Sedimentology and taphonomy of a shell bed assemblage from the Upper Cretaceous (Maastrichtian) Hell Creek Formation of eastern Montana

by Bentley Edward Shoup

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Aggregate shell bed accumulations within coastal marine sediments are numerous and . have been thoroughly studied. In contrast, terrestrial shell bed assemblages have received less attention due to their paucity within the existing strata. Such terrestrial shell bed assemblages provide a wealth of data concerning paleoenvironments, paleobiology, potential hydrocarbon reservoirs and diagenetic processes. A channelized shell bed discovered in the Upper Cretaceous Hell Creek Formation contains thousands of specimens representing 8 genera with 20 recognized species. This shell bed provides valuable insight into the paleoecologic and sedimentologic systems of the Hell Creek Formation.

Field data was collected during the summer of 2000. Geologic data was collected for regions laterally and vertically contiguous with the shell bed. Seventeen different lithofacies were identified in the study area on the basis of grain size and sedimentary structures. Lithofacies associations were subsequently determined for the characterization of depositional environments. Architectural element analysis was employed to aid in the recognition of discrete depositional facies. Taphonomic data was collected within the shell bed with a primary focus on the molluskan fauna present. Data collection included taxonomic identification, shell articulation and modification, and shell orientation.

Three distinct deposystems are recognized within the study area. The first is a fluvially dominated channel belt with tidal influence. Moving up-section, the second deposystem is characterized by a transgressing lacustrine system with subsequent clastic infilling. The youngest deposystem represents anoxic small lake and backswamp environments with limited clastic input and significant organic accumulation. The shell bed represents the basal member of a channelized turbidite sequence. Taphonomic and geologic data suggest that the shell bed formed from an event concentration with minimal time-averaging. A high degree of preservation is recorded by a vast majority of the shells.

SEDIMENTOLOGY AND TAPHONOMY OF A SHELL BED ASSEMBLAGE FROM THE UPPER CRETACEOUS (MAASTRICHTIAN) HELL CREEK FORMATION OF EASTERN MONTANA

by

Bentley Edward Shoup

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSUTY
Bozeman, Montana

April 2001

APPROVAL

of a thesis submitted by

Bentley Edward Shoup

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

James G. Schmitt ____________________ 4-19-01
(Signature) Date

Approval for the Department of Earth Sciences

James G. Schmitt ____________________ 4-19-01
(Signature) Date

Approval for the College of Graduate Studies

Bruce McLeod ____________________ 4-19-01
(Signature) Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment for the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowed only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Request for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature ______________________

Date 4-19-01

Acknowledgments

I would like to thank, above all others, Jim Schmitt for acting as a mentor and a friend, for his moral and financial support, for the opportunity to be in the MSU master's program and for being the best advisor a student could ever have. I would like to thank Jack Horner for showing interest in my enthusiasm for paleontology by providing me with a challenging and stimulating project and for providing financial and intellectual support for my field research. I would like to thank Dave Varricchio for providing useful information about presentation of data, taphonomic issues and his never-ending endeavors as the backbone of the "Boneheads" over the past few years. I would also like to thank Joe Hartman for aiding in the identification of mollusks as well as his stimulating comments in the field. My field data collection was significantly mediated by the labor provided from the members of the Montana Conservation Corps. My colleagues, Jeff LaRock and Joe Cooley, as members of the high court of the graduate office, provided substantial academic advice as well as the indulgence of inebriating circumstances. I need to thank Al for being Al – and for allowing me to Americanize him, although he may not ever be the best horseman. I also extend my thanks to the other graduate students who helped and harassed me – Jim, Chuck, and Cal. Thank you to the members of my family who have been supportive of my goals. Most of all, I especially thank Kerri for understanding I love what I do and for sticking around. I know how much she just loves when I leave for the field season. Thanks to everyone who has helped me get this far.

TABLE OF CONTENTS

TABLE OF CONTENTS – CONTINUED

TABLE OF CONTENTS – CONTINUED

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES – CONTINUED

ABSTRACT

Aggregate shell bed accumulations within coastal marine sediments are numerous and have been thoroughly studied. In contrast, terrestrial shell bed assemblages have received less attention due to their paucity within the existing strata. Such terrestrial shell bed assemblages provide a wealth of data concerning paleoenvironments, paleobiology, potential hydrocarbon reservoirs and diagenetic processes. A channelized shell bed discovered in the Upper Cretaceous Hell Creek Formation contains thousands of specimens representing 8 genera with 20 recognized species. This shell bed provides valuable insight into the paleoecologic and sedimentologic systems of the Hell Creek Formation.

Field data was collected during the summer of 2000. Geologic data was collected for regions laterally and vertically contiguous with the shell bed. Seventeen different lithofacies were identified in the study area on the basis of grain size and sedimentary structures. Lithofacies associations were subsequently determined for the characterization of depositional environments. Architectural element analysis was employed to aid in the recognition of discrete depositional facies. Taphonomic data was collected within the shell bed with a primary focus on the molluskan fauna present. Data collection included taxonomic identification, shell articulation and modification, and shell orientation.

Three distinct deposystems are recognized within the study area. The first is a fluvially dominated channel belt with tidal influence. Moving up-section, the second deposystem is characterized by a transgressing lacustrine system with subsequent clastic infilling. The youngest deposystem represents anoxic small lake and backswamp environments with limited clastic input and significant organic accumulation. The shell bed represents the basal member of a channelized turbidite sequence. Taphonomic and geologic data suggest that the shell bed formed from an event concentration with minimal time-averaging. A high degree of preservation is recorded by a vast majority of the shells.

CHAPTER 1

INTRODUCTION

Studies of large shell bed accumulations in coastal marine deposits are numerous (Fursich and Flessa, 1987; Kidwell and Bosence, 1991; Kidwell,1991). However, in the terrestrial realm large accumulations of shelly fauna receive less attention. This is unfortunate, in that such shell deposits may provide a wealth of information regarding depositional environments (Elliot, 1978), implications for paleobiologic populations (Hartman and Kihm, 1996), and even reservoir data in exploration for hydrocarbon resources (Chatfield, 1972). Terrestrial depositional settings lack extensive lateral continuity of individual deposits. For this reason, large shell bed accumulations are inherently useful as both stratigraphic position markers and tools for unraveling deposystems (Russell, 1976). However, the paucity of literature dealing with terrestrial shell beds may simply be a reflection of the scarcity of such deposits. Taphonomic processes that affect such shell accumulations play a commanding role in their potential for preservation.

The taphonomic history of a shell accumulation is successfully reconstructed by interpreting specific features of the shells themselves, in addition to characterizing the depositional environment (Behrensmeyer and Kidwell, 1985). A confident interpretation of the depositional environment begins with a detailed lithofacies analysis of the shell-bearing unit, as well as all the surrounding strata (LaRock, 2000). Associations of these lithofacies are subsequently used to characterize the depositional setting of the shell accumulation. In understanding the processes of accumulation, inferences may be made concerning paleo-ecosystems. In an attempt to obtain the most useful information from the assemblage, detailed investigation of the shells must be undertaken while they remain *in situ*.

Individual shells and small shell assemblages are common in the Upper Cretaceous Hell Creek Formation (Maastrichtian) of Montana. Many of these occurrences were initially described in the early 1900's when the geology and paleontology of the formation was first explored (Brown, 1907). However, large cumulate shell beds are much less common, especially when associated with vertebrate remains and a noticeable amount of organic material. To date, little to no work has been done on large shell accumulations in the Hell Creek Formation with respect to paleoecologic implications. In the 1999 field season of the Hell Creek Project in association with the Museum of the Rockies, a very conspicuous shell assemblage was discovered. Such an assemblage provokes interest in the sedimentary processes that occurred, taphonomic features responsible for preservation, and implications for the paleoecology of the system.

The purpose of this study is to determine the depositional environment and taphonomic processes responsible for the accumulation of the shell bed. In specific, goals addressed by this research include determining: (1) the depositional environment of the shell bed as well as laterally and vertically contiguous strata by implementing detailed lithofacies analysis, (2) the stratigraphic position of the shell bed with respect to the K-T boundary (Z-coal), (3) degree of shell modification, (4) process(es) responsible for the shell accumulation, (5) amount of time represented by the assemblage.

Location and Geologic Setting

The shell bed is located on Bureau of Land Management property adjacent to the Charles M. Russell Wildlife Refuge in Garfield County, approximately 24 miles north of Jordan, Montana and about 3.5 miles south of the Hell Creek Recreation Area on Fort Peck Reservoir (Figure 1). The shell bed is exposed in badlands topography at the base of a large domed hill immediately to the west of the unimproved School Section Divide Road (Figure 2).

Stratigraphically, the shell bed is located in the Upper Cretaceous (Maastrichtian) Hell Creek Formation, deposited during the final stages of the Cretaceous Period (Figure 3). The formation is exposed around the Fort Peck Reservoir in eastern Montana (Figure 4), and represents a regressive systems tract of the Western Interior foreland basin in terms of sequence stratigraphy of continental strata (Kaufman and Caldwell, 1993; Shanley and McCabe, 1994). During the transition from Cretaceous to Tertiary time, a combination of forced regression and loss of accommodation space limited sediment progradation. Sediments within the Western Interior basin began to aggrade. The sediment supply to the basin also decreased during this transition, reflected by an increase in organic sedimentation with the respective decrease in terrigenous clastic sedimentation (Ayers, 1986). A paleoenvironmental change is observed in the stratigraphy from a fluvially dominated to a swampy lacustrine system in the upper third of the section.

The Hell Creek Formation as whole is time-transgressive, demonstrating minimal lateral continuity of strata. The formation is bounded below by the Cretaceous Fox Hills Sandstone and above by the Tertiary Tullock Formation in eastern Montana (Figure 3).

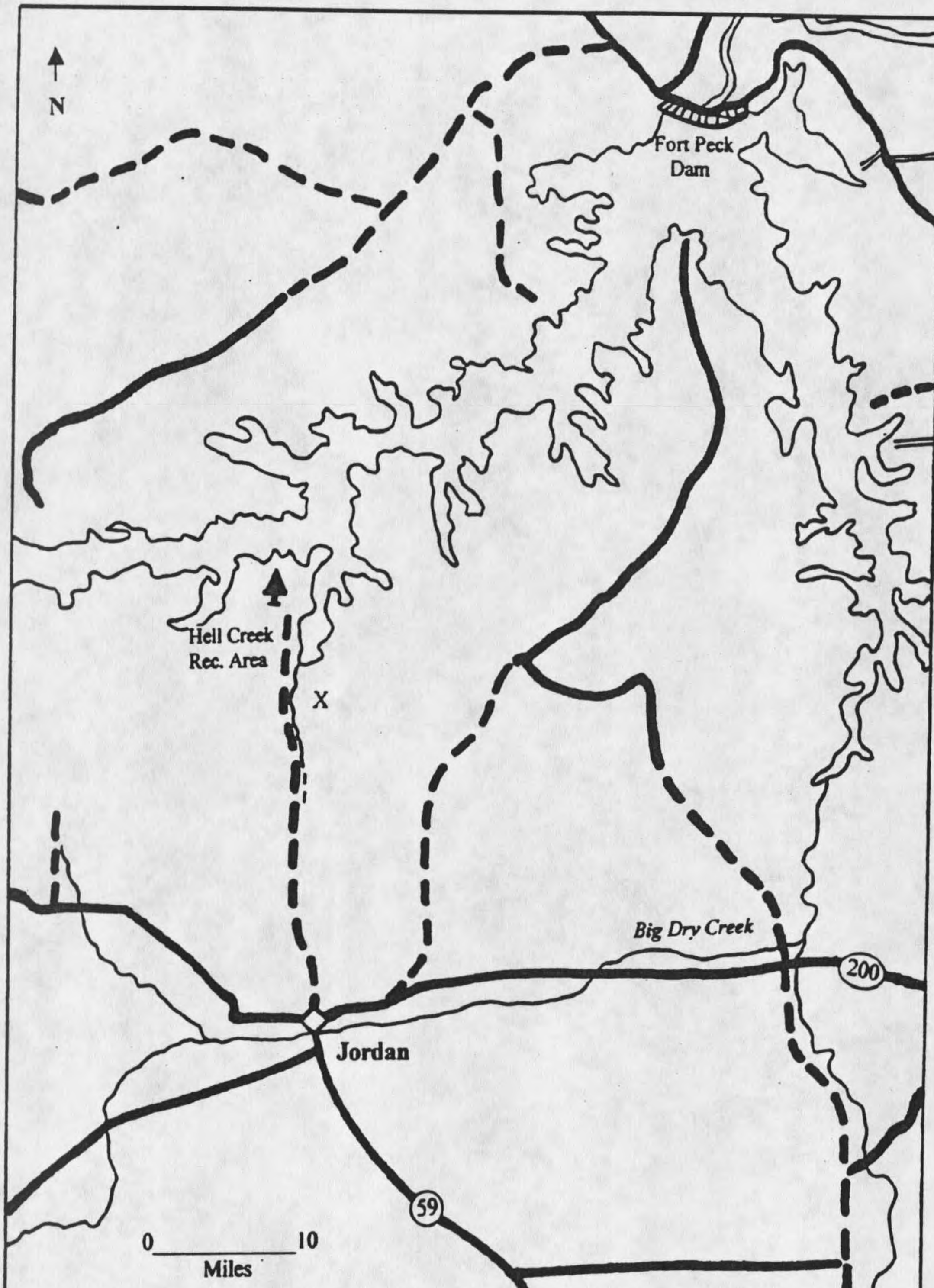


Figure 1. Regional location of the shell bed (X) in eastern Montana.

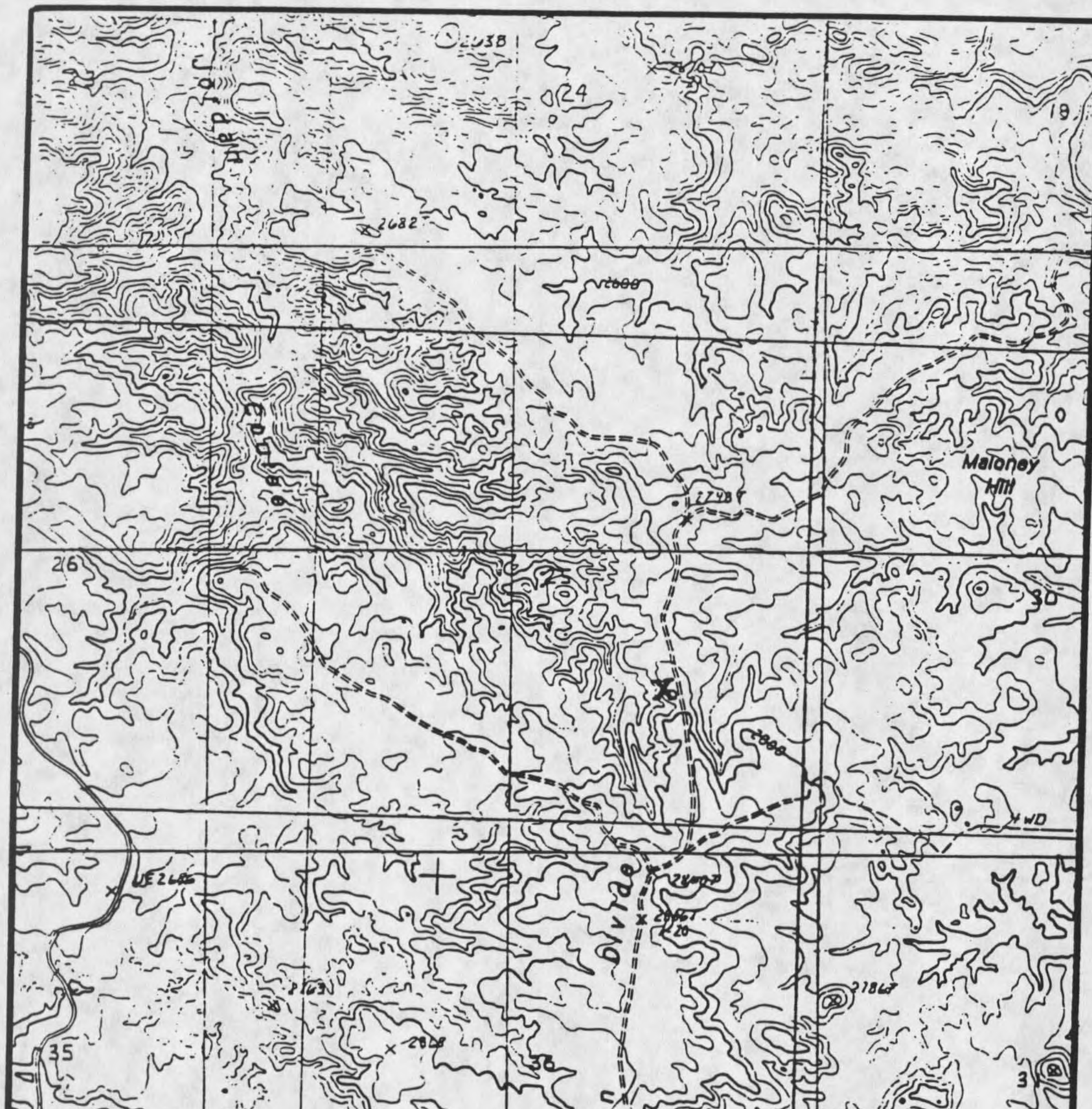


Figure 2. Topographic setting of the study area containing the shell bed. Shell bed is marked by the X. Scale = 1:24,000 (Maloney Hill Quadrangle)

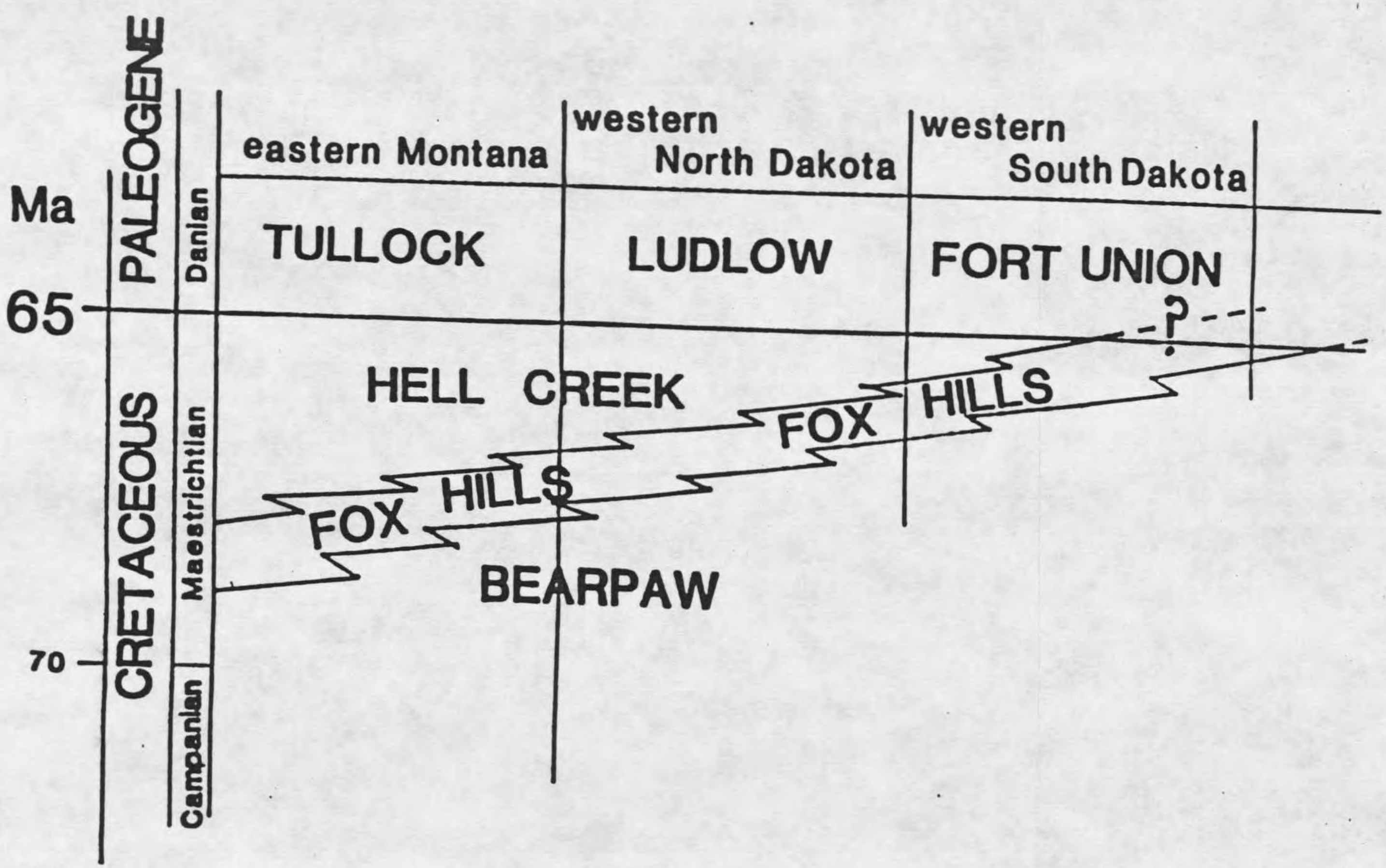


Figure 3. Stratigraphic position and relationships of the Hell Creek Formation (Fastovsky, 1986a).

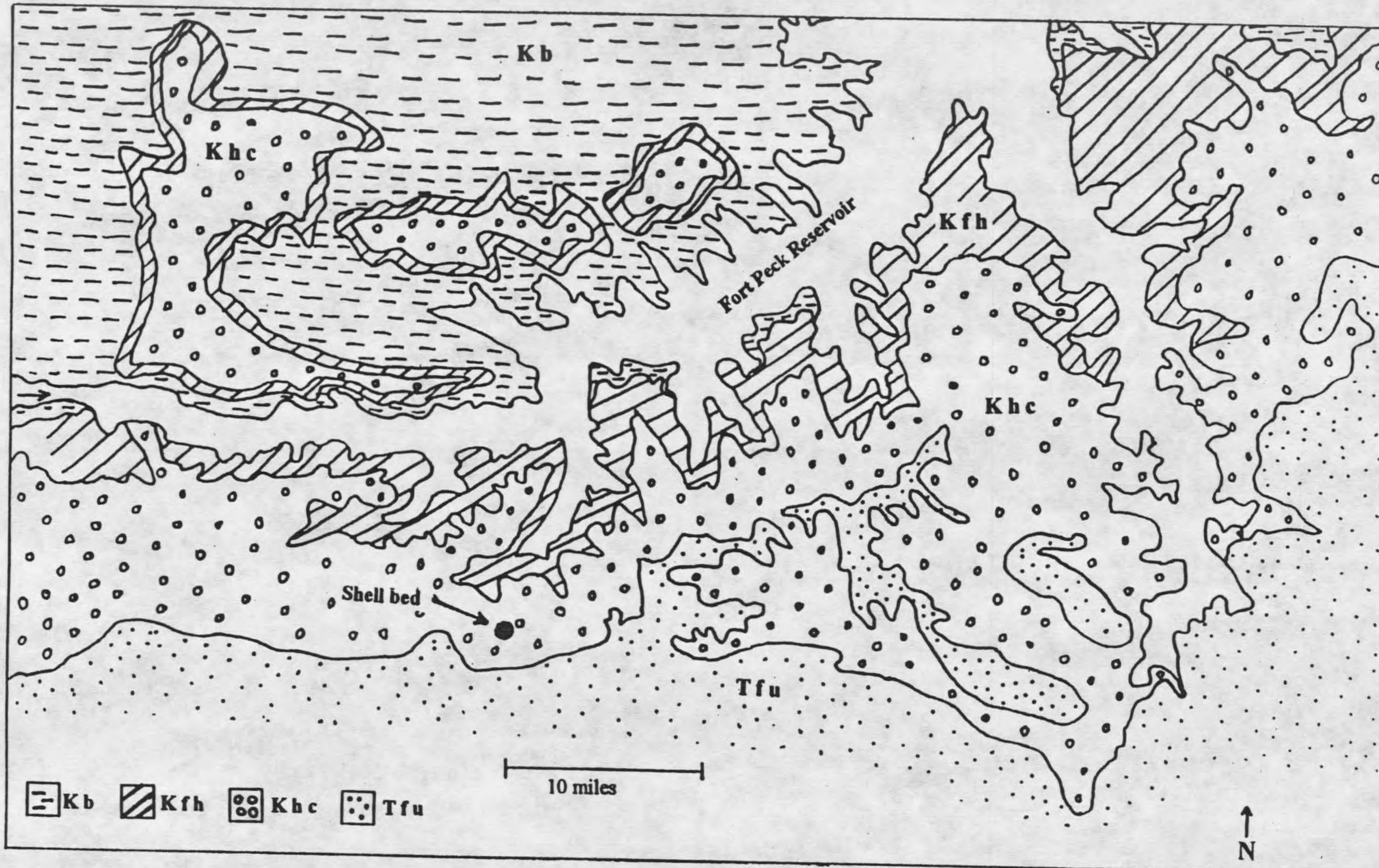


Figure 4. General geologic mapof the study region compiled from Ross et al. (1955). Formations exposed: K b - Bearpaw Shale, K f h - Fox Hills, K h c - Hell Creek, T f u - Fort Union.

Further East, in North Dakota, the upper contact occurs with the Tertiary Ludlow Formation, a Tullock and Fort Union equivalent (Brown, 1952).

In the study area, approximately 22 meters of the uppermost portion of the Hell Creek Formation are exposed. Where present, less than 3 meters of the Tullock Formation is exposed. A wide variety of lithologies are present within these formations, including conglomerate, sandstone, siltstone, mudstone, claystone and coal. Fossil remains encompass a wide array of organisms from dinosaurs and turtles to mollusks and plants.

Methods

Fieldwork was carried out during the summer of 2000, from late May through early August. Detailed studies of sedimentology, taphonomy and paleoecology were performed to accurately interpret the deposit. The first few days involved a general overview of the study area, creating a spatial understanding of the deposit. A 360-degree photo mosaic of the terrain surrounding and including the shell bed was produced for later interpretation of interfingering strata.

Active excavation first involved the collection of taphonomic data from the shell bed. Since the top of the shell bed created a flat pediment surface, it made detailed excavation possible. The excavation pit was approximately 1 meter wide and 0.4 meters deep, encompassing the vertical extent of the shell bed. Initially, the assemblage was photographed and described as a whole unit in vertical outcrop. Next, the unit was dissected 1cm at a time. By using this discrete method of excavation, subtle changes within the assemblage, not seen in outcrop, could readily be observed. Individual specimens were carefully collected using brushes, ice picks and dental tools. Specimens were covered with a thin coating of hardener to prevent damage. Samples that were collected for thin section analysis did not get coated with any hardener. Taphonomic data collected include degree of articulation, degree of preservation, size distribution, orientation of shells, identification of taxa (Hartman, 2000, pers. com.), sediment texture and composition, and detailed descriptions of non-molluskan fauna and flora present.

After excavation, the unit was traced out in an attempt to determine lateral extent, interfingering lithofacies and unit geometry. Stemming from this endeavor, detailed stratigraphic sections were measured in four different localities. In badly weathered outcrops, trenches were made at least 30cm deep in order to obtain an accurate depiction of the sediment. Volunteers from the Montana Conservation Corps were enlisted to aid in the creation of many exceedingly useful trenches. Careful attention was paid to produce complete lithofacies descriptions based on procedures from Miall (1985). This included in-depth descriptions of grain size and composition, texture and sedimentary structures. Many of these lithofacies were also photographed. In a further attempt to understand the architectural elements, the nature and geometries of contacts were also intensely observed and described. In many localities, lateral correlatives could not successfully be determined due to the presence of massive ferruginous concretions.

After all necessary field data were collected, data compilation and laboratory analyses were performed. First, individual lithofacies were conscribed into lithofacies associations needed for paleoenvironmental interpretations. Taphonomic observations were also characterized for interpretation. These observations included the biologic range and specifics of taxa present within the assemblage with regard to classification, maturity and stratigraphic range. The abundance of individual species of mollusks was also noted.

CHAPTER 2

LITHOFACIES

The Hell Creek Formation is composed of several major lithologies within the area of study, none of which appear conspicuously dominant. Lithologies include conglomerate, sandstone, siltstone, mudstone, claystone and lignite coal. Eighteen different lithofacies are described based on grain size and sedimentary structures. These lithofacies include conglomerates described in Table 1, fine-grained clastics and non-clastics described in Table 2, and sandstones described in Table 3.

Conglomerate Lithofacies

Massive Matrix-Supported Intraformational Conglomerate (Gmmi)

Description. This massively bedded, sandy, matrix-supported, conglomerate is derived from within the formation (Figure 5a). The matrix is a fine-grained, well sorted sublitharenite. The clasts contain sand of the same composition in addition to a mud constituent, consequently named a sandy-mudstone. The clasts range from spherical to elliptical in form, are well rounded to subrounded and have no preferred orientation. Clasts range form 2cm to 8cm in maximum length. This lithofacies (Gmmi) conformably overlies both ripple cross-laminated sandstone (Sr) and wave-ripple cross-laminated sandstone (Swr). The upper contact cannot be found within the field area due to the lack of outcrop exposure.

CONGLOMERATE LITHOFACIES		
Lithofacies		**Description**
Gmmi	Massive matrix-supported intraformational conglomerate	Matrix: well sorted, fine-grained sand; clasts: well-subrounded sandy mudstones, spherical-elliptical in form, 2cm-8cm in maximum length, randomly oriented; unit: ungraded, massive, conformable lower contact
Gbcm	Massive bioclast-supported polytypic conglomerate	Matrix: poorly sorted, medium-grained sand to mud; clasts: >95% mollusk shells ranging form large pelecypods (~10cm) to small gastropods (<0.3cm), dinosaur bone fragments, champsosaur, turtle, crocodile and gar remnants are rare; unit: may contain organics, fines crudely upward

Table 1. Summarized lithofacies descriptions for conglomerates.

FINE-GRAINED CLASTIC AND NON-CLASTIC LITHOFACIES		
Lithofacies		**Description**
Fl	Interlaminated very fine-grained sand, silt, and mud	Individual lamina range from 0.5cm-2cm thick, unit thickness ranges from 0.3m to 1.25m, lacks bioturbation and rootlets, laminated organic fragments common
Fs	Siltstone	Typically massive, 5cm-60cm thick, organic content is variable, color varies
Fmm	Massive mudstone	Beds range from 4cm-60cm, widely variable organic content, light to dark gray
Fml	Laminated mudstone	Unit thickness is 4cm-120cm, organics very common, gray, brown and purple
Fcl	Laminated claystone	Unit thickness is 4cm-25cm, organics always present, dark brown to light gray
C	Lignitious coal	Laminated and loosely condensed, very dark brown to black

Table 2. Summarized lithofacies descriptions for fine-grained clastic and non-clastic deposits.

SANDSTONE LITHOFACIES		
Litofacies		**Description**
Sh	Horizontally stratified sandstone	Occurs in medium-grained, well sorted sand, contacts may be sharp or gradational, commonly associated with facies Sm, may be intercalated with facies Shes
St	Trough cross-stratified sandstone	Occurs in coarse to medium-grained, moderately to well sorted sand, organics are common, St found within facies Seh, lower contact may be associated with facies Se
Sr	Ripple cross-laminated sandstone	Occurs in medium to fine-grained, well sorted sand, angle of climb varies from low to nearly vertical, contacts may be abrupt to gradational but never erosive
Shes	Hummocky cross-stratified sandstone	Occurs in medium-grained, well sorted sand, irregular swaley appearance, typically Intercalated with facies Swr and sometimes facies Sh, may be only facies present
Sm	Massive sandstone	Usually occurs in medium-grained sand, may occur in fine sand, 0.3m to 2m thick, lacks bedforms or grading, contacts are highly variable
Se	Erosional scouring sandstone	Occurs in coarse to fine-grained, moderate to well sorted sand, mud rip-up clasts always present, ~2cm to 10cm thick, lower contact typically convex
Seh	Heterolithic epsilon cross-stratified sandstone	Occurs as a couplet between sand and mud, sand ranges form moderately sorted, coarse-grained to well sorted, medium-grained, frequency of low angle mud drapes on sands increases upward, sand grain size decreases upward, muds typically contain high percentage of organics
Swr	Wave ripple cross-laminated sandstone	Occurs in medium-grained, well sorted sand, contains bidirectional sets which create symmetrical wave crests, typically associated with facies Shes and facies Sr
Smi	Sandstone with amorphous to stringy mudstone intraclasts	Occurs in medium-grained, well sorted sand, contains varying sizes of mud intra-clasts which may be amorphous blobs to sinusoidal ribbons, 20cm to 40cm thick, sand is pushed into the mud at the lower contact

Table 3. Summarized lithofacies descriptions for sandstones.

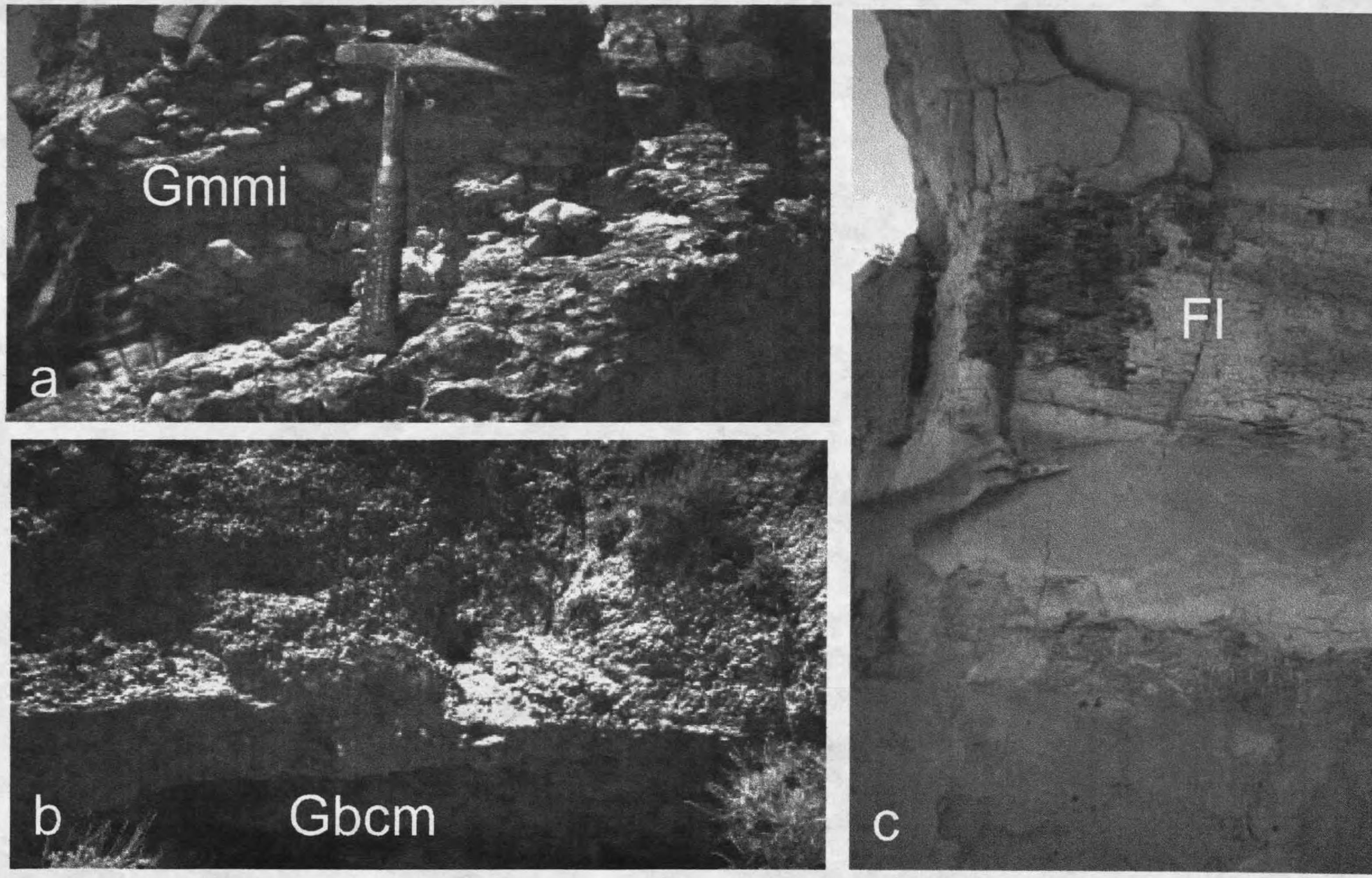


Figure 5. Lithofacies seen in outcrop: a.) massive, matrix-supported, intraformational conglomerate, b.) massive, bioclast-supported conglomerat, c.) interlaminated sand, silt and mud

Interpretation. This intraformational conglomerate is interpreted to have formed by penecontemporaneous deformation of subaqueous semi-consolidated sediment with consequent redeposition fairly close to the site of deformation (Boggs, 1995). Causes include storm waves and sediment gravity flows. Further interpretation, based on random clast orientation, the absence of bedding or grading and the high proportion of mud to sand within the clasts suggests a cohesive sediment gravity flow (Nemec et al., 1984).

Massive Bioclast-Supported Polytypic Conglomerate (Gbcm)

Description. This lithofacies occurs in only one stratigraphic position locally, ranging from 15cm to 25cm in thickness. The matrix is a poorly sorted association of grain sizes encompassing everything from mud to medium-grained sand (Figure 5b). The clasts are composed almost exclusively of mollusk shells which range in size from large pelecypods (~10cm) to very small gastropods (< 0.3cm). Other clasts, although exceedingly rare, include badly weathered ceratopsian bone fragments as well as turtle, champsosaur, crocodile and gar remnants. A significant portion of plant material is also present in this lithofacies as both carbonized and charcoal. As a whole, the clasts are randomly oriented illustrating an exceptionally crude fining-upward trend. This lithofacies (Gbcm) possesses an undulating basal contact overlying a deformed siltstone (Fs). The upper contact is a massive, muddy sandstone (Sm) that fines upward into a massive mudstone (Fmm) with an increasing proportion of organic material.

Interpretation. Interpretation for the genesis of this massive, bioclast-supported conglomerate is strongly associated with the overlying lithofacies and the nature of the

Trough Cross-Stratified Sandstone (St)

Description. Trough cross-stratified sandstone in the study area comprises coarse to medium-grained sand that is moderately to well sorted. Organic material is common, including whole leaves, fig-like fruits and small plant debris. The manner in which this lithofacies occurs is fairly unusual. Single sets and cosets are contained within the heterolithic epsilon cross-stratified lithofacies (Seh). The lower contact in this area is exclusively erosional, dissecting mudstones and incorporating flat, disk-like rip-up clasts. This contact will be described herein as an erosional sandstone lithofacies (Se). The upper contact of individual sets, where observable, is a thin, organic rich mudstone stringer, part of the heterolithic epsilon cross-stratified lithofacies (Seh). The uppermost contact of the unit as a whole is badly weathered, cropping out on a vertical cliff face. Subsequently, this contact could not be accurately described.

Interpretation. Trough cross-stratified sandstone, occurring under low flow regime conditions, is interpreted to be produced by the migration of subaqueous dunes (Miall, 1977). The organic matter present represents plant material that accumulated on the lee side of dunes, readily positioned for rapid burial.

Ripple Cross-Laminated Sandstone (Sr)

Description. Ripple cross-lamination occurs in fine to medium-grained, well sorted sandstone (Figure 6a). The crests of the ripples are asymmetric. The angle of climb for sets within cosets varies from low to nearly vertical. Contacts may be gradational or abrupt, but are never erosional. This lithofacies is seen in thin sandstone sheets, at the top of and within massive sandstones (Sm), as well as associated with wave ripple cross

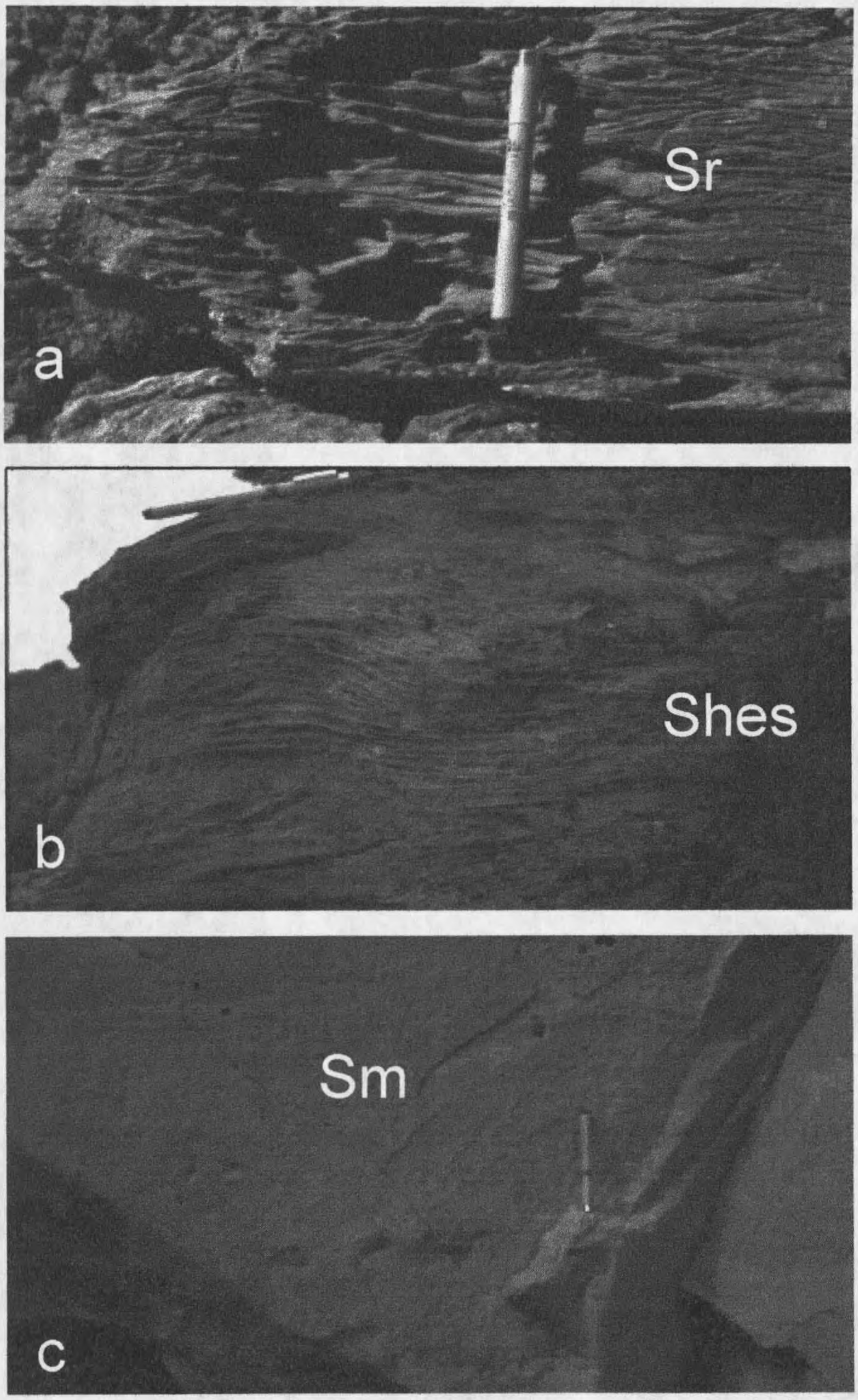


Figure 6. Lithofacies in outcrop: a.) ripple cross-lamination, b.) hummocky cross-stratification, c.) massive sandstone.

lamination (Swr). Upper and lower contacts vary significantly, including anything from conglomerates (Gmmi) to mudstones (Fml, Fmm).

Interpretation. Sandstones containing ripple cross-lamination are interpreted to have formed under low flow regime conditions, produced by the migration of subaqueous ripples in shallow water (Miall, 1977). The asymmetric crests are indicative of unidirectional flow.

Hummocky Cross-Stratified Sandstone (Shes)

Description. This lithofacies is found in medium-grained, well sorted sandstone. Strata are irregular and swaley in shape (Figure 6b). Hummocky cross-stratified sandstone is typically intercalated with wave ripple cross-laminae (Swr) and sometimes with horizontal stratification (Sh). In some sandy beds, this is the only facies present.

Interpretation. Oscillating wave currents and combining flows of unidirectional and oscillatory currents typically produce hummocky cross-stratified sandstones (Cheel and Leckie, 1993). Storm conditions producing swales in shoreface and offshore environments often deposit this lithofacies (Shes) (Walker and Bergman, 1993).

Massive Sandstone (Sm)

Description. Massive sandstone lacks sedimentary structures and grading. It typically occurs in medium-grained sandstone, but fine-grained units are present (Figure 6c). Bed thickness varies from 0.3m to ~2m. Upper contacts are usually gradational, although some may be abrupt. Common associations include ripple cross-laminated (Sr) and horizontally stratified sandstones (Sh). Less common, but still present, is the association of siltstones (Fs) and mudstones (Fmm, Fml). Lower contacts demonstrate both sharp and gradational transitions. Gradational transitions with massive sandstone containing stringy, amorphous mudstone intraclasts (Smi) are quite common. In at least one stratigraphic locality, this facies (Sm) grades downward into an erosional scouring sandstone containing elongate pebble-like mud chips (Se). It is also common to find small (<5cm) limonite concretionary spheres within this lithofacies (Sm).

Interpretation. The formation of massive sandstone has several interpretations. This facies (Sm) may be the result of sediment gravity flows, bank collapse in small channels or postdepositional modification induced by bioturbation and dewatering (Miall, 1996). More simply, massive sandstones may be the result of the weathering profile of the outcrop in that sedimentary structures may not be visible.

Erosional Scouring Sandstone (Se)

Description. Erosional scouring occurs in coarse-grained to fine-grained, moderate to well sorted sandstones. Intraformational rip-up clasts are always present. Rip-ups are commonly flattened elliptical pebble-sized mudstones. This facies (Se) may be up to ~30cm thick but is commonly very thin at less than 10cm. It is exclusively underlain by mudstone (Fmm, Fml) everywhere within the study area. The upper contact is always gradational with trough cross-stratified sandstone (St) or massive sandstone (Sm). This facies may also be interstratified with trough cross-stratified sandstone (St).

Interpretation. Erosional scouring sandstones are interpreted to form from channel avulsions dissecting floodplain overbank deposits, such as siltstones (Fs) and mudstones (Fmm, Fml) (Rust, 1978).

Heterolithic Epsilon Cross-Stratified Sandstone (Seh)

Description. Epsilon cross-stratification occurs as a heterolithic intercalated couplet comprising two major lithologies, sandstone and mudstone (Figure 7a). The sandstone ranges from moderately sorted, coarse-grained sand to well sorted, medium grained sand. The mudstone typically contains a high percentage of laminated plant material. The epsilon cross-stratification is formed by intervals of low angle mudstone stringers within the sandstone. These mudstone stringers vary in thickness from ~2cm to ~6cm. The frequency of thick to thin mudstone stringers increases towards the top of the unit. The unit, as a whole, fines upward from coarse-grained to medium-grained sandstone. In this lithofacies (Seh) the sandstone component consists of trough cross-stratification (St) which is present between the mudstone stringers. The lower contact is gradational into the erosional scouring sandstone facies (Se). The upper contact is interlaminated very fine sand, silt and mud (Fl).

Interpretation. The heterolithic epsilon cross-stratified facies has been interpreted by Smith (1987) to represent lateral accretion of point bars in a low energy fluvial system with microtidal to mesotidal influence. All of the criteria presented by Smith for this deposystem are present in this facies (Seh). The mudstone drapes were deposited out of suspension on the lateral accretion surfaces when flow was mediated by the element of tidal influence (Jackson, 1981).

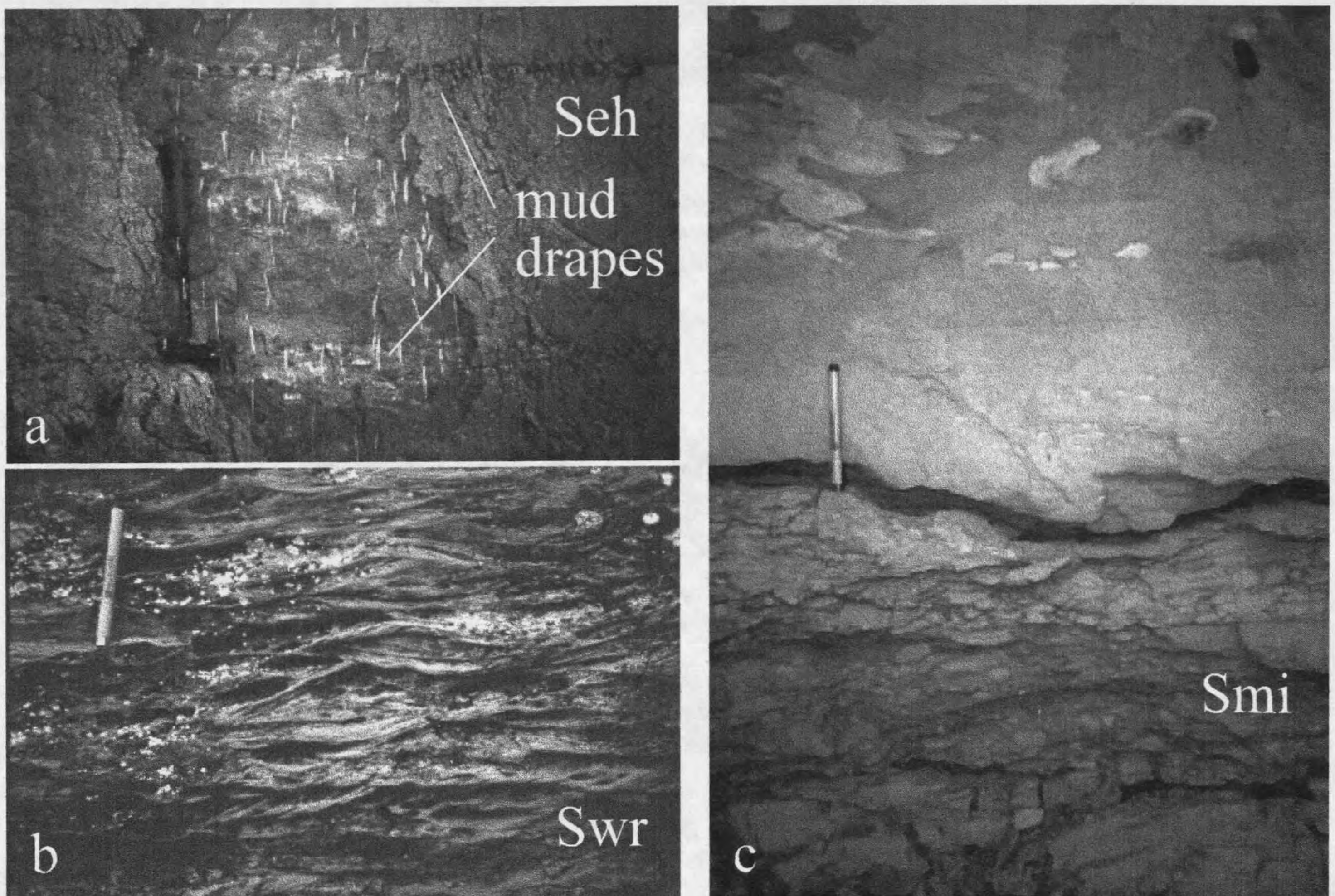


Figure 7. Lithofacies in outcrop: a.) heterolithic epsilon cross-stratification, b.) wave ripple cross-lamination, c.) sandstone with amorphous to stringy mudstone intraclasts.

Wave Ripple Cross-Laminated Sandstone (Swr)

Description. Wave ripple cross-lamination occurs in medium-grained, well sorted sandstone (Figure 7b). This bedform exhibits symmetrical ripple crests with equal angles of repose on both the lee and stoss sides. Different unidirectional sets combine to form the bidirectional wave ripple cross-laminae. This lithofacies is commonly found interstratified with hummocky cross-stratification (Shes) and ripple cross-lamination (Sr). The lower contact, exclusively gradational, may be massive sandstone (Sm) or hummocky cross-stratified sandstone (Shes). The upper contact is eroded everywhere in the field area except one locality. At that location, the upper contact is a non-erosional intraformational conglomerate (Gmmi).

Interpretation. Wave ripples form in shallow water under the influence of bidirectional, oscillatory motion for which the forward and backward orbital wave velocities are equal (Clifton, 1976). If the difference between backward and forward wave velocities is less than 1cm/s, symmetrical ripples develop. If the orbital velocity exceeds 5cm/s asymmetric ripples develop. Clifton (1976) suggests that symmetrical wave ripples typically occur within a sequence of bedforms. The sequence grades from symmetrical wave ripples in deeper water to asymmetrical ripples, lunate megaripples (hummocks) and planar flat beds in a landward direction as seen in oceans and lakes.

Sandstone with Amorphous to Stringy Mudstone Intraclasts (Smi)

Description. This lithofacies occurs with massive, medium-grained, well sorted sandstone and massive mudstone (Fmm). The sandstone contains varying size ranges of mudstone intraclasts (Figure 7c). The intraclasts may be large amorphous blobs or gradational. The sharp contact, which is conformable and non-erosive, occurs with massive sandstone (Sm). At the gradational contact, this facies (Fl) fines upward into a laminated mudstone (Fml).

Interpretation. Several interpretations exist for this facies. In fluvial systems, interlaminated very fine sand, silt and mud (Fl) has been interpreted as overbank regions representing suspension deposition and weak traction currents (Miall, 1996). In fluvio-lacustrine environments, this sequence (Fl) has been interpreted as a muddy marsh with occasional fine sand input from bank-breaching events (Smith, 1987). Castle (1990) suggests that this facies (Fl) may represent episodic flooding of mudflats or lacustrine fine-grained sequences affected by occasional storm generated sand pulses.

Siltstone (Fs)

Description. Siltstone in the study area varies a great deal in color, including gray, tan, brown, purple and orange tints. This variation stems from a combination of characteristics, such as organic content, mineralogy, weathering, oxidation and diagenetic processes. Thickness ranges from ~5cm to 60cm. The upper and lower contacts also exhibit a significant degree of variation. Lower contacts may be massive sandstone (Sm) or mudstone (Fmm, Fml), depending on whether the siltstone is part of a fining-upward or coarsening-upward sequence. The same is true for the upper contact. However, the upper contact may also be erosive in some localities. In this case, massive sandstone (Sm) dissects the siltstone (Fs).

Interpretation. Siltstone is interpreted to have settled out of suspension in standing water (Reading, 1996). Generally, the thicker the unit, the deeper the water. Following this, thick siltstone beds (> 25cm) were likely deposited from lake water while thin siltstone beds (< 10 cm) and laminae were likely deposited in fluvial overbank floods.

Massive Mudstone (Fmm)

Description. Massive mudstone illustrates a narrow margin of colors, just shades of gray. The amount of organic content varies widely within the study area. This facies (Fmm) occurs in two associations. First, massive mudstone may have an erosional upper contact with either trough cross-stratified sandstone (St) or massive sandstone (Sm) creating the scouring erosional sandstone facies (Se). Second, massive mudstone (Fmm) may have an undulating, but non-erosive, upper contact with hummocky cross-stratified sandstone (Shes). The lower contact is with siltstone, hence the massive mudstone is part of a fining-upward sequence. Bed thickness ranges from a few centimeters to ~60cm.

Interpretation. Massive mudstone is interpreted to have settled out of suspension in standing water. Depending on thickness, this facies may have either fluvial or lacustrine origins. In a fluvial system it (Fmm) may be part of overbank levee and floodplain deposits (Miall, 1977). However, thick mudstone deposits can also accumulate in lakes from the suspended load and from the upper portion of subaqueous sediment gravity flows (Castle, 1990). The lack of lamination may be due to bioturbation, dewatering or mass event deposition.

Laminated Mudstone (Fml)

Description. Laminated mudstone posses a wide array of colors including variations of gray, brown, and purple. Laminated organic material is usually very common except for one locality. Upper and lower contacts of this facies show dramatic variation throughout the study area. They may be conformable, as part of fine-grained bedding sequences, or erosive, being dissected by scouring sandstones (Se). The thickness of this unit ranges from roughly 4cm to 120cm.

Interpretation. Laminated mudstone is interpreted to be the result of suspension deposition in standing water over finite periods of time. That is, a depositional hiatus occurs between laminae (Reading, 1996). This may occur in marshes or offshore lake environments (Picard and High, 1972), or in fluvial overbank regimes (Miall, 1996).

Laminated Claystone (Fcl)

Description. Laminated claystones are typically dark brown to light gray in color. This facies (Fcl) always contains horizontally laminated organic material, sometimes in excessive amounts (carbonaceous claystone). Individual units of this facies are usually interbedded with siltstone (Fs) and laminated mudstone (Fml). Only in one locality is this facies (Fcl) a thick cap on a fining-upward sequence. In both interbedded units and the fining-upward sequence the contacts are non-erosive and always conformable, whether they be sharp or gradational. Bed thickness for this facies (Fcl) ranges from a few centimeters to 25cm.

Interpretation. Laminated claystone has been interpreted to have formed exclusively in fairly large bodies of standing water by suspension deposition onto the subaqueous basin floor (Picard and High, 1972). High concentrations of organic material and lack of bioturbation indicate anoxic conditions in which bacterially mediated decay could not occur.

Non-Clastic Lithofacies

Lignitious Coal (C)

Description. Lignitious coal, or lignite, is found in only one stratigraphic position in the study area. It is the boundary marker between the Hell Creek Formation (Cretaceous) and the Tullock Formation (Tertiary). This facies is very dark brown to black in color. The coal is typically laminated and loosely packed. No exact thickness could be determined because this unit is the highest point in the study area and its upper contact has been eroded.

Interpretation. Lignitious coal is interpreted to have formed in lacustrine swamp environments (Ayers, 1986). Two conditions had to persist for this to occur: (1) the clastic sediment supply rate should be significantly lower than the supply rate of organic matter; and (2) the accumulation rate of organic matter must exceed the rate of degradation due to inorganic and microbial oxidation (Reading, 1996).

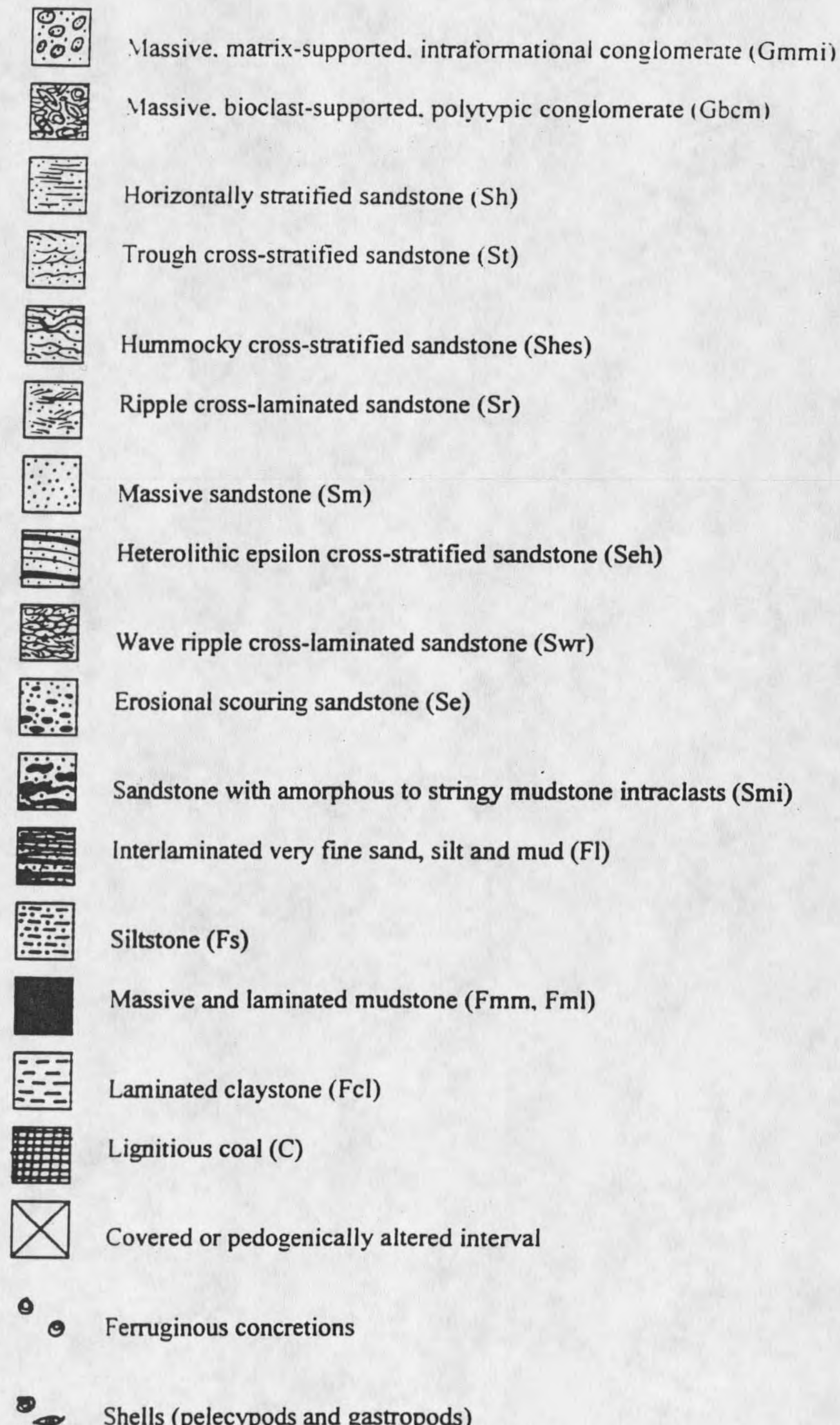


Figure 8. Legend for Lithofacies Associations A-F illustrated in stratigraphic sections.

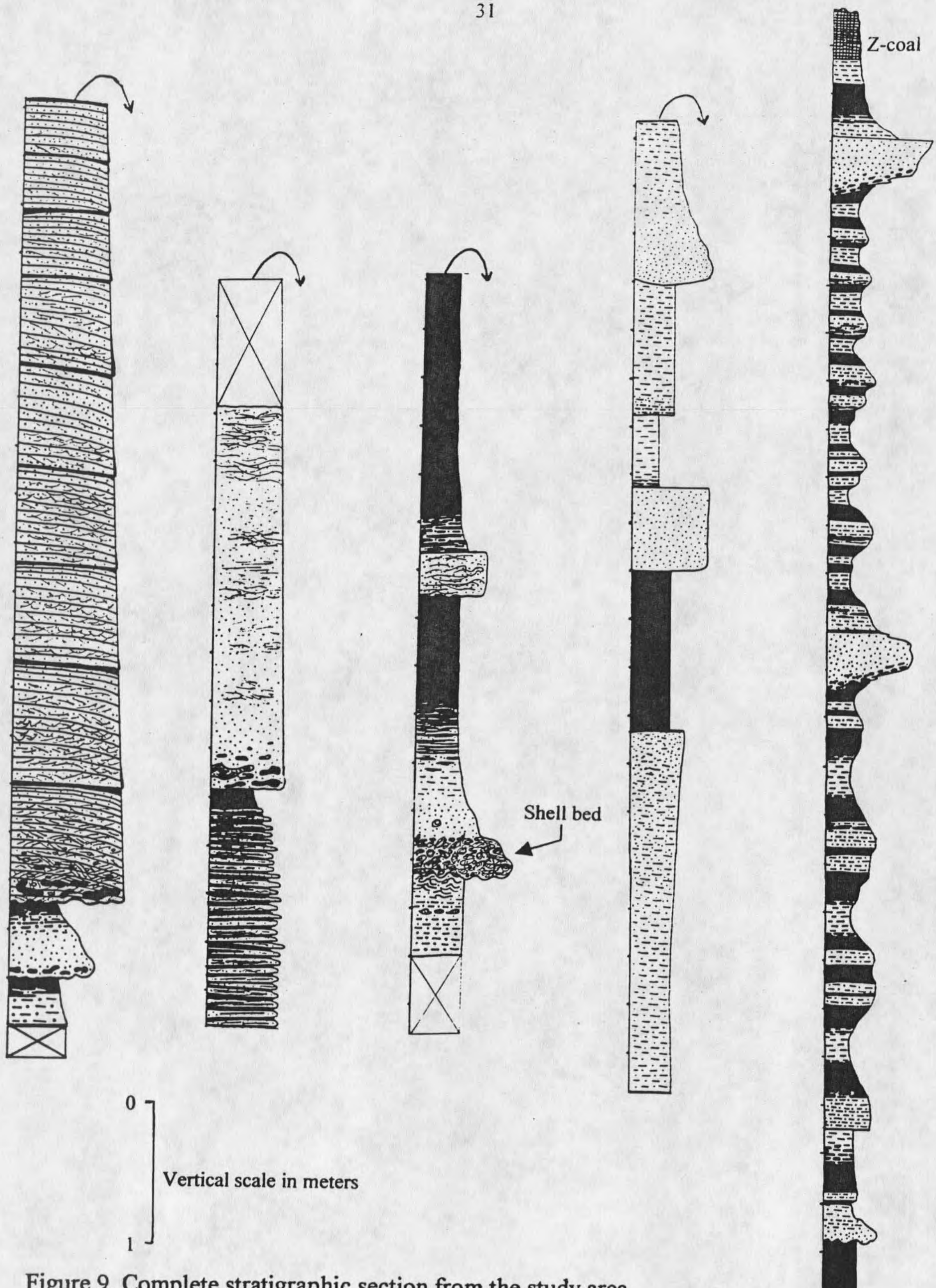


Figure 9. Complete stratigraphic section from the study area.

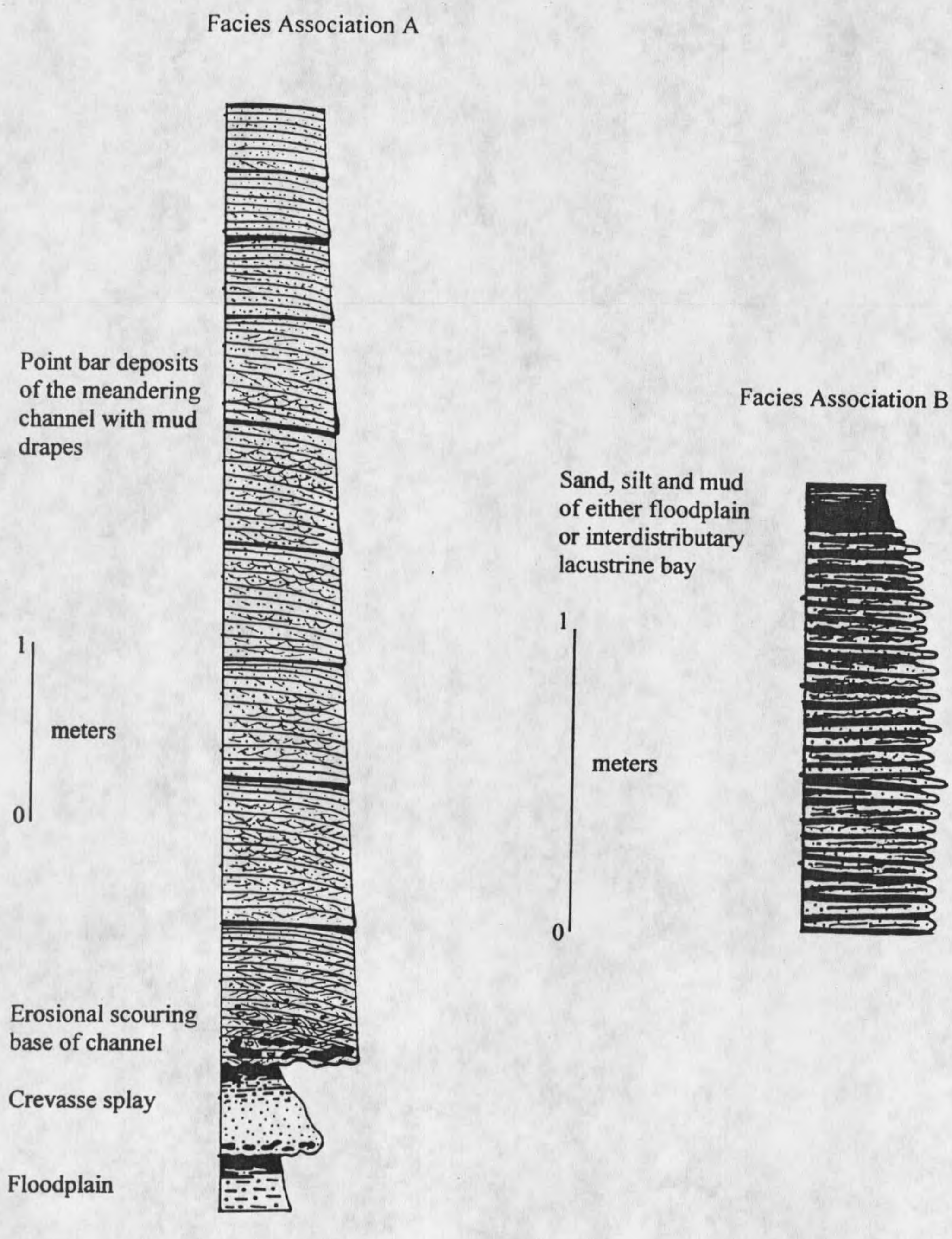


Figure 10. Paleoenvironmental descriptions of stratigraphic sections for facies associations A and B based on lithofacies interpretations.

stratified sandstone (Seh), which incorporates the other two, (Se, St). As a whole, this epsilon cross-stratified sequence is 5.2m thick. Abundant plant fragments are very common within the mud drapes. Organics within the sand are rare.

Interpretation. The lowest unit in facies association A, siltstone (Fs) fining upward to mudstone (Fmm) containing root traces, is interpreted as a distal floodplain overbank region (Fastovsky, 1986b). This interpretation is supported by the massive nature of the sediments, lack of sand sized grains, and the presence of vertical root traces. The next unit up-section, fine-grained, scouring sandstone (Se) normally graded to mudstone (Fmm), is interpreted as a crevasse splay deposit near the source (i.e. channel) (Miall, 1996). This interpretation gains support from the thin nature of the deposit, the normal grading and the presence of fine-grained sand. Finally, the uppermost unit of facies association A, generalized as heterolithic epsilon cross-stratified sandstone (Seh), is interpreted to record lateral accretion of a point bar in a tidally-influenced meandering channel (Jackson, 1981; Smith, 1987; Thomas et al., 1987). The intercalated trough cross-stratification is interpreted as dunes migrating across the lateral accretion surfaces (Smith, 1987). Based on the stratigraphic thickness, the channel was approximately 5 meters deep. This interpretation is highly reinforced by the structure, thickness and vertical facies relations of this unit. Overall, facies association A represents a large meandering channel laterally migrating across a floodplain. The crevasse splay deposit between the floodplain and the channel units marks the incipient lateral migration of the channel.

floodplain associated with a large meandering channel. The second interpretation hinges on the assumption that the lower contact is nonconformable. If so, the sequence of facies association B suggests subaqueous suspension settling with intermittent surges of clastic input. The laminated plant detritus lends significant support to suspension settling. Fastovsky (1986a) suggests that this association represents low energy ponded environments. However, the lateral extent of this facies association (B) is large enough to suggest an environment significantly larger than a pond. A more suitable environment illustrated by this facies association would be an interdistributary bay of a lacustrine margin (Behrensmeyer et al., 1992). The interlaminated sand, silt and mud (Fl) represents the distal transition zone of a lacustrine margin (Castle, 1990). It marks the transition from exclusively lacustrine suspension sediments to transported and wave-worked sediments of the lower shoreface. High concentrations of plant detritus on laminae were deposited out of suspension. Large bodies of water, especially lakes, in humid environments are commonly associated with perimeter swamps (Picard and High, 1972). The plant detritus may have been transported by episodic flood currents passing through marginal swamps, displacing the organics into the lacustrine water column (Davies-Vollum and Wing, 1998). The preservation of this plant material reflects anoxic conditions, hindering bacterial decay (Reading, 1996). Further support for an interdistributary bay of a lacustrine margin stems from the wavy, adulterated laminations. This feature is caused by soft sediment deformation and minor storm reworking (Eugster and Surdam, 1973).

Facies Association C (Figure 11)

Description. Five major and one minor lithofacies compose facies association C. The 5 major lithofacies present always occur in the same order grading up-section. From lowest to highest, they include sandstone with amorphous to stringy mud intraclasts (Smi), massive sandstone (Sm), horizontally stratified sandstone (Sh), hummocky cross-stratified sandstone, and wave ripple laminated sandstone (Swr). The minor lithofacies present, interlaminated sand, silt and mud (Fl), is about 25cm thick and occurs in one locality, intercalated within massive sandstone (Sm). The laminae undulate in thickness and sometimes cannot be distinguished. Individual lithofacies thickness varies widely throughout this facies association. The upper contact of this association (C) forms the modern land surface in the study area, consequently creating speculation as to unit thickness. This facies association as a whole has an accurate thickness measurement in only one locality where it is capped by a conglomerate (Gmmi). Here the thickness is approximately 4 meters. The lower contact, depicted by lithofacies Smi and flame structures, occurs with the laminated mudstone cap (Fml) of facies association B. Minor lateral variations in facies association C are common, yet non-extensive. Eventually, facies association C pinches out to the northeast, where it interfingers with facies association B. This relationship is observed clearly and definitively in outcrop. Outcrops of this sequence do not exist to the west due to erosion and lack of exposure.

Interpretation. Facies association C is interpreted as shoreface lake deposits with distributary bars. This interpretation is heavily supported by the sequence of lithofacies present. Sandy prograding lacustrine shorefaces are described by Castle (1990) to contain

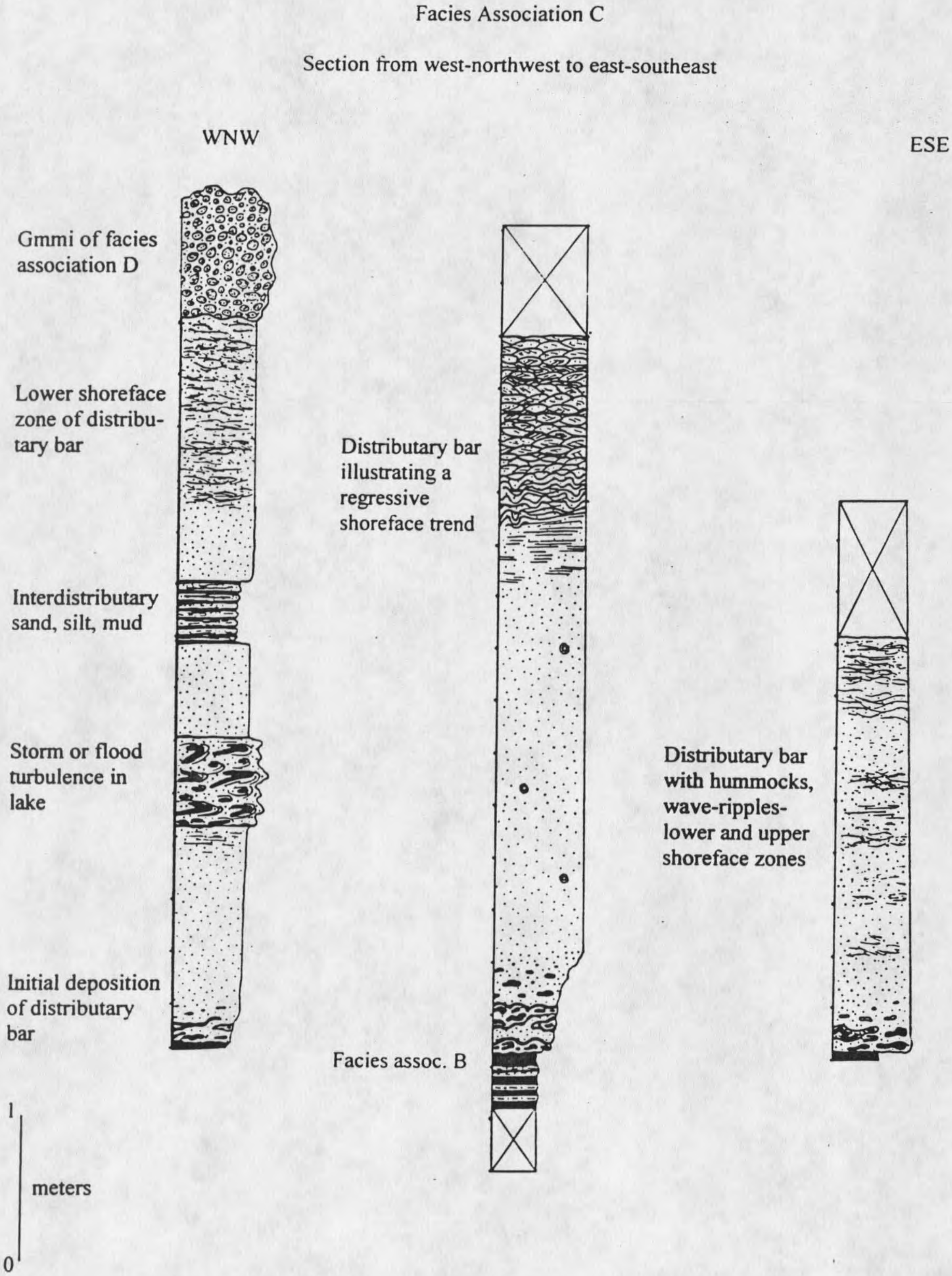


Figure 11. Paleoenvironmental descriptions of stratigraphic sections for facies association C in three localities.

wave ripple cross-lamination, hummocky cross-stratification, and horizontal stratification with respect to increasing energy. These structures were produced primarily by longshore currents and shoaling waves. The wave ripples are found in the lower shoreface, the hummocks in the upper shoreface, and the horizontal beds in the swash zone (Castle, 1990). In the study area, all of these sedimentary structures are present, only in reverse order. This suggests a prograding shoreline (Clifton, 1976). At any stratigraphic position within this facies association, a lateral relationship can be demonstrated supporting this regressive shoreline trend, as long as the sedimentary structures are preserved. The basal contact of this facies association, lithofacies Smi, represents the initial deposition of sand as distributary bars into standing water. The amorphous and stringy muds, along with the flame structures, demonstrate that the underlying mud was saturated during sand progradation, hence indicating a subaqueous environment (Elliot, 1978; Castle, 1990). Moving up-section, massive sandstone (Sm) is the next lithofacies. It composes a majority of facies association C. Expected sedimentary structures are absent, likely reflecting post-depositional bioturbation, reworking and dewatering (Miall, 1996). Higher up section, preserved bedforms suggest rapid burial, excluding reworking wave processes (Wheeler, 1983). The one instance of interlaminated very fine sand, silt and mud (Fl) intercalated with the massive sandstone (Sm) represents a mudflat or lagoon associated with the backshore zone (Eugster and Surdam, 1973). Sediment was deposited in this zone by washover, storm surges and suspended load fallout. This occurrence is local, pinching out laterally within 12 meters.

Facies Association D (Figure 12).

Description. Facies association D is characterized by pulses of fining-upward sequences. Three distinct sequences are found in the study area, two of which have conglomerates at the basal portion. The first is composed exclusively of a massive, matrix supported, intraformational conglomerate (Gmmi). The upper contact is eroded everywhere within the study area. The lower contact occurs with the wave-rippled cap unit of facies association C. This contact is non-erosive. A detailed description of this lithofacies (Gmmi) is provided in Chapter 2. The other two sequences in the study area occur in the same outcrop, one directly above the other. These sequences overly and interfinger with facies association B. The first has an undulating, erosive base composed of a massive, bioclast supported, polytypic conglomerate (Gbcm). The sequence fines upward into massive sandstone (Sm), siltstone (Fs), massive mudstone (Fmm), and finally laminated mudstone (Fml). As grain size decreases, organic content increases significantly. This sequence is about 1.8m thick. Moving up-section, the basal unit of the next sequence is composed of hummocky cross-stratified, medium-grained sandstone (Shes) that erodes the upper lithofacies (Fml) of the lower sequence. This sequence contains more mud than the lower one. The sandstone (Shes) fines rapidly upward from siltstone (Fs) to massive mudstone (Fmm) then laminated mudstone (Fml). This sequence is 1.9m thick and is conformably capped by a siltstone (Fs).

Interpretation. Facies association C is interpreted as cohesive, subaqueous sediment gravity flows (Nemec et al, 1984; Bouma et al., 1985; Normark and Piper, 1991). In the first sequence, the massive, matrix supported, intraformational

Facies Association D

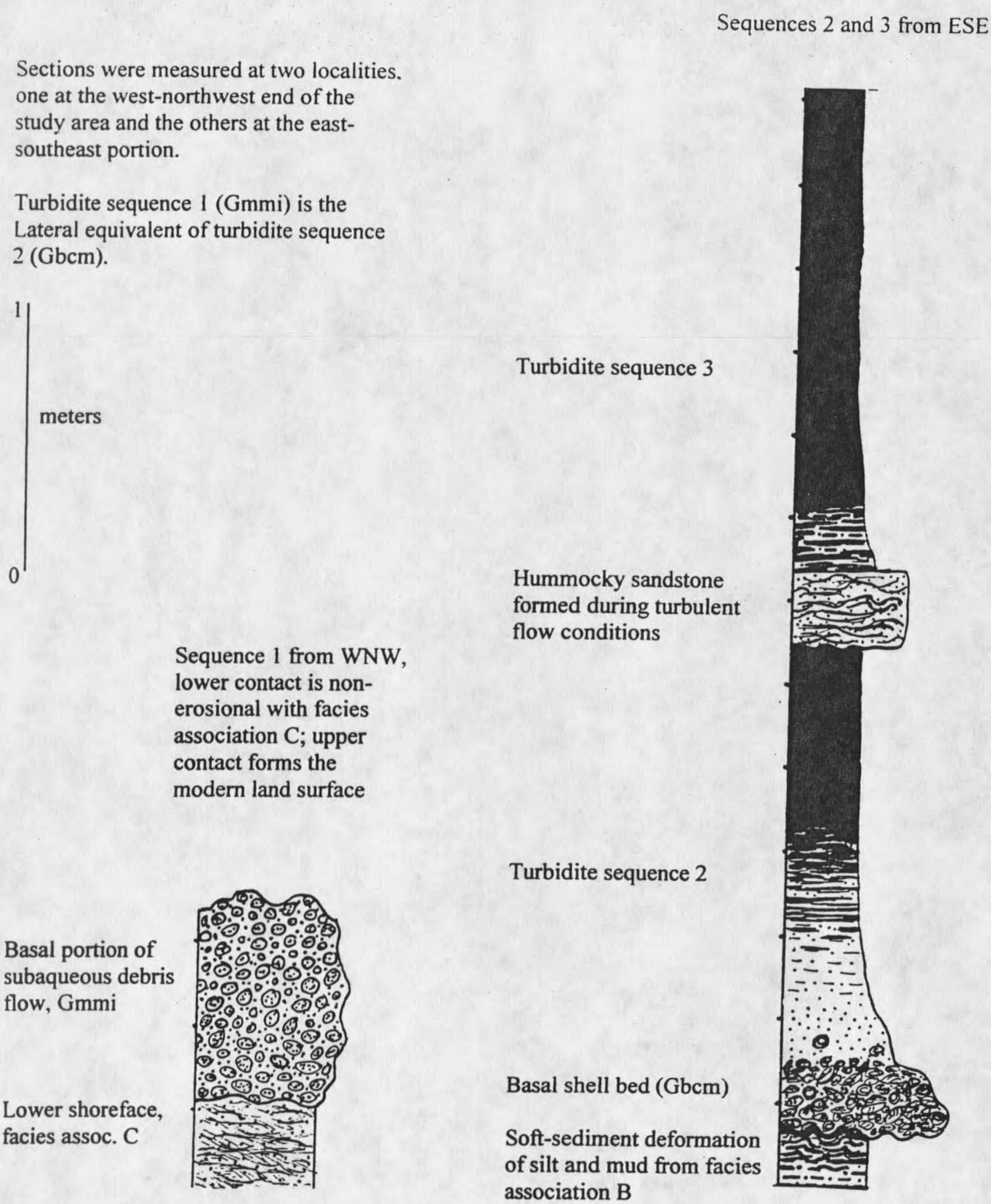


Figure 12. Paleoenvironmental descriptions of stratigraphic sections for facies association D in two localities.

conglomerate (Gmmi) illustrates many characters of subaqueous debris flows. The muddy nature of the sand, the random orientation of clasts, and the lack of bedding or grading all support this interpretation (Nemec et al., 1984). Further support comes from the non-erosive contact with facies association C, where this lithofacies (Gmmi) overlies wave-rippled sandstone. This portion (Gmmi) of facies association D was deposited in the lower shoreface as described by Castle (1990). The other two mud-rich sequences are interpreted as the channelized portion of subaqueous turbidity flows (Normark and Piper, 1991). The undulating geometry of the basal units, the fining upward sequences, the abundant plant debris in fine-grained sediments, and the structures present all support this interpretation (Collinson and Thompson, 1982; Bouma and Stone, 2000). In addition to features inherent to this facies association (D), the interfingering with facies association B also supports this interpretation. These turbidites are channeled through the interlaminated sands, silts and muds (Fl) of interdistributary bays (Bouma et al., 1985). These channels act as conduits to the distal offshore fan (Normark and Piper, 1991). The laminated mudstones (Fml) capping these sequences represent suspension settling after the turbidity flows. Further discussion of this interpretation follows in this chapter under Shell Bed Geology.

Facies Association E (Figure 13)

Description. Facies association E is 6.2m thick and displays a wide range of lithofacies variations. These include siltstone (Fs), massive sandstone (Sm), laminated mudstone (Fml) and laminated claystone (Fcl). Many of the lithofacies present are part of

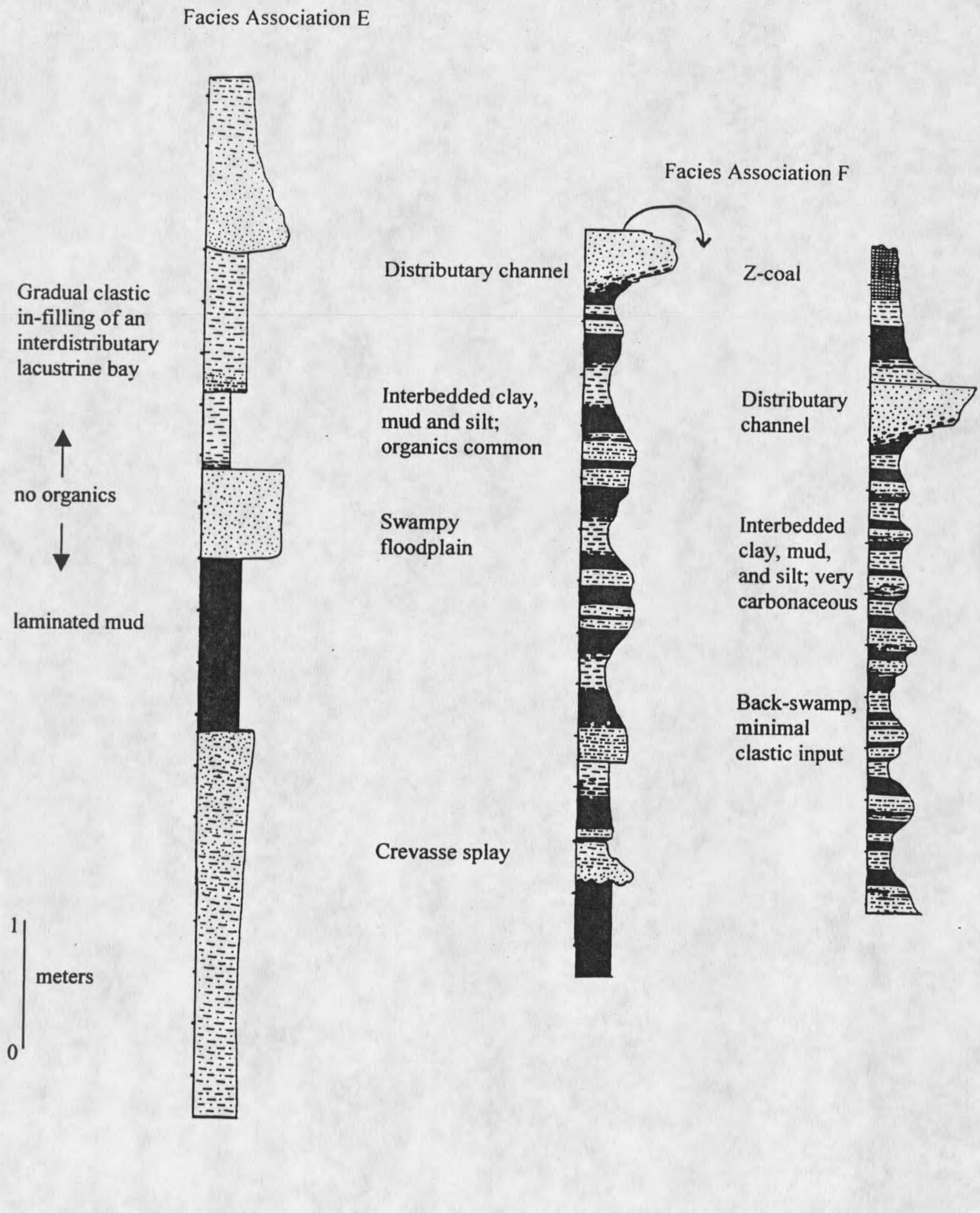


Figure 13. Paleoenvironmental descriptions of stratigraphic sections for facies associations E and F.

graded sequences, both normal and inverse. Most sequences fine upward and are usually less than one meter thick. None of the basal sandstones contain rip-up clasts. Contacts may be sharp, but they are never erosive. As a whole, organics are very rare throughout this facies association (E). A few badly weathered bone fragments were found in one of the sandstones. These fragments were always less than 10cm in length. The lower contact is conformable with the upper laminated mudstone (Fml) of facies association D. The upper contact is very sharp, changing from a siltstone (Fs) to an organic-rich laminated mudstone (Fml). The outcrop of this facies association (E) in the field area is highly vegetated and pedogenically altered. Any bedforms or sedimentary structures that may have been present are no longer observable.

Interpretation. The lack of sedimentary structures in facies association E and the limited exposure makes its interpretation problematic. The lack of plant material may be the result of a highly oxygenated system facilitating decay, or it may simply reflect taphonomic process (Spicer and Wolfe, 1987). The gradational contacts of individual lithofacies suggests velocity changes by the mode of deposition (Miall, 1996). The relatively thin, fining-upward sequences containing non-erosive sand at the base likely represent sediment pulses prograding into standing water (Picard and High, 1972). The relatively thick sets (50cm-105cm) of laminated muds (Fml) and clays (Fcl) represent suspension settling over extended periods of time without coarse-grained clastic input (Elliot, 1978). The single occurrence of an inversely graded unit at the base of this facies association (E), siltstone (Fs) to fine-grained sandstone (Sm) about 2m thick, represents a mud-dominated lower shoreface (Pujos and Javelaud, 1991). Overall, based on the stratigraphic position of lithofacies, facies association E represents the clastic in-filling of an interdistributary bay (Hancock, 1975; Ayers, 1986).

Facies Association F

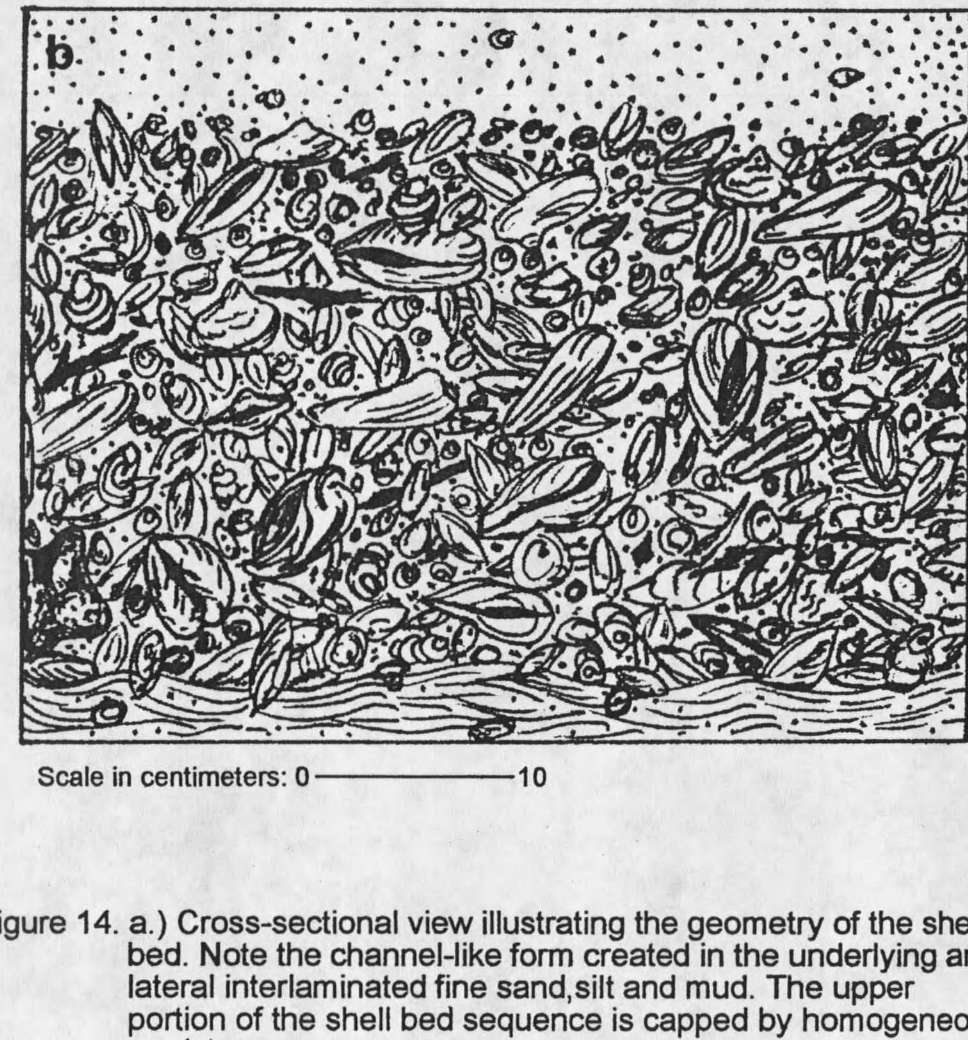
Description. Facies association F is dominated by fine-grained lithofacies with the exception of three minor sandstone units and one coal unit. The fine-grained lithofacies present include siltstone (Fs), massive mudstone (Fmm), laminated mudstone (Fml) and laminated claystone (Fcl). These lithofacies are typically thin and highly interbedded. The three sandstone units present are all less than 50cm thick and have an erosional scouring base (Se). Two of the three can be traced laterally, where they pinch-out into fine-grained beds. A lignite coal (C) is the uppermost unit in this facies association. This is recognized as the "Z-coal", which represents the Cretaceous-Tertiary boundary in the study area. As a whole, organic material is very common in concentrated amounts throughout facies association F. Many of the laminated claystones (Fcl) are on the verge of lignite coal classification. The lower contact occurs sharply between an organic-rich mudstone and the uppermost siltstone of facies association E. The upper contact does not exist due to erosion. The coal at the top of this facies association is the highest point in the immediate study area. The overall thickness of facies association F is about 7.5m.

Interpretation. Facies association F is interpreted as a fluvio-lacustrine system consisting of low energy, swampy shallow ponds and back-swamp floodplains with intermittent distributary channels (Rice and Gautier, 1983; Ayers, 1986; Fastovsky, 1986b; Reading, 1996; Davies-Vollum and Wing, 1998). A low energy system is indicated by the laminated fine-grained lithofacies as well as the abundant laminated organic material, all of which suggest suspension settling (Miall, 1996). The erosional scouring sandstones (Se) represent small distributary channels avulsing through laminated swamp sediments (Davies-Vollum and Wing, 1998). The preservation of organic rich mats within laminations represents an anoxic environment with minimal clastic input (Reading, 1996). This facies association (F) denotes a transition from clastic-dominated lacustrine sedimentation to organic-rich, minimized clastic back-swamp sedimentation (Ayers, 1986).

Shell Bed Stratigraphy and Geology

The shell bed is located in the upper third of the Hell Creek Formation. It crops out approximately 17m below the "Z-coal", or K-T boundary. The shell bed delineates the basal portion of facies association D. It is intimately connected with the fining upward sequence above. This is evident based both on structure and geometry. Interfingering of the shell bed and the fining upward sequence occurs with lithofacies Fl and Fmm. The cross-section of this sequence illustrates a concave body with thin limbs (Figure 14a). The undulated base of the shell bed pushes into the underlying mudstones and siltstones, creating soft sediment deformation structures. The shell assemblage is 25cm thick in the center and thins to <10cm on the limbs. The width of the assemblage varies with thickness. In the lower thick portion, the width is 0.85m. From distal limb to distal limb the bed varies around 2.5m. Additional outlying shells also occur. The shells are randomly oriented, tightly packed and very crudely graded. Most of the small gastropods are concentrated towards the top of the assemblage, although they do exist

Scale in meters: 0 —— 1



Scale in centimeters: 0 —— 10

Figure 14. a.) Cross-sectional view illustrating the geometry of the shell bed. Note the channel-like form created in the underlying and lateral interlaminated fine sand,silt and mud. The upper portion of the shell bed sequence is capped by homogeneous mudstone.
b.) Close up cross-sectional view of the shell bed assemblage. Shells show tight packing and random orientation. The unit underlying the shell bed shows soft-sediment deformation.

throughout. Organic material, including charcoal and macerated plant fragments, is intertwined with the poorly sorted matrix of the assemblage.

Due to the badlands topography, the shell bed crops out in several localities of the study area. The outcrops are reliably correlative to each other, therefore allowing accurate calculations to be made regarding the paleotopography. The shell bed decreases in elevation from southwest to northeast. Precise elevation measurements were obtained at five different outcrops over 650 meters. The regional dip of the Hell Creek Formation is roughly 1.5 degrees. Taking this into consideration, the shell bed has a calculated plunge of 7.3 degrees trending 48 degrees northeast.

Interpretation

The shell bed (Gbcm), as the basal member of facies association D, is interpreted to represent the coarse lower member of a channel-constrained turbidity flow (Middleton, 1967; Bouma and Stone, 2000). Two- dimensional evidence and support for this interpretation is discussed in Facies Association D of this chapter. The geometry, interfingering relationships and the degree of plunge all add significant support to this interpretation (Bouma et al., 1985). The concave shape with thinning limbs, the dimensions, the lithofacies relations and the plunge are all concordant with the channeled portion of turbidity flows (Normark and Piper, 1991). Overall, the shell bed is interpreted as the basal portion of a channeled turbidite that flowed into an interdistributary bay of a lake.

CHAPTER 4

TAPHONOMIC DATA

Taxonomic Data

The shell bed assemblage is predominantly composed of mollusks, nearly all identifiable to a species level. Charcoal and plant fragments are somewhat common, yet the majority is unidentifiable to taxon. Minor vertebrate elements exist within the assemblage, although fragmentary and rare. An associated ceratopsian skull (MOR 1110) was found in close proximity to the shell bed but not within it. The skull lacks any signs of significant transport. Abrasion and breaks are absent. All of the cranial elements represent weathering stage 0 described by Behrensmeyer (1978).

The molluskan fauna present is dominated by pelecypods with a significant proportion of gastropods. The pelecypods belong to family Unionidae, of which five genera were identified (Russell, 1976; Hartman, pers. com.). These include *Plethobasus*, *Pleiodon*, *Plesielliptio*, *Proparreysia*, and *Quadrula*. Fifteen individual species were identified from these genera. Based on shell morphology and extant relatives, these species are inferred to have lived in high energy, fresh water environments (Hartman and Kihm, 1996). Three genera of gastropods were also identified, including *Viviparus*, *Lioplacodes*, and *Campeloma*. Four species were satisfactorily identified, one of which was determined to be a new species by Hartman. Molluskan species identified are presented in Table 4. All species identified temporally coexisted (Hartman and Kihm, 1996; Hartman, 1998).

Molluskan Fauna of the Shell Bed Assemblage

Class	Genus	Species
Pelecypoda	*Plethobasus*	*aesopiformis*
		Biesopoides
	Plesielliptio	*whitfieldi*
		gibbosoides
		brachyopisthus
	Proparreysia	*verricosiformis*
		barnumi
		percorrugata
		letsoni
		retusoides
		corbiculoides
		paucinodosa
		pyramidella
	Pleiodon	*sp.*
	Quadrula	*cylindricoides*

Class	Genus	Species
Gastropoda	*Viviparus*	*thompsoni*
		sp.
	Lioplacodes	*limneaformis*
		tenuicarinata
	Campeloma	*sp. nov. A*

Table 4. Taxonomic breakdown of the mollusk species present in the shell bed.

Vertebrate elements present within the shell bed were highly fragmented and mostly small. An attempt to identify elements to a low taxonomic level was determined to be unnecessary for the purpose of this study. The common elements present included garfish scales, turtle scutes, crocodile teeth and bone fragments, and champsosaur and fish vertebrae. Two large, badly weathered vertebrae were found, both belonging to a ceratopsian (Horner, pers. com.).

Shell Articulation and Modification

Articulation is defined as the connectedness of skeletal shell parts based on life morphology, including halves or segments (Kidwell and Holland, 1991). At first glance, the shells appear highly weathered and disarticulated in outcrop. However, this is simply a result of modern surficial weathering. Careful excavation revealed that a majority of the shells were articulated. In many cases, the ligaments of pelecypods were actually well preserved. Disarticulated specimens tended to encompass the frail, less robust species. Nonetheless, even in these species, many individuals were articulated. Overall, the degree of articulation is greater than 90%. Such high levels of articulation in pelecypods reflect infaunal habitats, intact connective tissue and the strong fit of skeletal elements (Alexander, 1990; Martin, 1999).

Shell modification includes abrasion, desiccation and breakage (Driscoll, 1967). Parameters involving transport, such as flow velocity and substrate composition, inherently affect the degree of shell modification (Driscoll and Weltin, 1973). The degree of preservation of the shells within the assemblage is extremely high. The surfaces look as though the specimens died only a few years ago, hence signs of desiccation are absent.

Abrasion of the shells is minimal to nonexistent, reflected by the level of articulation and the preservation of surface morphology detail. Many specimens, especially members of the genus *Plesielliptio*, possess a remarkably well preserved ligament. The only breakage that occurs is post-fossilization, developed by lithostatic loading (Martin, 1999). Shell surface modification is at an absolute minimum. This minimal surface modification reflects non-abrasive transport with respect to shell-shell collisions and a non-abrasive substrate (Feldmann and Palubniak, 1975).

Shell Orientation

The orientation of individuals within the assemblage is random, demonstrating no preferred direction of flow (Figure 14b). At the base of the assemblage, many of the shells are pushed into the underlying muds and silts. Shell to shell contacts predominate throughout the assemblage. The top of the shell bed contains some individuals which "float" into the overlying sand. Size distribution of pelecypods is ambiguous, lacking any sense of grading, a common feature of high density flows (Collinson and Thompson, 1982). However, small gastropods are more concentrated near the top of the shell bed. The same is not true for large gastropods. This likely reflects a relationship between surface area and buoyancy (Martin, 1999). One specific point of interest, noted at only one locality as a single occurrence, involved escape structures associated with a vertically oriented specimen of *Plesielliptio gibbosoides*. This demonstrates that at least this individual was alive at the time of deposition. Based on the associated sedimentology, level of articulation, and shell orientations there are no signs of biologic or physical reworking within the shell bed. The assemblage reflects the initial process of deposition, in that no evidence of reworking could be demonstrated (Kidwell and Bosence, 1991).

CHAPTER 5

DISCUSSION

Interpretation

The shell bed assemblage provides an interesting and rare example of a terrestrial molluskan accumulation. Lithofacies associations, shell bed architecture and taphonomic data suggest that the shell bed represents single event-deposition.

In the large scope of depositional events in the study area, the shell bed records only a single minor event. Overprinting this single event, a significant transition is recognized in major modes of deposition through the upper third of the Hell Creek Formation in the study area. Three distinct deposystems can be recognized.

The first deposystem is dominated by a large, tidally influenced meandering channel belt (Jackson, 1981; Smith, 1987). Eberth and Brinkman (1997) have suggested that the effects of tidal influence in the Upper Cretaceous of Alberta may have occurred as far inland as hundreds of kilometers, in exclusively freshwater systems. This system was characterized in facies association A. Sedimentary microenvironments include floodplains, crevasse splays, channel scours, lateral accretion bars and mud drapes. Aside from the likelihood of a tidal influence, the heterolithic couplet comprising facies Seh may be representative of sporadic large-scale storms which created hydraulic backwater effects (Thompsan et al., 1987; Wood et al., 1988). These backwater events may have allowed for the deposition of the non-cyclic mud drapes. In this system, the amount of clastic input was substantial, highly outweighing that of organic accumulation. This fluvially dominated system abruptly changes up-section. This abrupt change gives rise to the second deposystem recognized in the study area.

The second deposystem is dominated by lacustrine facies attributed to a large transgressing lake (Clifton, 1976; Castle, 1990). Facies associations B, C, D and E characterize this deposystem (Figure 15). Marginal swamps and interdistributary bays circumvented the lake margin, interpreted from the presence of facies association B (Picard and High, 1972; Behrensmeyer et al., 1992). Distributary bars prograded into the standing lake waters, disturbing the saturated muds and silts of the lake bay floor as seen in facies association C (Elliot, 1978; Wheeler, 1983). The sandy bars were consequently reworked by wave energy as demonstrated by preserved sedimentary structures inherent to the lower and upper shoreface, as well as the swash zone (Castle, 1990). Subsequent to establishment of the shoreface, possible flood events or distributary channel avulsions transported mollusks and coarse-grained sediment through the marginal swamps, eventually emptying their load into subaqueous channels of the lake (Middleton, 1967; Normark and Piper, 1991). Support for a channel passing through the swamp is drawn from the presence of macerated plant debris as well as interfingering with the swamp facies. The sediment and mollusks were then transported via turbidite channels to bay-floor fans (Bouma, et al., 1985; Bouma and Stone, 2000). However, only one of these channeled event deposits contained mollusks. An intraformational non-channeled sediment gravity flow (Gmmi) overlies the lower shoreface at lateral equivalence to the shell bed. This may have been produced by the same event that triggered the shell transport. After initial deposition of the coarse lower members of the channeled turbidite

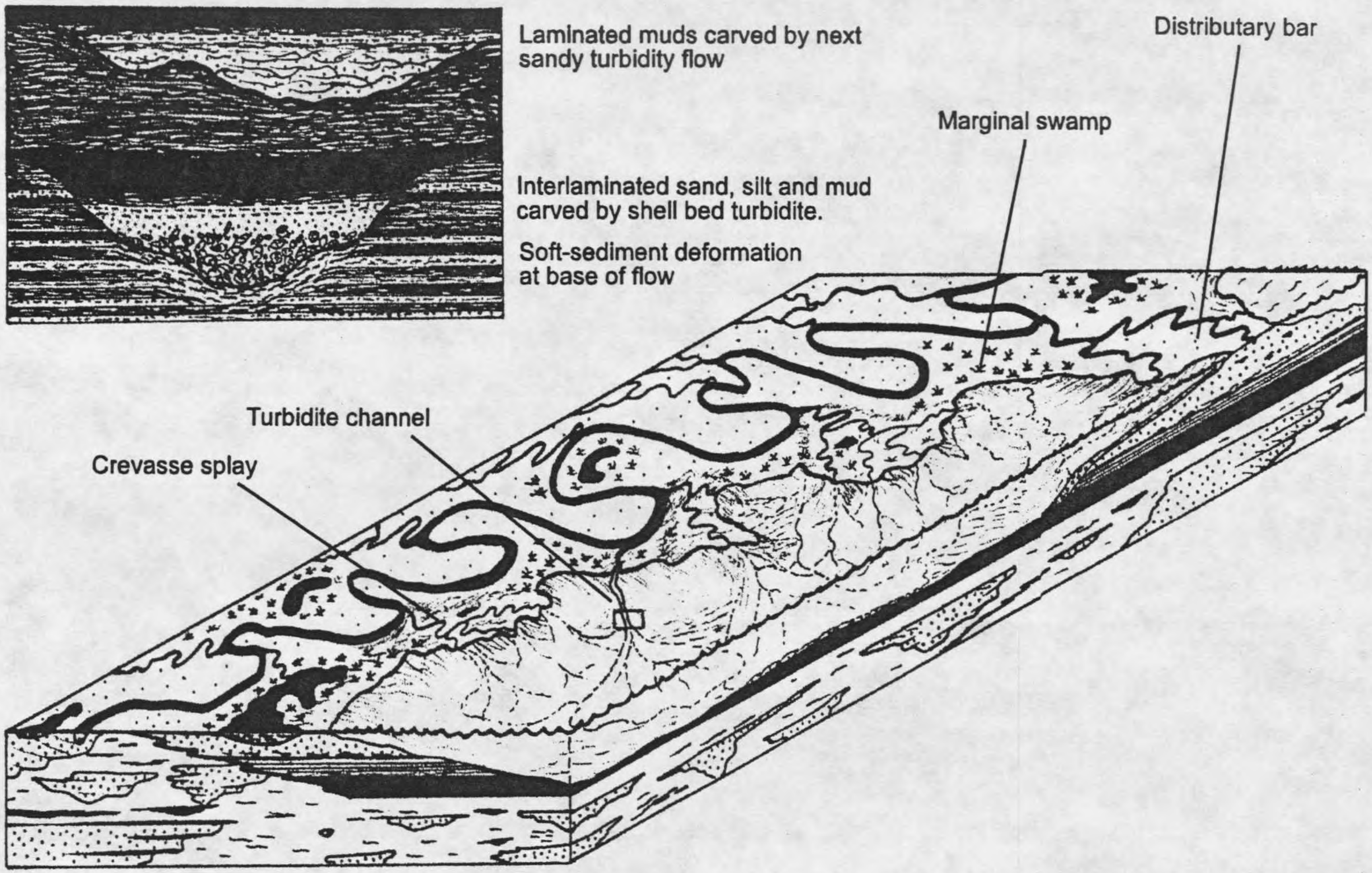


Figure 15. Paleogeographic reconstruction of an interdistributary lake bay being fed sediment by crevasse splays from a meandering river system. Marginal swamps surround the bay. Turbidity channels carry sediment to the bay floor. The enlarged rectangle shows the cross-sectional view of the turbidity channel containing the shell bed.

flows, thick mud beds were deposited preventing the escape of any living individuals. These turbidity events were followed by suspension settling of mud laminations. Eventually, the interdistributary bay begins to fill with clastic sediment shown by facies association E (Hancock, 1975; Ayers, 1986). Organic material becomes very rare, possibly reflecting oxygen-rich water (Spicer and Wolfe, 1987; Reading, 1996). Pulses of sand and silt enter the lake, creating normally and inversely graded sequences. This marks the transition to the third deposystem.

The third deposystem recognized is characterized in facies association F. There is a significant decrease in clastic sedimentation. Grain sizes consist of mostly silt, mud and clay. Organic laminae increase in thickness and abundance. Carbonaceous claystones are very common due to the decrease in clastic input (Ayers, 1986). Minor sandy distributary channels exist, but are not common (Fastovsky, 1986b). This denotes ponded depressions in a back-swamp floodplain with intermittent distributary channels (Rice and Gautier, 1983; Ayers, 1986; Davies-Vollum and Wing, 1998). From this last deposystem, the transition occurs to the coal beds of the Tertiary Tullock Formation.

Time-Averaging and Paleoecology

In addition to the sedimentological features of the shell bed in the lacustrine system, taphonomic data clearly indicate event-deposition. Even though a majority of the shells were allochthonous to the lake, all species temporally coexisted (Russell, 1976; Hartman, 1998). All specimens demonstrate similar degrees of articulation and surface modification, suggesting a primary deposit (Kidwell and Bosence, 1991). The high levels of articulation, ligament preservation and at least one instance of escape structures, suggests that the mollusks were alive at the time of deposition (Driscoll, 1973; Fursich and Flessa, 1987). Physical and biological reworking was inhibited by thick homogeneous mud capping the deposit. All of the features of the shell bed, including random shell orientation, are concordant with event-concentrations as described by Kidwell (1991). Since turbidity flows are recognized in modern systems to occur over a short duration (usually less than an hour) and all of the species present temporally coexisted while illustrating similar degrees of modification, it is reasonable to say that time-averaging in the shell bed is absolutely minimal (Kidwell and Bosence, 1991; Bouma and Stone, 2000). Time-averaging may be minimal for the mollusks, however it is quite likely that the fragmentary and badly weathered vertebrate remains reflect reworking (Behrensmeyer, 1978). These elements may have been incorporated in the shell bed from pre-existing deposits. Most of the elements were small and easily transportable.

All of the mollusks within the shell bed, with the exception of one species of gastropod, are interpreted to be high energy channel dwelling species (Russell, 1976; Hartman, 1998). Since the deposit is part of a turbidite sequence, it is necessary to realize that the mollusks were transported from the environment in which they lived. Nonetheless, transport was likely minimal as indicated by high degrees of articulation and minimal surface modification (Driscoll, 1967; Feldmann and Palubniak, 1975). The channel where the mollusks lived was near the lake where they were deposited. The high proportion of plant material in the deposit reflects transport through a plant rich area, such as a marginal swamp (Picard and High, 1972). The cause of death for the mollusks is rather simple. The turbidity flow carried the mollusks in subaqueous channels. Inherent to fine-grained turbidite deposition, thick homogenous mud capped the sequence (Bouma and Stone, 2000). This significantly depleted oxygen in the unit and prevented escape (Fursich and Flessa, 1987). Essentially, the mollusks were buried and asphyxiated. This lack of oxygen also inhibited bacterial decay, allowing for the high level of preservation (Reading, 1996).

CHAPTER 6

CONCLUSIONS

Recently, the discovery of a large extensive shell bed in the Upper Cretaceous (Maastrichtian) Hell Creek Formation of eastern Montana yielded an extraordinary assemblage of well-preserved mollusks. The assemblage contained mostly pelecypods with some gastropods. Sedimentological evidence suggests that the deposit represents the coarse lower member of a channel-constrained turbidity flow. Interfingering facies associations and paleoecology imply that the deposit consisted of transported material from a channel environment, which passed through a marginal swamp and eventually emptied into subaqueous lacustrine turbidite channels feeding a bay-floor fan.

Transitional modes of deposition record three distinct deposystem regimes in the study area. The first consists of a tidally influenced meandering channel belt indicative of a coastal fluvial system. Paleo-microenvironments include floodplains, crevasse splays and large channels. The second deposystem is characterized as fluvial-lacustrine. Subaerial paleo-microenvironments include marginal swamps, distributary bars, backshore mudflats and ponds, swash zones and small distributary channels. Subaqueous paleo-microenvironments include interdistributary bays, lower and upper shorefaces and turbidite systems. The third deposystem marks a transition to a clastic supply-limited environment. This deposystem is characterized as a back-swamp floodplain rich in organics with minimal clastic input by small intermittent sandy channels. This deposystem is the transition to the coal-rich units of the Tertiary Tullock Formation.

Eight different mollusk genera with a total of twenty species were identified from the shell bed. All species within the assemblage temporally coexisted. Most individual species possess robust morphologies indicative of high energy channel environments. One genus of gastropod could thrive in both channels and standing bodies of water, such as lakes. Shells within the assemblage are randomly oriented with no distinct grading. Articulation of individual shells is greater than 90%. Abrasion and surface modification is minimal to nonexistent. The only shell breakage is post-depositional caused by lithostatic loading. All of these parameters are concordant with infaunal event-deposition, demonstrating absolutely minimal time-averaging.

Subsequent to their deposition, the mollusks were protected from any possible escape, physical or biological reworking and bacterial decay. The shells were immediately capped by a thick homogeneous mudstone immediately after deposition. This is concordant with the processes of fine-grained turbidity flows. The thick mudstone cap facilitated preservation by creating an oxygen-depleted realm, reducing the possibility for bacterial decay as well as hindering sedimentologic and biologic reworking mechanisms.

REFERENCES CITED

Alberdi, M. T., et al., 2001, Vertebrate taphonomy in circum-lake environments: three cases in the Guadix-Baza Basin (Granada, Spain): Paleogeography, Paleoclimatology, Paleoecology, v. 165, p. 1-26.

Alexander, R. R., 1990, Disarticulated shells of Late Ordovician brachiopods: inferences on strength of hinge and valve architecture: Journal of Paleontology, v. 64, p. 524-532.

Ayers, W. B., 1986, Lacustrine and fluvial-deltaic depositional systems, Fort Union Formation (Paleocene), Powder River Basin, Wyoming and Montana: American Association of Petroleum Geologists Bulletin 70, American Association of Petroleum Geologists, p. 1651-1673.

Behrensmeyer, A. K., 1978, Taphonomic and ecologic information from bone weathering: Paleobiology, v. 4, p. 150-162.

Behrensmeyer, A. K., and Kidwell, S. M., 1985, Taphonomy's contributions to paleobiology: Paleobiology, v. 11, p. 105-119.

Behrensmeyer, A. K., et al., 1992, Terrestrial ecosystems through time: Chicago, University of Chicago Press, 568 p.

Boggs, S., Jr., 1995, Principles of sedimentology and stratigraphy: Englewood Cliffs, New Jersey, Simon & Schuster Co., 774 p.

Bouma, A. H., Normark, W. R., and Barnes, N. E., ed., 1985, Submarine fans and related turbidite systems: New York, Springer-Verlag, 351 p.

Bouma, A. H. and Stone, C. G., ed., 2000, Fine-grained turbidite systems: American Association of Petroleum Geologists Memoir 72, American Association of Petroleum Geologists, p. 1-20.

Brown, B., 1907, The Hell Creek beds of the Upper Cretaceous of Montana: American Museum of Natural History Bulletin 23, p. 823-845.

Brown, R., 1952, Tertiary strata in eastern Montana and western North and South Dakota: Billings Geological Society Guidebook, Billings Geological Society, v. 3, p. 89-92.

Castle, J. W., 1990, Sedimentation in Eocene Lake Uinta (Lower Green River Formation) Northeastern Uinta Basin, Utah, *in* Katz, B. J., ed., Lacustrine Basin Exploration: American Association of Petroleum Geologists Memoir 50, American Association of Petroleum Geologists, p. 243-263.

Chatfield, J., 1972, Case history of Red Wash field, Uintah County, Utah, *in*, King, R. E., ed., Stratigraphic Oil and Gas Fields-Classification, Exploration Methods and Case Histories: American Association of Petroleum Geologists Memoir 16, American Association of Petroleum Geologists, p. 342-353.

Cheel, R. J., and Leckie, D. A., 1992, Coarse-grained storm beds of the Upper Cretaceous Chungo Member (Wapiabi Formation), southern Alberta, Canada: Journal of Sedimentary Petrology, v. 62, p. 933-945.

Cheel, R. J., and Leckie, D. A., 1993, Hummocky cross-stratification: Sedimentology Review, v. 1, p. 103-122.

Clifton, H. E., 1976, Wave-formed sedimentary structures: A conceptual model, *in* Davis, R. A., and Ethington, R. L., ed., Beach and Nearshore Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 24, Society of Economic Paleontologists, p. 126-148.

Collinson, J. D., and Thompson, D. B., 1982, Sedimentary structures: London, George Allen & Unwin, 437 p.

Davies-Vollum, K. S., and Wing, S. L., 1998, Sedimentological, taphonomic, and climatic Aspects of Eocene swamp deposits (Willwood Formation, Bighorn Basin, Wyoming): Palios, v. 13, p. 28-40.

Driscoll, E. G., 1967, Experimental field study of shell abrasion: Journal of Sedimentary Petrology, v. 37, p. 1117-1123.

Driscoll, E. G., and Weltin, T. P., 1973, Sedimentary parameters as factors in abrasive shell reduction: Paleogeography, Paleoclimatology, Paleoecology, v. 13, p. 275-288.

Eberth, D. A., and Brinkman, D. B., 1997, Paleoecology of an esturine, incised-valley fill in the Dinosaur Park Formation (Judith River Group, Upper Cretaceous) of southern Alberta, Canada: Palios, v. 12, p. 43-58.

Elliot, T., 1978, Clastic shorelines, *in*, Reading, H. G., ed., Sedimentary environments and facies: New York, Elsevier, p. 143-177.

Eugster, H. P., and Surdam, R. C., 1973, Depositional environment of the Green River Formation, Wyoming-A preliminary report: Geological Society of America Bulletin, v. 84, p. 115-1120.

Fastovsky, D. E., 1986a, Paleoenvironments of vertebrate-bearing strata at the Cretaceous-Paleogene boundary in northeastern Montana and southwestern North Dakota: Doctoral Thesis, University of Wisconsin, Madison.

Fastovsky, D. E., 1986b, Sedimentology, stratigraphy and extinction during the Cretaceous-Paleogene transition at Bug Creek, Montana: Geology, v. 14, p. 279-282.

Feldmann, R. M., and Palubniak, D. S., 1975, Paleoecology of Maestrichtian oyster assemblages in the Fox Hills Formation, *in*, Caldwell, W. G., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, Geological Association of Canada, p. 211-233.

Fursich, F. T., and Flessa, K. W., 1987, Taphonomy of tidal flat mollusks in the Northern Gulf of California: Paleoenvironmental analysis despite the perils of preservation: Palaios, v. 2, p. 543-559.

George, 1994, Tidal sedimentation in part of the Late Silurian Grampians Basin, southeastern Australia: Journal of Sedimentary Research, v. 64, p. 311-325.

Hancock, J. M., 1975, The sequence of facies in the Upper Cretaceous of northern Europe compared with that in the Western Interior, *in*, Caldwell, W. G., ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, Geological Association of Canada, p. 83-118

Hartman, J. H., 1998, The biostratigraphy and paleontology of latest Cretaceous and Paleocene freshwater bivalves from the western Williston Basin, Montana, USA, *in*, Johnston, P. A., and Haggart, J. W., ed., Bivalves: An eon of evolution - Paleobiological studies honoring Norman D. Newell: University of Chicago Press, Calgary, p. 317-345.

Hartman, J. H., and Kihm, A. J., 1996, Bio- and magnetostratigraphy of the Uppermost Cretaceous and the lower Tertiary strata of North Dakota: Paleontological Society Special Publication 8, Paleontological Society, University of Tennessee, Knoxville, 163 p.

Jackson, R. G., II, 1981, Sedimentology of muddy fine-grained channel deposits in meandering streams of the American Middle West: Journal of Sedimentary Petrology, v. 51, p. 1169-1192.

Kidwell, S. M., and Bosence, W. J., 1991, Taphonomy and time-averaging of marine shelly faunas, *in*, Allison, P. A., and Briggs, D., ed., Taphonomy, releasing the data locked in the fossil record, p. 116-188.

Kidwell, S. M., and Holland, S. M., 1991, Field description of coarse bioclastic fabrics: Palios, v. 6, p. 426-434.

Kidwell, S. M., 1991, The stratigraphy of shell concentrations, *in* Allison, P. A., and Briggs, D., ed., Taphonomy, releasing the data locked in the fossil record, p. 211-279.

LaRock, J. W., 2000, Sedimentology and taphonomy of a dinosaur bonebed from the Upper Cretaceous (Campanian) Judith River Formation of north central Montana: Masters of Science Thesis, Montana State University, Bozeman.

Martin, R. A., 1999, Taphonomy: A process approach: Chicago, Chicago University Press, 508 p.

Miall, A. D., 1977, A review of the braided river depositional environment: Earth Science Reviews, v. 13, p. 1-62.

Miall, A. D., 1985, Architectural element analysis: A new method of facies analysis applied to fluvial deposits: Earth Science Reviews, v. 22, p. 261-308.

Miall, A. D., 1996, The geology of fluvial deposits: New York, Springer, 582 p.

Middleton, G. V., 1967, The orientation of concave-convex particles deposited from experimental turbidity currents: Journal of Sedimentary Petrology, v. 37, p. 229-232.

Nemec, W., Steel, R. J., Porebski, S. J., and Spinnanger, A., 1984, Domba Conglomerate, Devonian, Norway: process and lateral variability in a mass flow-dominated, lacustrine fan-delta, *in*, Koster, E. H., and

Steel, R. J., ed., Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists Memoir, Canadian Society of Petroleum Geologists, p. 295-320.

Normark, W. R., and Piper, D. J. W., 1991, Initiation process and flow evolution of turbidity currents: Implications for the depositional record, *in*, Osborne, R. H., ed., From Shoreline to Abyss: Contributions in Marine Geology in Honor of Francis Parker Shepard: SEPM (Society for Sedimentary Geology) Special Publication 46, Society of Economic Paleontologists and Mineralogists, p. 207-230.

Picard, M. D., and High, L. R., Jr., 1972, Criteria for recognizing lacustrine rocks, *in* Rigby, J. K., and Hamblin, W. K., ed., Recognition of Ancient Sedimentary Environments: Society of Economic Paleontologists and Mineralogists Special Publication 16, Society of Economic Paleontologists and Mineralogists, p. 108-145.

Reading, H. G., 1996, Sedimentary environments: Processes, facies and stratigraphy: London, Blackwell Science, 688 p.

Rice, D. D., and Gautier, D. L., 1983, Patterns of sedimentation, diagenesis, and hydrocarbon accumulation in Cretaceous rocks of the Rocky Mountains: Society of Economic Paleontologists and Mineralogists Short Course 11, Society of Economic Paleontologists and Mineralogists, p. 6-1 – 6-41.

Ross, C. P., 1955, Geologic Map of Montana: Montana Bureau of Mines and Geology.

Russell, L. S., 1976, Pelecypods of the Hell Creek Formation (Uppermost Cretaceous) of Garfield County, Montana: Canadian Journal of Earth Science, v. 13, p. 365-388.

Rust, B. R., 1978, Depositional models for braided alluvium, *in* Miall, A. D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir, Canadian Society of Petroleum Geologists, p. 605-625.

Shanley, K. W., and McCabe, P. J., 1994, Perspectives on sequence stratigraphy of continental strata: American Association of Petroleum Geologists Bulletin, American Association of Petroleum Geologists, v. 78, p. 544-568.

Smith, D. G., 1987, Meandering river point bar lithofacies models: Modern and ancient examples compared, *in* Ethridge, F. G., et al., Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication 39, Society of Economic Paleontologists and Mineralogists, p. 83-91.

Spicer, R. A., and Wolfe, J. A., 1987, Plant taphonomy of late Holocene deposits in Trinity (Clair Engel) Lake, northern California: Paleobiology, v. 13, p. 227-245.

Thomas, R. G., Smith, D. G., Wood, J. M., Calverley-Range, E. A., Visser, J., and Koster, E. H., 1987, Inclined heterolithic stratification-terminology, description, interpretation and significance: Sedimentary Geology, v. 53, 123-179.

Walker, G. W., and Bergman, K. M., 1993, Shannon Sandstone in Wyoming: A shelf ridge complex reinterpreted as lowstand shoreface deposits: Journal of Sedimentary Petrology, v. 63, p. 839-851.

Wheeler, K. L., 1983, Maastrichtian shoreline sedimentation in northeastern Montana: Master of Science Thesis, University of Iowa.

Wood, J. M., 1989, Alluvial architecture of the Upper Cretaceous Judith River Formation, Dinosaur Provincial Park, Alberta, Canada: Bulletin of Canadian Petroleum Geology, v. 37, p. 169-181.

Wood, J. M., Thomas, R. G., and Visser, J., 1988, Fluvial processes and vertebrate taphonomy: The Upper Cretaceous Judith River Formation, south-central Dinosaur Provincial Park, Alberta, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 66, p. 127-143.