is strongly controlled by grain size: the coarser the sediment, the higher the angle of dip of the bed set (Russel and McIntire, 1965).

MODERN CONCEPTUAL MODELS OF NON-BARRED NEARSHORE AREAS

Clifton and others (1971) were the first to document facies relationships within nearshore areas. They systematically observed and described wave generated depositional structures within the non-barred high-energy nearshore area along the southern coast of Oregon. The nearshore area was first defined as "a relatively narrow zone extending seaward of the shoreline and somewhat beyond the breaker zone" (Shepard, 1963). It has since been redefined as the area extending from the shoreline to mean storm-weather wave base (Clifton et al., 1971). The area seaward of mean storm-weather wave base is termed offshore (Clifton et al., 1971). A non-barred nearshore area is a nearshore area that lacks the presence of nearshore bar(s) (Russel, 1958).

Five shore-parallel sedimentary facies were identified within the non-barred high-energy nearshore area along the southern coast of Oregon. From offshore to onshore, they are defined as follows (Figure 4): (1) an asymmetrical ripple facies, consisting of seaward inclined ripple cross laminations; (2) a lunate megaripple facies, consisting of medium scale, shoreward-dipping foresets; (3) an outer planar facies, consisting of horizontal laminations; (4) an inner rough facies, consisting of multi-directional medium scale foresets; and (5) an inner planar facies, consisting of gently seaward-dipping beds (Clifton et al., 1971).

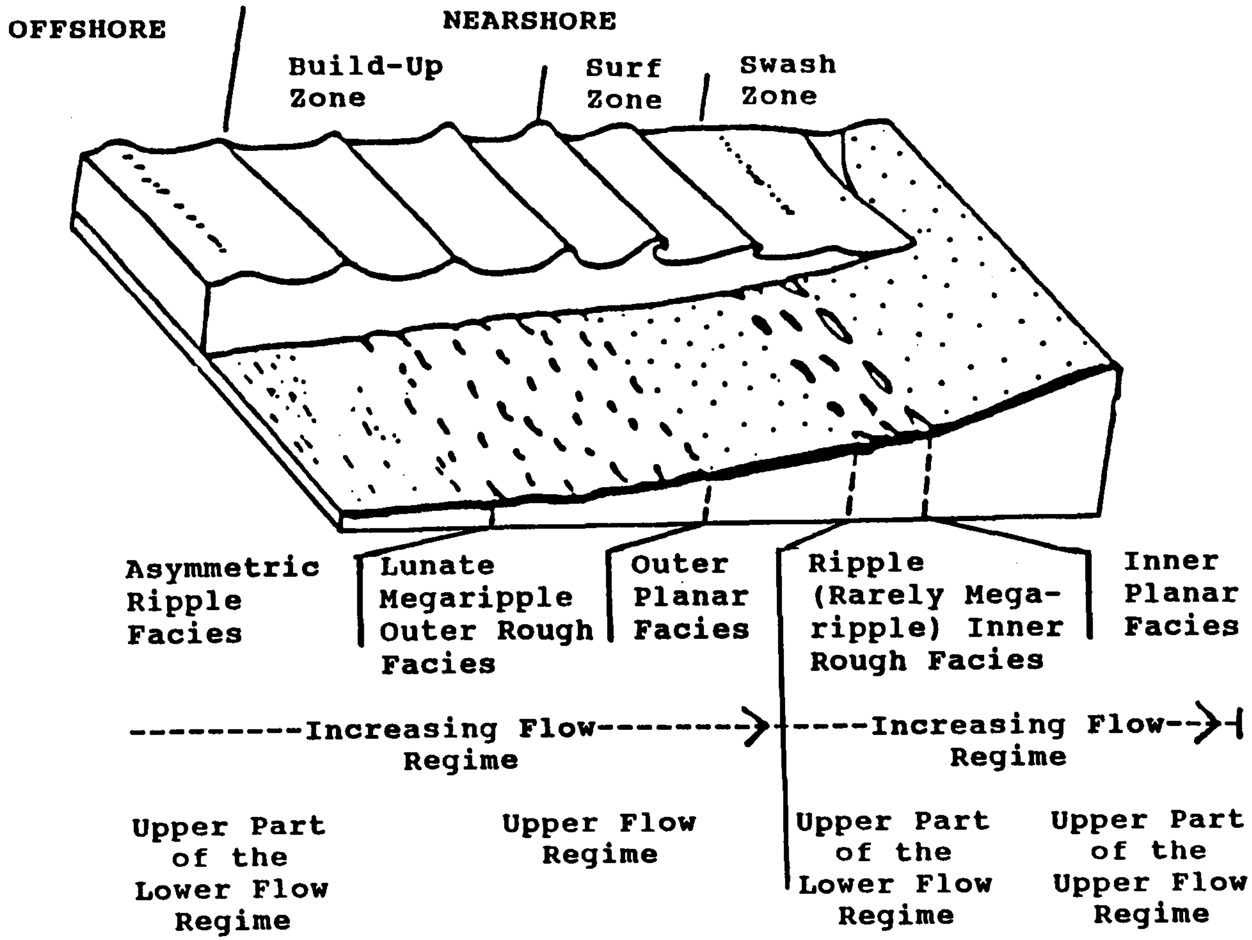


Figure 4. Facies model of a non-barred nearshore area illustrating wave transformation zones, characteristic sedimentary structures, and flow regimes (modified from Clifton et al., 1971).

All five sedimentary facies were interpreted in terms of flow regime (see Figure 4) (Clifton et al., 1971). The outer three facies results from increasing flow regime conditions, from the lower part of the lower flow regime to the upper flow regime, associated with a landward directed wave surge. The inner planar facies results from the upper part of the upper flow regime conditions associated with a seaward directed wave surge. The inner rough facies results from upper, lower flow regime conditions associated with a complex and variable wave surge.

The study by Clifton and others (1971) was based upon observations of bedforms on the depositional surface formed during low-energy wave conditions. Later studies by Hunter and others (1979) and Howard and Reineck (1979) were based on box cores. Box cores revealed that high-energy bedforms could be preserved beneath a veneer of low-energy bedforms on the depositional surface.

Hunter and others (1979) defined the non-barred wave-dominated nearshore area in terms of five environments (Figure 5): offshore, nearshore-offshore transition, surf, swash-trough transition, and swash. However, Howard and Reineck (1979) defined the non-barred wave-dominated nearshore area in terms of four facies associations (see Figure 5): offshore, lower shoreface, upper shoreface and foreshore deposits. It is specifically Howard and Reineck's (1979) four facies associations which would later be recognized as the SVS

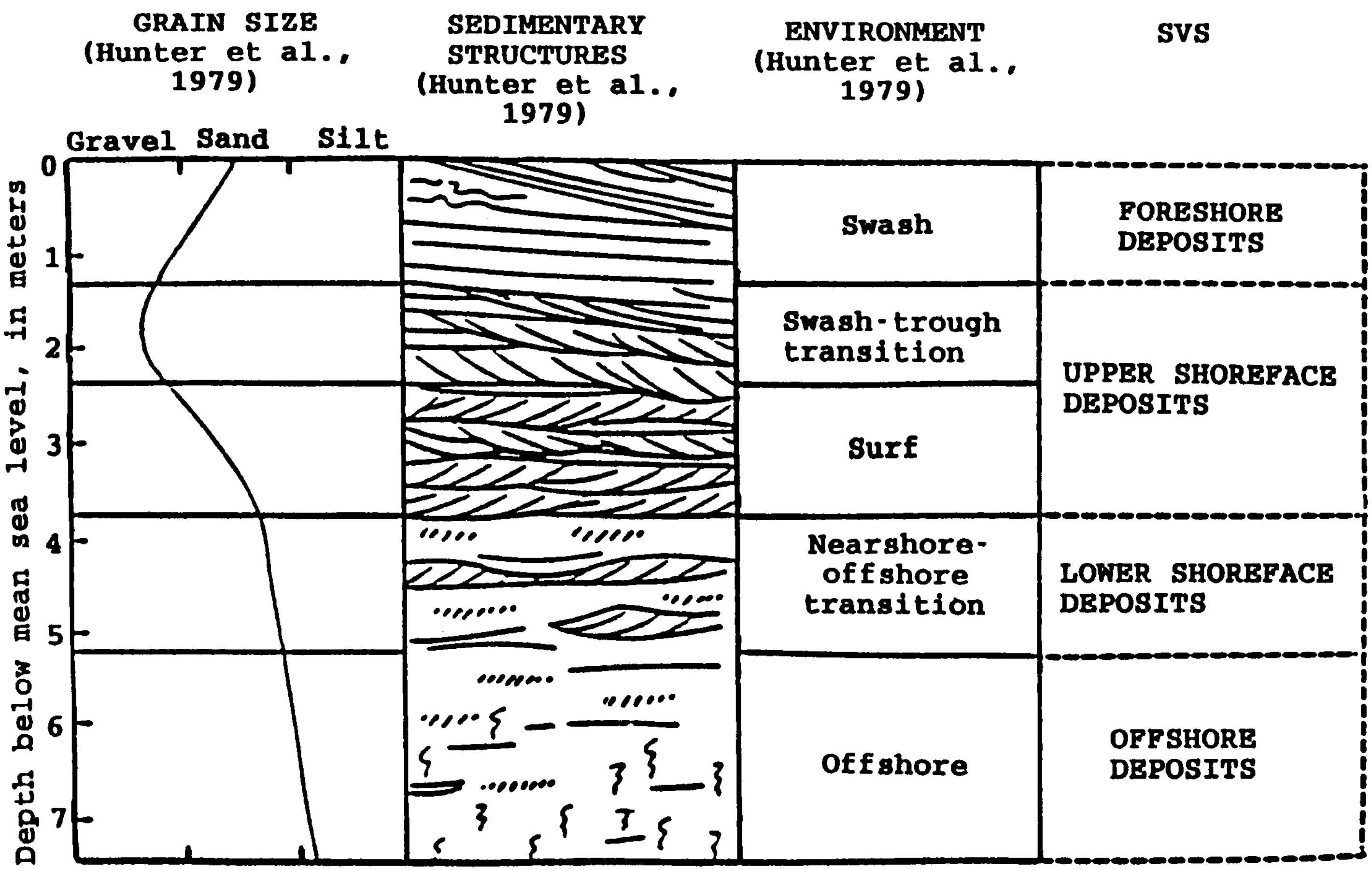


Figure 5. The vertical sequence of grain sizes, sedimentary structures, and environments formed by the progradation of a wave-dominated non-barred nearshore area (Hunter et al., 1979) as it relates to the vertical sequence of offshore, lower shoreface, upper shoreface, and foreshore deposits (Howard and Reineck, 1979) shown as the standard vertical succession (SVS).

(McCubbin, 1981; Taylor and Lovell, 1992; O'Byrne and Flint, 1995; Kamola and Van Wagoner, 1995; Van Wagoner, 1995) (see Figure 1).

MODERN CONCEPTUAL MODELS OF BARRED NEARSHORE AREAS

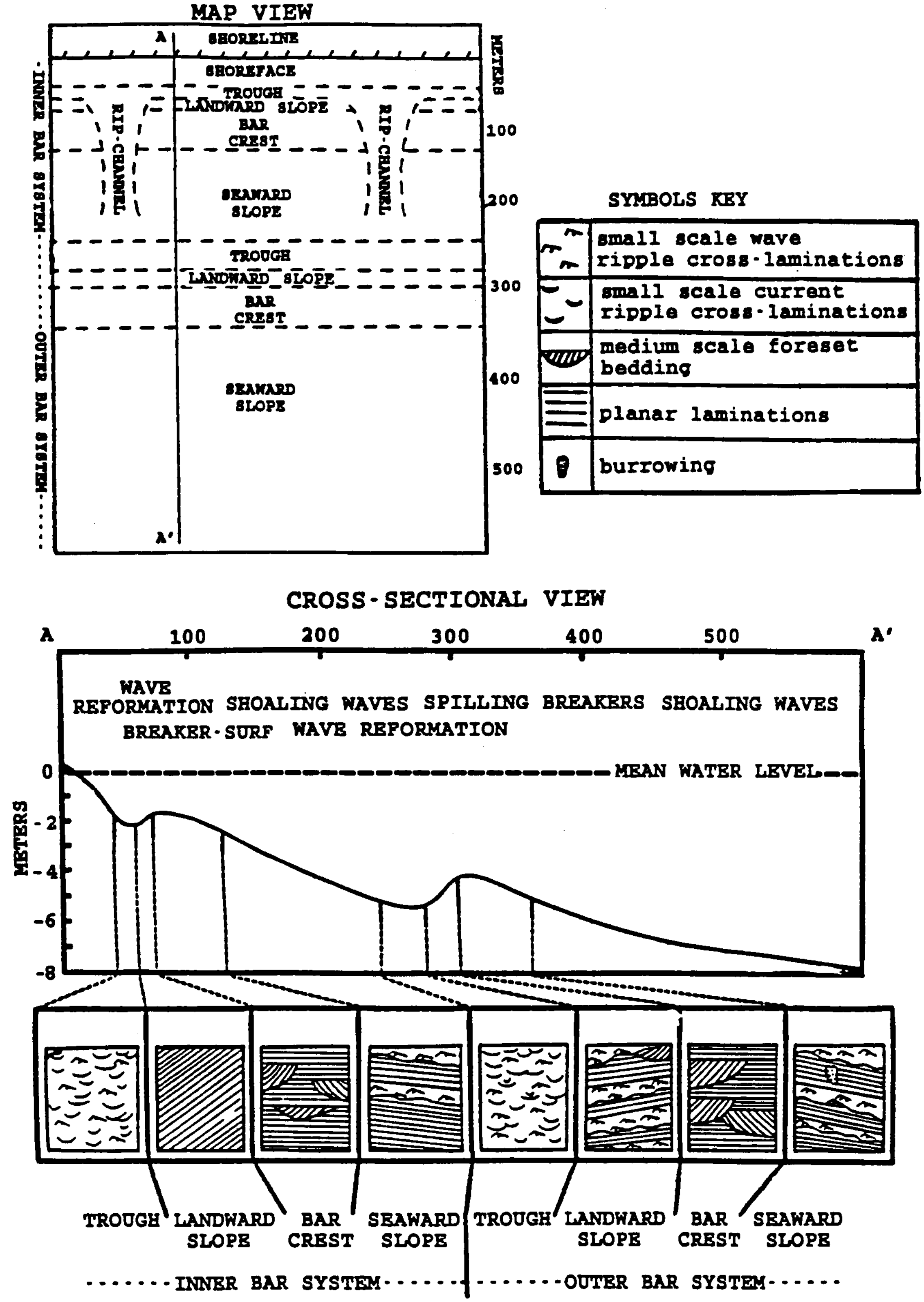
Barred nearshore areas are seldom as straight and uncomplicated as non-barred nearshore areas (Davidson-Arnott and Greenwood, 1976; Howard and Reineck, 1979; Hunter et al., 1979; Ly, 1982; Shipp, 1984; Greenwood and Mittler, 1985). Barred nearshore areas are commonly bulged and curved with spits and bars (Russel, 1958). These areas are also commonly composed of more than one bar system (Bajorunas and Duane, 1967).

Davidson-Arnott and Greenwood (1976) were the first to document facies relationships within barred nearshore areas. They identified five shore-parallel sedimentary facies within two distinct bar systems within the nearshore area of Kouchibouguac Bay, New Brunswick, Canada (Figure 6): an inner bar system and an outer bar system.

The inner bar system was described as being variable, complex, and rapidly changing. It occurred about 100 meters offshore in one to five meters of water. It consisted of one to three discontinuous bars that were frequently crescentric in form, although straight and transverse bars also occur. Each discontinuous bar is approximately 1 meter tall, and is breached at both ends by rip-channels.

The outer bar system was described as being relatively stable. It occurred about 300 meters offshore in four to eight meters of water. It consists of a single continuous

Figure 6. Facies model of a barred nearshore area illustrating characteristic sedimentary structures and wave transformation zones (modified from Davidson-Arnott and Greenwood, 1976).


MAP VIEW
A
SHORELINE
SHOREFACE
TROUGH
LANDWARD SLOPE
BAR
CREST
SEAWARD
SLOPE
TROUGH
LANDWARD SLOPE
BAR
CREST
SEAWARD
SLOPE
A'
RIP-CHANNEL
RIP-CHANNEL
METERS
100
200
300
400
500
INNER BAR SYSTEM
OUTER BAR SYSTEM
SYMBOLS KEY
small scale wave ripple cross-laminations
small scale current ripple cross-laminations
medium scale foreset bedding
planar laminations
burrowing
CROSS-SECTIONAL VIEW
A
100
200
300
400
500
A'
WAVE
REFORMATION
SHOALING WAVES
SPILLING BREAKERS
SHOALING WAVES
BREAKER-SURF
WAVE REFORMATION
MEAN WATER LEVEL
METERS
0
-2
-4
-6
-8
TROUGH
LANDWARD SLOPE
BAR CREST
SEAWARD SLOPE
TROUGH
LANDWARD SLOPE
BAR CREST
SEAWARD SLOPE
INNER BAR SYSTEM
OUTER BAR SYSTEM

bar that runs the length of the barrier island it fronts. This bar stands up to 2.5 meters tall, and is not breached by rip channels (Greenwood and Davidson-Arnott, 1975).

Of the five sedimentary facies, the first four occur in both the inner and outer bar systems, while the last occurs only in the inner bar system (see Figure 6): (1) a seaward slope facies, consisting of small scale oscillation, ripple cross-laminations and seaward dipping plane beds (bioturbation is common in the outer bar system); (2) a bar crest facies, consisting of subhorizontal plane beds and medium scale cross beds resulting from the migration of lunate megaripples; (3) a landward slope facies, consisting of oscillatory ripple cross-laminations, trough cross-laminations, and landward dipping plane beds in the outer bar system, and consisting of high angle, landward dipping medium scale cross-beds in the inner bar system; (4) a trough facies, consisting of poorly preserved oscillatory and current ripple cross-laminations and commonly associated with a distinct organic component; and (5) a rip-channel facies, only found within the inner bar system, consisting of seaward dipping medium scale cross-beds associated with megaripple migration under the influence of rip-currents.

Davidson-Arnott and Greenwood (1976) recognized that only the bedforms on the seaward slope do not fit with Clifton's (1976) hierarchial sequence of bedforms produced under shoaling waves (ripples, megaripples, flat beds; Figure 7).

SEAWARD---------------------------------------> LANDWARD

<---SYMMETRICAL BEDFORMS   ASYMMETRICAL BEDFORMS------------------->

RIPPLES---------------------> MEGARIPPLES---> FLAT BEDS

INCREASING FLOW REGIME----------------------------------->

LOWER FLOW REGIME   UPPER FLOW REGIME

Figure 7. Sequence of bedforms produced by shoaling waves (modified from Clifton, 1976).

Davidson-Arnott and Greenwood (1976) described ripple cross-laminations directly overlaying planar laminations. The lack of medium scale foreset bedding separating these two types of laminations suggested that megaripples were not produced on the seaward slope. Davidson-Arnott and Greenwood (1976) proposed that the lack of megaripples was the result of a symmetric oscillatory flow regime sequence, a sequence slightly different from Clifton's (1976) asymmetric oscillatory flow regime sequence, which occurs on the inner shelf and seaward slope (Figure 8). They suggested that the transition from ripples directly into flat beds is a function of grain size diameters (being less than 0.18 millimeters) and mean orbital velocities.

Howard and Reineck (1979) and Hunter and others (1979), were the first to model the vertical sequence of deposits formed by prograding barred nearshore areas. These models predicted that the vertical sequence of deposits would not approximate the lateral sequence of deposits observed on modern barred profiles from beach to offshore. Both Howard and Reineck (1979) and Hunter and others (1979) proposed that a seaward translating rip-channel system would destroy seaward slope, bar crest, and landward slope deposits, resulting in a vertical sequence of deposits nearly identical to the SVS (Figure 9). Therefore, not only are prograding non-barred nearshore areas proposed to produce the SVS, but prograding barred nearshore areas were predicted to produce the SVS as

ASYMMETRIC OSCILLATORY FLOW REGIME SEQUENCE

SEAWARD------------------------------------>			LANDWARD
NO MOVEMENT-->	RIPPLES-->	MEGARIPPLES-->	FLAT BEDS
INCREASING FLOW REGIME--------------------------->			
	LOWER FLOW REGIME		UPPER FLOW REGIME

SYMMETRIC OSCILLATORY FLOW REGIME SEQUENCE

SEAWARD------------------------------------>		LANDWARD
NO MOVEMENT---------->	RIPPLES---------->	FLAT BEDS
INCREASING FLOW REGIME--------------------------->		
	LOWER FLOW REGIME	UPPER FLOW REGIME

Figure 8. Suggested flow regime sequences for barred nearshore systems. An asymmetric oscillatory flow sequence is proposed to occur everywhere within barred nearshore areas except along the seaward slope, where a symmetric oscillatory flow sequence is proposed to occur (modified from Davidson-Arnott and Greenwood, 1976).

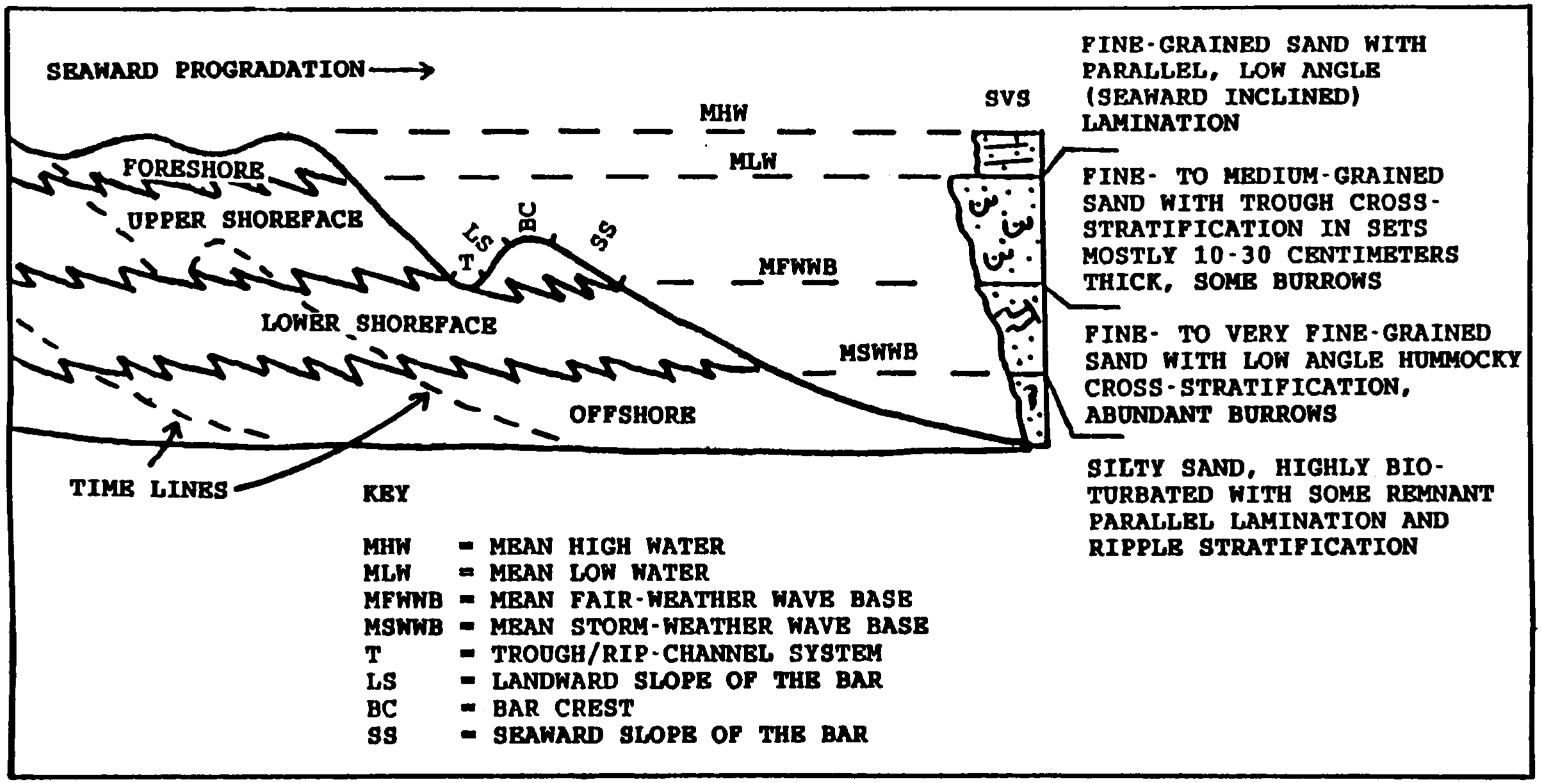


Figure 9. During shoreface progradation of a barred wave-dominated nearshore area, the seaward translating rip-channel system rips away all evidence of landward slope, bar crest, and seaward slope deposits (Howard and Reineck, 1979) resulting in the standard vertical succession (SVS) (modified from McCubbin, 1981).

well.

The vertical sequence model for barred nearshore areas proposed by Howard and Reineck (1979) is almost identical to the vertical sequence model for barred nearshore areas proposed by Hunter and others (1979). The Hunter and others (1979) model differed by suggesting that a coarse lag associated with the rip-channel facies would be preserved (Figure 10), and would be the only sedimentary record of a bar in the stratigraphic record. This coarse lag would occur between the upper and lower shoreface deposits. Howard and Reineck (1979), however, suggested it would be very difficult to distinguish between rip-channel facies deposits and upper shoreface deposits, especially if the rip-channel facies system lacked coarse material. Howard and Reineck (1979) believed there would be no evidence for recognizing barred nearshore deposits in the stratigraphic record.

Unlike the Howard and Reineck (1979) and the Hunter and others (1979) barred sequence models, a barred shoreface model that predicts partial preservation of the seaward slope facies was proposed by Shipp (1984) (Figure 11). Shipp's (1984) model suggests that any part of the seaward slope located below the deepest reaches of the seaward translating rip-channel system could be preserved. With the exception of the possible preservation of a coarse lag associated with the rip-channel system as evidence of barred nearshore deposits in the stratigraphic record (Hunter et al., 1979), this is the first

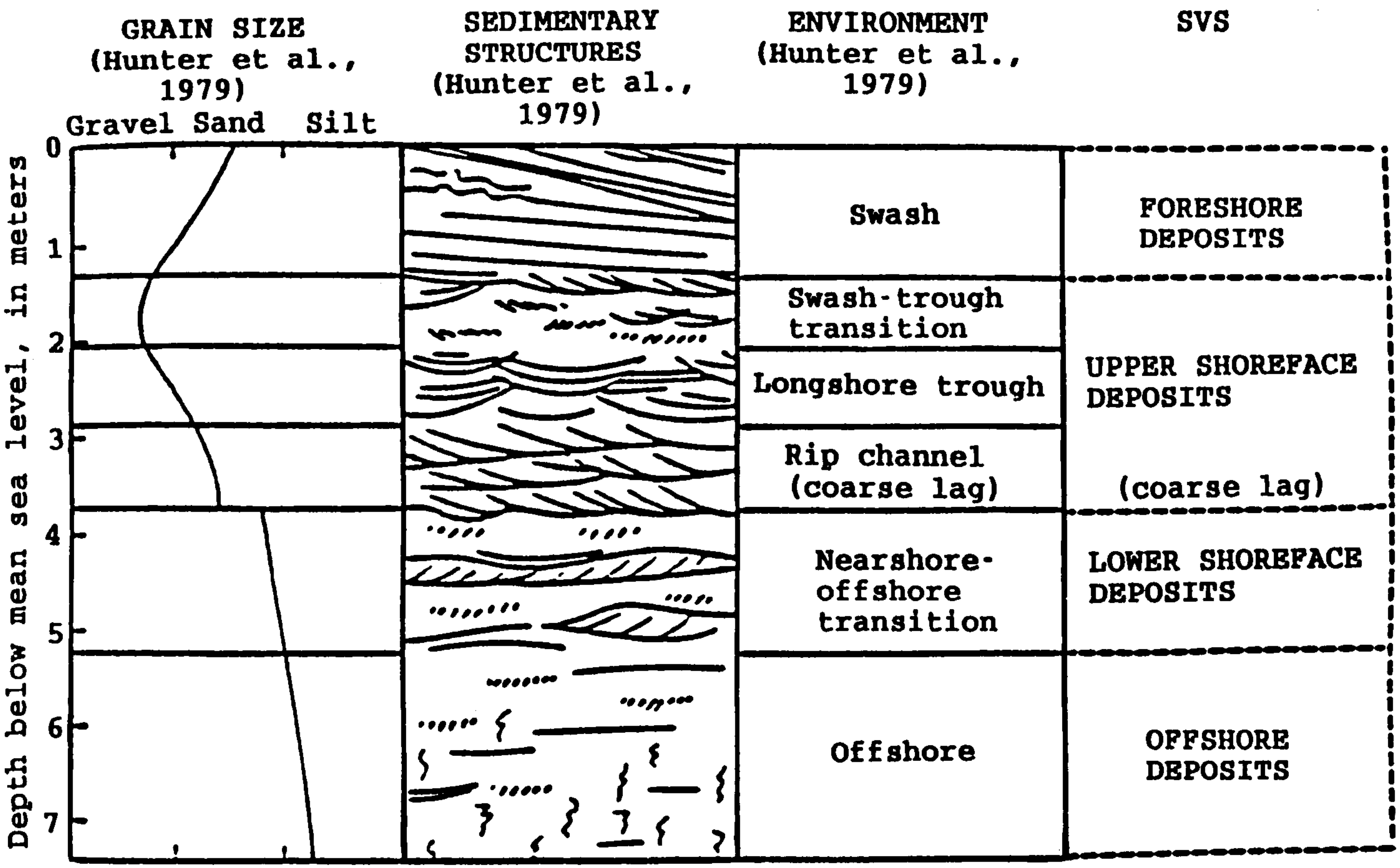


Figure 10. The vertical sequence of grain sizes, sedimentary structures, and environments formed by the progradation of a wave-dominated barred nearshore area (Hunter et al., 1979) as it relates to the vertical sequence of offshore, lower shoreface, upper shoreface, and foreshore deposits (Howard and Reineck, 1979) shown a the standard vertical succession (SVS).

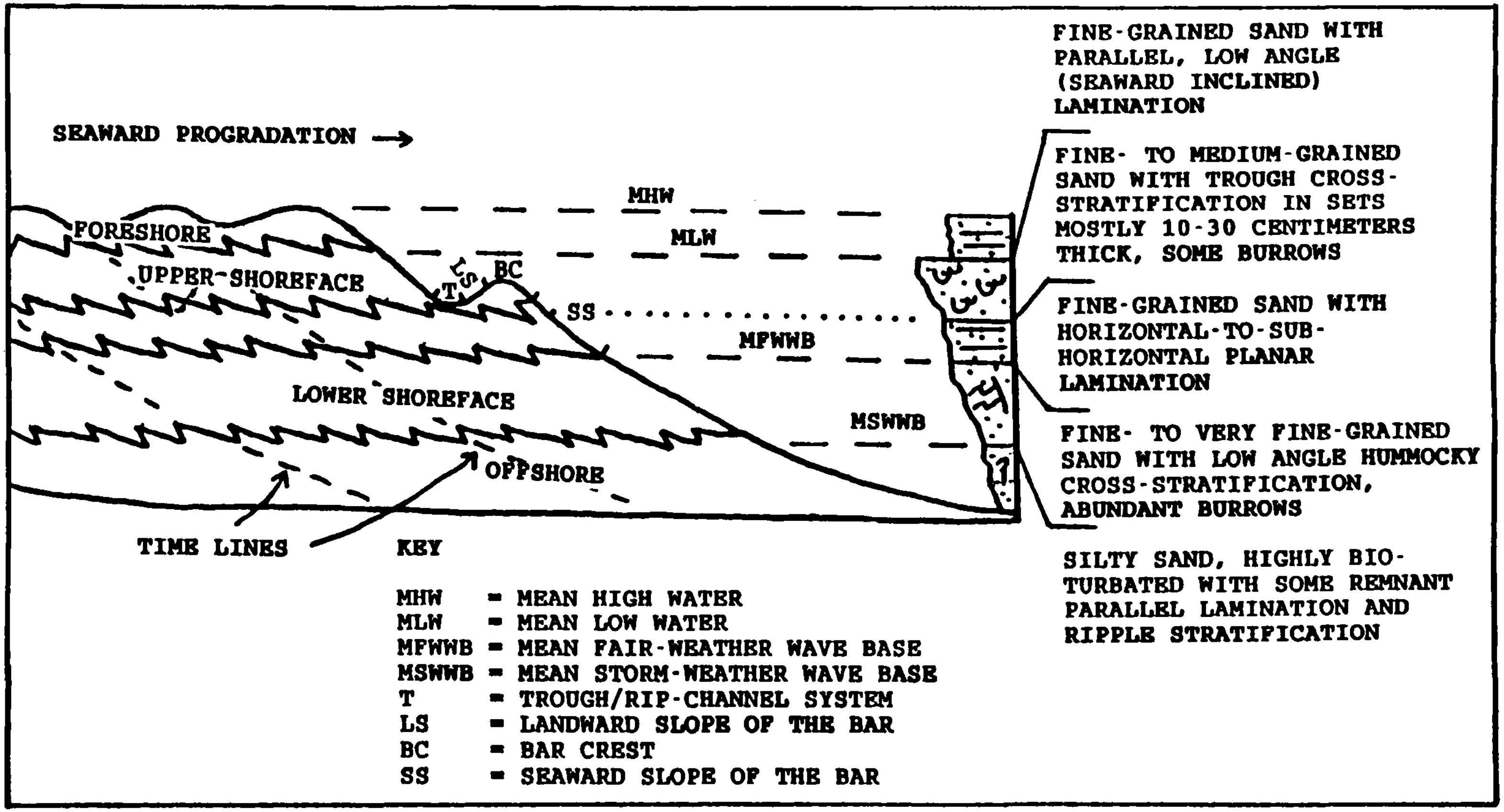


Figure 11. During shoreface progradation of a barred wave-dominated nearshore area, seaward slope deposits may be preserved if they are located deeper than the deepest reaches of the seaward translating rip-channel system (Shipp, 1984). Under these circumstances, the resulting vertical succession of deposits will consist of offshore, lower shoreface, seaward slope, upper shoreface, and foreshore deposits (Shipp, 1984) (modified from McCubbin, 1981).

model to predict partial preservation of the bar form during shoreface progradation.

Greenwood and Mittler (1985) suggested that even though evidence of barred nearshore systems could have survived the seaward translating rip-channel system (Hunter et al., 1979; Shipp, 1984), the bar would have been destroyed during profile adjustments due to storms and/or longshore sediment transport. Greenwood and Mittler (1985) predicted that any nearshore bar deposits that survived the seaward translating rip-channel system would have been totally reworked as the bar form shifted landward or basinward as a result of changing wave climates, and as the bar form moved shore-parallel as a result of the longshore current. Once again it is suggested that the recognition of barred nearshore systems in the stratigraphic record would be difficult and, indeed, only possible under the unusual conditions that an entire subaqueous, wave-formed bar is preserved (see Ly, 1982).

MIDDLE SHOREFACE (MSF) INTERVALS WITHIN THE BLACKHAWK FORMATION

Modern conceptual models of nearshore areas adequately explain the SVS, but they do not explain similar successions containing an additional MSF interval. However, MSF intervals have been identified within the Upper Cretaceous (Campanian) Blackhawk Formation, east-central Utah. Specifically, MSF intervals have been identified within the Sunnyside Member (as a part of this study), the Aberdeen Member (Kamola, unpublished work), and the Spring Canyon Member (Kamola and Van Wagoner, 1995).

GEOLOGIC SETTING OF THE BLACKHAWK FORMATION

The Blackhawk Formation is exposed within the Book Cliffs of east-central Utah (Figure 12). The Book Cliffs extend for approximately two hundred and fifteen miles of exposure from the Wasatch Plateau in central Utah eastward to the Grand Mesa in western Colorado. These cliffs are part of the Colorado Plateau Province which is located between the Southern Rocky Mountain and Basin and Range provinces. Strata within the Book Cliffs is relatively flat-lying (dipping only a few degrees northeastward) with minor faults and folds (Fisher et al., 1960). Cliff exposure is associated with structural uplift to the south associated with the San Rafael Swell, a

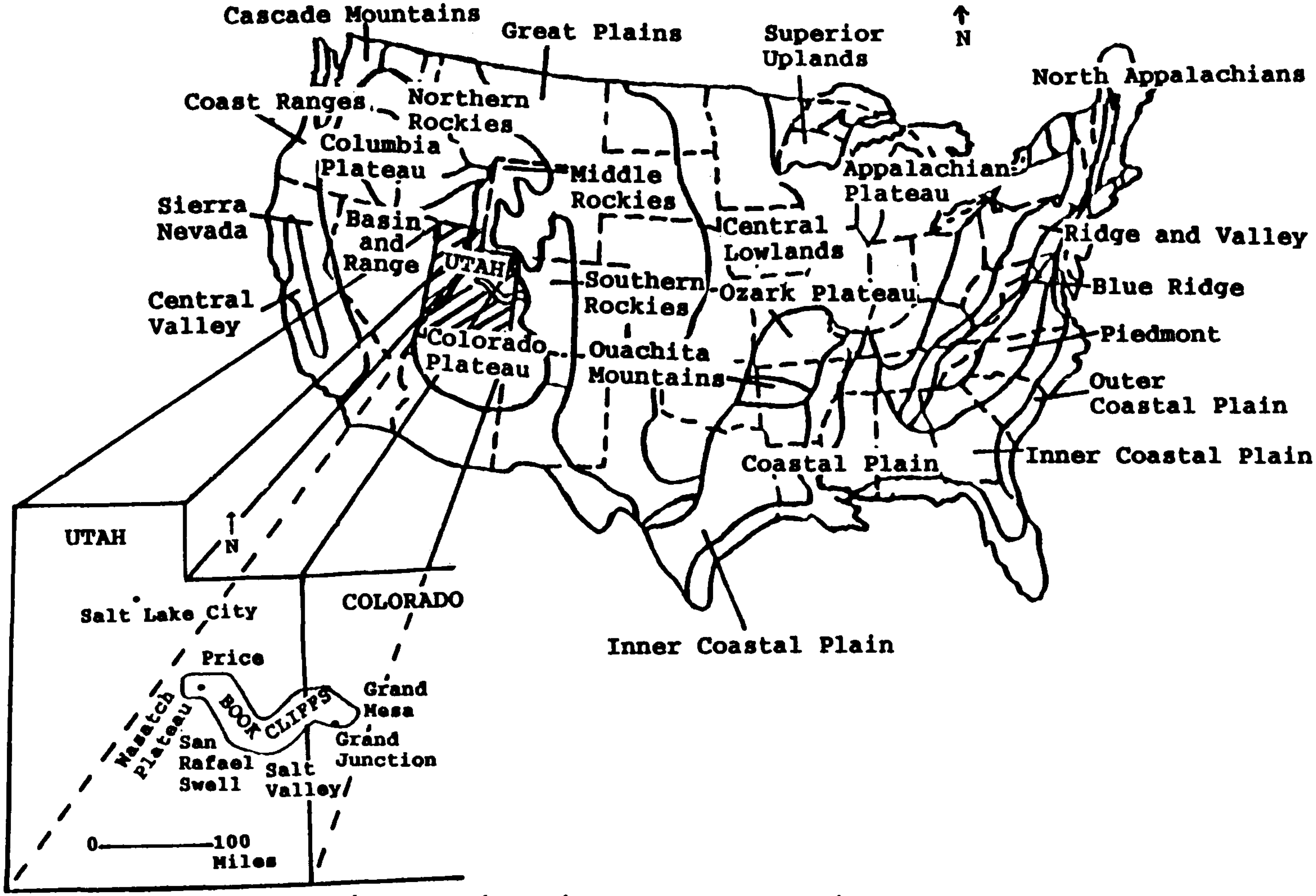


Figure 12. The geographic relationship of the Book Cliffs of Utah and Colorado to the physiographic regions of the United States (modified from Atwood, 1964).

domal structure, and to a lesser extent the Salt Valley, a faulted anticline.

GEOLOGIC HISTORY OF THE BLACKHAWK FORMATION

During the Cretaceous, central and eastern Utah were part of a large asymmetrical foreland basin (Armstrong, 1968; Jordan, 1981). The foreland basin formed as a result of thrust sheet stacking associated with the north-south trending Sevier orogenic fold-and-thrust belt to its west (Lawton, 1983). A vast continental sea, the Cretaceous Western Interior Seaway, inundated the foreland basin from Albian to Maestrichtian times (Williams and Stelck, 1975) (Figure 13). Sediments of the Blackhawk Formation were derived from the Sevier orogenic belt and deposited along the western margins of the Cretaceous western Interior Seaway during the Campanian (Armstrong, 1968; Jordan, 1981)(Figure 14).

STRATIGRAPHY OF THE BLACKHAWK FORMATION

Spieker and Reeside (1925) defined the Blackhawk Formation as the middle coal-bearing formation within the Mesaverde Group. They designated the type section located at the Blackhawk mine (later called the King no.1 mine) near Hiawatha, Utah. Clark (1928) defined the top of the Blackhawk Formation at the base of the Castlegate Sandstone and the base

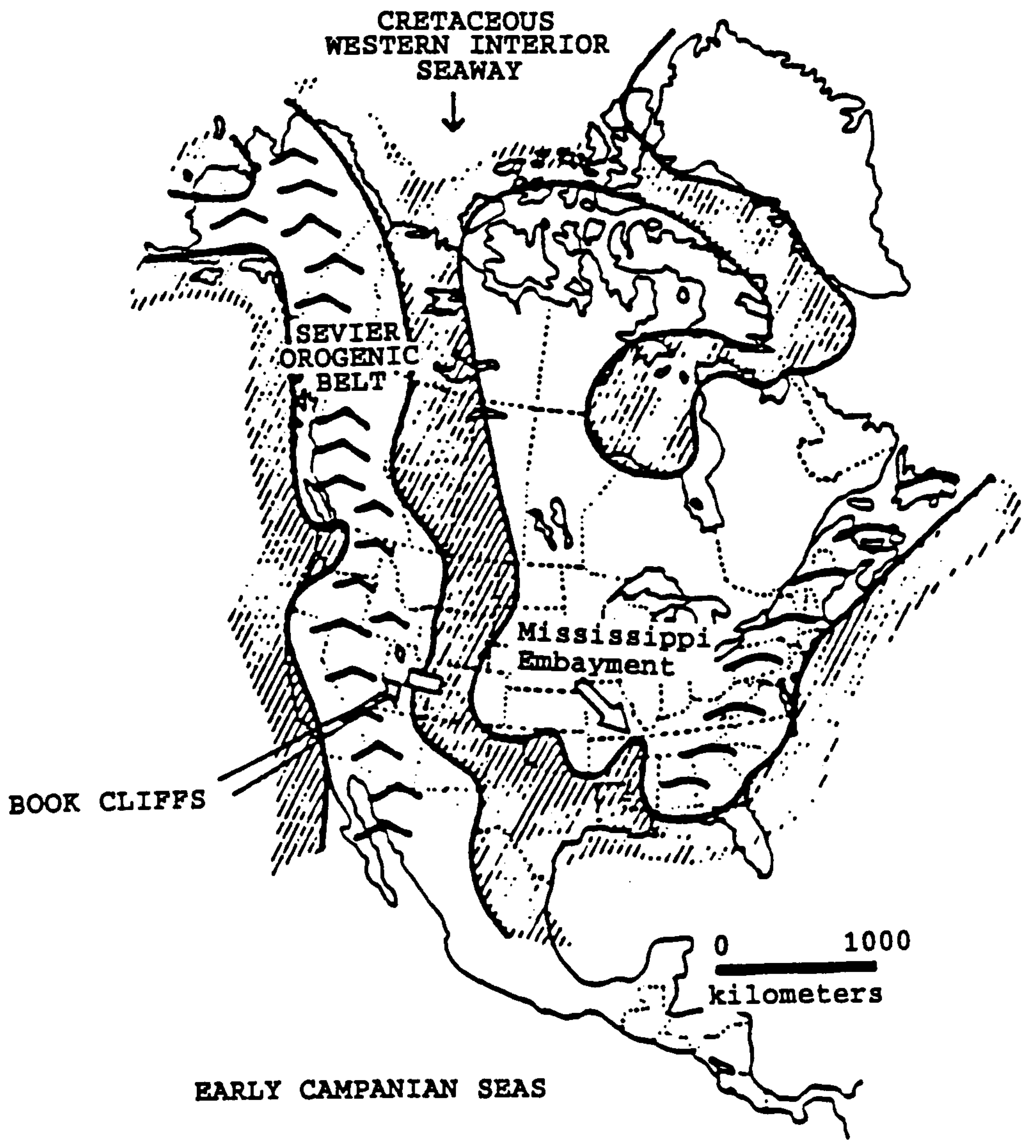


Figure 13. Paleogeography of North America during the early Campanian (taken from Williams and Stelck, 1975).

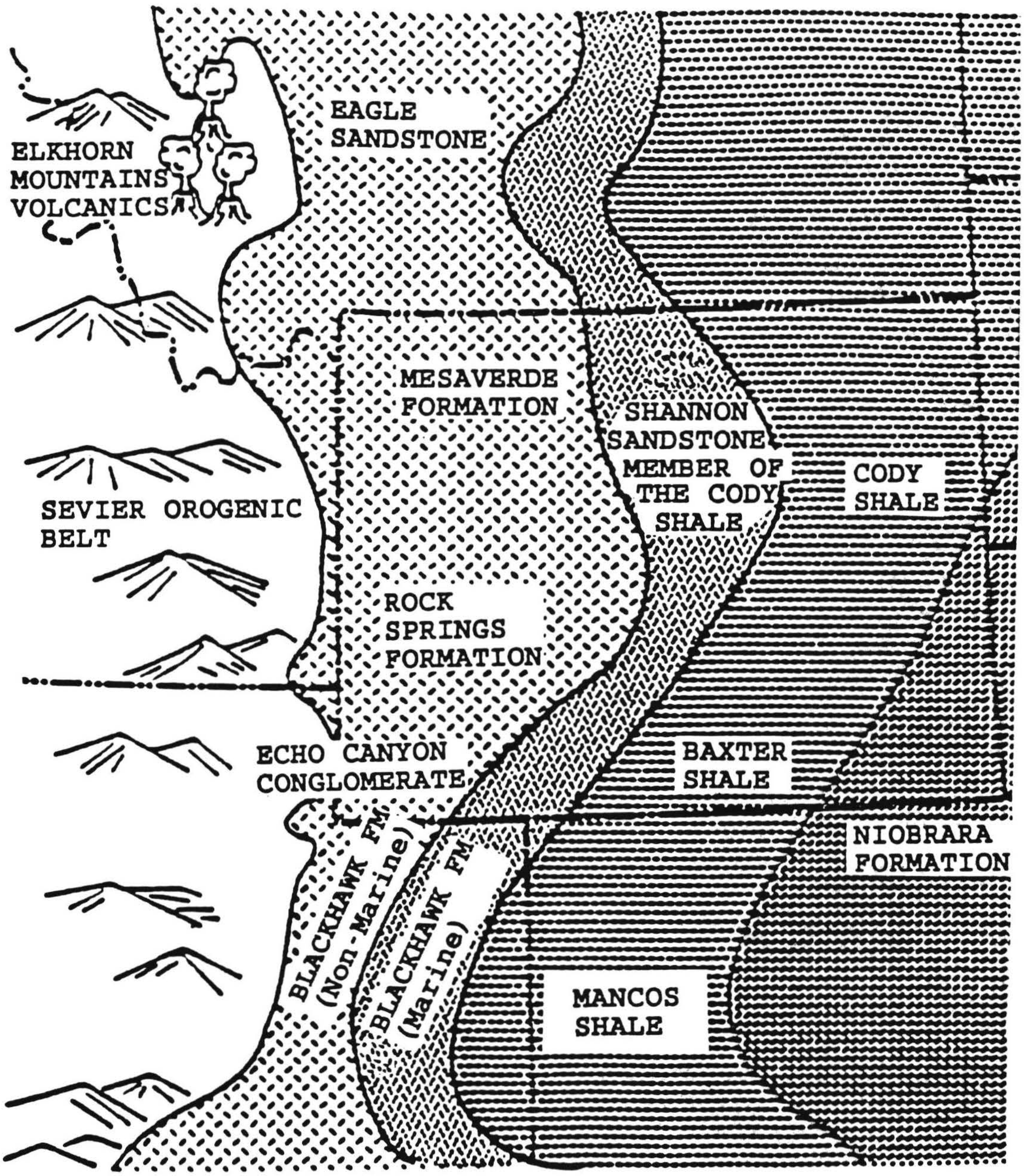


Figure 14. Generalized paleogeographic map showing Blackhawk deposition (modified from McGookey et al., 1972).

of the Blackhawk Formation at the bottom of the lowest coal bed. Clark (1928) was the first to describe the intertonguing relationship between the Mesaverde Group and the Mancos Shale. Speiker (1931) listed plant fossils to indicate the Blackhawk Formation to be medial Montana (Campanian) in age.

Young (1955) was the first to concentrate upon stratigraphic relationships. He began by redefining the lower boundary of the Blackhawk Formation to include the upper sandstone unit of the Star Point Formation. He divided the Blackhawk Formation into six lithostratigraphic members, all of which contain continuous non-marine through marine facies (Figure 15). These members are (from oldest to youngest) the Spring Canyon Member, the Aberdeen Member, the Kenilworth Member, the Sunnyside Member, the Grassy Member, and the Desert Member. Young noticed all six of these littoral marine sandstone members to project eastward and eventually lose their identity by grading into Mancos Shale (Spieker and Reeside, 1925; Clark, 1928; Erdmann, 1934; Fisher, 1936).

Both Young (1955) and Balsley (1980) have done regional studies on Campanian sections within the Book Cliffs. Young (1955) defined general stratigraphic relationships which provided the framework for detailed facies studies (ie., Balsley, 1980) within the Blackhawk Formation. Sequence stratigraphic and additional facies studies have been proposed for the Spring Canyon Member (Kamola and Van Wagoner, 1995); the Aberdeen Member (Kamola, unpublished data); the Kenilworth

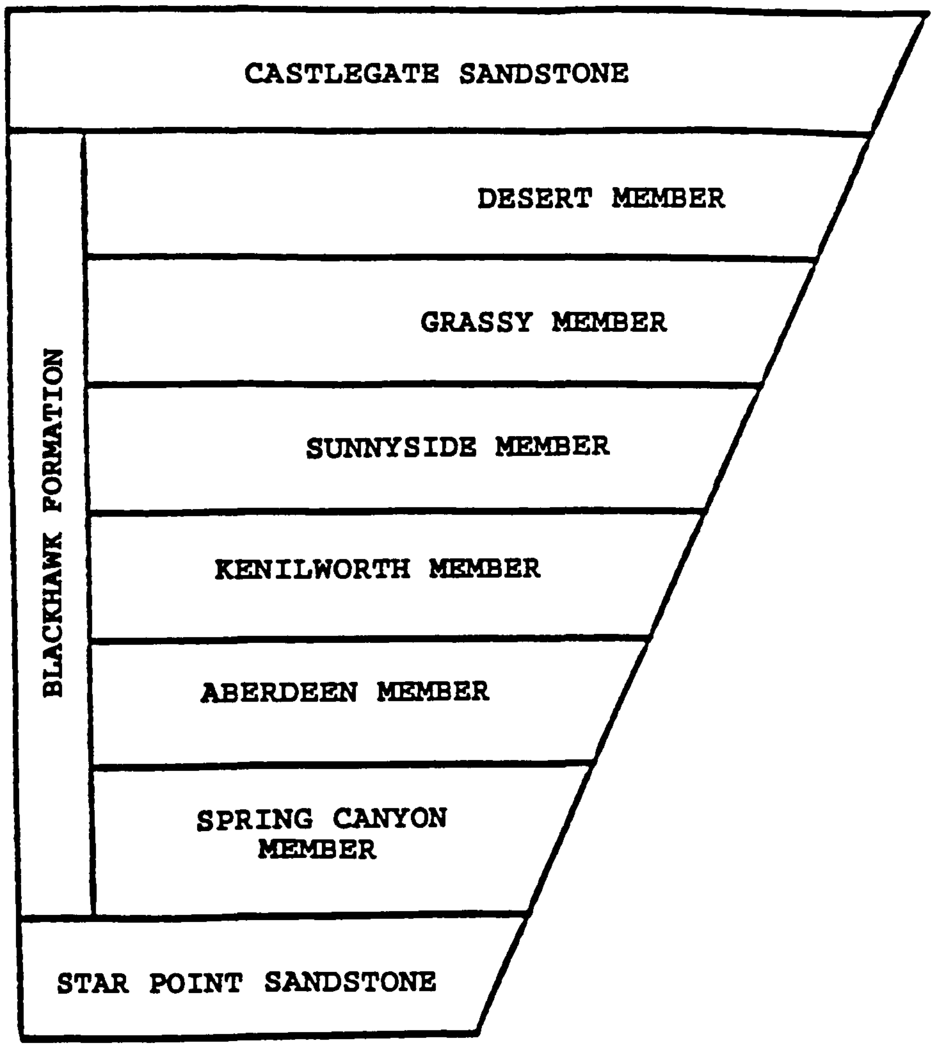


Figure 15. Stratigraphic column of the Blackhawk Formation showing its six members (modified from Young, 1955).

Member (Taylor and Lovell, 1992); the Grassy Member (O'Byrne and Flint, 1995); and the Desert Member (Van Wagoner, 1995).

SUNNYSIDE MEMBER MSF INTERVALS

Thirteen stratigraphic sections were measured within the marine portions of the Sunnyside Member for the purpose of documenting MSF intervals. These sections are located within the western section of the Book Cliffs from Soldier Creek Canyon to Price River Canyon, an area that covers approximately twenty-five kilometers of dip section and thirty-five kilometers of strike section (Figure 16). All sections are readily accessible with four-wheel drive vehicles and most are located on public lands. Sections were located using quadrangle maps published and distributed by the United States Geological Survey, National Mapping Program (Appendix A).

Eleven out of the thirteen stratigraphic sections measured within the marine portions of the Sunnyside Member displayed the SVS (Appendix B). Some of these measured sections show incomplete development of the shoreface due to limitations of shoreface progradation (e.g., Appendix B-9) or due to erosion associated with a sea level fall as indicated by a sequence boundary (e.g., Appendix B-8).

Only two of the thirteen stratigraphic sections measured within the marine portions of the Sunnyside Member displayed

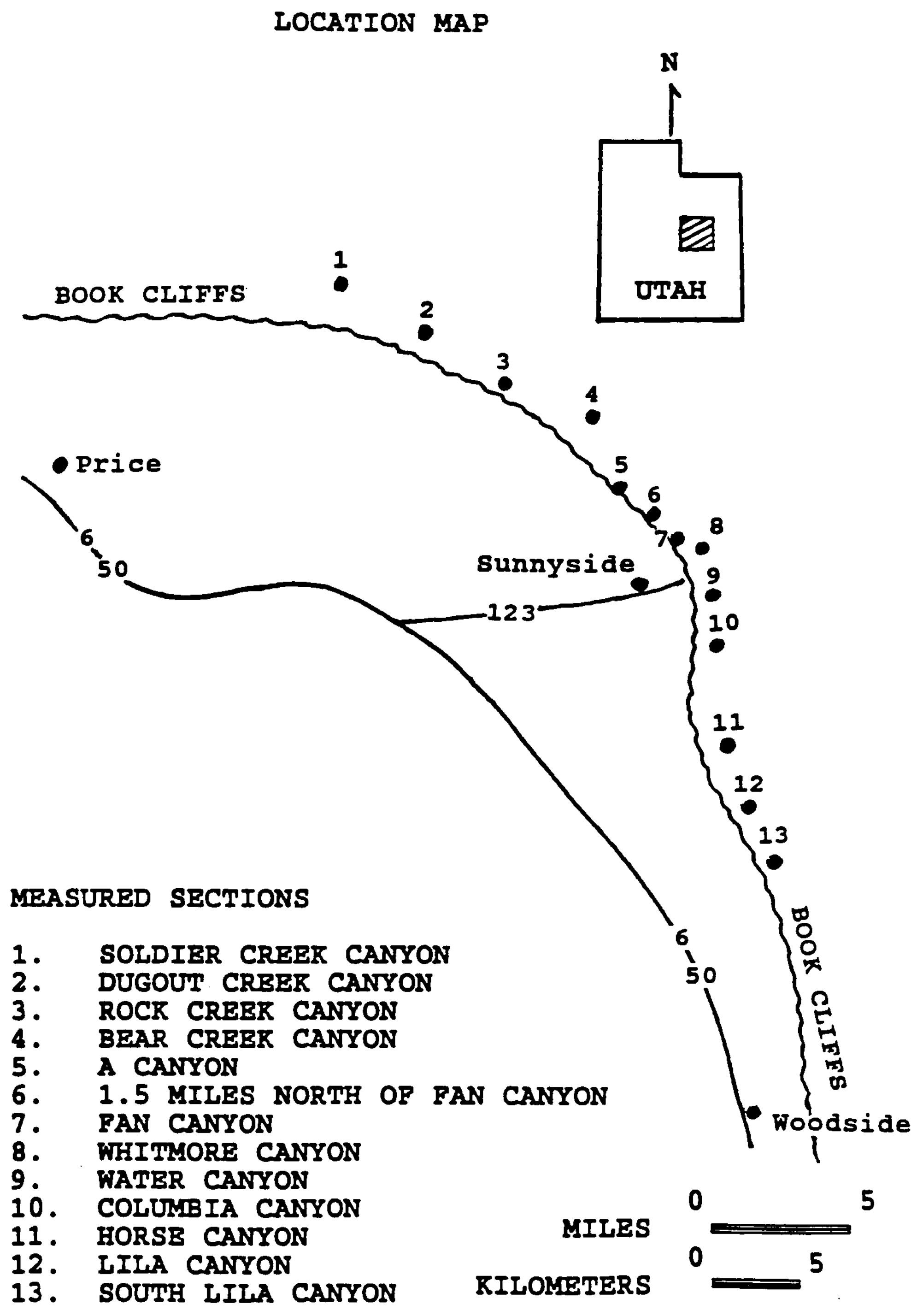


Figure 16. Location map showing Sunnyside Member measured sections within the Book Cliffs of east-central Utah.

marine deposits that were not associated with the SVS (Appendix C). Both of these sections, one measured at Bear Creek Canyon (Appendix C-2) and the other measured at Lila Canyon (Appendix C-3), display a MSF interval that occurs as an added interval within the SVS.

SPRING CANYON AND ABERDEEN MSF INTERVALS

MSF intervals are identified within the Spring Canyon (Kamola and Van Wagoner, 1995) and Aberdeen (Kamola, unpublished data) members. Of the ten stratigraphic sections within a published cross-section of the Spring Canyon Member (Kamola and Van Wagoner, 1995), five sections display six MSF intervals (Plate 1). Four Spring Canyon Member MSF intervals (one identified within the Spring Canyon #2 section, two identified within the Panther Canyon #2 section, and one identified within the Kenilworth Face section; Appendix D) are emphasized here to show detail. Of the thirteen stratigraphic sections within an unpublished cross-section of the Aberdeen Member (Kamola, unpublished data), six sections displayed eight MSF intervals (Plate 2). Three Aberdeen Member MSF intervals (one identified within the Kenilworth section, one identified within the Alrad section, and one identified within the CC1 section; Appendix E) are emphasized here to show detail.

COMPARISON OF MSF INTERVALS

Sixteen MSF intervals have been identified within the Spring Canyon, Aberdeen, and Sunnyside members of the Blackhawk Formation. While all sections are different, a number of similarities exist when all sixteen MSF intervals are compared. Each MSF interval occurs stratigraphically between upper and lower shoreface deposits, disrupting the SVS in no way other than adding to it. All but one MSF interval consists internally of fine grained (VFU-FU sands) amalgamated parallel to sub-parallel planar beds interbedded with fine grained (VFU-FU sands) burrowed, or bioturbated, beds. Only the MSF interval from the Alrad section of the Aberdeen Member consists entirely of planar beds (see Appendix E-3).

Of the MSF intervals which consist of planar-to-burrowed beds, the lower contact of the planar beds is sharp, while the upper contact is burrowed, suggesting that each planar-to-burrowed bed represents one event. Ophiomorpha is the only identifiable biogenic sedimentary structure. A close examination of many of the burrowed beds shows remnants of planar bedding. Figures 17 and 18 are photographs of MSF intervals.

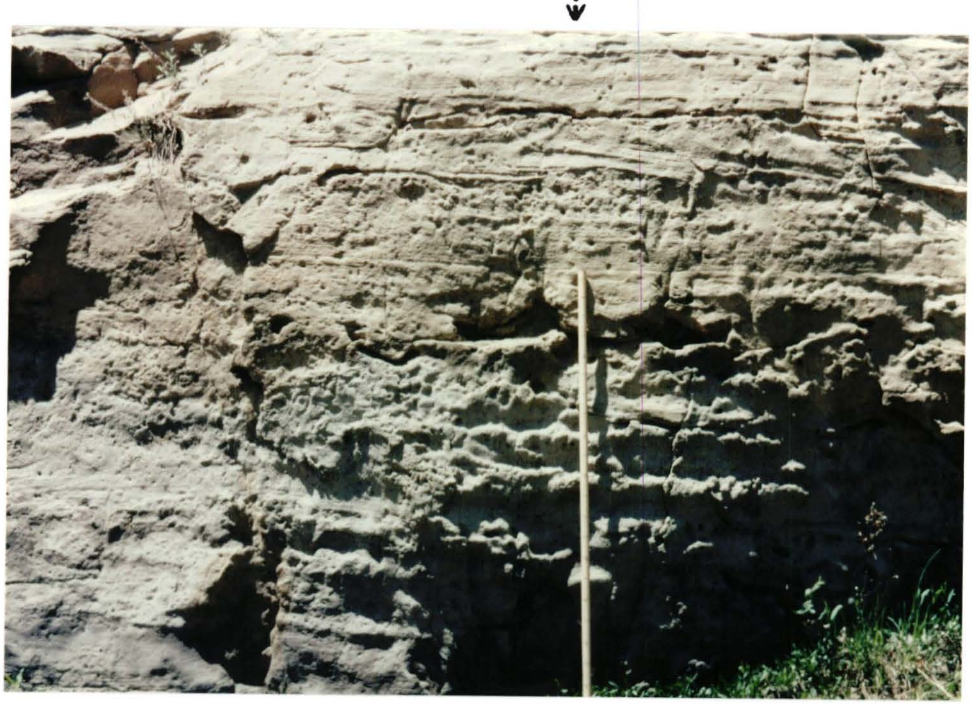
While internal similarities suggest that these intervals are related in the way they were formed, differences in thickness suggest these intervals were susceptible to subtle variations in the way they were preserved. The major

LENS CAP

SCALE

0 — 1 METER

Figure 17. Photograph of a planar-to-burrowed MSF interval, lens cap for scale.



SCALE

0 1 METER

Figure 18. Photograph of a planar-to-burrowed MSF interval, jacob staff for scale.

differences between the sixteen MSF intervals are in terms of total interval thickness and the thicknesses of the planar bedded and burrowed beds that comprise them. These intervals vary widely differ and the thicknesses of the planar bedded and burrowed beds that comprise them. The total thickness of MSF intervals ranges from 1.5 meters in the Lila Canyon section of the Sunnyside Member (see Appendix C-3) to 9.5 meters in the Kenilworth Face section of the Spring Canyon Member (see Appendix D-4). Similarly, the thicknesses of planar bedded and burrowed beds varies. Planar bedded beds range in thickness from ten centimeters to over four meters, while burrowed beds range in thickness from ten centimeters to nearly one meter.

INTERPRETATION OF MSF INTERVALS

The fact that ancient MSF intervals are internally different from all other deposits associated with the SVS and occur between upper and lower shoreface deposits suggests that they represent the preservation of a distinctly unique nearshore depositional environment. Furthermore, the fact that these intervals occur in association with HCS lower shoreface deposits, deposits many workers (Harms et al., 1982; Walker et al., 1983; Duke, 1985, 1987) have suggested formed beneath flows dominated by powerful wave-orbital motions, suggests that they were produced within wave-dominated nearshore areas.

While non-barred wave-dominated nearshore areas, consisting of offshore, lower shoreface, upper shoreface, and foreshore deposits (Howard and Reineck, 1979) (see Figure 1), produce a relatively straightforward progression of facies in the stratigraphic record, barred wave-dominated nearshore areas are interpreted to be associated with a distinctly unique depositional sub-environment that occurs between upper and lower shoreface deposits. Based on a comparison of modern studies (Greenwood and Davidson-Arnott, 1975; Davidson-Arnott and Greenwood, 1976; Howard and Reineck, 1979; Hunter et al., 1979; Shipp, 1984) with stratigraphic data collected from the Blackhawk Formation, MSF intervals within the Blackhawk Formation might well represent evidence of barred nearshore systems in the stratigraphic record.

The fact that planar beds have been identified within all three facies of a nearshore bar (i.e., see Figure 6; the landward slope facies, the bar crest facies, and the seaward slope facies) suggests that all three facies could have produced the planar beds described within MSF intervals. The problem with associating any of these facies with the MSF interval is that most studies predict that during shoreface progradation a seaward translating rip-channel system will destroy all evidence of a nearshore bar (Hunter et al., 1979; Howard and Reineck, 1979) (see Figure 9). However, Shipp (1984) did predict that the partial preservation of the seaward slope facies is possible if any part of the seaward slope occurred deeper than the deepest portions of the seaward translating rip-channel system (see Figure 11). Based on Shipps' (1984) model, MSF intervals may well represent ancient seaward slope deposits preserved in the stratigraphic record.

MSF INTERVALS: ANCIENT SEAWARD SLOPE DEPOSITS

Shipp (1984) and Davidson-Arnott and Greenwood (1976) indicated that a typical box core taken through the seaward slope of a bar consisted only of planar beds. However, Shipp (1984) discovered that while only one type of bedform was identified within these cores, there were a variety of bedforms that blanket this slope all year long during both high- and low-wave energy conditions. During high-wave energy conditions bedforms ranged from asymmetric ripples at the basinward toe of this slope up into megaripples, while during low-wave energy conditions bedforms ranged from symmetric ripples at the basinward toe of this slope up into asymmetric ripples.

The type and order of bedforms Shipp (1984) identified along the seaward slope compare to the hierarchial sequence of bedforms produced by shoaling waves (see Figure 7), as defined by Clifton (1976). The presence of megaripples during high-wave energy conditions indicates that these bedforms were produced within an asymmetric oscillatory flow regime sequence, and not a symmetric oscillatory flow regime sequence as initially thought by Davidson-Arnott and Greenwood (1976) (see Figure 8).

Shipp (1984) recognized that in response to the changing wave energy, bedforms on the seaward slope shifted up slope or down slope, accordingly. For example, he noticed that during low-wave energy conditions, the boundary between symmetric and asymmetric bedforms was as far as half way up the seaward slope, and as wave energy increased, that boundary shifted down slope. It is likely that only under extremely high-wave energy conditions, like those associated with large storm events such as hurricanes or tropical storms, could the asymmetric oscillatory flow sequence been shifted far enough basinward to have allowed planar beds to have been formed on the seaward slope (Figure 19).

However, it is unlikely that a bar form would have survived very long under such extremely high energy conditions. More likely, the bar form would have been washed out and its sediment reworked into planar bedded deposits. Therefore, it is possible that planar bedded seaward slope deposits (Davidson-Arnott and Greenwood, 1976; Shipp, 1984) are actually the reworked remnants of nearshore bars stacked one on top of the other through time.

Assuming that the planar bedded beds within MSF intervals were produced during extremely high energy storm events, the majority of the burrows necessary to produce the burrowed beds within these intervals were probably produced during much lower energy conditions between those storm events. However, it is unknown just how long after an extremely high energy storm event (days, months, years) that the majority of burrowing probably occurred. A recent study by Morton (1988) suggests that hurricane deposits can be totally reworked by burrowing organisms in as little as three months.

The only physical sedimentary structures observed within burrowed beds are remnant planar beds (e.g., the Kenilworth Face MSF interval (see Appendix D-4) and the Kenilworth MSF interval (see Appendix E-2)). This suggests that the physical sedimentary structures produced during normal high- and low-wave energy conditions on the seaward slope (i.e., ripples, megaripples (see Figure 19)) were either completely reworked

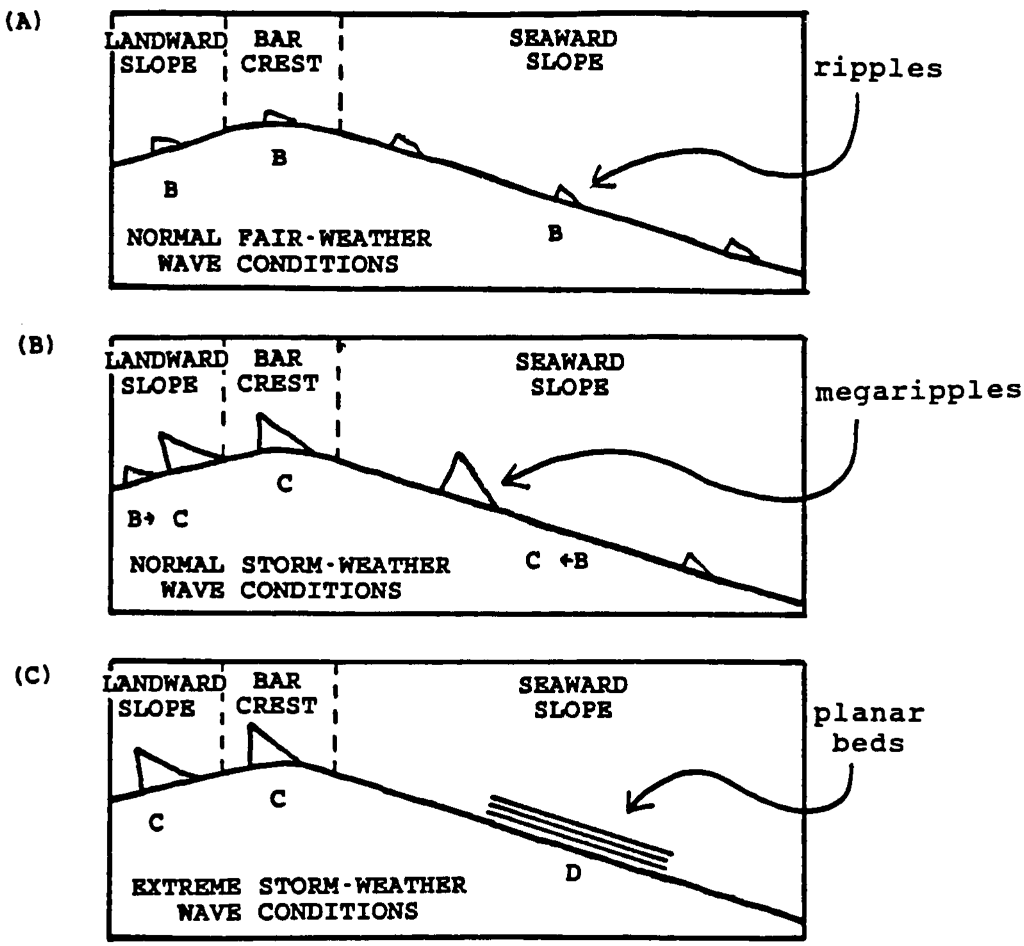


Figure 19. Type and order of bedforms produced on a nearshore bar during (a) normal fair-weather conditions and (b) normal storm-weather conditions (Shipp, 1984). Arrows indicate the direction the bedform sequences progress. It is possible that during (c) extreme storm-weather conditions, the sequence of bedforms produced under shoaling waves consisting of ripples-to-megaripples-to-planar beds (Clifton, 1976) could be shifted far enough basinward to allow planar beds to be produced on the seaward slope.

by burrowing or by the following extremely high energy storm event. Blackhawk Formation sequence stratigraphic data coupled with modern hurricane and tropical storm frequency data suggests that the latter is probably true.

Blackhawk Formation sequence stratigraphic data indicates that Blackhawk shorelines may have prograded at about 10 centimeters per year (Kamola, unpublished data). According to Barron (1989), the frequency of hurricanes that affected those potentially slowly prograding Cretaceous shorelines was slightly higher than the frequency of hurricanes affecting modern shorelines today, due to slightly higher sea surface temperatures (by 4 or 5 degrees celsius) and a rapidly developing North Atlantic Ocean. Barron (1989) also suggested that those hurricanes would have been directed northward into the Cretaceous Western Interior Seaway where they could have affected Blackhawk shorelines (Figure 20).

According to Pielke (1990), 809 hurricanes and/or tropical storms, approximately 8.1 per year, have affected the Atlantic, Gulf of Mexico, and Caribbean regions from 1890 through 1989. This breaks down to approximately 3 hurricanes and/or tropical storms that affect each region per year. However, it is unlikely that 3 hurricanes and/or tropical storms affected each region and/or each section of shoreline per year. It is more likely that the number of the storms that affected those regions varied from year to year. Some regions may even have been affected by as few as one hurricane

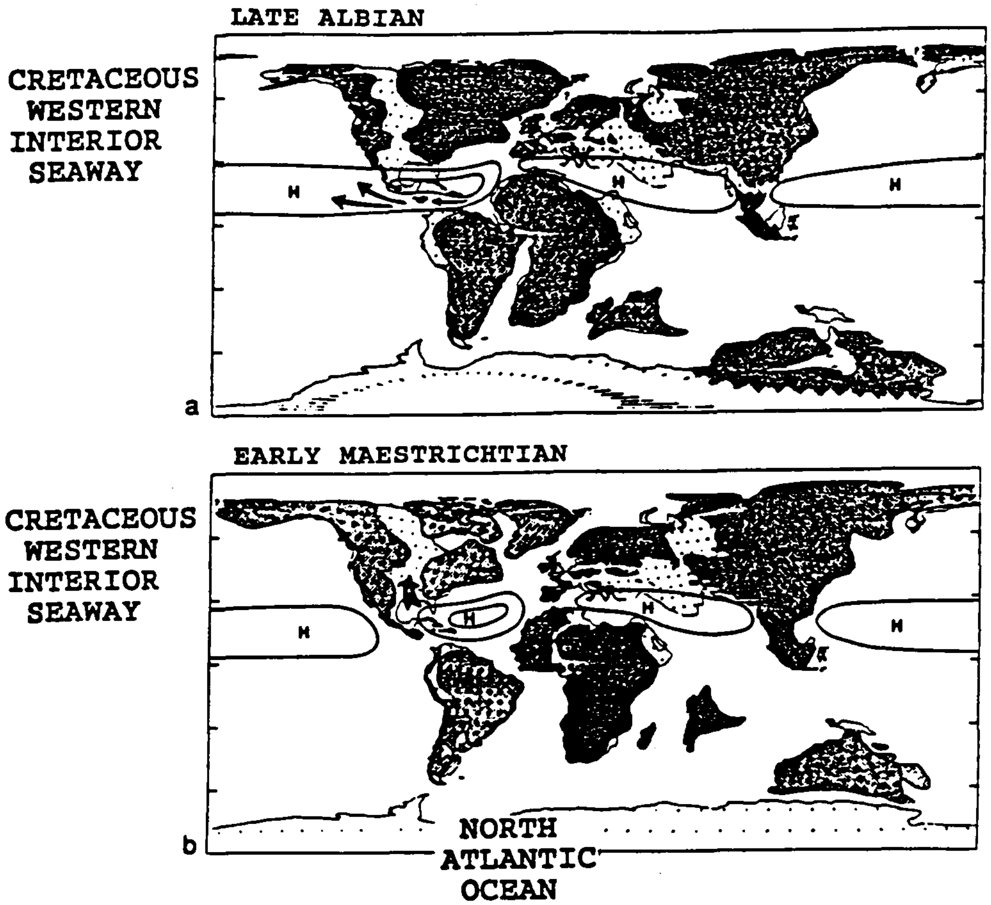


Figure 20. Schematic positions of subtropical high-pressure zones (designated by "H") in the Northern Hemisphere and inferred hurricane paths (designated by the arrows) for (a) late Albian and (b) early Maestrichtian paleogeography. With the development of the North Atlantic Ocean during the early Maestrichtian, a more cell-like subtropical high-pressure zone directed hurricanes northward into the Cretaceous Western Interior Seaway (taken from Barron, 1989).

every ten years. In addition, each hurricane and/or tropical storm that affected a region probably did not affect the entire length of shoreline within that region. Likewise, some sections of shoreline were probably affected more often by these storms than other sections of shoreline.

Assuming that as few as one hurricane or tropical storm every ten years affects modern shorelines today, according to Barron (1989) it would be reasonable to assume the same frequency for similar storm events that affected Blackhawk shorelines during the Cretaceous. One hurricane and/or tropical storm every ten years during the Cretaceous, each capable of eroding as much as two meters of sediment from the shoreface (Bea and Bernard, 1973), would have eroded the estimated one meter of sediment that would have accumulated between those storm events assuming that Cretaceous shorelines prograded at a rate of 10 centimeters per year. Therefore, the only deposits that could have been burrowed into between the extremely high energy storm events that affected Blackhawk shorelines were the planar beds laid down during a previous extremely high energy storm event.

PLANAR BEDDED-TO-BURROWED AND PLANAR BEDDED MSF INTERVALS

While planar bedded beds within MSF intervals are interpreted to have been produced during extremely high energy storm events, and burrowed beds within MSF intervals are interpreted to have been produced between those events, the alternation of these beds does not necessarily represent an accurate record of extremely high energy storm events through time. For example, if all burrowing that occurred between two successive extremely high energy storm events was ripped away by the next extremely high energy storm event, not only would evidence of the burrowing event be unaccounted for in the stratigraphic record, but the subsequent planar beds would no longer represent one, but rather two extremely high energy storm events stacked one on top of the other.

In this way, planar bedded and planar bedded-to-burrowed MSF intervals in the stratigraphic record may represent the product of three inter-dependent factors: (1) the thickness of the planar bedded deposits created during a single extremely high energy storm event; (2) the amount of burrowing, if in fact burrowing occurred, between two successive extremely high energy storm events; and (3) the depth to which sediment was reworked by the following extremely high energy storm event. Varying these three factors not only would change the number and thickness of the planar bedded and burrowed beds that will occur within a given MSF interval, it would also change the significance of these beds.

Figure 21 illustrates three scenarios in which alternating planar bedded-to-burrowed MSF intervals could have been produced. In scenario 1, each planar bedded bed and each burrowed bed represents the deposits produced during each

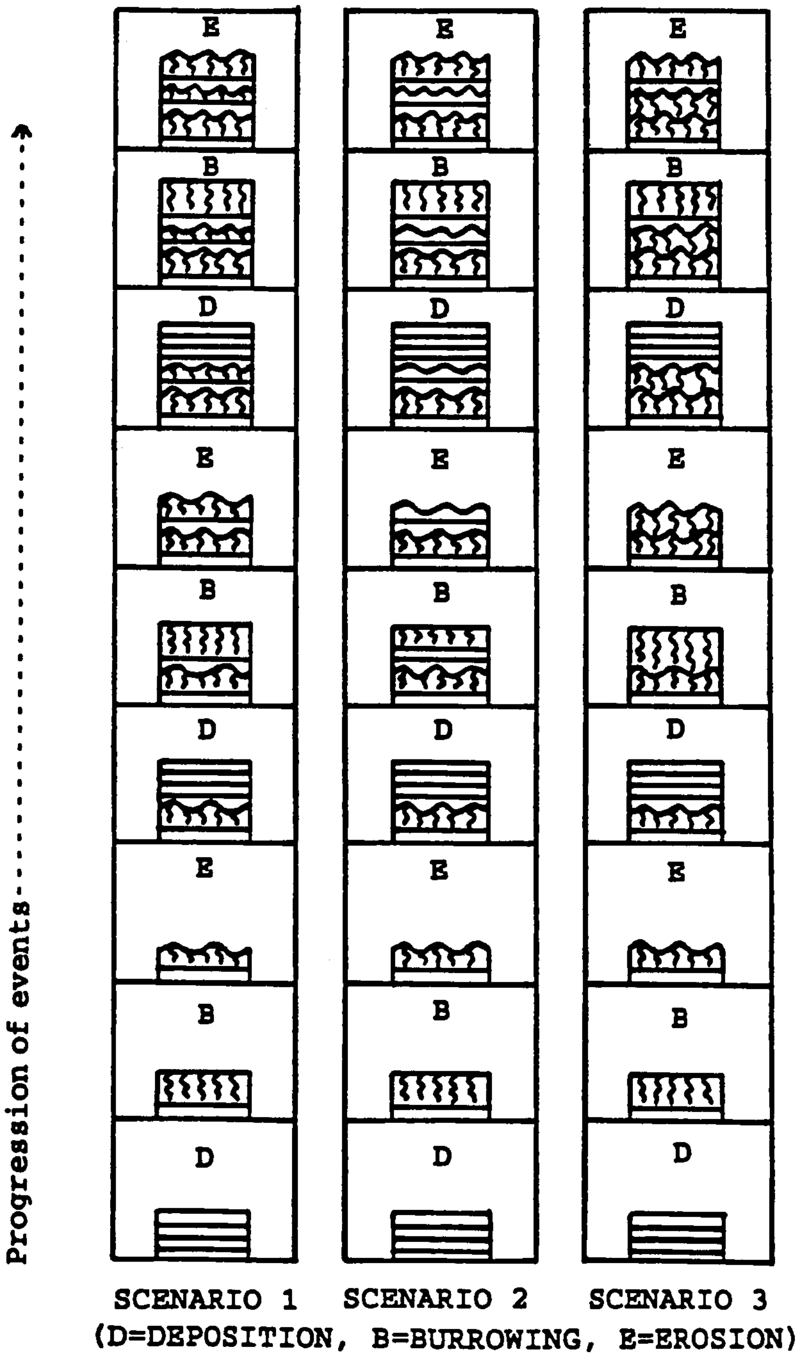
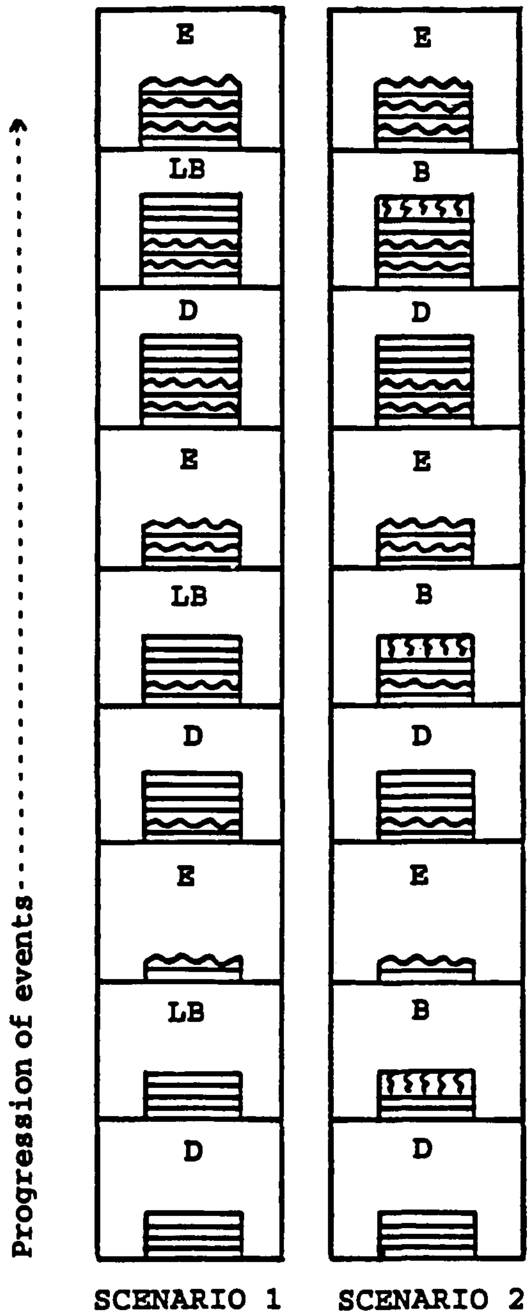


Figure 21. Three possible scenarios for the formation of planar bedded-to-burrowed MSF intervals.

extremely high energy storm event and between each extremely high energy storm event, respectively. In scenario 2, one of the resulting planar bedded beds actually represents planar bedded deposits that were produced during two successive extremely high energy storm events stacked one on top of the other. Stacking of planar bedded beds from two successive extremely high energy storm events is possible if the burrowing that occurred between these storm events is totally reworked by the most recent of the two storm events. In scenario 3, one of the resulting burrowed beds actually represents two successive burrowing events stacked one on top of the other. Stacking of burrowed beds from two successive burrowing events is possible if the planar bedded bed that was formed between those burrowing events was completely reworked during the most recent of the two burrowing events.

Figure 22 illustrates two scenarios in which planar bedded MSF intervals could have been produced. In scenario 1, burrowing simply never occurred between successive extremely high energy storm events. In scenario 2, burrowing occurred between successive extremely high energy storm events, but was always totally reworked by the following extremely high energy storm event.

Based upon the scenarios above, assuming that any combination of these scenarios is possible, just about any array of planar bedded-to-burrowed MSF intervals should occur within the stratigraphic record. It is therefore not



(D=DEPOSITION, B=BURROWING, LB=LACK OF BURROWING, E=EROSION)

Figure 22. Two possible scenarios for the formation of planar bedded MSF intervals.

surprising that this is exactly what is observed within MSF intervals from the Sunnyside (see Appendix C), Spring Canyon (see Appendix D), and Aberdeen (see Appendix E) members. These members display MSF intervals that consist of any number and thickness of planar bedded and burrowed beds, including one MSF interval that is composed entirely of planar beds (see the Alrad MSF interval, Appendix E-3).

EXPLAINING VARIATIONS IN TOTAL MSF INTERVAL THICKNESS

Based upon the dimensions of the bar that Shipp (1984) studied within the Long Island nearshore area (a rip-channel depth of 6 meters and the base of the seaward slope at 10 meters), it is possible for 4 meters of the seaward slope to be preserved during shoreface progradation. This scenario duplicated during the time of Blackhawk deposition could have resulted in the preservation of approximately 4 meters of seaward slope deposits, and could explain some MSF intervals (see the Panther Canyon MSF interval within the Hardscrabble Parasequence, Appendix D-3; and the Kenilworth MSF interval, Appendix E-2).

Variation in the thickness of MSF intervals found in the Blackhawk Formation may have resulted from subtle differences in the bar system itself. MSF intervals from the Sunnyside, Spring Canyon, and Aberdeen members range in thickness from 1.5 meters (see the Lila Canyon MSF interval, Appendix C-3) to

9.5 meters (see the Kenilworth Face MSF interval, Appendix D-4). Because sequence stratigraphic data from the Spring Canyon (Kamola and Van Wagoner, 1995) and Aberdeen (Kamola, unpublished data) members indicates no evidence of continual aggradation accompanying progradation, the extreme variation in MSF interval thickness was probably the result of variation in the depth of rip-channel systems and/or the depth of the basinward toe of seaward slopes, and/or periodic aggradation accompanying progradation.

Variation in the depth of rip-channel systems and/or the depth of the basinward toe of seaward slopes could explain the MSF intervals that are slightly thicker (see the CC1 MSF interval, Appendix E-4) or thinner (see the Alrad MSF interval, Appendix E-3) than the predicted four meter thickness, and possibly intervals that are much thinner. It is possible that extremely thin MSF intervals (see the Lila Canyon MSF interval, Appendix C-3) were the result of deeply incised seaward translating rip-channel systems. There is evidence within ancient nearshore studies to indicate that rip-channels systems could have incised as deep as nine meters into the shoreface (Rahmani and Smith, 1988). Deeply incising rip-channel systems are typical of extremely high energy nearshore conditions (Greenwood and Mittler, 1985; Morton, 1988), the types of conditions predicted here to produce the planar bedded portions of MSF intervals.

While an extremely deep rip-channel system could have resulted in MSF intervals much thinner than 4 meters, an extremely shallow rip-channel system, even coupled with an extended seaward slope toe depth, probably would not have resulted in MSF intervals more than twice the predicted 4 meter thickness (see the Kenilworth Face MSF interval, Appendix D-4) without an aggradational component to the shoreface system.

Extremely thick MSF intervals within shoreface systems that indicate no evidence of aggradation accompanying progradation may represent MSF intervals from two different progradational parasequences stacked one on top of the other in the stratigraphic record. Exaggerated thicknesses of other shoreface deposits (e.g., Helper Parasequence lower shoreface deposits overlaying Heiner Parasequence lower shoreface deposits within the Helper Canyon section of the Spring Canyon Member, see Plate 1) occur due to this stacking affect suggesting that this could also occur with MSF intervals. If a MSF interval actually represents two MSF intervals stacked one on top of the other, the contact between those two MSF intervals may be recognizable in terms of grain size changes (see the Bear Creek Canyon MSF interval, Appendix C-2) or changes in physical and biogenic sedimentary structures. However, these types of changes within a MSF interval will not always indicate a parasequence boundary (see the Spring Canyon #2 MSF interval, Appendix D-2), and may indicate variability in the processes responsible for forming the interval.

RESULTS AND CONCLUSIONS

In this study, two MSF intervals were identified within the marine portions of the Sunnyside Member of the Upper Cretaceous (Campanian) Blackhawk Formation. One MSF interval was identified within the Bear Creek Canyon section (Appendix C-2) and the other MSF interval was identified within the Lila Canyon section (Appendix C-3). These MSF intervals were then compared with MSF intervals previously identified within the Spring Canyon (Kamola and Van Wagoner, 1995) and Aberdeen (Kamola, unpublished data) members of the Blackhawk Formation and interpreted based upon modern conceptual models of nearshore areas.

MSF intervals from these three members range in thickness from 1.5 meters (see Appendix C-2) to 9.5 meters (see Appendix D-4). All of these MSF intervals, with the exception of the Alrad section MSF interval (see Appendix E-3), consist of alternating fine grained planar bedded-to-burrowed beds. The Alrad MSF interval consists entirely of fine grained planar beds. Planar bedded and burrowed beds within the MSF intervals that consist of alternating planar bedded-to-burrowed beds vary in thickness. Planar bedded beds range in thickness from less than 10 centimeters to over 4 meters, and burrowed beds range in thickness from less than 10 centimeters to nearly one meter.

MSF intervals, as their name implies, occur stratigraphically above lower shoreface deposits and below upper shoreface deposits. The fact that all of these MSF intervals occur within the SVS, a vertical succession of deposits that could only have been formed during shoreface progradation, suggests that these deposits too were also produced within a prograding nearshore areas. Based upon modern conceptual models of nearshore areas, the only planar bedded deposits that occur between upper shoreface and lower shoreface deposits and that could have been preserved during shoreface progradation are the seaward slope deposits of a nearshore bar. It has been suggested in this study that MSF intervals are the ancient equivalent to planar bedded seaward slope deposits.

Planar bedded seaward slope deposits are interpreted to have been produced during extremely high energy conditions. It is believed that only under such extreme conditions could the bedform sequence produced under shoaling waves (see Figure 7) have been shifted far enough basinward to have allowed planar beds to have been formed on the seaward slope. Therefore, planar beds within MSF intervals are interpreted to have formed during extremely high energy storms events such as hurricanes or tropical storms. On the other hand, burrowed beds within these intervals are interpreted to have been formed during the much lower energy conditions which dominated between these storm events.

Three inter-dependent factors are interpreted to have determined the number and thickness of planar bedded and/or burrowed beds within MSF intervals. These factors are (1) the thickness of the planar bedded deposits created during a single extremely high energy storm event, (2) the amount of burrowing, if in fact burrowing occurred, between two successive extremely high energy storm events and (3) the depth to which sediment was reworked by the next extremely high energy storm event.

Variation in total MSF interval thickness has been interpreted to be the result of variation in the depth of the rip-channel system and/or the depth of the basinward toe of seaward slope. However, shoreface aggradation may also have played a role in controlling the thickness of some MSF intervals. It is also possible that the true thickness of a MSF interval could be hidden if two MSF intervals from two parasequences are stacked one on top of the other. If this sort of stacking has occurred, it may be possible to differentiate between the two MSF intervals based upon grain size changes or changes in physical and/or biogenic sedimentary structures.

Even though Shipp (1984) had already suggested that the lower seaward slope deposits of a nearshore bar could be preserved during shoreface progradation, this is the first time that they have been recognized in the stratigraphic record. The recognition that MSF intervals are in fact ancient seaward slope deposits is important because it not only increases our understanding of nearshore facies models, it allows for the recognition of barred nearshore systems in the stratigraphic record.

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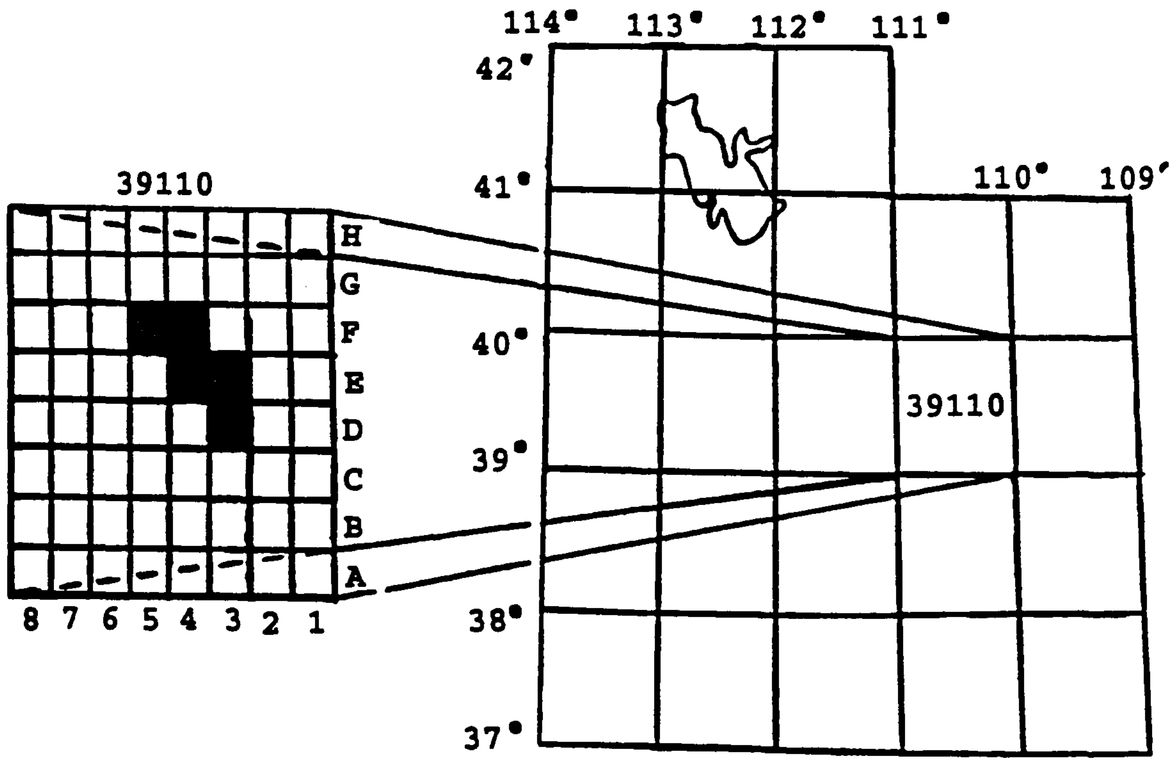
APPENDIX A

QUADRANGLE LOCATIONS OF SUNNYSIDE MEMBER MEASURED SECTIONS

NAME OF MEASURED SECTION	INDEX NUMBER ON LOCATION MAP (FIGURE 16)	U.S.G.S. QUADRANGLE MAP (APPENDIX A-2)
SOLDIER CREEK CANYON	1	39110 : F5
DUGOUT CREEK CANYON	2	39110 : F5
ROCK CREEK CANYON	3	39110 : F5
BEAR CREEK CANYON	4	39110 : F4
A CANYON	5	39110 : E4
1.5 MILES NORTH OF FAN CANYON	6	39110 : E4
FAN CANYON	7	39110 : E4
WHITMORE CANYON	8	39110 : E4
WATER CANYON	9	39110 : E3
COLUMBIA CANYON	10	39110 : E3
HORSE CANYON	11	39110 : D3
LILA CANYON	12	39110 : D3
SOUTH LILA CANYON	13	39110 : D3

U.S.G.S.
QUADRANGLE
MAPS



7.5 MINUTE QUADRANGLE NAMES

39110

- D3 LILA POINT
- E3 PATMOS HEAD
- E4 SUNNYSIDE
- F4 MOUNT BARTLES
- F5 PINE CANYON

(MAPS PUBLISHED AND DISTRIBUTED BY THE UNITED STATES GEOLOGICAL SURVEY, NATIONAL MAPPING PROGRAM)

APPENDIX B

SUNNYSIDE MEMBER MEASURED SECTIONS DISPLAYING THE SVS

KEY

GRAIN SIZE

VFL - very fine lower
VFU - very fine upper
FL - fine lower
FU - fine upper
ML - medium lower
MU - medium upper

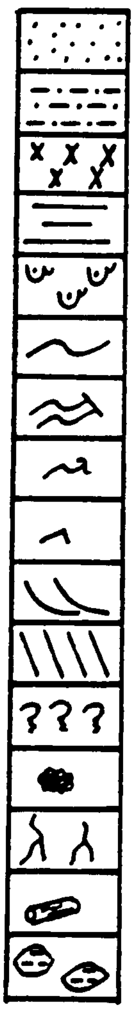
DEPOSITIONAL ENVIRONMENT INTERPRETATION

FS - foreshore deposits
USF - upper shoreface deposits
LSF - lower shoreface deposits
* the term "non-marine" is used to indicate any non-marine/ marginal marine depositional environment

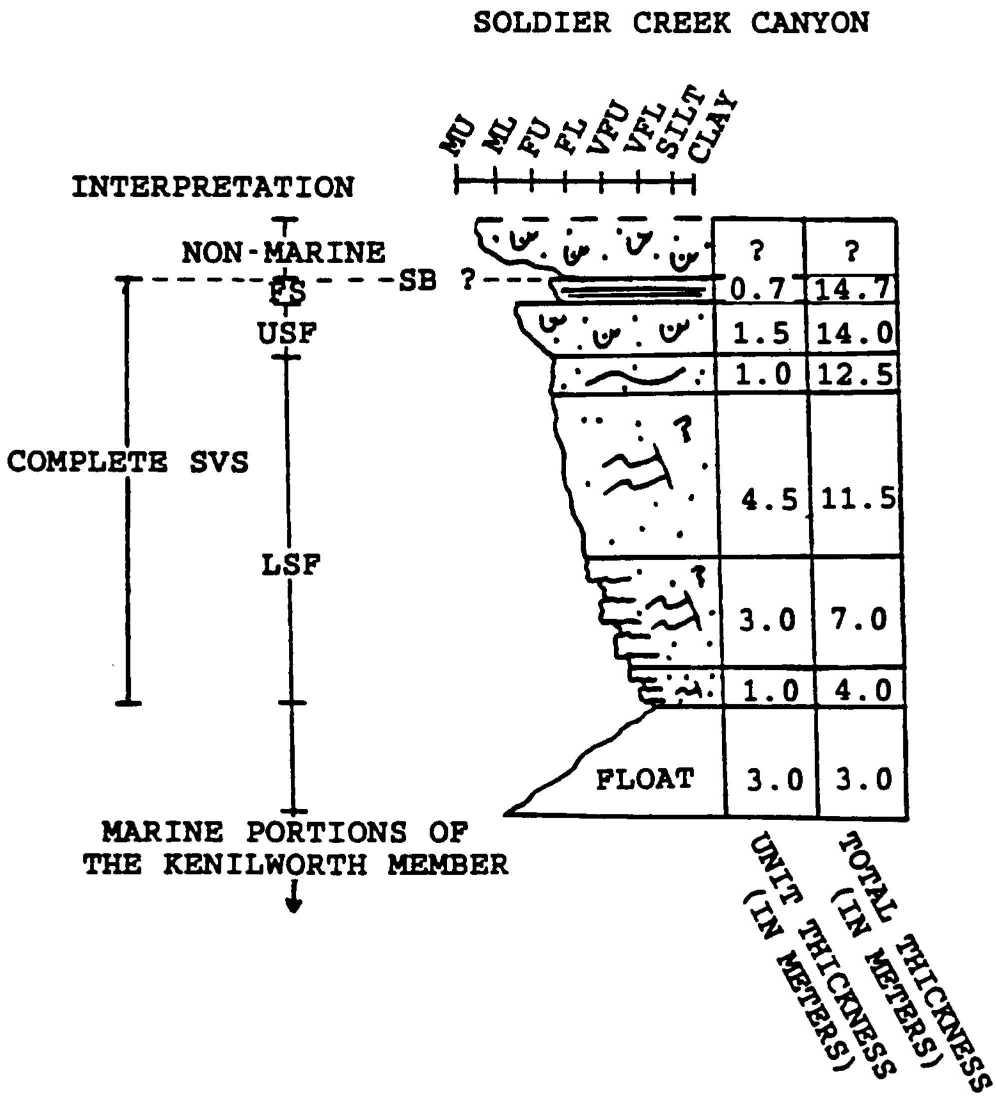
SEQUENCE STRATIGRAPHIC INTERPRETATION

PSB - Parasequence Boundary
SB - Sequence Boundary

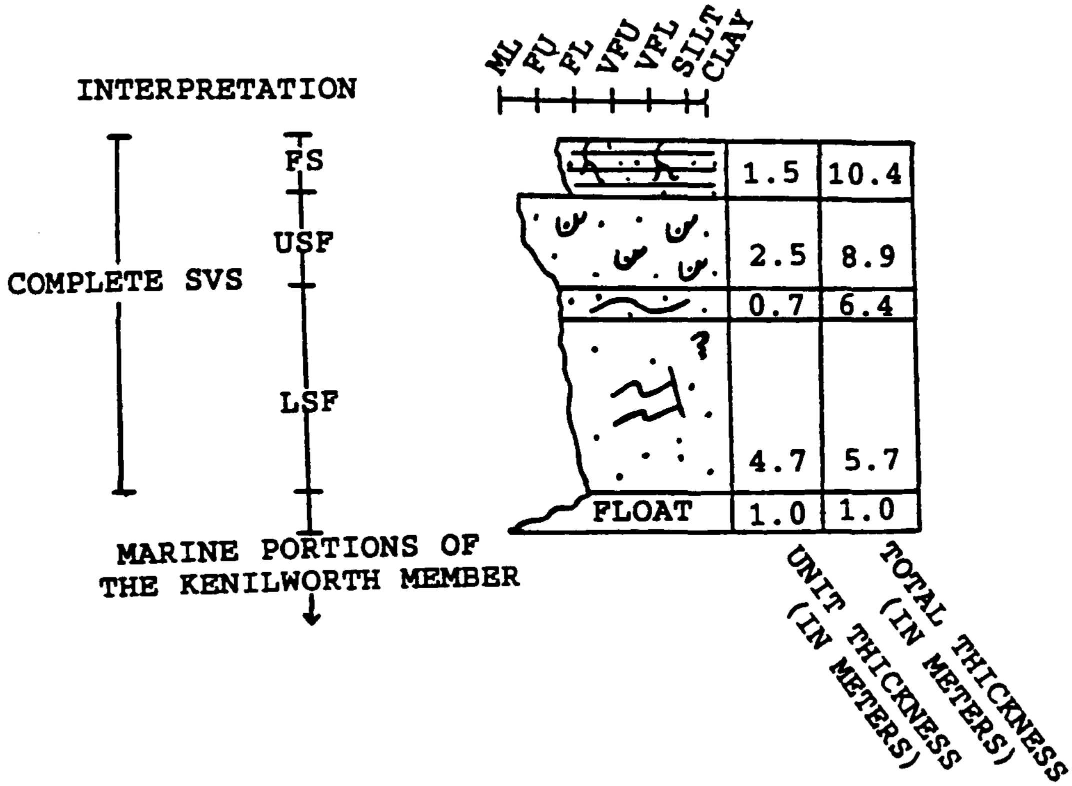
SYMBOLS



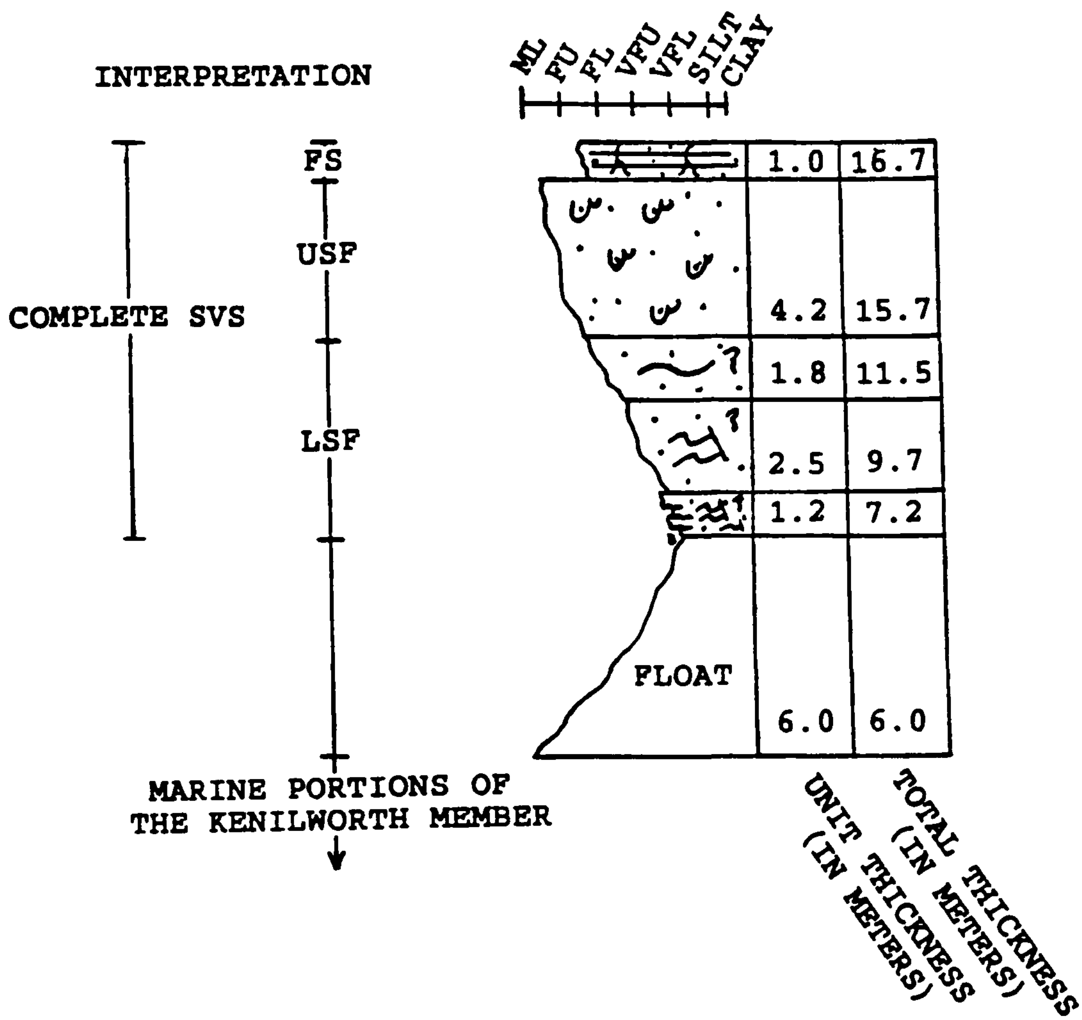
Sandstone
Siltstone
Coal
Planar Lamination
Trough Cross-stratification
Swaley Stratification
Hummocky Cross-stratification
Wave Ripples
Current Ripples
Internal Scour Surfaces
Lateral Accretion
Marine Trace Fossils
Teredolites (trace fossil: marine (in place) or marginal marine (transported) indicator)
Rooting
Wood
Shale Rip-up Clasts


SOLDIER CREEK CANYON
MU ML FU FL VFU VFL SILT CLAY
INTERPRETATION
NON-MARINE
FS
SB ?
USF
COMPLETE SVS
LSF
MARINE PORTIONS OF THE KENILWORTH MEMBER
FLOAT
? ?
0.7 14.7
1.5 14.0
1.0 12.5
4.5 11.5
3.0 7.0
1.0 4.0
3.0 3.0
UNIT THICKNESS (IN METERS)
TOTAL THICKNESS (IN METERS)

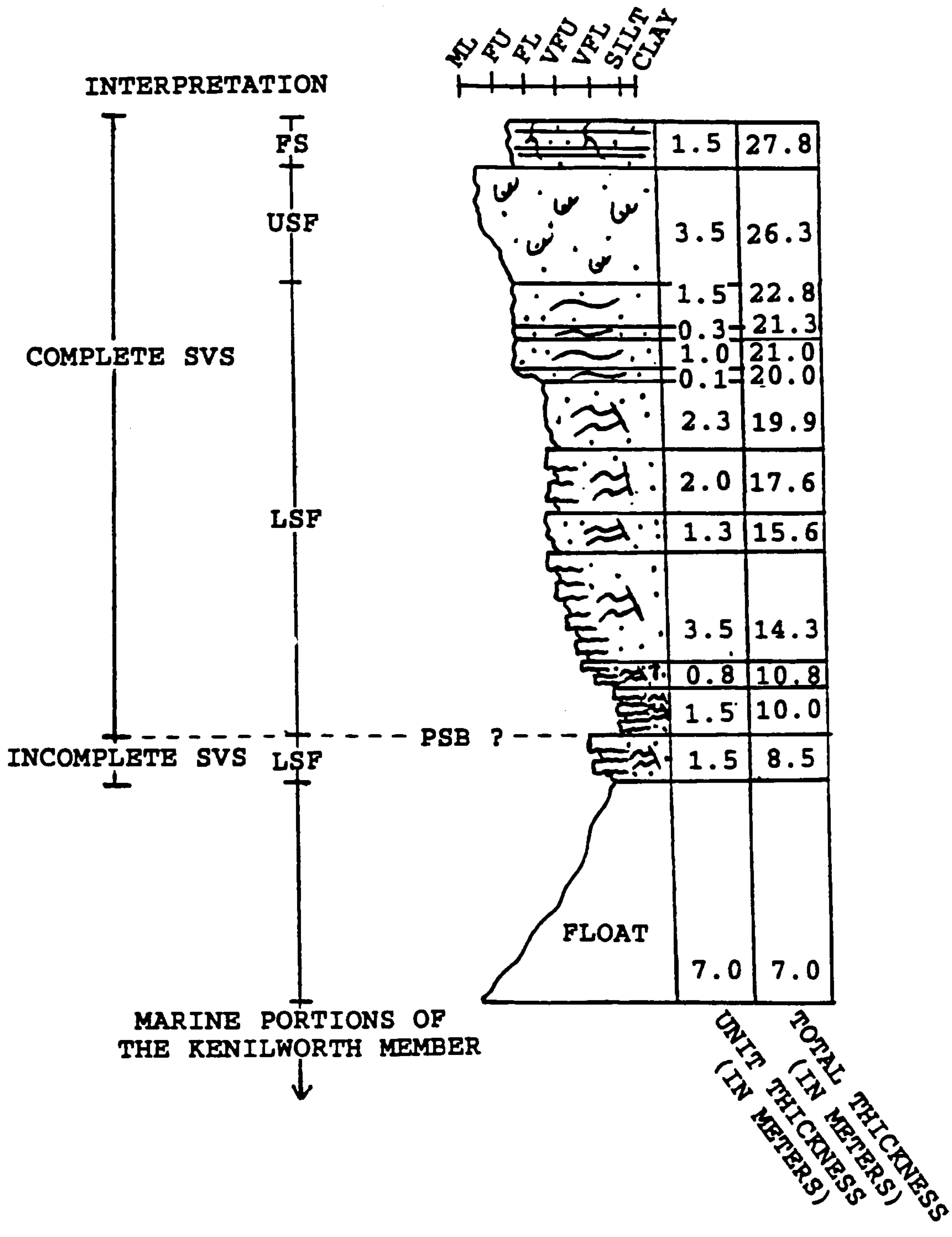
DUGOUT CREEK CANYON



ROCK CREEK CANYON

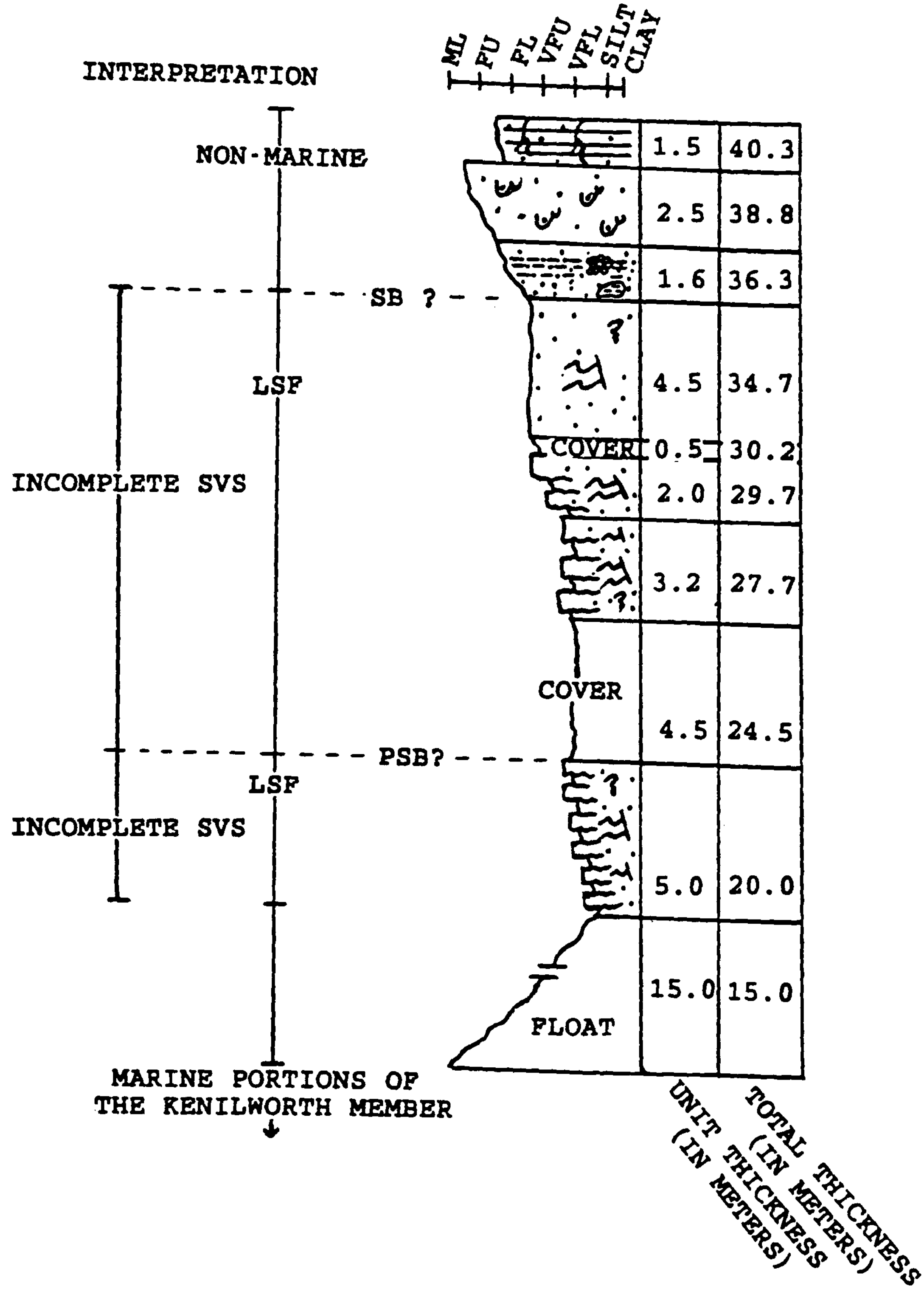


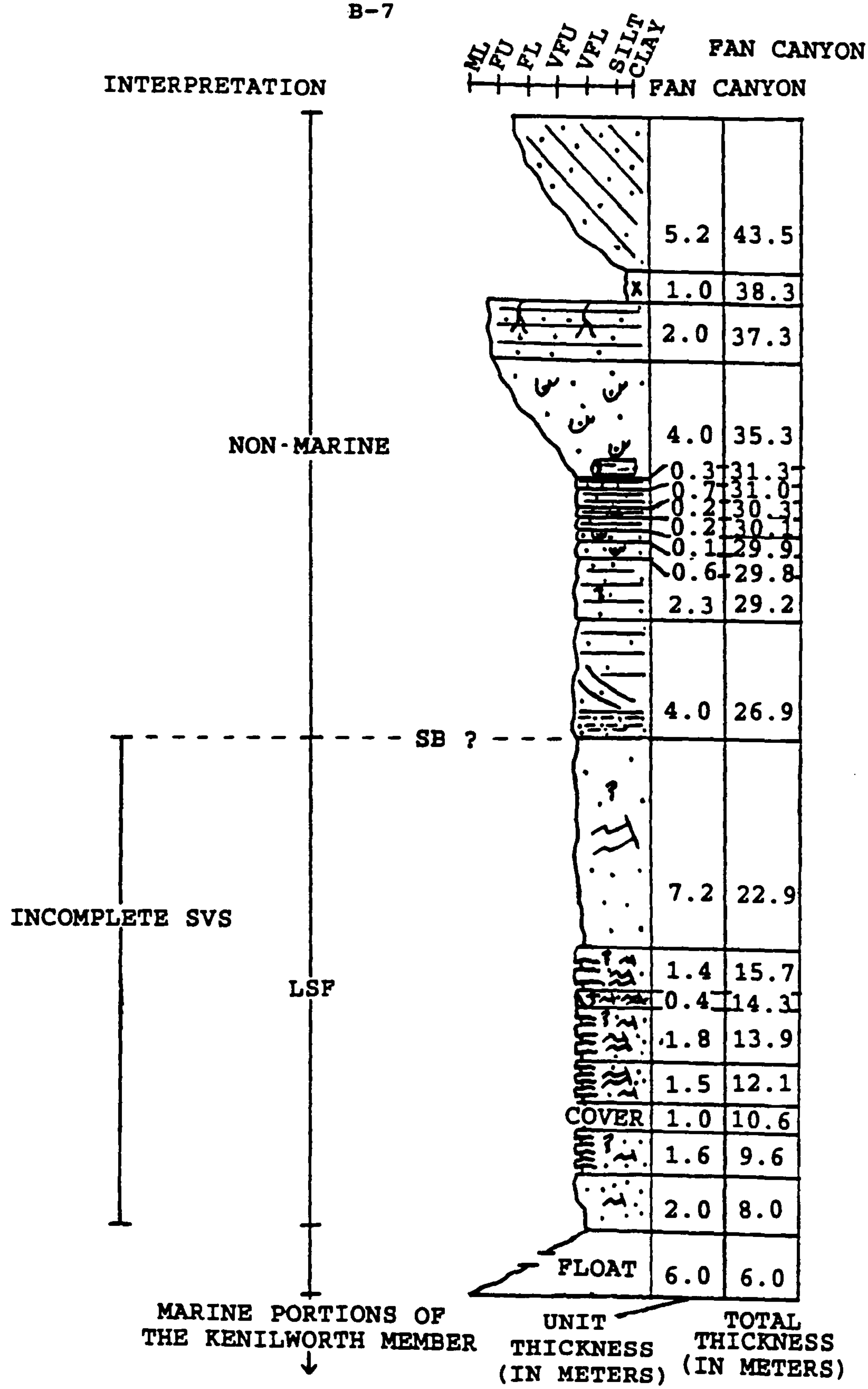
A CANYON

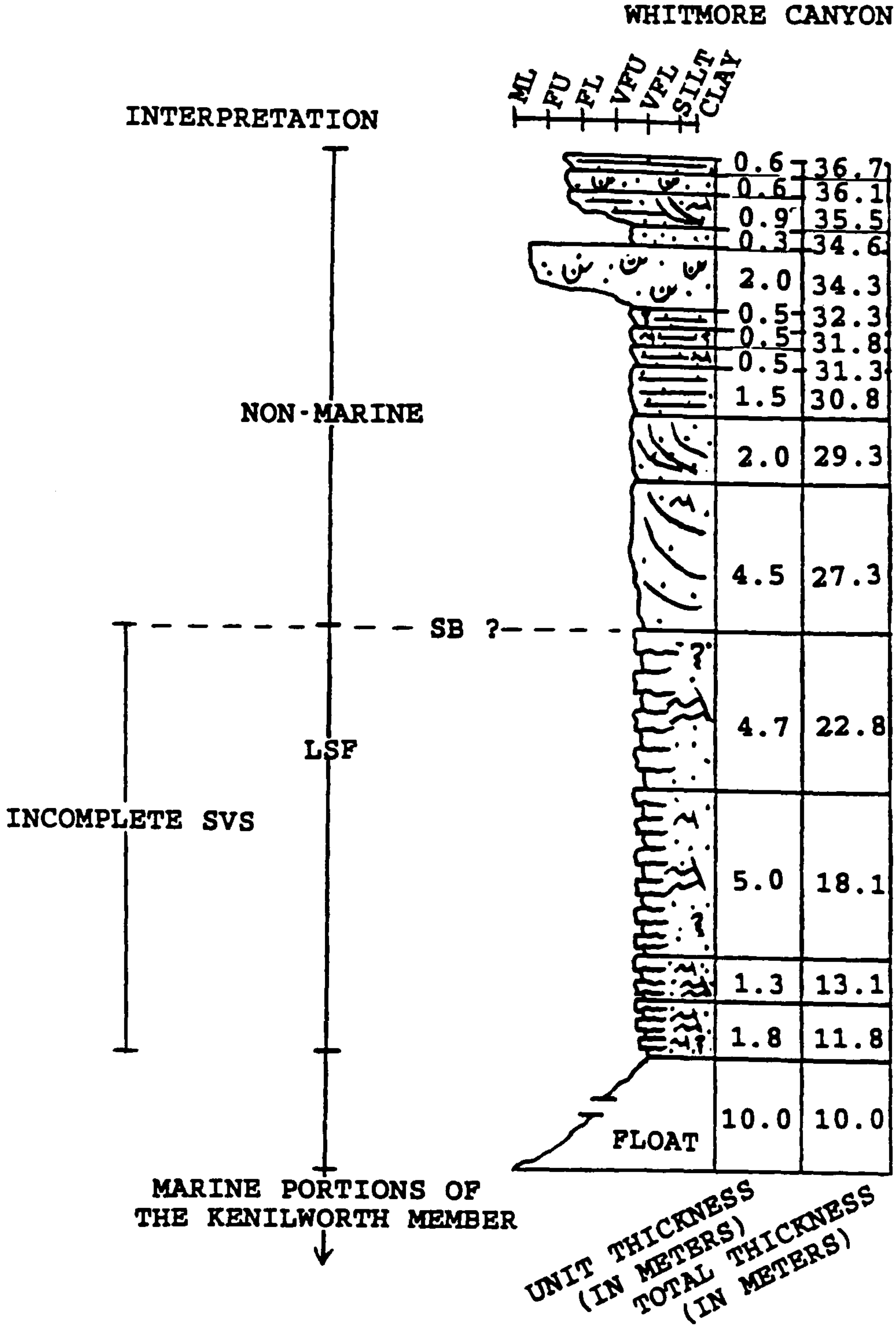

ML FU FL VFU VFL SILT CLAY
INTERPRETATION
COMPLETE SVS
FS
USF
LSF
PSB ?
INCOMPLETE SVS
LSF
MARINE PORTIONS OF THE KENILWORTH MEMBER
FLOAT
1.5 27.8
3.5 26.3
1.5 22.8
0.3 21.3
1.0 21.0
0.1 20.0
2.3 19.9
2.0 17.6
1.3 15.6
3.5 14.3
0.8 10.8
1.5 10.0
1.5 8.5
7.0 7.0
UNIT THICKNESS (IN METERS)
TOTAL THICKNESS (IN METERS)

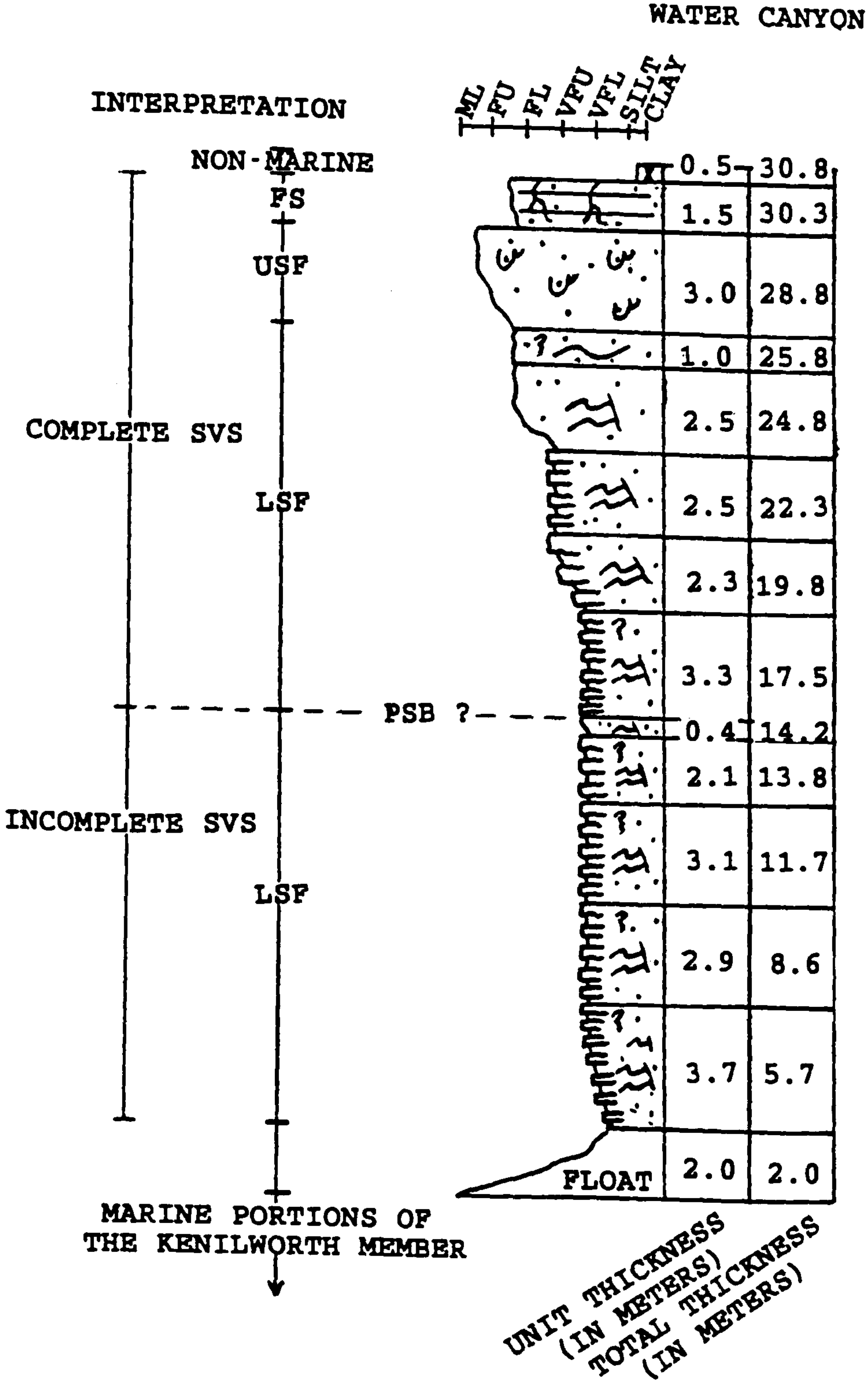
B-6

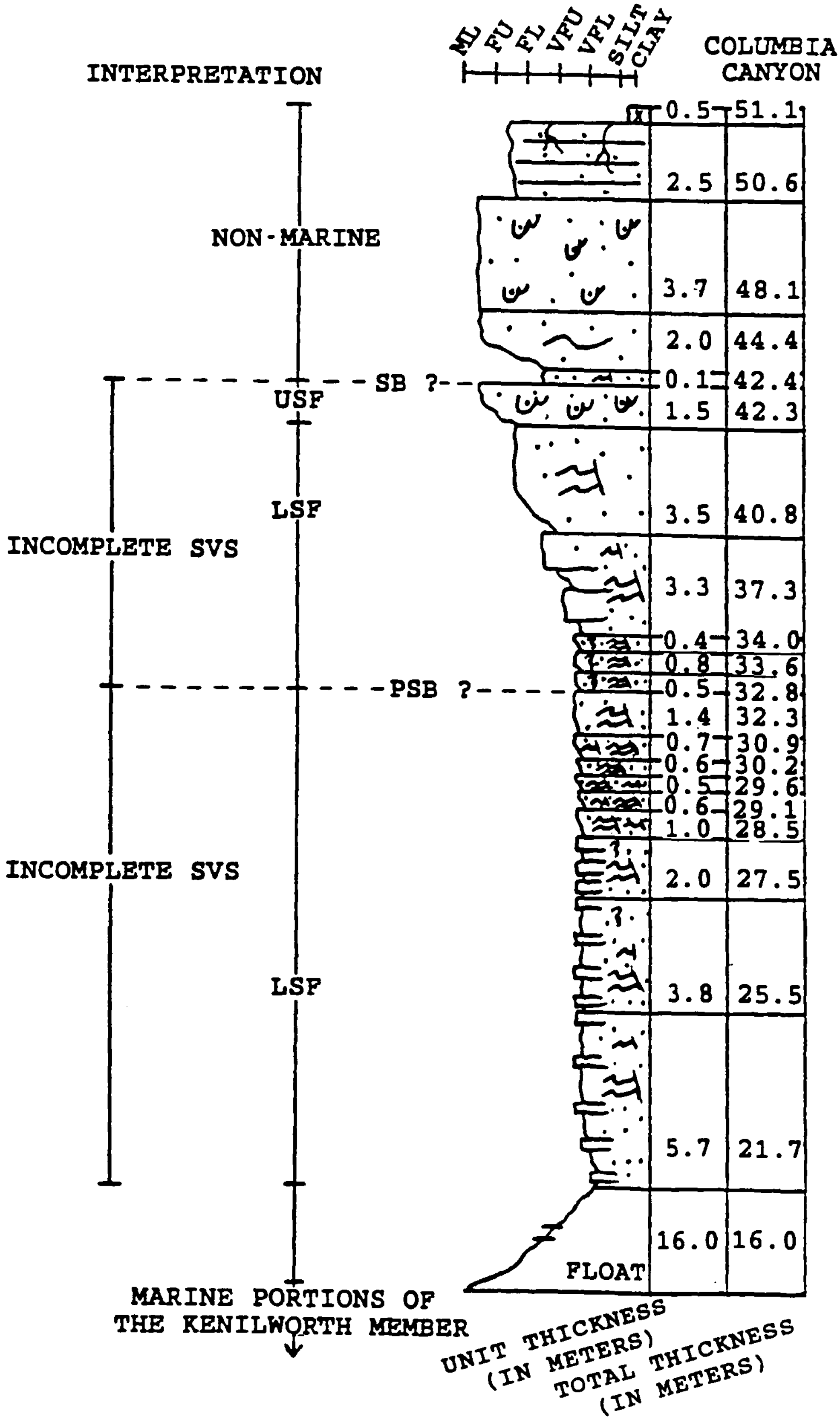
1.5 MILES NORTH OF FAN CANYON




FAN CANYON
ML FU FL VFU VFL SILT CLAY
FAN CANYON
INTERPRETATION
NON-MARINE
SB ?
INCOMPLETE SVS
LSF
MARINE PORTIONS OF THE KENILWORTH MEMBER
5.2 43.5
1.0 38.3
2.0 37.3
4.0 35.3
0.3 31.3
0.7 31.0
0.2 30.3
0.2 30.1
0.1 29.9
0.6 29.8
2.3 29.2
4.0 26.9
7.2 22.9
1.4 15.7
0.4 14.3
1.8 13.9
1.5 12.1
COVER 1.0 10.6
1.6 9.6
2.0 8.0
FLOAT 6.0 6.0
UNIT THICKNESS (IN METERS)
TOTAL THICKNESS (IN METERS)

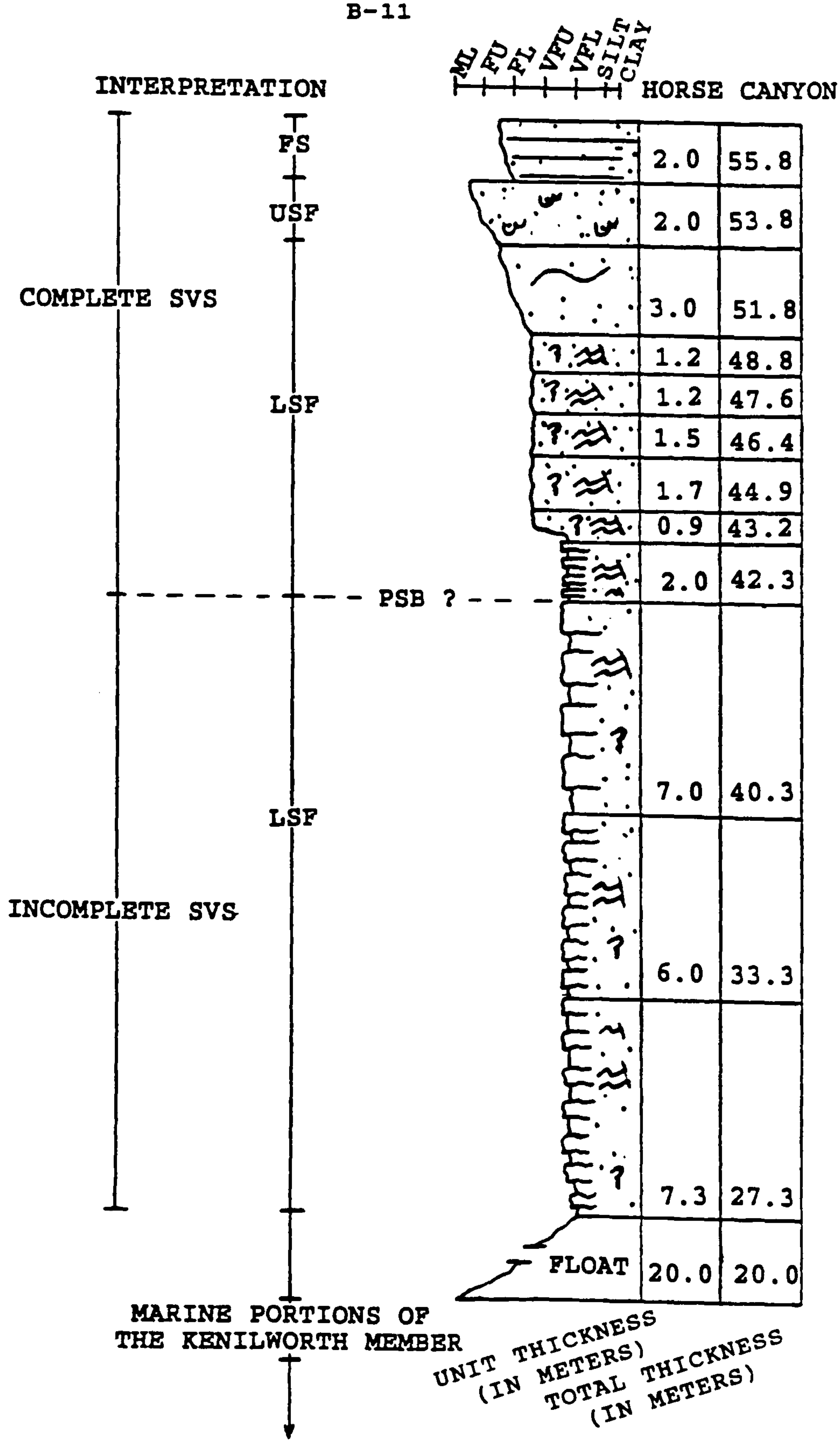

WHITMORE CANYON
INTERPRETATION
ML
FU
FL
VFU
VFL
SILT
CLAY
NON-MARINE
SB ?
LSF
INCOMPLETE SVS
FLOAT
MARINE PORTIONS OF
THE KENILWORTH MEMBER
0.6 36.7
0.6 36.1
0.9 35.5
0.3 34.6
2.0 34.3
0.5 32.3
0.5 31.8
0.5 31.3
1.5 30.8
2.0 29.3
4.5 27.3
4.7 22.8
5.0 18.1
1.3 13.1
1.8 11.8
10.0 10.0
UNIT THICKNESS
(IN METERS)
TOTAL THICKNESS
(IN METERS)

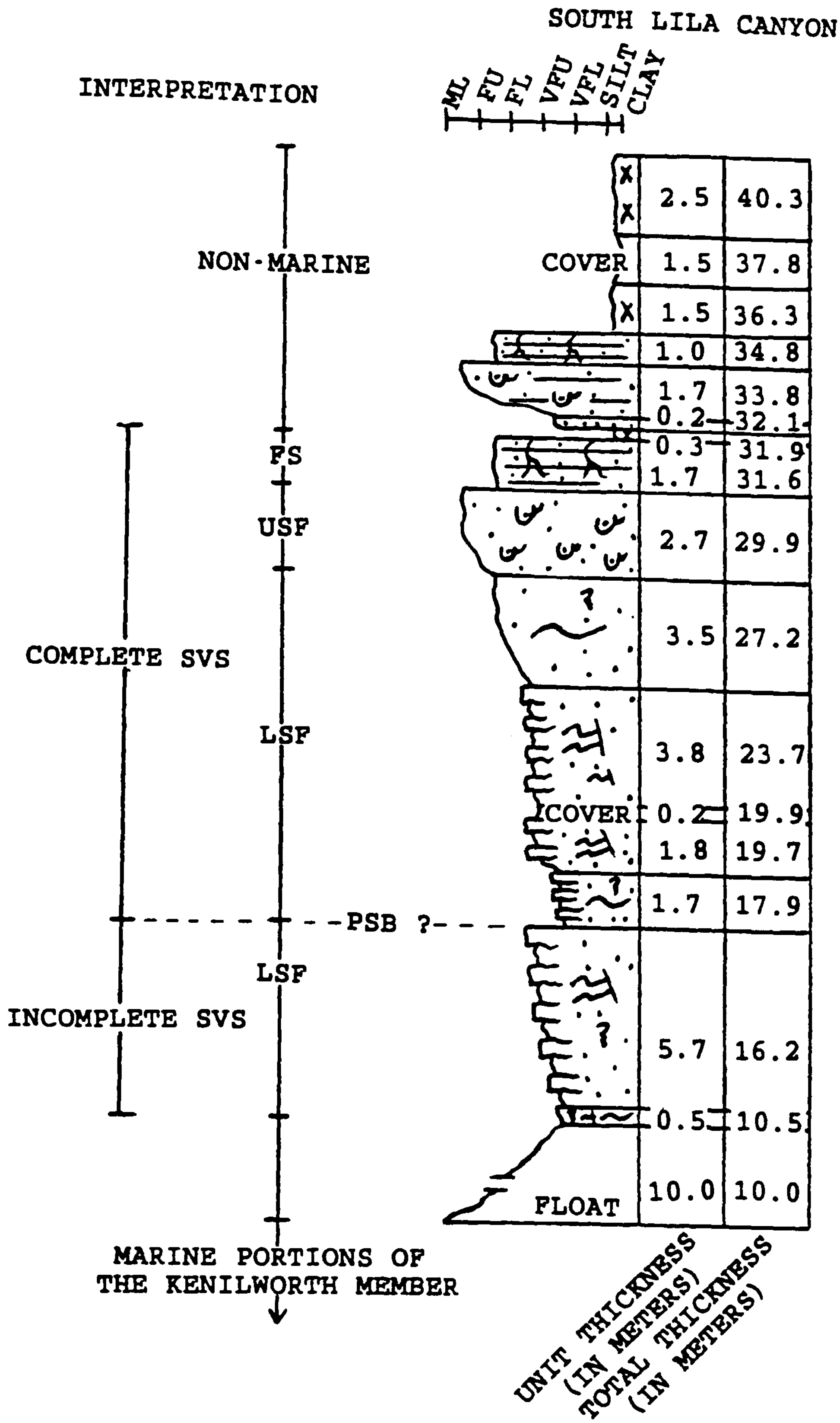

WATER CANYON
INTERPRETATION
ML
FU
FL
VFU
VFL
SILT
CLAY
NON-MARINE
FS
USF
COMPLETE SVS
LSF
PSB ?
INCOMPLETE SVS
LSF
MARINE PORTIONS OF
THE KENILWORTH MEMBER
FLOAT
0.5
30.8
1.5
30.3
3.0
28.8
1.0
25.8
2.5
24.8
2.5
22.3
2.3
19.8
3.3
17.5
0.4
14.2
2.1
13.8
3.1
11.7
2.9
8.6
3.7
5.7
2.0
2.0
UNIT THICKNESS
(IN METERS)
TOTAL THICKNESS
(IN METERS)



INTERPRETATION
ML FU FL VFU VFL SILT CLAY
COLUMBIA CANYON
NON-MARINE
SB ?
USF
LSF
INCOMPLETE SVS
PSB ?
INCOMPLETE SVS
LSF
MARINE PORTIONS OF THE KENILWORTH MEMBER
FLOAT
0.5 51.1
2.5 50.6
3.7 48.1
2.0 44.4
0.1 42.4
1.5 42.3
3.5 40.8
3.3 37.3
0.4 34.0
0.8 33.6
0.5 32.8
1.4 32.3
0.7 30.9
0.6 30.2
0.5 29.6
0.6 29.1
1.0 28.5
2.0 27.5
3.8 25.5
5.7 21.7
16.0 16.0
UNIT THICKNESS (IN METERS)
TOTAL THICKNESS (IN METERS)

B-11


INTERPRETATION
ML FU FL VFU VFL SILT CLAY
HORSE CANYON
FS
USF
COMPLETE SVS
LSF
PSB ?
LSF
INCOMPLETE SVS
2.0 55.8
2.0 53.8
3.0 51.8
1.2 48.8
1.2 47.6
1.5 46.4
1.7 44.9
0.9 43.2
2.0 42.3
7.0 40.3
6.0 33.3
7.3 27.3
FLOAT 20.0 20.0
MARINE PORTIONS OF
THE KENILWORTH MEMBER
UNIT THICKNESS
(IN METERS)
TOTAL THICKNESS
(IN METERS)


SOUTH LILA CANYON
INTERPRETATION
ML FU FL VFU VFL SILT CLAY
NON-MARINE
COVER
2.5 40.3
1.5 37.8
1.5 36.3
1.0 34.8
1.7 33.8
0.2 32.1
0.3 31.9
1.7 31.6
FS
USF
2.7 29.9
3.5 27.2
COMPLETE SVS
LSF
3.8 23.7
COVER 0.2 19.9
1.8 19.7
1.7 17.9
PSB ?
LSF
INCOMPLETE SVS
5.7 16.2
0.5 10.5
FLOAT 10.0 10.0
MARINE PORTIONS OF
THE KENILWORTH MEMBER
UNIT THICKNESS (IN METERS)
TOTAL THICKNESS (IN METERS)

APPENDIX C

SUNNYSIDE MEMBER MEASURED SECTIONS DISPLAYING A MSF INTERVAL

KEY

GRAIN SIZE

VFL - very fine lower
VFU - very fine upper
FL - fine lower
FU - fine upper
ML - medium lower
MU - medium upper

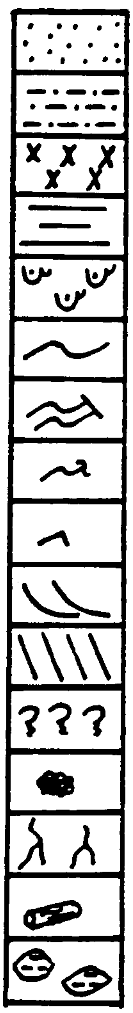
DEPOSITIONAL ENVIRONMENT INTERPRETATION

FS - foreshore deposits
USF - upper shoreface deposits
LSF - lower shoreface deposits
* the term "non-marine" is used to indicate any non-marine/ marginal marine depositional environment

SEQUENCE STRATIGRAPHIC INTERPRETATION

PSB - Parasequence Boundary
SB - Sequence Boundary

SYMBOLS



Sandstone

Siltstone

Coal

Planar Lamination

Trough Cross-stratification

Swaley Stratification

Hummocky Cross-stratification

Wave Ripples

Current Ripples

Internal Scour Surfaces

Lateral Accretion

Marine Trace Fossils

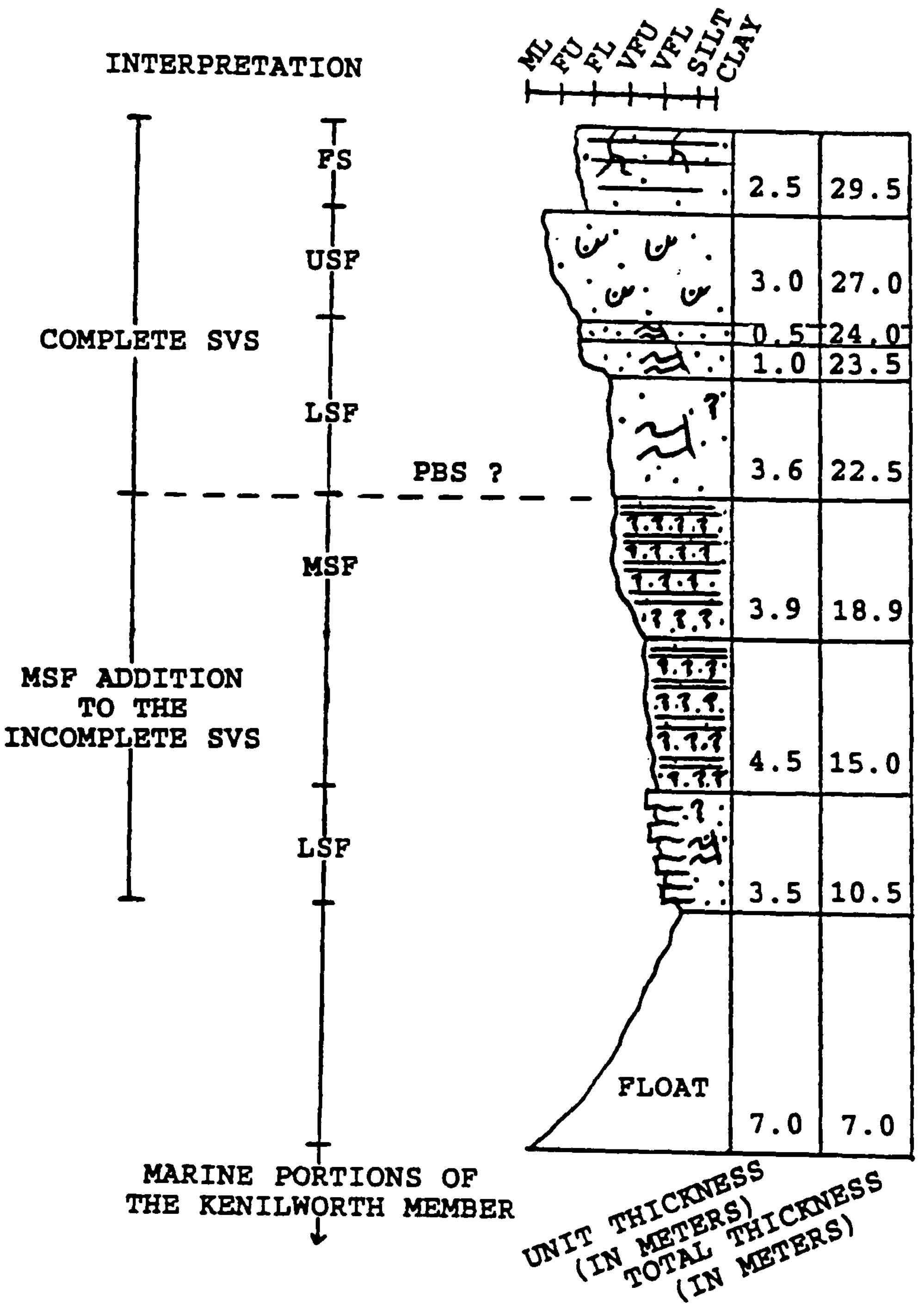
Teredolites (trace fossil: marine (in place) or marginal marine (transported) indicator)

Rooting

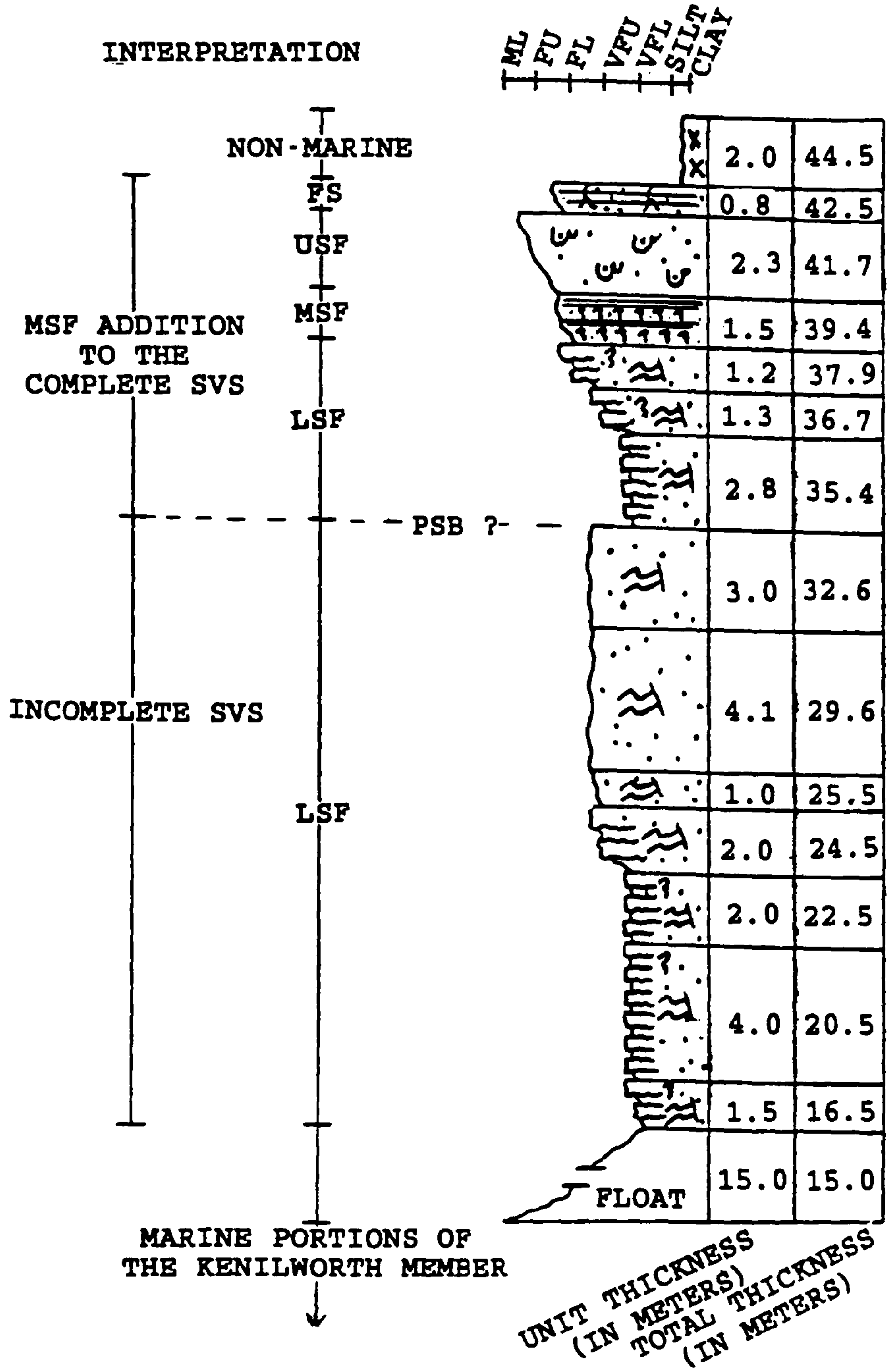
Wood

Shale Rip-up Clasts

BEAR CREEK CANYON



LILA CANYON

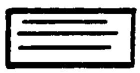

INTERPRETATION
ML
FU
FL
VFU
VFL
SILT
CLAY
NON-MARINE
FS
USF
MSF
MSF ADDITION TO THE COMPLETE SVS
LSF
PSB ?
INCOMPLETE SVS
LSF
MARINE PORTIONS OF THE KENILWORTH MEMBER
FLOAT
2.0 44.5
0.8 42.5
2.3 41.7
1.5 39.4
1.2 37.9
1.3 36.7
2.8 35.4
3.0 32.6
4.1 29.6
1.0 25.5
2.0 24.5
2.0 22.5
4.0 20.5
1.5 16.5
15.0 15.0
UNIT THICKNESS (IN METERS)
TOTAL THICKNESS (IN METERS)

APPENDIX D

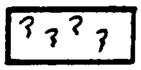
SPRING CANYON MEMBER MSF INTERVALS

D-1

KEY



PLANAR BEDDED (P) - beds on centimeter scale



BURROWED (B) - _Ophiomorpha_; traces approximately 1 centimeter in diameter

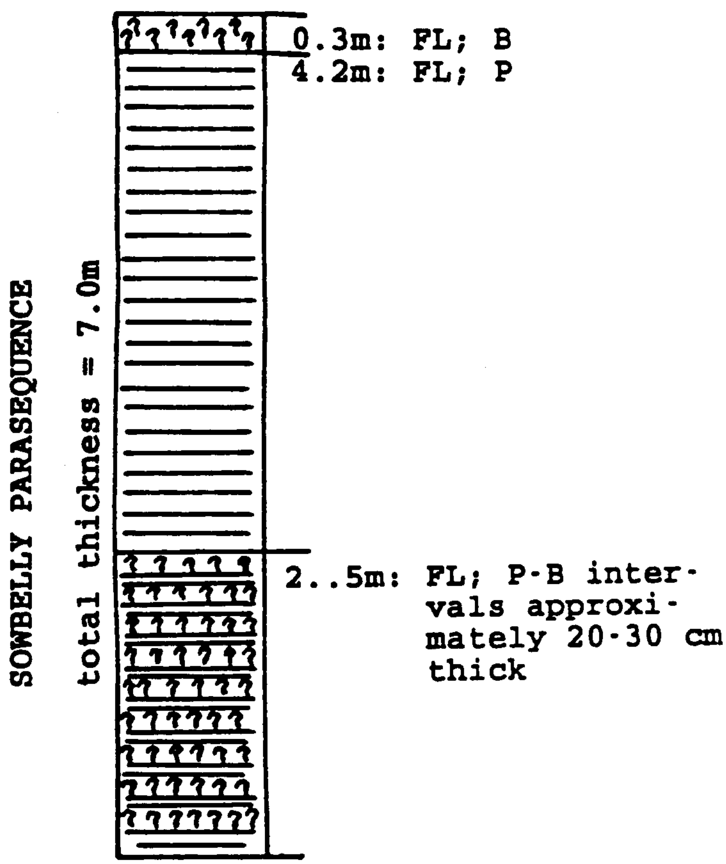
PLANAR BEDDED-TO-BURROWED (P-B) - base of the planar bedded interval is sharp; base of the burrowed interval is diffuse

meter = m
centimeter = cm
millimeter = mm

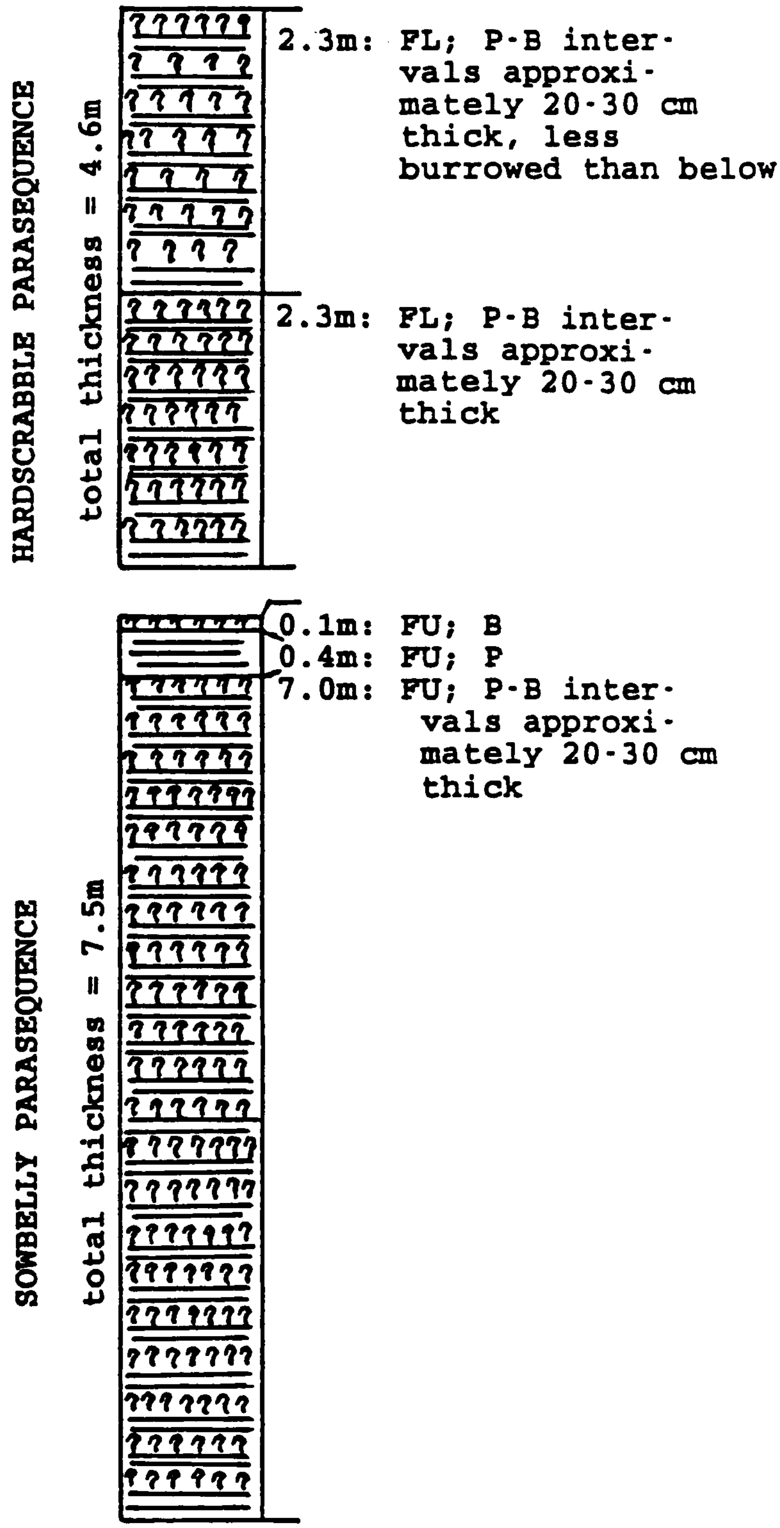
SAND SIZES (diameter in mm)

medium upper	(MU)	0.50 - 0.38
medium lower	(ML)	0.38 - 0.25
fine upper	(FU)	0.25 - 0.19
fine lower	(FL)	0.19 - 0.13
very fine upper	(VFU)	0.13 - 0.09
very fine lower	(VFL)	0.09 - 0.06

Unpublished data, sections measured by D. Kamola.

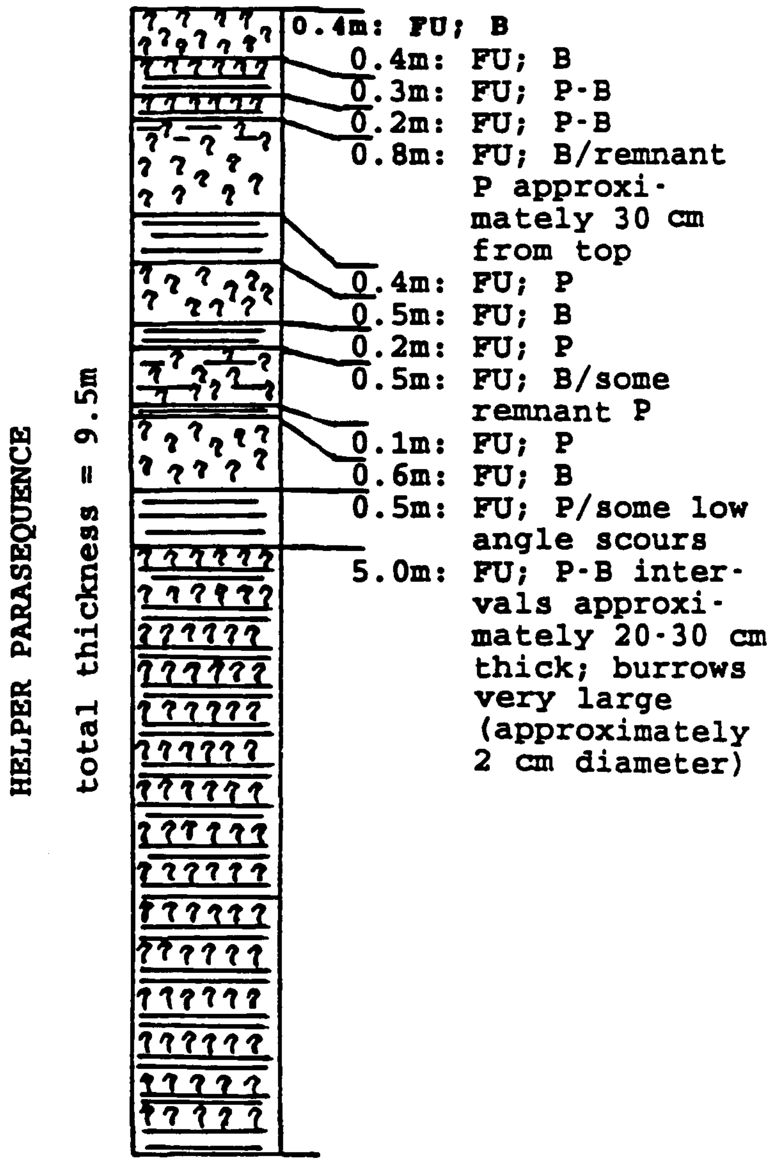


SPRING CANYON #2
MIDDLE SHOREFACE
INTERVAL



PANTHER CANYON #2
MIDDLE SHOREFACE
INTERVALS

D-4



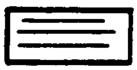
KENILWORTH FACE MEMBER
MIDDLE SHOREFACE
INTERVAL

APPENDIX E

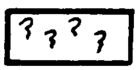
ABERDEEN MEMBER MSF INTERVALS

E-1

KEY



PLANAR BEDDED (P) - beds on centimeter scale



BURROWED (B) - Ophiomorpha; traces approximately 1 centimeter in diameter

PLANAR BEDDED-TO-BURROWED (P-B) - base of the planar bedded interval is sharp; base of the burrowed interval is diffuse

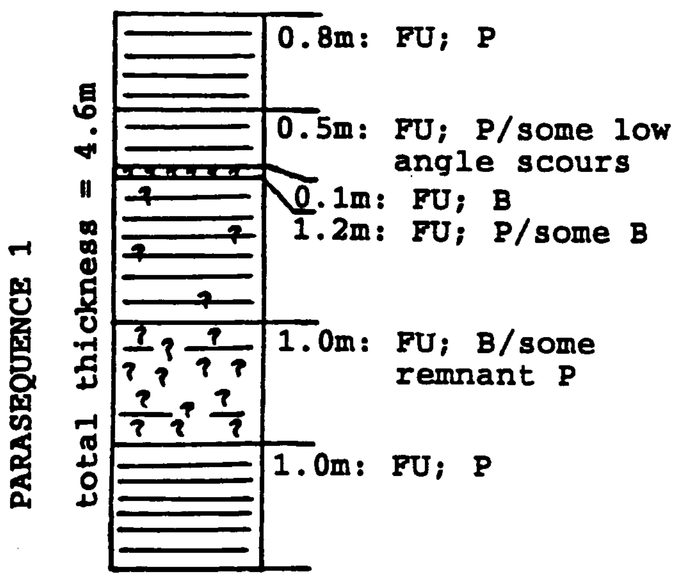
meter = m
centimeter = cm
millimeter = mm

SAND SIZES (diameter in mm)

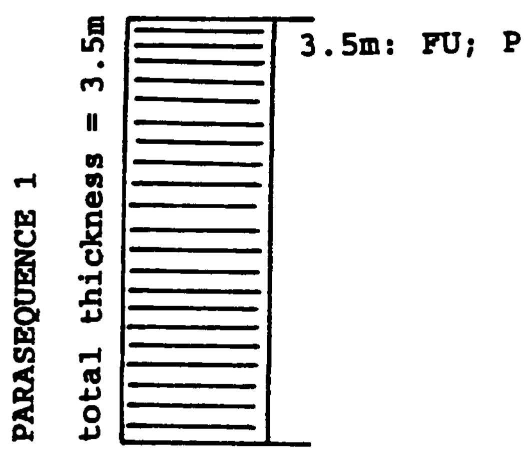
medium upper	(MU)	0.50 - 0.38
medium lower	(ML)	0.38 - 0.25
fine upper	(FU)	0.25 - 0.19
fine lower	(FL)	0.19 - 0.13
very fine upper	(VFU)	0.13 - 0.09
very fine lower	(VFL)	0.09 - 0.06

Unpublished data, sections measured by D. Kamola.

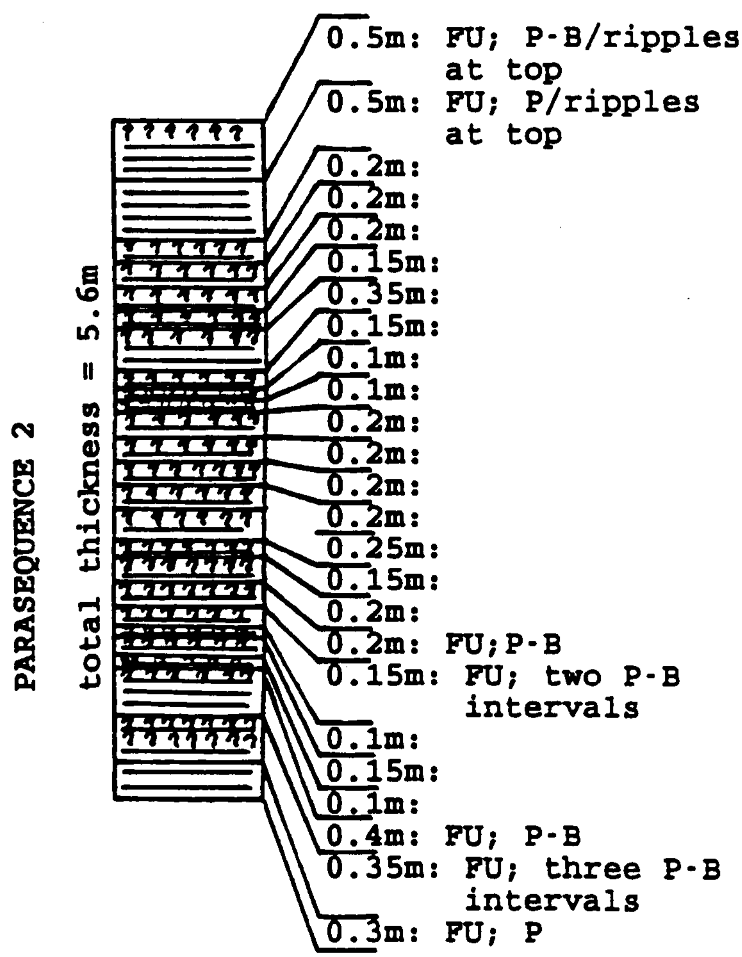
E-2



KENILWORTH
MIDDLE SHOREFACE
INTERVAL



ALRAD
MIDDLE SHOREFACE
INTERVAL



CC1
MIDDLE SHOREFACE
INTERVAL

VITA

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Professional Experience

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