SEQUENCE STRATIGRAPHIC ANALYSIS OF THE FOX HILLS AND HELL CREEK FORMATIONS (MAASTRICHTIAN), EASTERN MONTANA AND ITS RELATIONSHIP TO DINOSAUR PALEONTOLOGY

by

Jennifer Noël Flight

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APPROVAL

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Jennifer Noël Flight

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.

Dr. James G. Schmitt

Approved for the Department of Earth Sciences

Dr. David R. Lageson

Approved for the College of Graduate Studies

Dr. Bruce McLeod

STATEMENT OF PERMISSION TO USE

Jennifer N. Flight

April 19, 2004

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ABSTRACT

The Upper Cretaceous Hell Creek Formation near the Fort Peck Reservoir, eastern Montana, has received significant investigation due to the large variety and exceptional preservation of included fossil material. Workers have focused mainly on taphonomic and paleontologic issues, but lack of a stratigraphic framework within which to place fossil finds in order to address questions of evolution, population diversity, and paleoecology. This study uses sequence stratigraphy to correlate within the Fox Hills and Hell Creek Formations such that paleontologic data can be interpreted in relation to a series of linked depositional environments and their relationship through time.

Four key surfaces are present in the study area. First is a sequence boundary capping the Fox Hills marine shoreface strata. Incision occurs locally at this boundary and the resulting topography is filled by incised valley-fill strata of the Colgate Member of the Fox Hills Formation (lowstand and transgressive systems tracts). The second key surface is a flooding surface internal to the transgressive systems tract which is associated with extensive *Skolithos* burrows into the Colgate Member below (*Glossifungites* surface?). This flooding surface separates white, trough cross-stratified Colgate sandstone from thin carbonaceous, bioturbated and pedogenically altered units of the lower Hell Creek Formation. Capping this carbonaceous member is the maximum flooding surface which separates transgressive deposits below from highstand deposits above. Highstand deposition of the lower Hell Creek consists of the high accommodation, estuarine, inclined heterolithic sandstone which contains the most complete and associated *Tyrannosaurus rex*. The fourth key surface separates lower Hell Creek estuarine deposits from upper Hell Creek fluvial system deposits. These fluvial deposits consist of mixed sandstone, siltstone and mudstone which are interpreted to have formed on a flood plain through processes associated with meandering stream deposition and pedogenic alteration. These deposits reflect a return to low accommodation depositional patterns (lowstand systems tract).

Changes in accommodation during Maastrichtian time, as interpreted from regional stacking patterns, facies changes and facies tract dislocations can be used in conjunction with taphonomic data from paleontologic sites in order to understand and predict the nature of preservation and distribution of fossil material.

CHAPTER 1

INTRODUCTION

The study area for this thesis is located in the high plains physiographic province in eastern Montana along the western margin of the Williston Basin. It is bounded to the west by the Little Rocky Mountains, to the east by Poplar Dome, to the north by Bowdoin Dome, and to the south by Cat Creek anticline (Figure 1). Strata in this area are exposed in outcrops along the Fort Peck Reservoir created by post-glacial erosion of the west- east trending Missouri River. The oldest strata exposed are part of the Upper Cretaceous Bearpaw Formation, followed by the Fox Hills Formation and latest Cretaceous Hell Creek Formation, respectively. The youngest strata are from the Paleocene Fort Union Formation. In total, the outcrop exposures of Upper Cretaceous strata are over 200 kilometers in length and are oriented parallel to depositional dip. The availability of such an outcrop, with continuous badlands topography along the Fort Peck Reservoir make this location ideal for studying the final retreat of the Western Interior Cretaceous Seaway. Additionally, the abundance of fossil material in the Hell Creek Formation (including several specimens of *Tyrannosaurus rex*) and the stratigraphic position of this formation with respect to the Cretaceous-Tertiary boundary have historically generated a great deal of paleontologic interest regarding faunal diversity and evolution leading up the Cretaceous – Tertiary extinction event.

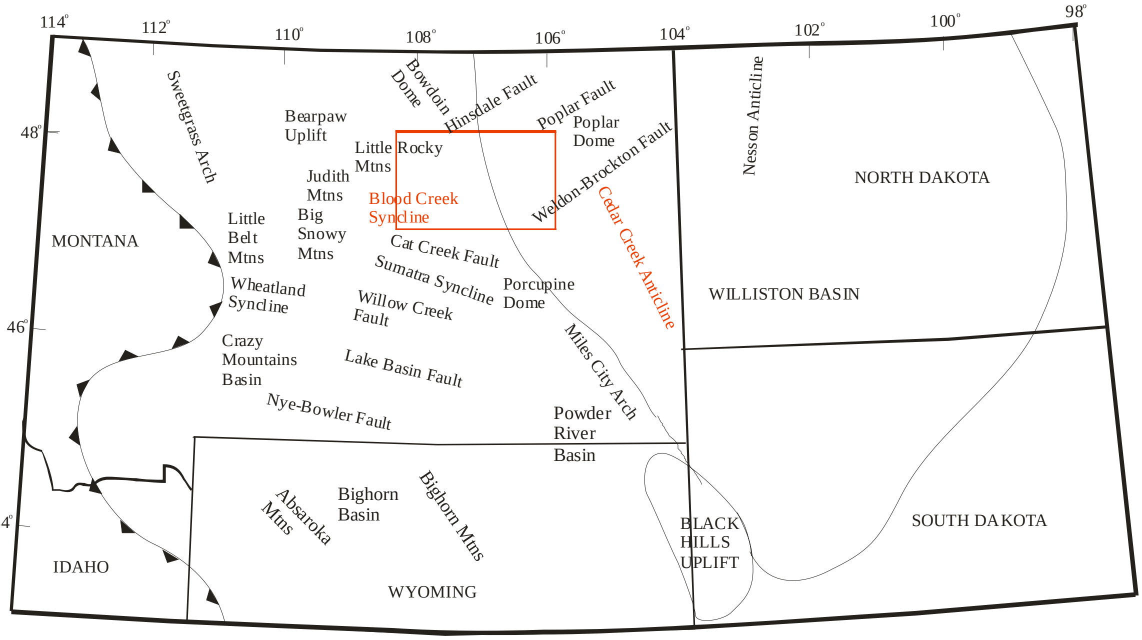


Figure 1: Location of field area (outlined in red) with respect to major tectonic features. Azimuth of writing indicates trend of tectonic feature. Red text indicates that the feature was active during the time of deposition of these latest Cretaceous strata. Figure modified from Peterson and MacCary (1987).

A more tightly constrained stratigraphic framework for the Bearpaw through Hell Creek Formations allows for correlation of fossil material, a more refined paleogeography and the determination of differential subsidence by examining stratal patterns with respect to chronostratigraphically significant surfaces. By identifying these surfaces throughout the field area, the relative ages of dinosaur fossils located between them can be constrained. This framework provides the ability to confidently associate facies that are not directly linked by outcrop, as well as the ability to geographically and stratigraphically locate zones of high accommodation (generally containing associated skeletons) and low accommodation (generally containing individual, disassociated bones). Previously, the lateral discontinuity of strata and lack of absolute age control made studies seeking to understand faunal evolution or population diversity extremely difficult.

For paleogeographic studies, this work refines the traditional schematics of straight shoreline geometries (e.g. Gill and Cobban, 1973; Krystinik and DeJarnett, 1995) and the belief in persistent progradational post-Fox Hills deposition (Anna, 1986). Marine influences in the Hell Creek have been previously identified in North Dakota (Seager et al., 1942; Laird and Mitchell, 1942; Frye, 1967, 1969; Hartmann, 2002) and southeastern Montana (Butler, 1980), so the idea of a higher frequency, higher order transgression is not new. The importance of this study is that it improves temporal and spatial resolution of a regression into northeastern Montana which was embayed during the flooding of a large incised valley during initial Hell Creek deposition.

Geologic Setting

The Upper Cretaceous Bearpaw through Hell Creek Formations near the Fort Peck Reservoir in eastern Montana were deposited during the last major regressive cycle (Figure 2) of the Western Interior Cretaceous Seaway (Anna, 1986; Jenkin, 1990; Hartmann and Kirkland, 2002), as “a wedge of progradational, largely unconsolidated, sediments derived from the uplifting Rocky Mountains near the beginning of the Laramide Orogeny” (Hartmann and Kirkland, 2002, p. 272). More specifically, Zaleha (1988, p. 94) determined that the source of Hell Creek sediment was “the Laramide ranges [presumably meaning the Sevier Cordillera] in northwestern Montana – southern Alberta , and possibly western Montana [which] supplied sedimentary and volcanic (andesitic and rhyolitic) detritus to the foreland basin of eastern Montana". In that study, the tectonic setting of the source was consistent with "highlands along the suture belts of collision orogens, thin-skinned foreland fold-thrust belts along the flanks of arc or collision orogens, and, of lesser significance, volcanic shields (capping the igneous belt) with associated metamorphic rock and flanking sediment cover" (Zaleha, 1988, p. 94) based on provenance studies performed after Dickinson and Suczek (1979) and Dickinson et al. (1983). Gill and Cobban (1973) also support the rising Cordillera to the west as the source of clastic Cretaceous sediment. Jenkin (1990) indicates that the active Overthrust belt, Elkhorn Mountain volcanics and the Crazy Mountain uplift provided significant sediment during deposition of the Hell Creek Formation. In Wyoming, Belt et al. (1997, p. 6) determined that the Lance Formation (Hell Creek equivalent) sandstones were sourced from "basement-cored Laramide uplifts in southern Montana and northern Wyoming".

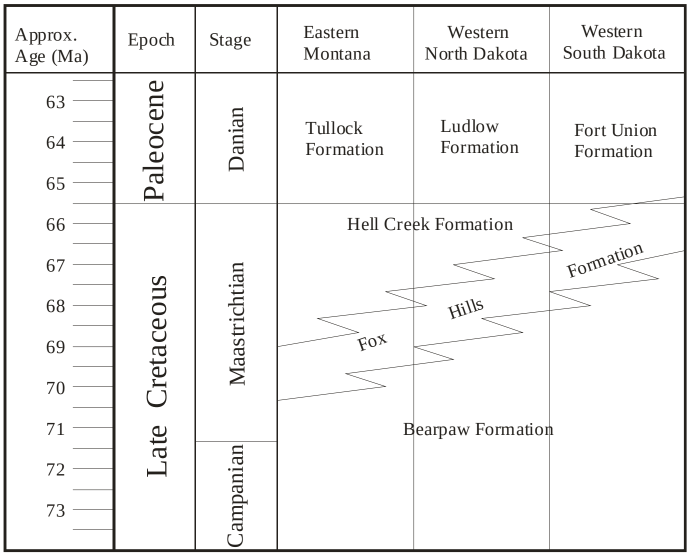


Figure 2: Regressive relationship of Bearpaw through Hell Creek Formations. Figure modified from Fastovsky (1986, p. 6, Figure 2).

Figure 1 indicates the location of the primary tectonic features in eastern Montana. The majority of these features reflect reactivation of Proterozoic suture zones or lineaments (Maughan, 1983; Maughan and Perry, 1986; Anna, 1986; Shurr and Rice, 1986; Gibson, 1995). The study area is outlined in red, suggesting those features that could be relevant to Fox Hills and Hell Creek strata. Of these, only the Blood Creek syncline (Shurr et al., 1989) and the Cedar Creek anticline (Clement, 1986) were active and therefore able to influence sedimentation patterns during latest Cretaceous time. Belt et al. (1997) claim that the activation of the Cedar Creek anticline post-dated Hell Creek deposition.

Previous Work

Study of stratigraphy in the Fort Peck area dates back to the original surveys of the western territories. At that time interest lay in the potential economic value of America's newly acquired property, so the stratigraphic focus of the Fort Peck area was on coal bearing strata of the Tertiary Fort Union, then referred to as the "Great Lignite Group". In 1862, Meek and Hayden refined this term to the Fort Union Formation. Hell Creek strata were not officially named until 1907 when Barnum Brown came into the area on a fossil collecting expedition. The name was taken from the type section approximately 25 miles north of Jordan, Montana. Brown distinguished the Hell Creek Formation from the Fort Union Formation above based on the absence of lignitic units and noted that the Hell Creek Formation was disconformable with the underlying Fox Hills Formation. The majority of Brown's work, however, was focused on procuring dinosaur specimens for the American Museum of Natural History. This was to be just the beginning of nearly a century's worth of work on Hell Creek flora and fauna. Other works have extensively documented the history of Hell Creek paleontology and the reader is referred to those works for further information. A listing of significant paleontologic work done on the Hell Creek Formation is presented in Table 1.

Table 1: Papers and theses on paleontologic aspects of the Hell Creek Formation.

Author	Year	Title
Clemens, W.A.	1964, 1966, and 1973	Fossils mammals of the type Lance Formation, Wyoming
Archibald, J.D.	1982a	A study of mammalian and geology across the Cretaceous-Tertiary boundary in Garfield County, Montana
Archibald, J.D.	1982b	Fossil Mammalia and Testudines of the Hell Creek Formation, and the geology of the Tullock and Hell Creek Formations, Garfield County, Montana
Dorf, E.	1940	Relationship between floras of type Lance and Fort Union Formations
Estes, R. and Berberian, P.	1970	Paleoecology of a Late Cretaceous vertebrate community from Montana
Dingus, L.	1984	Effects of stratigraphic completeness on interpretations of extinction rates across the Cretaceous-Tertiary boundary
Bryant, L.J.	1985	Non-dinosaur lower vertebrates across the Cretaceous-Tertiary boundary, northeastern Montana
Hutchison, H. and Archibald, J.D.	1986	Diversity of turtles across the Cretaceous-Tertiary boundary in northeastern Montana
Archibald, J.D. and Bryant, L.J.	1990	Differential Cretaceous-Tertiary extinctions of non-marine vertebrates: Evidence from northeastern Montana

Fastovsky, D.E.	1990	Rocks, resolution, and the record: A review of depositional constraints on fossil vertebrate assemblages at the terrestrial Cretaceous/Paleogene boundary, eastern Montana and western North Dakota
Keller, G. and Barrera, E.	1990	The Cretaceous-Tertiary boundary impact hypothesis and the paleontological record
Sheehan, P.M. and Fastovsky, D.E.	1992	Major extinctions of land-dwelling vertebrates at the Cretaceous-Tertiary boundary, eastern Montana
Williams, M.E.	1994	Catastrophic versus non-catastrophic extinction of the dinosaurs: Testing, falsifiability, and the burden of proof
Archibald, J.D.	1996a	Dinosaur extinction and the end of an era: What the fossils say
Archibald, J.D.	1996b	Testing extinction theories at the Cretaceous-Tertiary boundary using the vertebrate fossil record
Hunter, J.P., Hartmann, J.H., and Krause, D.W.	1997	Mammals and mollusks across the Cretaceous-Tertiary boundary from Makoshika State Park and vicinity (Williston Basin), Montana
Sheehan, P.M., Fastovsky, D.E., Barreto, C., and Hoffman, R,G,	2000	Dinosaur abundance was not declining in a ‘3 m gap’ at the top of the Hell Creek Formation, Montana and North Dakota
Nichols, D.J. and Johnson, K.R.	2002	Palynology and microstratigraphy of Cretaceous-Tertiary boundary sections in southwestern North Dakota
Pearson, D.A., Schaefer, T., Johnson, K.R., Nichols, D.J., and Hunter, J.P.	2002	Vertebrate biostratigraphy of the Hell Creek Formation in southwestern North Dakota and northwestern South Dakota

The Hell Creek Formation has received significant attention in the form of theses and published papers for not only its paleontologic significance but also for its geologic importance as part of the last regressive cycle of the Western Interior Cretaceous Seaway. The vast majority of these works (Table 2) have made use of measured sections to document depositional environments within the Hell Creek Formation itself with considerably less attention paid to the underlying Bearpaw and Fox Hills Formations. Published papers and theses focusing on these lower units are listed in Table 3.

Table 2: Papers and theses on geologic aspects of the Hell Creek Formation.

Author	Year	Title
Brown, B.	1907	The Hell Creek beds of the Upper Cretaceous of Montana
Dunlap, C.M.	1958	The Lewis, Fox Hills and Lance Formations of the Upper Cretaceous Age in the Powder River Basin, Wyoming
Frye, C.L.	1967	The Hell Creek Formation in North Dakota
Frye, C.L.	1969	Stratigraphy of the Hell Creek Formation in North Dakota
Moore, W.L.	1976	The stratigraphy and environments of deposition of the Cretaceous Hell Creek Formation (reconnaissance) and Paleocene Ludlow Formation (detailed), southwestern North Dakota
Butler, R.D.	1980	Stratigraphy, sedimentology, and depositional environments of the Hell Creek Formation (Late Cretaceous) and adjacent strata, Glendive area, Montana
Lepp, C.L., 1981	1981	Depositional environments of the Upper Cretaceous – lower Tertiary rocks, western Williston Basin, Montana
Crowder, R.K.	1983	Latest Cretaceous sedimentation and paleogeography, Western Interior, U.S.A.
Wheeler, K.L.	1983	Maestrichtian shoreline sedimentation in northeastern Montana
Fastovsky, D.E.	1986	Paleoenvironments of vertebrate-bearing strata at the Cretaceous-Paleogene boundary in northeastern Montana and southwestern North Dakota
Fastovsky, D.E. and Dott, R.H.	1986	Sedimentology, stratigraphy, and extinctions during the Cretaceous-Paleocene transition at Bug Creek, Montana
Murphy, D.A.	1986	Sedimentation of the Upper Hell Creek Formation (Upper Cretaceous), Carter County, southeast Montana

Fastovsky, D.E., and McSweeney, K.	1987	Paleosols spanning the Cretaceous-Paleogene transition, eastern Montana and western North Dakota
Zaleha, M.J.	1988	The Hell Creek Formation (Maastrichtian), Glendive area, Montana: Sedimentology, paleoenvironments, and provenance and their stratigraphic and taphonomic implications
Fastovsky,D.E., McSweeney, K., and Norton, L.D.	1989	Pedogenic development at the Cretaceous-Tertiary boundary, Garfield County, Montana
Jenkin, D.S.	1990	Stratigraphy and base-level changes across the Maastrichtian/Paleocene boundary of Montana and North Dakota
Lillegraven, J.A., and Ostresh, L.M.	1990	Late Cretaceous (earliest Campanian/Maastrichtian) evolution of western shorelines of the North American Western Interior Seaway in relation to known mammalian faunas
Gillespie, J.M., and Fox, J.E.	1991	Tectonically influenced sedimentation in the Lance Formation, eastern Wind River Basin, Wyoming
Tamm, V.	1993	Depositional environments of the Lower Hell Creek Formation (Maastrichtian), eastern Montana
Belt, E.S., Hicks, J.F., and Murphy, D.A.	1997	A pre-Lancian regional unconformity and its relationship to Hell Creek paleogeography in south-eastern Montana
Arens, N.C. and Jahren, A.H.	2002	Chemostratigraphic correlation of four fossil-bearing sections in southwestern North Dakota
Hartmann, J.H.	2002	Hell Creek Formation and the early picking of the Cretaceous-Tertiary boundary in the Williston Basin
Hicks, J.F., Johnson, K.R., Obradovich, J.D., Tauxe, L., and Clark, D.	2002	Magnetostratigraphy and geochronology of the Hell Creek and basal Fort Union Formations of southwestern North Dakota and a recalibration of the age of the Cretaceous-Tertiary boundary
Lund, S.P., Hartmann, J.H., and Banerjee, S.K.	2002	Magnetostratigraphy of the interfingering upper Cretaceous-Paleocene marine and continental strata of the Williston Basin, North Dakota and Montana
Murphy, E.C., Hoganson, J.W. and Johnson, K.R.	2002	Lithostratigraphy of the Hell Creek Formation in North Dakota

Table 3: Papers and theses on the Bearpaw and Fox Hills Formations.

Hayden, F.V.	1862	Sketch of the geology of the country about the headwaters of the Missouri and Yellowstone Rivers
Stanton, T.W., Hatcher, J.B., and Knowlton, F.H.	1905	Geology and paleontology of the Judith River beds
Thom, W.T. and Dobbin, C.E.	1924	Stratigraphy of the Cretaceous-Eocene transition beds in eastern Montana and the Dakotas
Dobbin, C.E. and Reeside, J.B.	1929	The contact of the Fox Hills and Lance Formations
Brown, R.W.	1939	Fossil plants from the Colgate Member of the Fox Hills sandstone and adjacent strata.
Cobban, W.A. and Reeside, J.B.	1952	Correlation of the Cretaceous formations of the western interior of the United States
Harms, J.C., MacKenzie, D.B., and McCubbin, D.G.	1965	Depositional environment of the Fox Hills Sandstones near Rock Springs, Wyoming
Waage, K.M.	1968	The type Fox Hills Formation, Cretaceous (Maastrichtian), South Dakota
Feldmann, R.M.	1972	Stratigraphy and paleoecology of the Fox Hills Formation (Upper Cretaceous) of North Dakota
Gill, J.R. and Cobban, W.A.	1973	Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North Dakota
Obradovich, J.D. and Cobban, W.A.	1975	A time scale for the Late Cretaceous of the western interior of North America
Cvancara, A.M.	1976	Geology of the Fox Hills Formation (late Cretaceous) in the Williston basin of North Dakota, with reference to uranium potential
Daly, D.J.	1984	The stratigraphy and depositional environments of the Fox Hills Formation, Bowman County, North Dakota
Wilde, E.M.	1985	Stratigraphy and petrography of the Fox Hills Formation in the Cedar Creek Anticline area of eastern Montana

Stratigraphic Overview

The Bearpaw Formation, 73.5 Ma to 71.5 Ma (approximated from Macauley, 1964) is the oldest formation described in this study. It was named by Stanton et al. (1905) for its exposures near the Bearpaw Mountains. The Bearpaw Shale is described as a dark clay shale containing calcareous concretions that was deposited in an offshore environment (Figure 3; Weimer, 1960; Balster, 1972; Weimer and Land, 1975; Jenkin, 1990). It was conformably deposited over the Judith River Formation during the last major transgression of the Western Interior Cretaceous Seaway (Weimer, 1960). Thickness of the Bearpaw Shale ranges from 183 to 348 meters, thinning to the west (Weimer, 1960; Jenkin, 1990). Lithostratigraphically correlative formations include the Pierre Shale in North Dakota and Wyoming (Figure 4; Gill and Cobban, 1973).

The Fox Hills Formation, 71.5 Ma to 67.5 Ma (approximated from Macauley, 1964), was named by Meek and Hayden (1861) at Fox Ridge in Dewey County, South Dakota. It is described as gray to white, fine- to medium-grained argillaceous sandstone, and reflects marine deposition at the base transitioning to non-marine deposition at the top when the Colgate Member is present (Figure 3; Bartram, 1937). Deposition occurred during the last regression of the Western Interior Cretaceous Seaway (Anna, 1986; Jenkin, 1990). Thickness of the Fox Hills Formation ranges from 30 to 152 meters. It is lithostratigraphically correlative to the Lennep Formation in central Montana (Figure 4).

The Colgate Member of the Fox Hills Formation (exact ages in the field area unknown, but constrained by ages of the Fox Hills Formation) was named by Calvert (1912) for its exposures by Colgate Station near Glendive, Montana. It is described as a white to grayish green, glauconitic, volcanic sandstone (Hartmann and Kirkland, 2002; Murphy et al., 2002). The depositional environment of the Colgate Member has been interpreted as marine, lagoonal, back-barrier beach, shallow subtidal or intertidal deposits associated with a distributary system, and non-marine fluvial deposits (Figure 3; Weimer and Land, 1975; Murphy et al., 2002, referencing Waage, 1968; Feldmann, 1972; Butler, 1980). It occupies the same lithostratigraphic position as the Whitemud Formation in southern Canada (Figure 4), though the two are not continuous (Jenkin, 1990, referencing Fraser et al., 1935, Fig 1; and Carlson, 1979, 1983).

The Hell Creek Formation, 67.5 Ma to 65.5 Ma (approximated from Macauley, 1964), was named by Brown (1907) for its exposures near Hell Creek, about 25 miles north of Jordan, Montana. The Hell Creek Formation is the youngest unit studied, representing deposition during the latest Cretaceous and ending at the Cretaceous-Tertiary boundary. It is described as interbedded sandstones, shales and lignites (Figure 3) and is lithostratigraphically correlative to the Lance Formation in Wyoming, the St. Mary River Formation in northwestern Montana, and the Frenchman, Battle and Willow Creek Formations in southern Canada (Figure 4). The use of 'lower Hell Creek Formation' and 'upper Hell Creek Formation' in this thesis are informal stratigraphic subdivisions based only on relationships in the study area.

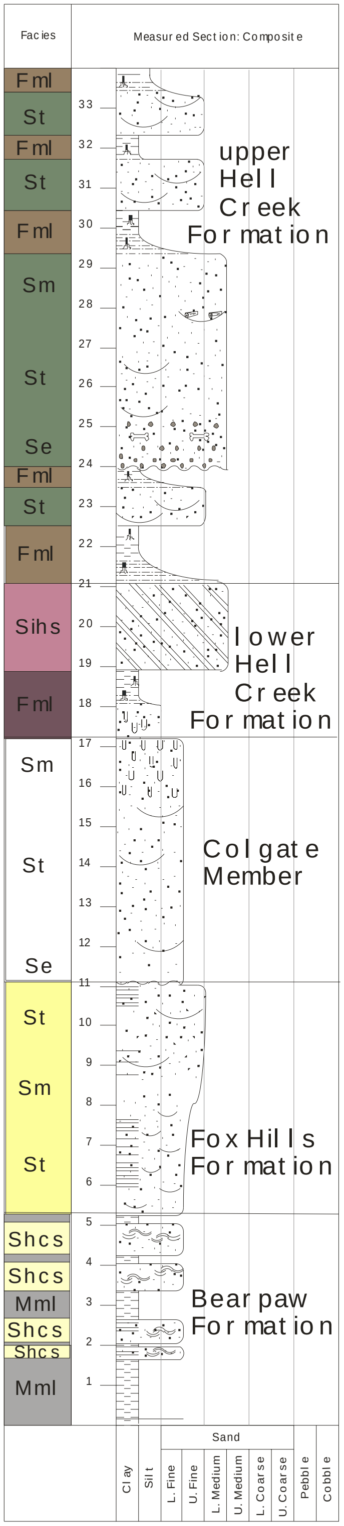


Figure 3: Composite stratigraphic column of the Bearpaw through Hell Creek Formations within the study area (equivalent to 'northeast Montana' section of Figure 4).

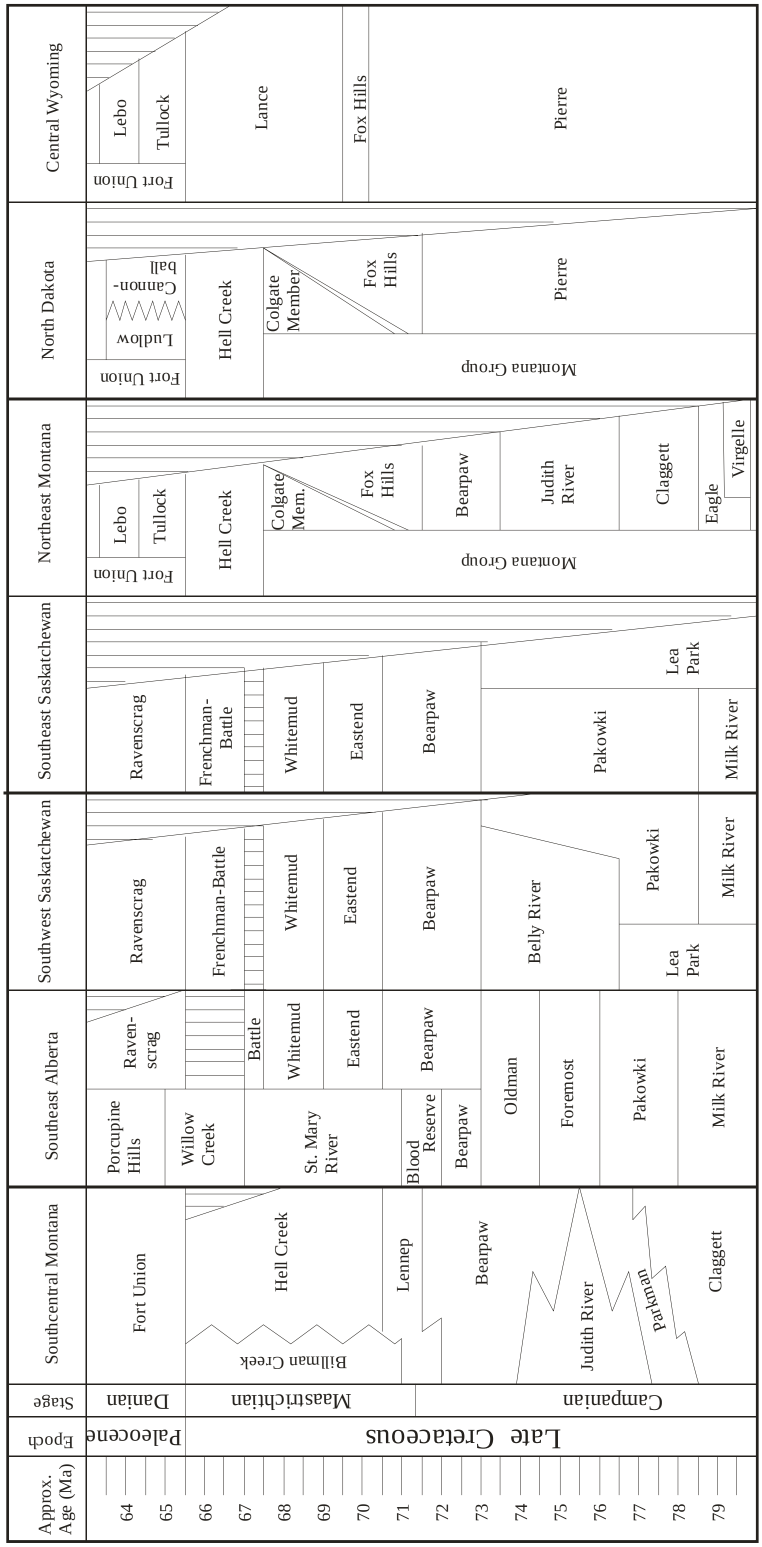


Figure 4: Modified from Macauley (1964) and Roberts (1972).

Purpose of Study

Given the tremendous volume of literature cited above, it is clear that the Hell Creek and adjacent formations have been carefully studied for decades. The purpose of this additional study in an area already so well documented is as follows:

1) Determine the dynamics of shoreline movement during latest Cretaceous time using stratal relationships interpreted within a sequence stratigraphic framework.

2) Locate sites of previously described dinosaur excavations within this framework in order to identify stratigraphic areas of preferential preservation as well as relative age relationships between various discoveries.

3) Determine depositional environments of the Bearpaw through Hell Creek Formations.

Field Methods

Fourteen stratigraphic sections were measured (Figure 5) using a Brunton compass and both a 1.5 meter Jacob staff graduated in decimeter increments and a 100 meter tape graduated to the same degree. Most sections were badly weathered and had to be trenched using shovels, picks and mattocks (Figure 6). Care was taken to trench deep enough as to be able to observe primary bedding, and to be beneath the zone of modern soil development. All measured sections are included in Appendix A.

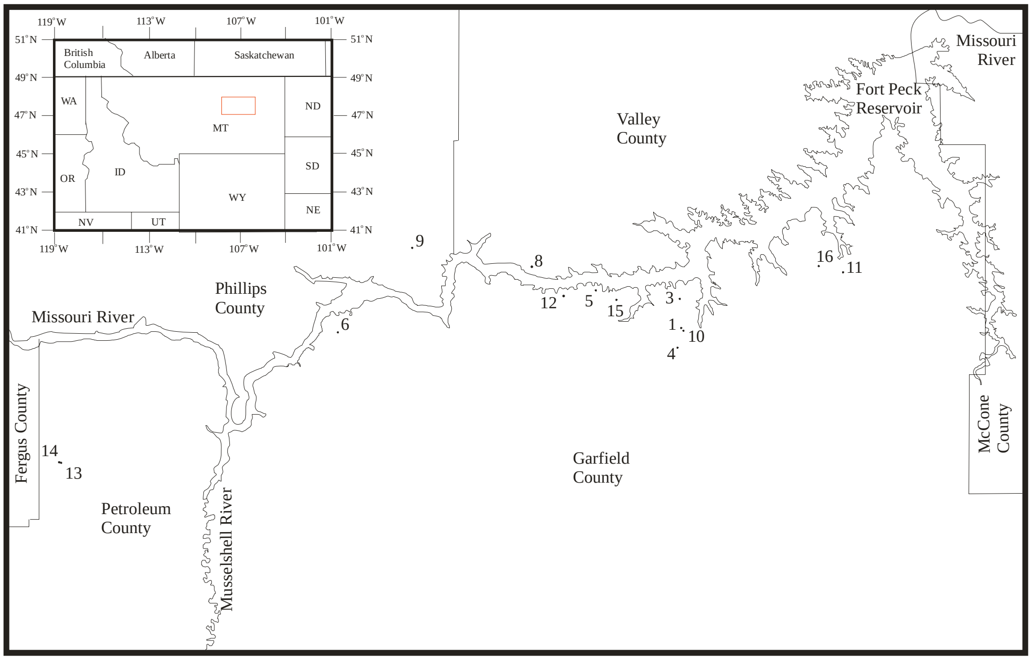


Figure 5: Location of fourteen measured sections along the Fort Peck Reservoir.

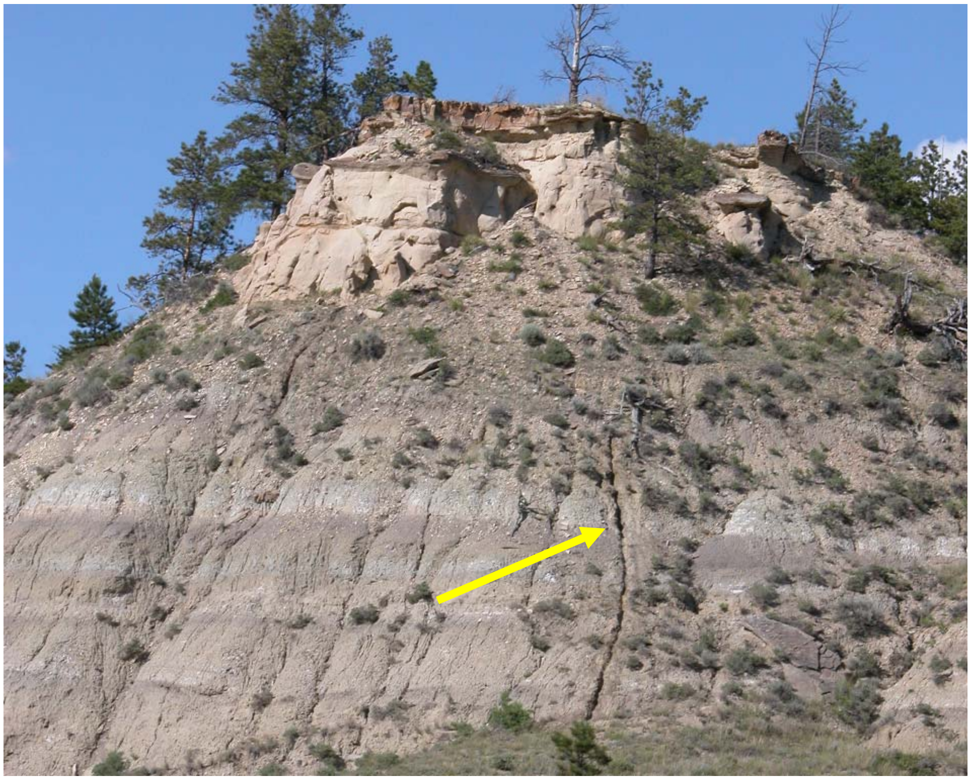


Figure 6: Photograph of trenching at Site #6. Trough location shown by yellow arrow.

Field descriptions of strata included lithology, grain properties, fabric, sedimentary and biogenic structures, thickness, outcrop character, degree of induration, color on fresh and weathered surfaces, natures of contacts, paleocurrent vectors and lateral continuity of these characteristics. Lithology was noted on a graphic log, a field name was designated, and then samples of each facies were taken for additional description in the laboratory. Grain properties and fabric were determined with the aid of a visual comparator and hand lens. Sedimentary and biogenic structures were classified according to Tucker (2003, p. 83-162) and then placed into appropriate lithofacies following the nomenclature of Miall (1977, 1978). Paleocurrent vectors were measured with a Brunton compass corrected to magnetic declination according to Tucker (2003, p. 179-190). Photographs of primary sedimentary structures, biogenic structures and large scale outcrop character were taken. Photomosaics were made for each measured section location. Surfaces identified from the measured sections were then transferred to the photomosaics and their lateral extent inferred from the photo as well as field notes from walking out key surfaces away from the measured section location.

Stratigraphic information about dinosaur sites was taken from sections measured by Shoup (2001). Three of these sections were field checked for this study, but no new sections were measured. Shoup's descriptions of strata and sketched sections were transferred to the same scale and format as sections from this study and are located in Appendix B. Locations of dinosaur sites that include measured sections are shown in Figure 7. These sites were incorporated into the framework developed from sections measured by the author and then interpreted relative to their sequence stratigraphic position.

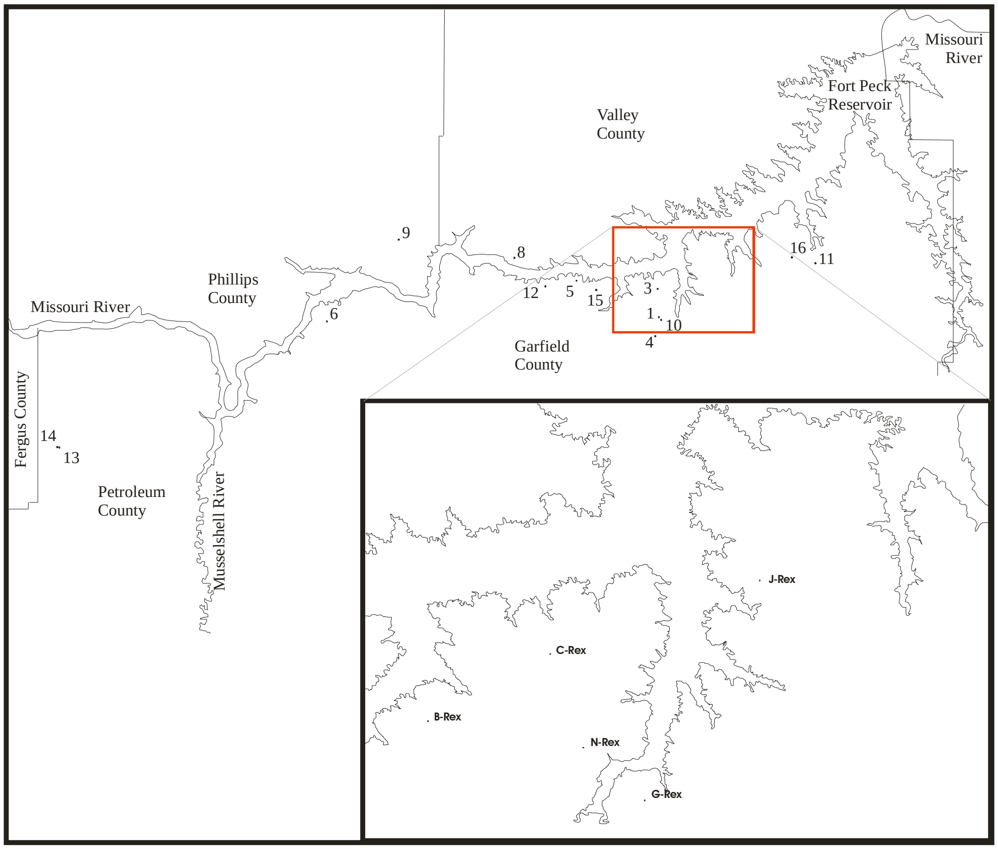


Figure 7: Location of dinosaur sites that have been placed in a stratigraphic section.

CHAPTER 3

BEARPAW FORMATION

In the sections measured here, the four lithofacies of the Bearpaw Formation reach a combined maximum thickness of 20 meters and are exposed laterally for tens of kilometers. All facies display sheet-like geometries. Figures 8 and 9 below are characteristic outcrop exposures of the Bearpaw Formation.

Figure 8: Typical outcrop appearance of the Bearpaw Formation (dark gray hummocky topography in the foreground). Photo taken near Site #6.

Figure 9: Photo near Site #5 with the transitional nature of the Bearpaw and Fox Hills formations in the foreground and hummocky topography of the Bearpaw in the background.

Massive to Laminated Mudstone (Mml)

Lithofacies Mml is characterized by massive to laminated, poorly consolidated, light gray to black, mottled, silty mudstone with few zones of iron oxidation. Where lamina are present bounding surfaces are marked by a color change and change in grain size, with finer grained lamina tending to be dark gray to black and silty to sandy lamina tending to be light gray (Figure 10). Exposures of Mml that are more massive are typically lighter in color, more silty and tend to show more mottling than laminated exposures (Figure 11). Mottling consists of roughly 3mm by 1mm lenses of darker, lenticular mudstone within the lighter, siltier mudstone. Iron oxidation can be present along lamina surfaces as well as blocky fractures that are throughout this facies.

Fragments of ammonites, specifically *Baculites* sp., are common in this lithofacies. Their frequency declines where Mml is interbedded with the sandier facies of the Bearpaw Formation. Lepp (1981) identified bivalves *Inoceramus* sp., *Protocardia* sp. and ammonite *Acanthoscaphites* sp. in the upper 21 meters of the Bearpaw Formation along the Missouri River (directly east of the sections measured for this work).

Figure 10: Typical appearance of Mml where the laminated nature is more apparent. Photo taken at Site #12.

Figure 11: Typical appearance of Mml where the massive nature is more apparent. Photo taken at Site #11. Scorpion for scale.

Hydrodynamic Interpretation

The well-sorted, fine-grained nature of facies Mml is indicative of deposition due to suspension settling in quiet water (Sanders, 1965; Burne, 1995; Boggs, 2001, p. 156). The presence of lamination in some exposures of Mml, especially where lamina are distinguished by grain size and color change, indicates fluctuations in current velocity (Sanders, 1965) and introduction of sediment by “discrete and gentle currents, at least some of which were bottom hugging” (Burne, 1995, p. 120). Mottling is commonly attributed to bioturbation (Davis, 1983, p. 458-9).

Facies Associations

Facies Mml is gradational above to Sm of the Fox Hills Formation or abruptly overlain by Shcs, Sm, and Sh of the Bearpaw Formation, Shcs, St and Sm of the Fox Hills Formation, Se of the Colgate Member, and Se of the upper Hell Creek Formation. Below this facies is transitional from Sm of the Bearpaw Formation, and Sm of the Fox Hills Formation, but can also abruptly overlie Shcs and Sm of either the Bearpaw or the Fox Hills Formations. No scour marks, tool marks, or other evidence of erosion is evident along any of the abrupt contacts. The most common facies associations are abrupt contacts both above and below with Sm and Shcs of the Bearpaw Formation.

Depositional Process

The abrupt contacts of facies Mml with Sm, Shcs and Sh represent hemipelagic deposition that is interrupted by deposition from higher energy, sand laden currents. These vertical transitions from mudstone to sandstone indicate shallowing of water depths or an increase in storm size and/or activity (Carr et al., 2003). Abrupt upper contacts from the Shcs below to Mml above indicate a return to lower energy conditions and the resumption of low energy, hemipelagic deposition.

Hummocky Cross-Stratified Sandstone (Shcs)

Lithofacies Shcs is characterized by hummocky cross-stratified, light tannish-gray, well-sorted, well-cemented, fine-grained sandstone. Individual hummocks within this facies are generally a few decimeters in diameter and less than 0.3 meters in height. Hummocky beds are up to 1 meter in thickness and are typically single depositional events. Rarely this facies exhibits bioturbation, as shown by *Skolithos* burrows in Figure 12.

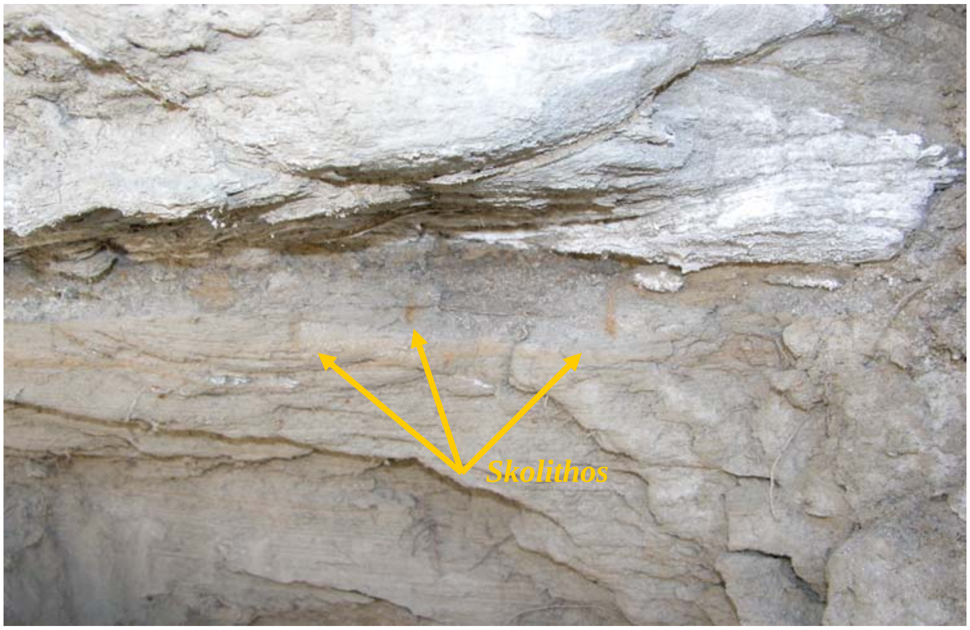


Figure 12: Example of bioturbation within facies Shcs. Photo taken at Site #1.

Hydrodynamic Interpretation

Hummocks have been interpreted to form under oscillatory flow conditions (Dott and Bourgeois, 1982), combined flow conditions that are very strongly oscillatory (Dott and Bourgeois, 1982), and a combination of both unidirectional and oscillatory flow conditions (Dott and Bourgeois, 1983; Walker et al., 1983; Swift et al., 1983, Duke et al., 1991; Cheel and Leckie, 1993). The source of these flows, however, is generally agreed to be surges that are generated by storm waves (Harms, 1975, 1982; Dott and Bourgeois, 1982; Duke et al., 1991, Cheel and Leckie, 1993).

Facies Associations

Facies Shcs is gradational above to Sm or abruptly overlain by Mml. Below, this facies is transitional from Sm and Sh, but can also abruptly overlie Mml. No evidence of erosion is apparent along any of the abrupt contacts. The most common facies associations are abrupt contacts above and below with Mml.

Depositional Process

The formation of hummocky cross-stratification is due to storm activity (Dott and Bourgeouis, 1982). A typical hummocky succession from base to top consists of: 1) an erosive base, potentially with tool or scour marks 2) hummocky cross-stratification deposited during oscillatory currents of waning storms 3) planar beds followed by ripple cross-stratification indicating a return to normal, fair-weather deposition 4) bioturbation of the upper plane bed and ripple surfaces indicating reoccupation of this environment by opportunistic organisms, and 5) bioturbated mudstone indicating a complete return to pre-storm conditions (Dott and Bourgeois, 1982; McCubbin, 1982). This succession suggests deposition contemporaneous with and subsequent to a single storm event (McCubbin, 1982). The degree to which each of these components is developed in a given area of hummocky cross-stratification can indicate the relative energy of the system. (Dott and Bourgeouis, 1982).

In the Shcs facies of the Bearpaw Formation, individual hummocky beds are thin and do not necessarily show the complete succession described above. The transition from some hummocky beds into Sm and then into the muddier facies of the Bearpaw Formation could indicate a complete depositional unit, while those Shcs beds that are simply encased in mudstone could represent incomplete, sand starved storm beds or more distal, deeper deposition.

Horizontally Stratified Sandstone (Sh)

Lithofacies Sh is characterized by horizontally stratified, light tannish-gray, well-sorted, often poorly cemented, fine-grained sandstone. Horizontally stratified beds are generally less than 0.3 meters in thickness. Some horizontally stratified beds exhibit bioturbation. Recognizable ichnofossils include *Ophiomorpha* and *Skolithos*.

Hydrodynamic Interpretation

Horizontal stratification can be found in both upper and lower flow regimes. Commonly Sh is characteristic of upper flow regime deposition, where beds are deposited rapidly and under changing flow conditions (Harms, 1975; Boggs, 2001, p. 94). Sh may also form in the lower flow regime, especially when flows are shallow or when flow velocities are below those necessary for ripple formation (Boggs, 2001, p.94).

Facies Associations

Facies Sh is gradational above to Shcs. Below, this facies abruptly overlies Mb. At the lower boundary, there is no evidence of erosion.

Depositional Process

The association of Sh as gradational to Shcs is consistent with deposition from storm currents. Although an idealized deposit from a single storm event places hummocky cross-stratified sandstones beneath horizontally stratified sandstones (Dott and Bourgeouis, 1982), their strong association with one another is still suggestive of deposition due to storm events (Carr et al., 2003).

Massive Sandstone (Sm)

Lithofacies Sm is characterized by massive, light tannish gray, well-sorted, poorly consolidated, lower fine-grained sandstone. Massive beds range in thickness from centimeter to meter scale with thicker beds more common higher in the section. No grading within beds is apparent.

Hydrodynamic Interpretation

The lack of sedimentary structure in facies Sm can be attributed to several factors: 1) disruption due to biogenic activity, 2) rapid deposition, and 3) homogeneity of grain size and sediment type. Typically in the absence of strong biologic activity, massive beds result from rapid deposition, such as ‘freezing’ from a grainflow type deposit (Reineck and Singh, 1980, p. 130; Leeder, 1982).

Facies Associations

Facies Sm can be gradational above to Shcs and Mb or abruptly overlain by Mml. Below, these facies relationships are the same as above, transitional from Shcs and Mml and abruptly over Mml. Most commonly, decimeter scale units are isolated and display abrupt vertical transitions to and from Mml.

Depositional Process

The characteristic facies associations of Sm with Mml suggest deposition from grain flows, as described and pictured in Leeder (1982, p. 81, Figure 7.9a). Additionally, the transitional relationships with Shcs are indicative of deposition from storm currents. Although massive units are not part of the idealized succession of storm deposition as proposed by Dott and Bourgeouis (1982), it is important to note that the massive nature observed here may not be primary. Reworking of primary depositional structures during waning flows or subsequent bioturbation can generate massive beds (Boggs, 2001, p. 387, referencing Dott, 1983; Gagan et al., 1988). Due to the intensely weathered nature of the exposures of the Bearpaw Formation, it is also possible that primary structures have been obscured. Therefore with the massive facies, it is extremely important to interpret their depositional process and environment in the context of surrounding facies.

Depositional Environment of the Bearpaw Formation

The predominance of facies Mml within the Bearpaw Formation, as well as the presence of marine fauna such as *Baculites* sp. and other marine ammonites and bivalves identified by Lepp (1981), suggest deposition in a quiet water marine setting, such as the offshore environment. This environment is defined as the zone below storm wave base, where deposition is characterized by bioturbated mudstones and few very fine-grained, massive sandstone beds (Harms et al., 1975; Walker, 1984).

Vertical transitions from mudstone (Mml) to sandstone facies (Shcs, Sm and Sh) indicate a change from dominantly quiet water, suspension deposition to higher energy marine deposition from storm currents. This increased energy is characteristic of the transition from upper offshore to the lower shoreface environment, where sedimentation takes place between storm wave base and fair-weather wave base (Walker, 1984). Other authors have indicated that this transitional zone begins “at the lower limit of fairweather (minimum) wave base, but where offshore processes continue to operate” (Reinson, 1984; MacEachern and Pemberton, 1992, p. 62). The former definition is the one used here.

Sand can be delivered to the lower shoreface by storm waves which erode beach and shoreface deposits and redeposit the sediment seaward (Reinson, 1984; Boggs, 2001, p. 384) or by turbidity currents (Walker, 1984). Once the sand is available it is then reworked by wave activity to form hummocky cross-stratification (Shcs), swaley cross-stratification and combined flow ripples deposited as storm currents wane (MacEachern and Pemberton, 1992). McCubbin (1982) and Boggs (2001, p. 351) include planar beds (Sh) as a dominant component of lower shoreface stratification. Trace fossil assemblages of this zone are predominantly of the *Cruziana* and *Skolithos* ichnofacies (MacEachern and Pemberton, 1992).

The transition from offshore to lower shoreface environment can occur because of a relative fall in sea-level, causing water depths to shallow and therefore placing the formerly offshore zone of deposition within the zone more strongly affected by storm deposition. Additionally, this transition can be caused by increased storm energy (Carr et al., 2003) which increases the depth to which storm currents can act.

The ratio of sandy facies (Shcs, Sm and Sh) to muddy facies (Mml) increases from the base to the top of the Bearpaw Formation. As can be observed from the measured sections of Appendix A, the increased sandstone to mudstone ratio is due to both increased thickness and abundance of sand bodies higher in the section. These sands are representative of more proximal, higher energy environments than the mudstones; therefore, their increased dominance stratigraphically higher in the section indicates that the shoreface succession was progradational (Selley, 1970, p. 106; Niedoroda et al., 1977, p. 610; McCubbin, 1982). Additionally, the predominance of hummocky cross-stratification and massive bedding within the sandy portions indicate that the shoreface succession was storm dominated (Boggs, 2001, p. 395, referencing Galloway and Hobday, 1983, p. 162; Hobday and Morton, 1984).

CHAPTER 4

FOX HILLS FORMATION

The six lithofacies of the Fox Hills formation reach a maximum combined thickness of 18 meters within the field area. The boundary between the Fox Hills Formation and the Bearpaw Formation is gradational, as discussed in the stratigraphic overview. Here it is placed at the base of the first hummocky cross-stratified unit that displays amalgamation. In the absence of a hummocky cross-stratified unit, the base becomes somewhat arbitrary as either at the base of a 'thick' massive sand, or at the base of a trough cross-stratified sand body. All facies described below display sheet like geometries. A typical outcrop exposure is shown in Figure 13.

Figure 13: Characteristic outcrop exposure of Fox Hills (Fox Hills Formation is reddish brown sand below the white and purple layers of the Colgate Member and lower Hell Creek Formation, respectively). Photo taken at Site #10.

Hummocky Cross-Stratified Sandstone (Shcs)

Lithofacies Shcs is characterized by hummocky cross-stratified, light tannish gray, well-sorted, well-cemented, lower fine-grained sandstone (Figure 14). Hummocks range in size from a few centimeters wide by one centimeter in height to several meters wide by a few decimeters in height. Hummocky bed sets are up to 4 meters in thickness and tend be amalgamated. In general, thinner sand bodies contain smaller scale bedforms.

Figure 14: Example of typical Fox Hills Shcs exposure. Photo taken at Site #8. Jacob staff to the right is taped in decimeter increments.

Hydrodynamic Interpretation

Hummocks have been interpreted to form under oscillatory flow conditions (Dott and Bourgeois, 1982), combined flow conditions that are very strongly oscillatory (Dott and Bourgeois, 1982), and a combination of both unidirectional and oscillatory flow conditions (Duke et al., 1991; Cheel and Leckie, 1993). The source of these flows is generally accepted to be surges generated by storm waves (Harms, 1975, 1982; Dott and Bourgeois, 1982; Duke et al., 1991, MacEachern and Pemberton, 1992; Cheel and Leckie, 1993).

Facies Associations

Facies Shcs is gradational above to St, Sm, Sr and Sl or abruptly overlain by Mml of the Bearpaw Formation. Below, this facies is transitional from Sm, but can also abruptly overlie Mml of the Bearpaw Formation. No evidence of erosion is apparent along any of the abrupt contacts. The most common facies associations are an abrupt basal contact with Mml of the Bearpaw Formation and a gradational upper contact to Sm of the Fox Hills Formation.

Depositional Process

The typical hummocky succession (erosive base followed by hummocky cross-stratification, planar beds, ripple cross-stratification, bioturbation of the upper plane bed and ripple surfaces and finally bioturbated mudstone) is not exposed in its entirety in the Fox Hills Formation. Instead, portions of the succession, especially the hummocky and massive units, are more developed. The increased bedform size and bedset thickness of the hummocky units within the Fox Hills Formation indicates that these were formed under higher energy conditions than the same bedforms of the Bearpaw Formation.

The abrupt contact of Shcs with Mml of the Bearpaw Formation below indicates a sudden increase in energy across the lower contact, while the upper contact to massive facies indicates the waning of storm currents. This “waning flow tends to erase structures made by increasing storm-flow velocity. If storm-generated structures do survive waning flow, they may not survive bioturbation” (Boggs, 2001, p. 387 summarizing the works of Dott, 1983 and Gagan et al., 1988).

Massive Sandstone (Sm)

Lithofacies Sm is characterized by massive, light tannish gray, well-sorted, lower fine-grained sandstone. Thickness of these beds ranges from one decimeter to several meters. No grading is apparent within the beds.

Hydrodynamic Interpretation

The lack of sedimentary structure in facies Sm can be attributed to both primary and secondary effects. Primary massive stratification can result from rapid deposition (Reineck and Singh, 1980, p. 130; Leeder, 1982) as well as a consistency of grain size and composition. These latter deposits will sometimes reveal evidence of primary structure when etched or viewed by x-ray (Miall, 1996, p. 123; Boggs, 2001, p. 96-7). As a secondary feature, massive stratification can be the result of reworking due to currents (Reineck and Singh, 1980, p. 130; Boggs, 2001, p. 387) as well as biogenic activity (Reineck and Singh, 1980, p. 130; MacEachern and Pemberton, 1992; Boggs, 2001, p. 387 – referencing Dott, 1983; Gagan et al., 1988).

Facies Associations

Facies Sm is gradational above to Shcs, St, Sl, Sr, and Mm of the Fox Hills Formation and Mml of the Bearpaw Formation or abruptly overlain by Mml of the Bearpaw Formation or St and Fm of the upper Hell Creek Formation. Below, this facies is transitional from Shcs, St, and Sl of the Fox Hills Formation and Mml of the Bearpaw Formation. Where Se, St and Sm of the upper Hell Creek Formation abruptly overlie Sm of the Fox Hills Formation, the contact is erosional. The most common facies associations are transitional from Shcs or an abrupt basal contact with Mml of the Bearpaw Formation and a gradational upper contact to St of the Fox Hills Formation.

Depositional Process

Because Sm does not commonly occur between abrupt contacts with either Mml of the Bearpaw Formation or Mm of the Fox Hills Formation, it does not fit the ideal characteristics of deposition from a grainflow, as described by Leeder (1982). Instead this structureless sand is generally transitional from other structured sands, such as Shcs and St. This indicates that Sm was deposited by similar, high energy currents such as unidirectional, lower flow regime currents of St or storm currents of Shcs. Additionally, it is likely that the massive nature of many of the Sm facies of the Fox Hills Formation was not the primary sedimentary structure. Due to the intensely weathered nature of Fox Hills outcrops, it is probable that the primary sedimentary structures of Sm have been obscured. In the case of Sm being transitional from Shcs, the massive nature likely resulted from waning flows and subsequent bioturbation erasing primary stratification (Boggs, 2001, p. 387 – referencing Dott, 1983; Gagan, et al., 1988).

Trough Cross-Stratified Sandstone (St)

Lithofacies St is characterized by trough cross-stratified, light grayish tan, well-sorted, poorly to moderately cemented, medium-grained sandstone (Figure 15). Trough dimensions average 1 – 2 meters in width and ~0.5 meters in height. Bedsets can reach total thicknesses of 8 meters. Bioturbation of facies St is minimal, but observed traces include *Thalassenoides* and *Planolites*, as shown in Figure 16 below. These traces are observable on bedding parallel surfaces and are often found together. Occasionally trace fossils of *Ophiomorpha* are present in this facies. Trough cross-stratification is the most abundant facies present within the Fox Hills Formation. Paleocurrent vectors measured from this facies were predominantly directed to the northeast (N30E), with a minor component of southeast (S60E).

Figure 15: St from the Fox Hills Formation. Photo taken near Site #6.

Figure 16: Photographs taken at Site #6 of *Thalassenoides* (left) and *Planolites* (right) on a bedding surface of facies St.

Hydrodynamic Interpretation

Trough cross-stratification can be formed by the migration of ripples as well as dune forms under lower flow regime, unidirectional current conditions (Harms, 1975; Boggs, 2001, p. 38, 101). Migration of the bedform leads to "formation of dipping foreset lamina owing to avalanching or suspension settling in the zone of separation on the lee side of these bedforms" (Boggs, 2001, p. 99). Trough formation can occur in sand grain sizes from fine to very coarse (Miall, 1996, p. 114). The troughs present in the Fox Hills Formation indicate a minimum flow depth of 1 meter (Harms et al., 1975)

Facies Associations

Facies St is gradational above to Sm, Sr and Mm (Figure 17) of the Fox Hills Formation (and can be interbedded with any of these facies) and Fml of the Upper Hell Creek Formation. Abrupt contacts above St include erosional contact with Se followed by St or Sm of the upper Hell Creek Formation. Below, this facies is transitional from

Shcs, Sm, Sr and Mm or abruptly overlies Mml of the Bearpaw Formation. The most common facies associations are transitional from Sm and gradational to Sm.

Figure 17: St units interbedded with Sr and Sm (the strongly indented portions of the photo). This is a larger view of Figure 15 above.

Where Se, St and Sm of the upper Hell Creek Formation abruptly overlie St of the Fox Hills Formation, the contact is not only erosional but also strongly pitted. These pits may or may not represent borings. In places the pits along the formation boundary are clearly weathering artifacts that represent the removal of centimeter scale concretions; however, in other locations these pits are formed by organisms burrowing into a hardground, creating a *Glossifungites* surface. In the vast majority of outcrops where St of the Fox Hills is erosively overlain by Se of the upper Hell Creek Formation, St below is a ledge former that is extremely well-cemented and contains significant amounts of iron oxide (Figure 18).

Figure 18: Photograph taken near Glendive, MT showing the regionally extensive bench characteristic of the Fox Hills outcrop. The top of this bench is the upper bounding surface of St of the Fox Hills Formation.

Depositional Process

The vertical transition from Shcs and Sm to St is marked by a grain size increase from fine to medium. This upward coarsening indicates that St was deposited in higher energy conditions than either Shcs or Sm. Transitions with Sm do not necessarily imply a change in depositional process, especially given the consistent grain size and composition between the two facies. Instead, the transitional nature of St and Sm may reflect preservation of the Sm facies.

The interbedded nature of St with Sm, Sr, and Mm is indicative of cyclic changes in flow conditions (Boggs, 2001, p. 458). These changes are likely the result of increased energy at the time of formation of trough cross-stratification, decreased energy forming the smaller bedforms (Sr), and finally the lowest energy depositing mudstone (Mm).

The erosional nature of the superjacent contact with Se (transitioning to St) of the upper Hell Creek Formation suggests an abrupt change in depositional process. St of the Fox Hills Formation is strongly associated with Shcs and Sm below and Sm to Sl above, while St of the upper Hell Creek is gradational above to pedogenically altered mudstones. Although the hydrodynamic condition may be the same for the formation of the trough cross-stratification, the vertical and lateral facies relationships indicate that these two St units were formed via different processes. St of the Fox Hills Formation is generally at the top of an overall coarsening upward succession, suggesting an increase in energy in the system through time, while St of the upper Hell Creek Formation is generally at the base of a fining upward succession, suggesting a decrease in energy through time.

Ripple Cross-Laminated Sandstone (Sr)

Lithofacies Sr is characterized by asymmetric, ripple cross-laminated, light tannish gray, well-sorted sandstone. Rippled beds are typically on the order of 0.2 meters thick and are only laterally persistent on the scale of meters. This facies is not abundant within the Fox Hills Formation.

Hydrodynamic Interpretation

Ripples are interpreted to form under lower flow regime conditions in very fine to medium sands due to the migration of ripple forms (Leeder, 1982, p. 95; Todd, 1996, p. 309; Boggs, 2001, p. 97; Bridge, 2003, p. 79-80). They may form under both unidirectional and oscillatory current conditions, creating asymmetrical and symmetrical bedforms, respectively (Boggs, 2001, p. 98). Ripples themselves are not diagnostic of flow depths as they can occur in a range of depths from shallow to very deep (Harms, 1975, p. 57), but they are most common in shallow water (Boggs, 2001, p. 98).

Facies Associations

Facies Sr is gradational above to Sm and Mm and can be interbedded with either of these facies. Abrupt contacts above Sr are erosional by St (Figure 19). Below, this facies is transitional from Shcs, Sm and Mm. The most common facies associations are transitional with Mm and Sm. As mentioned in the facies description of Sr, this facies association is specific to only one location, Site #6.

Depositional Process

Sr as part of a repetitive, fining upward sequence from St to Sm to Sr and finally Mm, indicates that the depositional process was cyclic. This cyclicity could either be due to oscillations in current velocity or sediment supply (Leeder, 1982, p. 95; Todd, 1996, p. 309). Sr represents a transitional phase between lower flow regime migration of dune forms (St) and slack water deposition of silts and clays (Mm). Sr as a transitional facies above Shcs indicates that it was likely formed due to waning flow conditions following a storm.

Massive Mudstone (Mm)

Lithofacies Mm is characterized by massive, dark brown to black, well-sorted, poorly consolidated silty mudstone to sandy siltstone (Figure 19). This facies is generally on the order of decimeters or less in thickness and is laterally continuous on the scale of meters.

Hydrodynamic Interpretation

Deposition of Mm is consistent with deposition from suspension in quiet water. The massive nature of Mm could either indicate that the deposit was reworked or that primary deposition was of extremely consistent grain size and composition.

Facies Associations

Facies Mm is found interbedded with St, Sm, and Sr (Figure 19). Abrupt contacts above include St and Sm where the relationship is erosional. Below, this facies is transitional from St, Sm, and Sr or abruptly overlies Sm. The most common facies associations are transitional relationships with Sm and Sr both above and below. In the measured sections presented in Appendix A, the interbedded and transitional nature are indicated by lines of the same width as the clay grain size (shown at the bottom of each page) throughout Fox Hills sandstones.

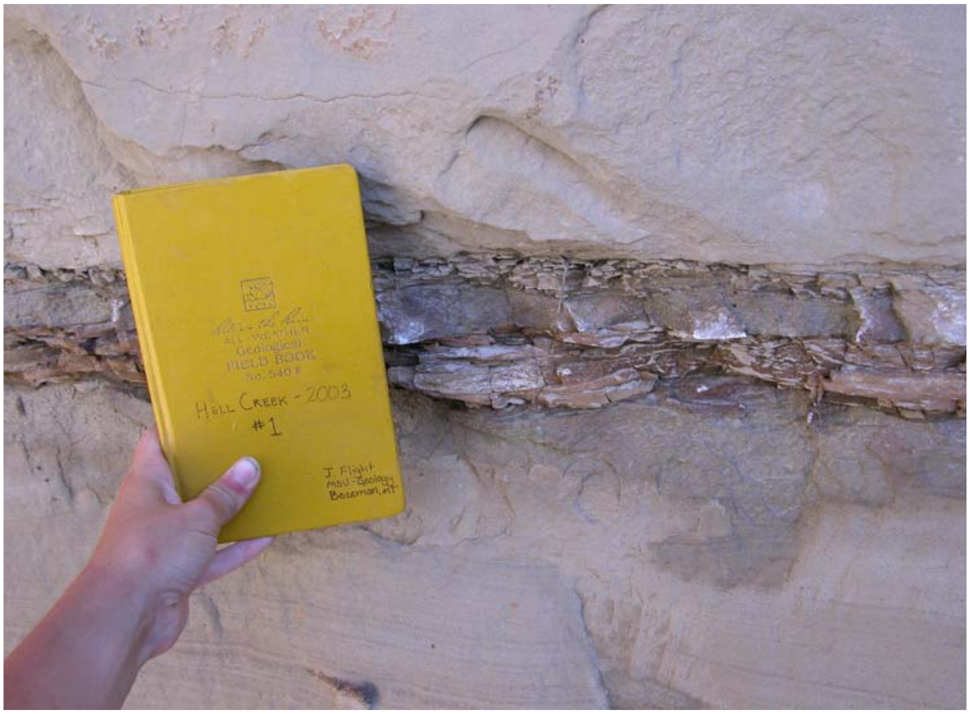


Figure 19: Gradational lower contact of Sr and Mm with St, and erosive upper contact of St into Sr and Mm.

Depositional Process

Mudstones of the Mm facies are in close association with ripple forms, as seen in Figure 19 above. Their relationship as the top of a fining upward sequence from the St, Sm, and Sr facies below suggest that they represent the lowest energy deposition in the cyclic deposition. Figure 17 shows the stacked packages of St, Sm, Sr, and Mm, supporting the repetitive nature of deposition from lower flow regime migration of dune forms, to lower flow regime migration of ripple forms, and finally slack water deposition of mudstone.

Low Angle Planar Sandstone (Sl)

Lithofacies Sl is characterized by low angle, planar laminated, light tannish gray, well-sorted medium- to coarse-grained sandstone. This facies was observed in the field but was not present in any of the sections measured by the author. In Chapter 13, where the stratigraphic interpretation is applied to dinosaur sites, the sections measured by Shoup (2001) do contain this facies, and therefore it is described here via a combination of the author's field notes and those from Shoup's 2001 field season.

Hydrodynamic Interpretation

Plane beds form via transport in the upper flow regime or at velocities below which ripples can not form (Boggs, 2001, p. 94). Low angle planar beds are commonly associated with 'swash and backwash' processes (Boggs, 2001, p. 94).

Facies Associations

Facies Sl is gradational above to Sm and can be abruptly overlain by Se and St of the upper Hell Creek Formation. Below, this facies is transitional from finer grained Sm and Shcs. Sl is only observed in two measured sections, both in the vicinity of Sites #1, 3, 4, 10.

Depositional Process

The transition of Shcs and Sm to Sl marks a gradual increase in grain size, flow velocity, and change in flow style. Shcs is found in fine-grained deposits and is indicative of oscillatory flow conditions (Dott and Bourgeois, 1982), combined flow conditions that are very strongly oscillatory (Dott and Bourgeois, 1982), or a combination of both unidirectional and oscillatory flow conditions (Dott and Bourgeois, 1983; Walker et al., 1983; Swift et al., 1983, Duke et al., 1991; Cheel and Leckie, 1993). All of these possibilities are generally accepted to be distal effects of storm waves (Harms, 1975, 1982; Dott and Bourgeois, 1982; Duke et al., 1991, Cheel and Leckie, 1993). Sl is attributed to ‘swash and backwash’, a higher energy and more directional process than oscillatory flow. The overall progression, therefore, from Shcs or Sm to Sl indicates a coarsening upward succession consistent with deposition from flows of increasing energy, as would be the result of shoaling wave processes.

Depositional Environment of the Fox Hills Formation

The upward coarsening succession of amalgamated Shcs, St, Sm, and Sl as well as the presence of marine ichnofossils suggest that the Fox Hills Formation was deposited in a shoreface environment, between storm wave base and the level of low tide (Harms et al., 1975; Walker, 1984; Reinson, 1984; Boggs, 2001, p. 346). This environment is typically divided into three zones: the lower shoreface, the middle shoreface, and the upper shoreface.

The lower shoreface , also known as the outer-shoaling zone, is a transitional zone that is mainly dominated by storm deposition (Walker, 1984; Reinson, 1984). Sedimentary structures of the lower shoreface typically consist of hummocky cross-stratification, swaley cross-stratification, combined flow ripples (MacEachern and Pemberton, 1992), and planar beds (McCubbin, 1982); Boggs , 2001, p. 351). Trace fossil assemblages of this zone are predominantly of the *Cruziana* and *Skolithos* ichnofacies (MacEachern and Pemberton, 1992). Abrupt vertical transitions from Mml of the Bearpaw Formation to the amalgamated hummocks of Shcs of the Fox Hills formation are consistent with transitions from the quiet water mudstone deposition of the offshore to strongly storm dominated deposition of the lower shoreface. The thicker and more amalgamated nature of Shcs beds of the Fox Hills Formation versus those of the Bearpaw Formation indicate that Fox Hills Shcs were deposited in either a more proximal location relative to the transitional Shcs of the Bearpaw Formation, or via more frequent or higher energy storms (Carr et al., 2003).

The middle shoreface, also known as the breaker zone, is a high energy depositional environment containing a complicated array of sedimentary structures. Predominant structures of the middle shoreface are "low angle wedge-shaped sets of parallel lamina, SCS and lesser HCS. Oscillation ripple lamina, combined flow ripple lamina, and trough cross-stratification are locally present" (MacEachern and Pemberton, 1992, p. 62); however, extreme variability in structures and textures can arise depending on the presence or absence of longshore bars (Reinson, 1984; McCubbin, 1982; MacEachern and Pemberton, 1992; Boggs, 2001, p. 350). Trace fossil assemblages of the middle shoreface are dominated by *Ophiomorpha* and *Skolithos* (Frey and Pemberton, 1984; MacEachern and Pemberton, 1992). Facies consistent with middle shoreface deposition are gradational transitions from Shcs to Sl, as well as between Shcs, Sm and St. Additionally, the dominant trace fossil seen in St is *Ophiomorpha*. The gradational lower boundary is placed where sedimentary structures change from being predominantly hummocky cross-stratification (Shcs) to predominantly trough cross-stratification (St) or low angle planar stratification (Sl). Paleocurrent analysis of troughs indicates flow direction to the northeast and the southeast, which supports facies St as part of either the middle or upper shoreface since flow in both zones is characterized by the interaction of shore parallel and shore normal currents.

The upper shoreface, also known as the surf-zone, is a high energy zone of deposition where shore parallel currents interact with shore normal currents (Reinson, 1984; MacEachern and Pemberton, 1992; Boggs, 2001, p. 350). Dominant sedimentary structures are trough cross-stratification and wedge sets of planar parallel bedding (Reinson, 1984). Paleocurrent measurements from troughs can be multi directional, depending on the relative dominance of longshore currents versus shore normal currents (Reinson, 1984; Boggs, 2001, p. 350). Similarly, the wedge sets of planar parallel bedding can display bidirectional currents (Reinson, 1984; Boggs, 2001, p. 350). Trace fossils assemblages are dominated by *Skolithos*, *Ophiomorpha nodosa* and *Conichnus conicus* (MacEachern and Pemberton, 1992). In the Fox Hills Formation, it is unclear whether facies Sl represents the swash and backwash facies of the upper shoreface to foreshore, or whether it is part of the low angle planar laminations of the middle shoreface. Because Sl was not part of measured sections completed by the author, orientation and ichnofossils of Sl beds are unknown. The interpretation of Sl beds as upper shoreface deposits capping a sequence of middle shoreface St and lower shoreface Shcs beds is supported by Harms et al. (1975) and Niedoroda et al. (1977).; however, the gradational association of Sl with Shcs makes the middle shoreface a more likely interpretation.

Finally, the shoreface environment of the Fox Hills Formation was progradational throughout the time of deposition. Niedoroda et al. (1977, p. 610) describes prograding shoreface deposits as follows:

> Prograding shoreface deposits appear in outcrop as distinctive sequences in which sandstone tempestites with hummocky cross-strata sets become thicker, coarser, and more closely spaced upsection and are capped in turn by: (1) A zone of amalgamated beds of hummocky cross-strata, (2) a zone of sandstone with trough cross-strata sets (surf facies), and (3) a zone of low-angle large-scale wedge-shaped cross-strata sets (swash and beach facies).

These are the exact relationships that are observed in the Fox Hills Formation. Shcs of the lower Fox Hills Formation tend to be thick and amalgamated units, and they are capped by coarser grained units of St and Sm. Above St and Sm are the characteristic wedge planar sets of Sl (though as discussed above, the upper shoreface versus middle shoreface association is unclear for this facies). Similar progradational sequences are described by Harms et al. (1975), Hunter et al. (1979), Reineck and Singh, (1980, p. 387), McCubbin (1982), and Walker (1984).

CHAPTER 5

COLGATE MEMBER OF THE FOX HILLS FORMATION

The Colgate Member of the Fox Hills Formation is present in five of the measured sections and consists of five lithofacies. The maximum combined thickness of these lithofacies is 15 meters. Typically the Colgate Member is a bright white cliff former, as seen in Figures 20 and 21.

Figure 20: Aerial view of a typical Colgate Member (white) outcrop exposure. Lower Hell Creek (purple band directly above the Colgate Member) and upper Hell Creek strata (variegated units above the purple band of the lower Hell Creek) cap the Colgate. Colgate Member is sitting directly on the Bearpaw Formation here. Photo taken near Billy Coulee.

Figure 21: View of Colgate Member outcrop (white) near Site #13. Units above consist of lower Hell Creek (purple band capped by brown band) and upper Hell Creek (variegated units above the lower Hell Creek).

Erosional Scour (Se)

Lithofacies Se is characterized by a regionally extensive scour surface. This erosional surface beneath the Colgate Member of the Fox Hills Formation has significant relief where present, but is only occasionally present within the field area. There was no lag observed on this surface, though Wheeler (1983) did identify a coarse-grained facies in a similar stratigraphic position and called it the “Billy Creek lithofacies” after the type locality. Wheeler confirmed the likely interpretation of her Billy Creek lithofacies as a lag on this lower bounding surface of the Colgate Member (pers. comm. 2003).

Otherwise, the only evidence for an erosional surface is the significant amount of relief on this surface (at least 6 meters, but more likely in excess of 20 meters).

Hydrodynamic Interpretation

Erosional structures such as Se are typically formed by currents, but may form from mass movements (Boggs, 2001, p. 109). The identification of a cobble lag above this surface indicates rapid deposition of a poorly sorted bedload (Miall, 1996, p. 123). Deposition of trough cross-stratified sandstone directly above the erosional surface indicates unidirectional, tractional transport of sand.

Facies Associations

Facies Se is either gradational above to Sm and St or abrupt with Sihs of the lower Hell Creek Formation. Below, this facies always has an abrupt lower contact, either with Sm of the Fox Hills Formation, or Mml of the Bearpaw Formation. The boundary between Se and Sm of the Fox Hills Formation below is often very well-cemented with iron oxide, forming a characteristic ledge throughout the exposures, and is often extensively pitted. In some places this pitting has the appearance of burrows of the *Glossifungites* ichnofacies. Se deposits display a linear, shoestring geometry, but the surface itself is regionally extensive.

Depositional Process

The emplacement of Se over facies such as Mml of the Bearpaw Formation implies a significant change in sedimentary process. Mml was formed by suspension settling in a quiet water environment while Se was likely formed by the same higher energy flow that was responsible for deposition of St. The relief along Se (at least 6 meters but more likely in excess of 20 meters) and the linear geometry indicates that the process that formed the erosional surface was not active basin-wide and suggests channelization.

Furthermore, the change in geometry between Sm of the Fox Hills Formation and Sm of the Colgate Member indicates that the processes of formation were not the same. Sm of the Fox Hills Formation has a sheet like geometry that is laterally continuous on the order of kilometers. The erosional surface that places Sm of the Colgate Member over Sm of the Fox Hills Member is regionally extensive, but locally creates linear, shoestring-like valleys.

The abrupt contact between Sm of the Fox Hills Formation and Se of the Colgate Member also implies a change in process. The pitted surface observed along this contact appears to be the result of weathering out of small concretions in some places, but in others there are indications of a *Glossifungites* ichnofacies. This assemblage contains boring type traces, indicative of the formation of a hardground post deposition of Sm of the Fox Hills Formation, and perhaps associated with the formation or filling of the Se scour.

Massive Sandstone (Sm)

Lithofacies Sm is characterized by massive, bright white, micaceous, clay rich, well-sorted, upper fine- to medium-grained sandstone. Planar zones of oxidation are present within this facies at a random spacing on the scale of meters. In some of the basal exposures of facies Sm the white color is more of a yellowish gray, but is otherwise lithologically identical. Bioturbation of this facies is quite extensive, but limited to the *Skolithos* variety (Figure 22). Sm displays a similar linear geometry to Se.

Figure 22: Photograph of *Skolithos* burrows from facies Sm of the Colgate Member taken at Site #6.

Hydrodynamic Interpretation

Massive beds that form from primary deposition are rare. They can be generated from rapid deposition, such as freezing from a grainflow (Leeder, 1982; Reineck and Singh, 1980, p. 130) or can be 'apparently massive' due to consistent grain size and composition. Often the latter type of massive bed will show traces of the primary depositional structure when etched (Boggs, 2001, p. 96-7). In cases where massive facies contain significant trace fossils, it is likely that the massive nature is actually secondary and as a result of reworking by biogenic activity (Reineck and Singh, 1980, p. 130; MacEachern and Pemberton, 1992).

Facies Associations

Facies Sm is abruptly overlain by Fml of the lower Hell Creek Formation, or Se and Fml of the upper Hell Creek Formation. Below, this facies is transitional with Se or St.

Depositional Process

The close association of Sm with St, and the appearance of 'ghosts' of trough cross-stratification within Sm, indicates that many of the Sm facies were likely formed by the same processes as St. Secondary reworking by biogenic activity has destroyed much of the primary stratification of Sm. The geometry of facies Sm is controlled by the topography of Se below.

Trough Cross-Stratified Sandstone (St)

Lithofacies St is characterized by trough cross-stratified, bright white, micaceous, clay rich, well-sorted upper fine to medium-grained sandstone. St is only observed in one section (Site #6) where average trough size is between one and two meters in width and 0.5 – 1.0 meters in depth. Bioturbation of the trough cross-stratified unit observed there can be quite extensive, though limited in variety to only *Skolithos*. Figure 23 below is a map view photo of *Skolithos* burrows into the upper surface of an St bed.

Figure 23: *Skolithos* burrows on upper bounding surface of an St bed. Photo taken near Site #13.

In some portions of St at Site #6, laterally continuous beds of dark reddish brown oxidation approximately three to four millimeters in thickness are present in a vertical column with a spacing of one to two meters. These thin zones of oxidation are planar and do not cut through primary stratification. St units of the Colgate Member display linear, shoestring geometries as controlled by the topography along Se below.

Hydrodynamic Interpretation

Trough cross-stratification reflects movement of three dimensional dune forms in sands from fine to very coarse (Harms et al., 1975; Todd, 1995, p. 312; Miall, 1996, p. 114; Boggs, 2001, p. 38, 101). Cosets of trough cross-stratification imply migration within unidirectional currents (Harms et al., 1975) under lower flow regime conditions

(Boggs, 2001, p. 39). The dune forms seen in St of the Colgate Member imply a minimum flow depth of 1-2 meters (Harms et al., 1975).

Facies Associations

Facies St is only observed in one section, where it directly overlies Se and is transitional above to Sm. Other areas that are classified here as Sm contain ‘ghosts’ of trough cross-stratification. St and Sm partially fill in the topography above Se.

Depositional Process

The upward transition from St to Sm is accompanied by an upward increase in traces of *Skolithos*. This transition reflects an upward increase in favorable conditions for suspension feeders (MacEachern and Pemberton, 1992). The *Skolithos* ichnofacies is found in areas of “moderate to relatively high-energy conditions; slightly muddy to clean, well-sorted, shifting sediments; subject to abrupt erosion or deposition” (Frey and Pemberton, 1984). Since cosets of St are indicative of primarily unidirectional currents (Harms et al., 1975) the transition from St to Sm could indicate a transition from unidirectional currents to currents with shifting orientations.

The three dimensional geometry of St is also an indication of the depositional process that created it. Because of the shoestring, linear nature of St, the process that created it was active in a confined, channelized setting rather than over a broad, regional area.

Planar Horizontally Bedded Sandstone (Sh)

Lithofacies Sh is only present in Site #13 where it is characterized by planar, horizontal, bright white, micaceous, clay rich, well-sorted, upper fine- to medium-grained sandstone. Sh contains zones of iron oxidation that are both parallel and oblique to bedding planes. *Skolithos* burrows are abundant in this facies (Figure 24) and often display preferential iron oxide cementation (Figure 25).

Figure 24: Photograph taken near Site #13 of oxidation around *Skolithos* burrows facies Sh.

Figure 25: Preferential iron-oxide cementation of *Skolithos* burrows.

Hydrodynamic Interpretation

The structure of Sh indicates deposition from the upper plane bed flow regime and generally represents single event deposition. The theories of formation of horizontal stratification are summarized in Todd (1996, p. 309), Bagnold (1966), and Allen and Leeder (1980) as occurring when sufficient sediment is carried by bedload within the flow, preventing the turbulent fluid from interacting with the bed surface. Without the interaction of the fluid with the bedform, the formation of upper flow regime plane beds is favored.

Facies Associations

Facies Sh is abruptly overlain by Fml of the lower Hell Creek Formation. Below, this facies is transitional with Sm. This facies was only observed in one location, Site

#13, so the vertical relationships above are the only relationships observed in the field area.

Depositional Process

The lower, gradational relationship from Sm to Sh is here interpreted to be a gradational relationship between a facies that was originally trough cross-stratified and which was post depositionally reworked to form Sm. The likelihood of this interpretation is supported by the transitional nature of Sm and St, preservation of trace fossils within Sm, as well as the 'ghosts' of trough cross-stratification that are occasionally visible in Sm. Since St is representative of the migration of lower flow regime, sinuous crested dune forms, the formation of Sh above St indicates a transition to higher velocity flows or shallower flow depths (Walker and Cant, 1984). Finer grain sizes would also favor the formation of Sh over St, however, as is seen in the measured sections, there is no grain size variation from St to Sh. The abrupt upper contact of Sh with Fml of the lower Hell Creek Formation indicates an abrupt decrease in energy, favoring deposition in slack water rather than in the upper flow regime.

Massive Mudstone (Mm)

Lithofacies Mm is characterized by massive, dark brown, well-sorted silty mudstone. Mud units are generally less than 5 cm in thickness and are laterally persistent on the order of tens of meters. Zones of iron oxidation are oriented preferentially with the linear zones of mudstone (Figure 26).

Figure 26: Photo taken near Site #13 showing mud interbedded mudstone (Mm) with massive sandstone (Sm) in the Colgate Member.

Hydrodynamic Interpretation

The presence of fine-grained mudstone indicates deposition within quiet water. The massive nature of Mm suggests that either grain size and composition of Mm are extremely consistent, or that the deposit was reworked. No evidence of reworking indicates that the former interpretation is more likely.

Facies Associations

In the one section (Site #13) that exposes Mm, it is gradational both above and below with Sh and Sm. The contacts of Mm with the sands above and below are undulatory, however there is no evidence of internal rippling or structure of any kind within the mud.

Depositional Process

The interbedded nature of Mm with Sm and Sh indicates a cyclic process that oscillated between slack water and high energy flows, respectively. These mud layers are only found near the top of the Colgate Member, within several meters of the contact with the lower Hell Creek Formation, indicating that the oscillatory nature of the flow was only occurring in the last stages of Colgate deposition.

Depositional Environment of the Colgate Member

The vertical succession of facies within the Colgate Member of Se, St, Sm, Sh, and Mm is consistent with the vertical relationship of meandering stream facies described by Cant (1982, p. 127) as follows:

> Beds of channels and lower point bars are covered by large dunes which deposit sets of trough cross-beds. In very sinuous rivers with relatively fine sediment, the scale of the cross-beds and grain size of sands decline upward through the trough zone. Locally, on the slope of the point bar, upper flow regime plane beds may form, depositing lenses of parallel-laminated sands intercalated with the trough cross-bedded sands. These lenses presumably occur because of the presence of local areas of high flow velocity during flood stages. Near the top of the point bar, rippled sands and mud drapes are deposited at moderate river stages.

The notable differences between a fluvial facies succession and the one observed in the Colgate Member are the large amounts of massively bedded sandstone and the presence of the *Skolithos* ichnofacies. This ichnofacies is primarily found in the foreshore subenvironment of the shoreface (Frey and Pemberton, 1984; MacEachern and Pemberton, 1992), but can also occur in tidally influenced settings, such as estuarine point bars (Frey and Pemberton, 1984). Further evidence of a tidal setting includes the cyclicity indicated by the interbeds of Sh and Sm towards the top of the Colgate Member section. These couplets (flaser bedding) are indicative of deposition in “pulsatory or even cyclic flow, reflecting periodic flood, seasonal or tidal flow” (Todd, 1996, p. 309). Without the *Skolithos* burrows, interbeds of Sh and Mm could be attributed to seasonal changes in flow, which would be consistent with the purely fluvial origin suggested by Cant (1982). With the presence of marine ichnofacies, however, the periodicity could also be attributed to tidal processes. Both of these primary pieces of evidence for an estuarine origin are limited to the upper reaches of the Colgate Member.

Reineck and Singh (1980, p. 317 – referencing Van Beek and Koster, 1972) suggest that the distinguishing features of a fluvial environment that is transitional to estuarine are: lower deposits characterized by unidirectional, downstream oriented paleocurrents while upper are bimodal; lower deposits are unburrowed while upper are burrowed by appropriate fauna; and, physical sedimentary structures of the lower deposits are dominated by trough cross-stratification, while those of the upper reflect interbedded sands and mud which tend to ripple cross-stratified to planar laminated. These criteria are consistent with the facies associations observed in the Colgate Member. Therefore, given the geometry, orientation, and well-matched physical and biogenic sedimentary structures, it is interpreted that the Colgate Member was deposited initially by a non-marine fluvial system that became progressively influenced by tidal processes in an estuarine setting to form tidally influenced channels.

CHAPTER 6

LOWER HELL CREEK FORMATION

The lower Hell Creek Formation consists of two lithofacies which never exceed a combined thickness of 6.5 meters in the field area. Both facies display sheet like geometries. Figure 27 below is a characteristic outcrop photo of the lower Hell Creek Formation.

Figure 27: Shown above is the transition from the Colgate Member to facies Fml of the lower Hell Creek Formation and finally into the inclined heterolithic facies (Sihs). The inclined heterolithic facies is seen in this photo near Site #13 as the last unit before the skyline. This photo is looking roughly north.

Massive to Laminated Mudstone (Fml)

Lithofacies Fml is characterized by laminated, dark brown to black, organic rich well-sorted siltstone and mudstone. The carbonaceous material consists mainly of twigs and stems with lesser amounts of leaf material. Individual beds are on the scale of decimeters or less. This facies is extensively bioturbated and pedogenically altered. The only identifiable trace is *Skolithos*, which is concentrated in the lower beds of Fml (Figure 28).

Figure 28: Intensive burrowing of the lowermost part of facies Fml. Photo taken at Site #13.

In map view, the root traces appear similar to *Skolithos* burrows, but in cross section the two can be distinguished by the downward branching of the root trace versus the single thread vertical burrow of *Skolithos* (Figure 29). Root traces always contain a carbonaceous filling, whereas the *Skolithos* burrows may or may not. Roots and burrows penetrate into Sm of the Colgate Member below (Figure 30). The total thickness of Fml never exceeds 3 meters within the study area. Generally facies Fml displays a broad, sheet like geometry.

Figure 29: Photo from the same surface as the *Skolithos* of Figure 28 above, only this vertical feature is a root cast filled with carbonaceous material. Notice the branching evident to the right of the feature. Photo taken near Site #13.

Figure 30: Root cast penetrating into Colgate Member facies Sm. Photo at Site #10.

Hydrodynamic Interpretation

Facies Fml represents suspension to weak traction current deposition in a quiet water environment (Sanders, 1965; Burne, 1995; Miall, 1996, p. 123; Boggs, 2001, p. 156). Occasional laminations due to slight grain size differences suggest that deposition occurred during slight fluctuations in current velocity (Sanders, 1965) and was not strictly from quiet water.

Facies Associations

Facies Fml is abruptly overlain by Sihs of the Lower Hell Creek Formation or Sm of the Upper Hell Creek Formation. Below, this facies abruptly overlies Sm or Sh of the Colgate Member (Figure 31). No evidence of erosion is apparent along any of the abrupt contacts.

Figure 31: Abrupt contact of Sm of the Colgate Formation and Fml of the lower Hell Creek Formation above. Photo taken at Site #10.

Depositional Process

The abrupt transition from Sm of the Colgate Member to Fml (with root traces) of the lower Hell Creek Formation suggests the rapid flooding of the area and occupation by a standing body of water. Transport processes changed from deposition via traction transport to quiet water deposition. The presence of root traces indicates vegetation in the area syn- and/or post-depositional with Fml. The abrupt upper contact of Fml with Sihs indicates an increase in energy to cyclic flows that alternately deposited sand and mud.

Inclined Heterolithic Sandstone (Sihs)

Lithofacies Sihs is characterized by inclined, shallowly dipping heterolithic beds that are alternating planar and trough cross-stratified, light gray to white, well-sorted fine sand and dark brown to black mudstone. Typically inclined strata dip gently to the east on the order of ten degrees; however in Figure 27 above, the dip is to the west. The sandier beds are generally three to four times the thickness of the alternating mudstones, averaging around 0.3 meters. These sandier units are often rippled (Figure 32) and at times exhibit flaser bedding. Bimodal paleocurrents are observed in one section (Site #10) where the sandstone is well-cemented and bedding is unusually apparent. The thinner, muddier beds range from 5cm to 10cm in thickness and contain an abundance of plant fossils. The mud occurs in small aggregates of a few millimeters in diameter (Figure 33). Both units contain secondary iron concretions ranging in diameter from centimeters to decimeters. They are more common in the fine sand portion.

Figure 32: Photo of westward directed ripples within the Sihs facies. Photo taken at Site #10 looking south.

Figure 33: Photo of pelletized mud along one of the muddy layers of facies Sihs near Site #13.

Hydrodynamic Interpretation

The regularly spaced interbeds of sand and mud indicate that Sihs formed from a cyclic process in which flows oscillated between traction transport and deposition primarily from suspension (Thomas, 1987; Todd, 1996, p. 309). In order to preserve a mud layer between the layers of tractional transported sand, mud must be sufficiently cohesive and consolidated as to withstand the current velocity accompanying the following cycle of sand deposition (Thomas, 1987). Typically this suggests that the mud is “deposited not as individual silt- and clay sized particles but as larger, higher settling velocity aggregates, such as flocs, fecal pellets and intraclasts” (Thomas, 1987, p. 162).

Facies Associations

Facies Sihs is gradational above to Fml or St of the upper Hell Creek Formation. Sihs may be abruptly overlain by Se and St of the upper Hell Creek Formation. Below, this facies is transitional from Sm, but can also abruptly overlie Fml. The most common facies associations are abrupt basal contacts with Fml and abrupt upper contacts with Sm of the upper Hell Creek Formation.

Depositional Process

The association with purely quiet water deposition below indicates that Sihs was formed under higher energy and more oscillatory conditions than Fml. Cyclic flows that could be responsible for such stratification include seasonal flows, tidal cycles and periodic floods (Todd, 1996, p. 309).

Depositional Environment of the lower Hell Creek Formation

The physical and biogenic sedimentary structures of the lower Hell Creek Formation are consistent with deposition in a tidally influenced environment, such as a salt marsh or mud flat overlain by tidally influenced fluvial deposits. Physical structures of mud flats include predominantly mud deposition and thinly interbedded sands with abundant mudcracks; however their most diagnostic features are extensive burrows, especially of the *Skolithos* ichnofacies, and root traces (Reineck and Singh, 1980, p. 359, 428; Boggs, 2001, p. 371). Mudflats are also commonly cross cut by a series of tidal channels, but facies Fml appears to form a continuous blanket of carbonaceous mud over the Colgate Member throughout the entire field area. This abrupt emplacement of Fml over the sandy deposits of Sm and Sh of the Colgate Member below indicates that there was either an abrupt deepening across the boundary (to allow for a suspension deposition to dominate over traction transport) or that the body of water transporting Sm and Sh sands rapidly became stagnant.

Deposits of Sihs over Mml are strongly characteristic of lateral migration of tidally influenced point bars. Typically such stratification has been referred to and confused with epsilon cross-stratification, which forms from the lateral migration of point bars within small meandering streams (Thomas et al., 1987 – referencing Allen, 1965). Alternating sand and mud couplets of these systems are caused by the cyclicity of seasonal high and low flow. Mud drapes within tidal systems, however, form during slack water periods of tidal cycles (Thomas et al., 1987). Criteria that distinguish tidally influenced point bars from wholly fluvial point bars are described by Thomas et al. (1987, p. 165).as follows:

> 1) Tidal creek channel-floor lag deposits contain abundant shell material (brackish water and some “fully” marine species). Shells (predominantly pelecypods and gastropods) are also present in the point-bar sediments. 2) Upper point-bar sequences will contain wave and current-ripple structures plus linsen and flaser bedding. 3) Interbedded sands and muds constitute much of the point-bar deposits. 4) Point-bar sediments will be characterized by intense bioturbation. 5) Plant material deposited on the point bars will be dominated by brackish water (tidal salt-marsh) species. 6) Rose diagrams of current indicators from point bar sequences will be bimodal to bipolar, reflecting flow reversals. Actual herringbone stratification, however, will be restricted to ripple structures in the upper portion of the point bar.

For Sihs of the lower Hell Creek Formation, the most applicable characteristics are the extensive bioturbation by fauna of marine affinity and rhythmic bedding. In particular, the pelletized nature of the mudstone layers is significant, as in other studies “it appears certain that flocculation, and especially pelletization, must play a very significant role in the deposition of mud in tidal environments” (Thomas, 1987, p. 162).

CHAPTER 7

UPPER HELL CREEK FORMATION

The upper Hell Creek Formation consists of five lithofacies that reach a total combined thickness of 59 meters in the field area. Facies display either sheet like or laterally discontinuous, lenticular geometries. Figure 34 below is a characteristic outcrop photo of the upper Hell Creek Formation.

Figure 34: Characteristic appearance of upper Hell Creek Formation. Photo taken near Site #15.

Erosional Scour (Se)

Lithofacies Se is characterized by a regionally extensive erosional surface which is generally overlain by a cobble lag. Relief along this surface is at least 15 meters, though variations in depositional thickness beneath the unconformity may locally enhance or diminish the apparent erosional relief. The cobble lag consists of moderately rounded clasts ranging in size from a few centimeters to nearly one meter in diameter. Typically these clasts are composed of: 1) a well-sorted gray to purple mudstone that often contains root casts, 2) a white, micaceous, lower fine sandstone, 3) iron-concretions of lower-fine sandstone, and 4) dinosaur bone.

Hydrodynamic Interpretation

Regionally extensive erosional features such as Se are typically formed by current activity (Boggs, 2001, p. 109). Cobbles in a sandy matrix that blanket the scour surface are indicative of rapid deposition of a poorly sorted bed load (Miall, 1996, p. 123).

Facies Associations

Facies Se is gradational above to St or Sm. Below, this facies abruptly overlies Sm of the Colgate Member (Figure 35), Mm, Sm, St and Shcs of the Fox Hills Formation, or Mml of the Bearpaw Formation. Evidence of erosion exists at all of the lower boundaries of Se.

Figure 35: Erosional contact of Se with Sm of the Colgate Member below. The head of the hammer lies in the Se facies of the upper Hell Creek, and the handle crosses down into the Sm facies of the Colgate below.

Depositional Process

The process responsible for the formation of Se is strongly dependent on the facies associations both above and below the scour surface (Miall, 1996, p. 123). A scour surface such as Se that is regionally extensive for kilometers will have a different interpretation both in terms of time significance as well as process than a localized scour on the order of meters. The erosional contact of Se over facies such as Mml of the Bearpaw Formation indicates the removal of several meters to tens of meters of Fox Hills Formation and places deposits of very different processes adjacent to one another. Mml of the Bearpaw Formation indicates suspension deposition in quiet water, while St beds superjacent to Se deposits indicate traction transport in a unidirectional current.

In the case of Se eroding into sandy units such as St and Sm of the Fox Hills Formation or the Colgate Member, the hydrodynamic interpretation of the bedforms across the boundary may be similar, but the facies associations indicate that vastly different processes were acting above and below Se. Facies below Se are upward coarsening and indicative of successively higher energy deposition. Facies above Se fine upward and are indicative of successively waning flows.

Trough Cross-Stratified Sandstone (St)

Lithofacies St is characterized by trough cross-stratified, tan, well-sorted upper fine- to lower coarse- grained sandstone. Often the sand sized clasts are composed of bone, carbonaceous material, plant material and clam shells, though siliciclastics are the dominant components. Thickness of bedsets can be over 30 meters with individual beds in the 1-2 meter range. The thicker beds tend to have coarser grains, such as medium to lower coarse sands and larger bedforms on the order of 4-5 meters in width and 1 meter in depth (Figure 36). The largest trough noted in this facies was in a lower coarse sand, having a width greater than 6 meters and a depth of 2 meters. Within the more typical upper fine to lower medium sand, troughs have an average size of 1.5 – 2 meters in width and less than 0.5 meters in height (Figure 37). Average trough size is between one and two meters in width and 0.5 – 1 meter in height. Laterally, these sand bodies can be continuous on the scale of meters to hundreds of kilometers, with the thicker sand bodies generally being the more laterally persistent.

Figure 36: Large trough cross-stratification of the upper Hell Creek. Photo taken at Site #8.

Figure 37: Smaller scale trough cross-stratification. Photo taken stratigraphically above Figure 36.

Both coarse- and medium-grained sands of this facies contain zones of secondary iron precipitation. These concretions tend to be either on the scale of centimeters in diameter or large, lenticular, parallel bodies up to several meters in width and length. Other secondary features include root casts. These features are more common in the smaller, finer grained sand bodies of St.

Hydrodynamic Interpretation

Trough cross-stratification is formed by the migration of three dimensional dune forms along a cohesionless, sandy bed (Harms et al., 1975; Jackson, 1976; Collinson and Thompson, 1989; Todd, 1996, p. 312). Flow depth can be inferred from the trough depths to be a minimum of 2 - 4 meters (Harms et al., 1975).

Facies Associations

Facies St is gradational above to Sm and Sr or less commonly Fml. Below, this facies is both transitional and erosive into these same units. Most commonly St is gradational to St above and erosive into Fml below.

Depositional Process

The decrease in trough size and gradual transition to facies Sr and Sm indicate a gradual decrease in flow velocity (Walker and Cant, 1984). Across the lower boundary, where St is erosive into Fml, there is an abrupt change in process from quiet water suspension and weak traction current deposition to deposition from sandy bedforms in the lower flow regime.

Massive Sandstone (Sm)

Lithofacies Sm is characterized by massive, tan, well-sorted upper fine to lower coarse-grained sandstone. Generally sands are of upper fine to lower medium grain size but there are occasional beds that display larger grain sizes (up to lower coarse). Individual beds are always well-sorted. Sands contain similar fragmentary material as facies St (bone, invertebrate shells, carbonaceous and plant material) but as with St, these are not the dominant composition. Secondary iron precipitation is also common as both spherical nodules up to a decimeter in diameter as well as lenticular sand bodies on the scale of several meters. Root casts are extremely common in this facies, favoring the thinner, finer grained sand bodies.

Hydrodynamic Interpretation

The lack of sedimentary structure in facies Sm can be attributed to both primary and secondary effects. Primary massive stratification can result from rapid deposition (Reineck and Singh, 1980, p. 130; Leeder, 1982; Boggs, 2001, p. 97) as well as a consistency of grain size and composition. These latter deposits will sometimes reveal evidence of primary structure when etched or stained (Boggs, 2001, p. 96-7). As a secondary feature, massive stratification can be the result of reworking due to currents (Reineck and Singh, 1980, p. 130; Boggs, 2001, p. 387) as well as biogenic activity (Reineck and Singh 1980, p. 130; MacEachern and Pemberton, 1992; Boggs, 2001, p. 97, 387 – referencing Dott, 1983; Gagan et al., 1988).

Facies Associations

Sm is often gradationally capped by Sr or Fml. Below it can be gradational from St, or in sharp contact with Fml.

Depositional Process

The gradational association of Sm with Fml above indicates a gradual decrease in energy that favored deposition in a weak flow to quiet water (Walker and Cant, 1984). Gradational relationships with Fml below Sm indicate that flow became progressively stronger. The abrupt transition from Fml to Sm indicates a rapid change in process that replaced quiet water deposition with traction transport.

Ripple Cross-Laminated Sandstone (Sr)

Lithofacies Sr is characterized by ripple cross-laminated, tan, well-sorted upper fine-grained sandstone (Figure 38). Ripple height and wavelength are generally on the order of a few centimeters. In very rare cases, Sr exhibits a climbing ripple geometry, but mainly Sr forms small scale cross-stratification. This facies is laterally persistent on the order of several meters.

Figure 38: Sr of the upper Hell Creek Formation. Photo taken at Site #6.

Hydrodynamic Interpretation

Ripples are interpreted to form under lower flow regime conditions in very fine to medium sands due to the migration of ripple forms (Leeder, 1982, p. 95; Todd, 1996, p. 309; Boggs, 2001, p. 97; Bridge, 2003, p. 79-80). They may form under both unidirectional and oscillatory current conditions, creating asymmetrical and symmetrical bedforms, respectively (Boggs, 2001, p. 98). Ripples themselves are not very diagnostic of flow depths as they can occur in a range of depths from shallow to very deep (Harms, 1975, p. 57), but they are most common in shallow water (Boggs, 2001, p. 98).

Facies Associations

Laterally, Sr is typically gradational to Sm. In a vertical section, Sr is gradational below with St or Sm and gradational above with Sm or Fml. Sr may sharply overlie Fml.

Depositional Process

The gradational association of Sm and St to Sr above indicates a gradual decrease in energy of the system (Walker and Cant, 1984). This decrease in energy continues above Sr with the deposition of Fml.

Massive to Laminated Mudstone (Fml)

Lithofacies Fml is characterized by massive to laminated, light green, purple and dark brown, well-sorted silty mudstones. Where present laminations are on the scale of several millimeters and are often marked by a color change or a small grain size change. Root traces are common within this facies as are fragments of bone, plant material and small coal streaks. Secondary iron oxide precipitation and gypsum cement are common along as well as oblique to laminations.

Hydrodynamic Interpretation

The predominance of mud indicates that Fml was deposited from suspension or weak traction currents (Sanders, 1965; Burne, 1995; Miall, 1996, p. 123; Boggs, 2001, p. 156). The presence of laminations due to slight grain size differences suggests that deposition was occurring during slight fluctuations in current velocity (Sanders, 1965) and was not strictly from quiet water.

Facies Associations

Generally, Fml has a gradational lower contact with either Sm or less commonly St. The upper contact is typically abrupt with Sm or St.

Depositional Process

As the uppermost facies of an overall fining upward sequence, Fml represents deposition from the lowest energy processes of the upper Hell Creek Formation. Gradational relationships with Sm and St below indicate a gradual decrease in energy from lower flow regime deposition to that of nearly quiet water (Walker and Cant, 1984), while abrupt upper contacts indicate a resumption of traction transport.

Depositional Environment of the upper Hell Creek Formation

Deposits of the upper Hell Creek Formation are consistent with the lateral migration of a point bar, the main environment of deposition in a meandering stream (Walker and Cant, 1984). Selley (1970, p. 23) summarizes the work of Mackin (1937), Allen (1964) and Visher (1965) on point bar successions as follows:

> At the base is an erosion surface overlain by extraformational pebbles, intraformational mud pellets, fragmented bones and waterlogged drift wood. These originated as a lag deposit on the channel floor and are overlain by a sequence of sands with a general vertical decrease in grain size. Massive, flat bedded and trough cross-bedded sands grade up into tabular planar cross-bedded sands of diminishing set height. These in turn pass up into micro-cross-laminated and flat-bedded fine sands which grade into silts of the floodplain subfacies.

This fining upward sequence is also supported by Walker and Cant (1984) who add that the reason that this progression occurs is due to helical flow in a meander loop. This creates diminished flow velocity on the point bar side of the meander, and results in progressively finer sediment and smaller bedforms being deposited towards the top of the bar (Walker and Cant, 1984).

In the upper Hell Creek strata, the erosion surface (Se) is blanketed with clasts of intraformational mud and bone, just as suggested in the model above. This is capped by trough cross-stratification (St) associated with migration of three dimensional dune forms near the thalweg of a channel (Allen, 1965; Williams and Rust, 1969; Coleman, 1969; Collinson, 1970; Williams, 1971; Jackson, 1975, 1976; Todd, 1996, p.312). Vertical transitions to Sr indicate deposition from waning flows or shallower water environments, such as bar tops (Miall, 1996, p. 149). Finally, muds of facies Fml are characteristic of suspension deposition, as would be associated with abandoned channels, bar tops and floodplains (Miall, 1996, p. 171; Williams and Rust, 1969; Bluck, 1976; Allen and Williams, 1982; Hubert and Hyde, 1982; Todd, 1996, p. 328; Cant, 1982). These subenvironments commonly contain vertebrate and plant remains (Miall, 1996, p. 149), which are observed in the upper Hell Creek Formation in several thick successions of Fml (e.g. Site #5).

CHAPTER 8

SEQUENCE STRATIGRAPHIC OVERVIEW

Sequence stratigraphy is a tool that organizes linked depositional environments based on their relationship to a relative sea-level curve, or more formally it is “the study of rock relationships within a chronostratigraphic framework wherein the succession of rocks is cyclic and is composed of genetically related stratal units” (Posamentier et al., 1988). The roots of sequence stratigraphy are in the unconformity bound stratal packages of Sloss (1963), followed by seismic stratigraphy (e.g. Payton, 1977), where improved technology of the late 1970’s allowed for the imaging of basin scale unconformity bound successions (Van Wagoner et al., 1990). By the early 1980’s sequence stratigraphic ideas generated from stratal patterns seen in seismic reflections were applied to well logs, cores and outcrops, giving rise to high resolution sequence stratigraphy (Van Wagoner et al., 1990). Traditionally sequence stratigraphy has been used in the marine to deep water strata, given the close association of stratal cyclicity to that of relative sea-level. More recently authors such as Shanley and McCabe (1991, 1993, 1994), and volumes such as Sequence “Stratigraphy of Foreland Basin Deposits” (Van Wagoner and Bertram, 1995) and “The Relative Role of Eustasy, Climate and Tectonism in Continental Rocks” (Shanley and McCabe, 1998) have convincingly brought sequence stratigraphy to the non-marine setting.

Although the original use of sequence stratigraphy was to predict the geometry and location of oil prone facies, the tool can really be applied to the prediction of any facies specific question. This study uses sequence stratigraphy to place dinosaur bearing facies into a sequence stratigraphic framework. As will developed further in Chapter 13, location and degree of preservation of dinosaur fossils in the Hell Creek Formation is closely associated with their sequence stratigraphic position.

Depositional Sequences

A depositional sequence is defined as “a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities” (Van Wagoner et al., 1990’ Mitchum et al., 1977). All sequence boundaries are chronostratigraphically significant, though they themselves are diachronous, because they separate all younger strata above from all older strata below (Mitchum et al., 1977; Van Wagoner et al. 1990). Additionally, sequence boundaries are significant in a sequence stratigraphic framework because they are “the only key surface within a sequence whose timing is independent of sediment supply” (Posamentier and Allen, 1999, p. 34)

In the Bearpaw through Hell Creek Formation stratal succession, there are two significant sequence boundaries, Se of the Colgate Member and Se of the upper Hell Creek Formation, which divide the succession into three depositional sequences. The succession beneath Se of the Colgate Member consists of the Bearpaw and Fox Hills Formations, has a sheet like geometry and is present everywhere in the field area. The strata between the two sequence boundaries consist of the Colgate Member, the lower Hell Creek Formation and minor deposits of the upper Hell Creek Formation. This depositional sequence is narrow and has a linear, channel-like geometry. Above Se of the upper Hell Creek, the third depositional sequence consists of the upper Hell Creek Formation facies which initially have sheetlike geometries directly above the sequence boundary but then change upward to more lenticular geometries. Figure 39 schematically displays a cross section of the three depositional sequences and their corresponding sequence boundaries.

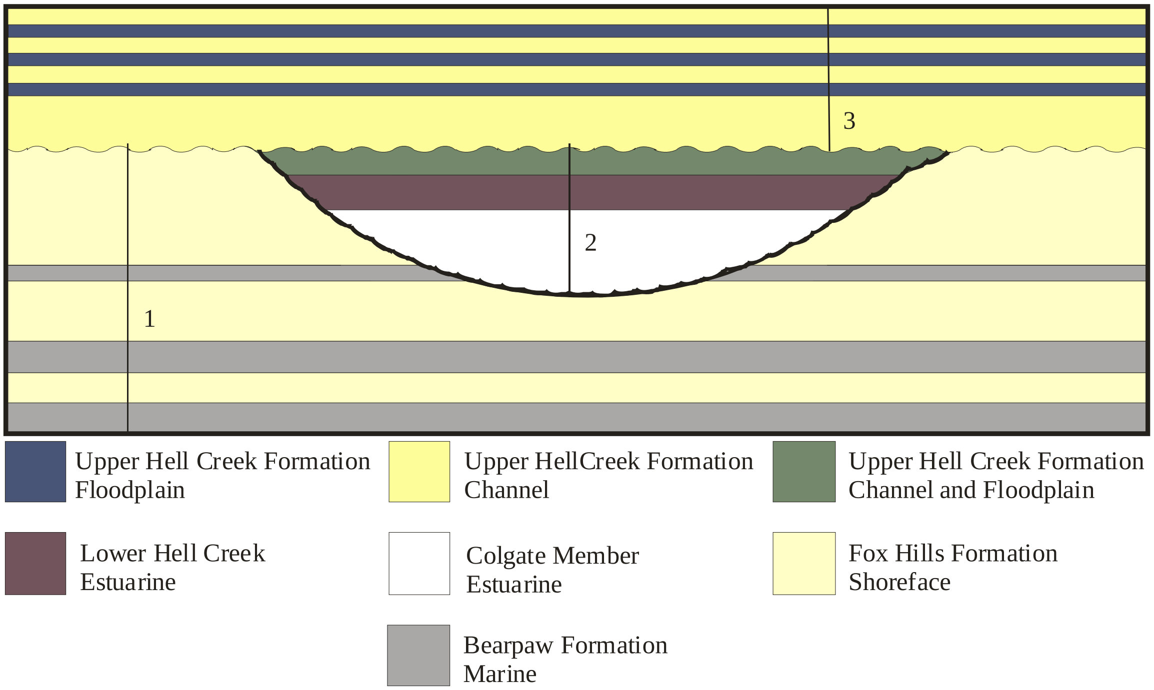


Figure 39: Schematic cross section through the three depositional sequences.

The sequence boundaries themselves are both significantly erosive and are both blanketed by a lag. Se of the Colgate Member is actually a composite sequence boundary forming on top of lowstand, forced regression deposits of the Fox Hills and Bearpaw Formations below. Where Se of the Colgate Member is present it forms localized valleys where erosion is at least 6 meters. Interfluves of this valley would be the location of a correlative conformity, however these surfaces are removed by the sequence boundary of the upper Hell Creek Formation above. Thus, deposits of the middle depositional sequence are an accommodation remnant (*sensu* Martinsen, 2003). Se of the upper Hell Creek Formation has at least 15 meters of erosional relief and is more laterally extensive than Se of the Colgate Member below.

Systems Tracts

Depositional sequences are subdivided into systems tracts, defined as linked, contemporaneous depositional environments and characterized based on their stratal stacking patterns and facies associations (Brown and Fischer, 1977; Van Wagoner et al., 1990). Each depositional sequence contains a lowstand, transgressive and highstand systems tract. These divisions reflect the interaction of relative sea-level (the combined effects of eustasy and subsidence; Figure 40) with sediment supply.

The lowstand systems tract is deposited between the lowermost sequence boundary of the depositional sequence and the first flooding surface. Posamentier and Allen (1999, p. 33) define the lowstand as including “all the deposits accumulated after the onset of relative sea-level fall as well as the initial rise, that is, until the rate of rise exceeds the rate of sediment accumulation” (Figure 41). Regressions caused purely by changes in relative sea-level are termed “forced regressions” (Van Wagoner, 1995; Posamentier and Allen, 1999).

The transgressive systems tract is deposited between the first flooding surface and the maximum flooding surface, or as defined by Posamentier and Allen (1999, p. 37) it “comprises the deposits accumulated from the onset of coastal transgression until the time of maximum transgression of the coast, just prior to renewed regression" (Figure 41). This systems tract is a consequence of the rate relative sea-level rise exceeding the rate at which sediment is supplied (Posamentier and Allen, 1999). Unlike the formation of a sequence boundary, the formation of a flooding surface can therefore be caused by either an increase in accommodation (eustatic and/or tectonic) or a decrease in sediment supply (Posamentier and Allen, 1999). A purely eustatic cause of transgression has been coined a "forced transgression" by Chough and Hwang (1997).

The highstand systems tract is deposited between the maximum flooding surface and the next sequence boundary (Figure 41). This systems tract begins when the rate of increase of relative sea-level rise is less than the rate of sediment supply and ends when relative sea-level begins to fall (Posamentier and Allen, 1999, p. 39).

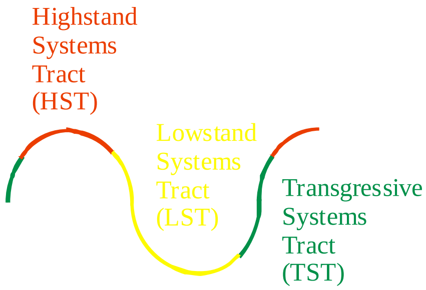


Figure 40: Location along the relative sea-level curve in which each systems tract is formed (given constant sediment supply).

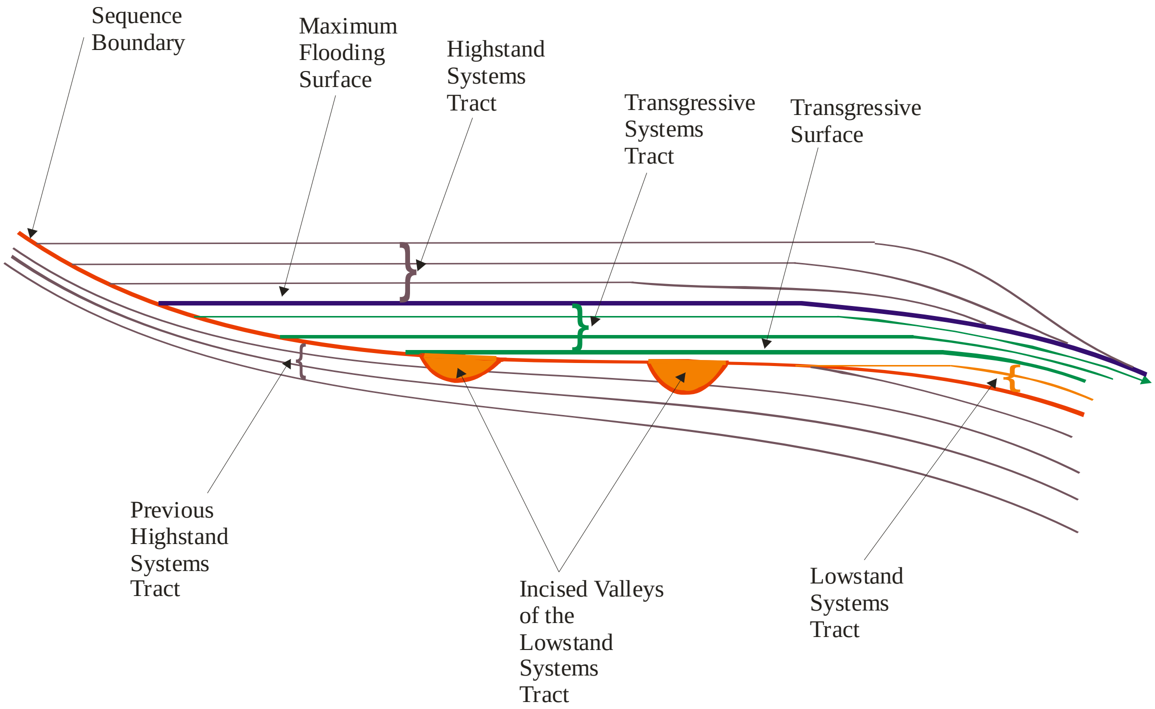


Figure 41: Stratal patterns of highstand, lowstand and transgressive systems tracts below. Figure modified from Van Wagoner et al. (1990, p. 28).

The Bearpaw and Fox Hills Formations of the oldest depositional sequence were deposited in the highstand systems tract during a relative sea-level stillstand and as a forced regression of the lowstand systems tract during the subsequent sea-level fall. These two systems tracts are separated by a correlative conformity related to the formation of Se of the Colgate Member during the initial drop in sea-level. This correlative conformity is not readily recognizable in the field. Its existence is based on the forced regression geometry of the Fox Hills and Bearpaw Formations as well as the composite sequence boundary (Se of the Colgate Member) that caps these units. This composite sequence boundary is the lower bounding unconformity of the second depositional sequence and formed during continued relative sea-level fall associated with the lowstand systems tract. The Colgate Member itself was deposited during the lowstand systems tract and subsequent transgressive systems tract, during a time of relative sea-level stillstand and the early stages of relative sea-level rise. The capping units of the lower Hell Creek Formation are associated with the maximum transgression of the transgressive systems tract (facies Fml) and continued but slower rate of sea-level rise associated with the early highstand systems tract (facies Sihs). In some sections there are meandering stream deposits (facies St, Sm, Fml of the upper Hell Creek) deposited between Sihs of the lower Hell Creek Formation and Se of the upper Hell Creek. These units are interpreted to represent highstand deposition of the second depositional sequence. They are capped by a sequence boundary (Se of the upper Hell Creek Formation) that separates them from the third depositional sequence. Facies St and Sm above Se of the upper Hell Creek are highly amalgamated sand bodies representing non-marine deposition in the lowstand systems tract of the third depositional sequence. Finally, isolated, lenticular sand bodies associated with fining upward meandering stream deposits indicate a transition to the transgressive and highstand systems tracts of this last depositional sequence.

Parasequence Sets

Systems tracts are composed of parasequence sets, defined by Van Wagoner et al. (1990, p. 17) as successions "of genetically related parasequences forming a distinctive stacking pattern bounded by major-marine flooding surfaces and their correlative surfaces". Parasequence sets can have progradational, aggradational or retrogradational geometries based on the internal stacking of their component parasequences (Van

Wagoner, 1985). Parasequences of the lowstand systems tracts are typically difficult to recognize but are commonly progradational, while those of the transgressive systems tract are deposited in retrogradational stacking patterns, and those of the highstand systems tract are characterized by aggrading to prograding geometries (Van Wagoner et al., 1990; Posamentier and Allen, 1999).

Parasequence sets are only visible in the Bearpaw and Fox Hills Formations. As shown by the measured sections in Appendix A, the facies of the Bearpaw and Fox Hills Formations display an upward coarsening, upward shallowing stacking pattern indicating their progradational nature. Forced regression parasequences can be recognized by the emplacement of middle and upper shoreface sands (Sm, St and Sl of the Fox Hills Formation) onto offshore mudstones (Mml of the Bearpaw Formation). In the facies of the Colgate Member and the Hell Creek Formation parasequence sets cannot be distinguished at the outcrop scale. In these units there are no repetitive depositional patterns that indicate overall shallowing or deepening trends. Parasequence sets are only discussed in the interpretation of the Bearpaw and Fox Hills Formations, where distinct marine flooding surfaces can be identified. In the Colgate Member and the Hell Creek Formation, where no marine flooding surfaces were identified, only the systems tracts and their respective facies associations are discussed.

Parasequences

A parasequence is the smallest organizational unit of sequence stratigraphy, defined as "a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces” (Van Wagoner, 1985). All individual parasequences are progradational and upward shallowing (Van Wagoner, 1990). The flooding surfaces that define parasequences are of higher order and higher frequency than those that bound parasequence sets.

Parasequences are difficult to identify in this area, especially in the estuarine and fluvial units. The rate of relative sea-level change, the rate of sediment supply and the slope of the shelf will dictate the formation and geometry of individual parasequences (Posamentier and Allen, 1999). On a ramp setting such as that of the Western Interior Cretaceous Seaway, small changes in sea-level translate to large lateral shifts in the shoreline position. Therefore parasequences may end up ‘strung out’ along the shallow slope and may not stack up as would be expected in a system with a shelf slope break or in a region of higher subsidence rates. Parasequences can be observed in the Bearpaw and Fox Hills Formations as the individual coarsening upward units from Mml of the Bearpaw Formation to Sm and Shcs (of either formation). Individual parasequences cannot be identified in succeeding depositional sequences.

Significance of Sequence Stratigraphy In This Study

The assignment of facies associations to systems tracts and depositional sequences is significant in this area due to the large number of fossil sites and their preservational variety. The application of sequence stratigraphy enables paleontologists to 1) have a relative age control on fossil sites 2) explore for future sites based on kinds of preservation desired 3) geographically locate specific facies with the understanding of their respective geometries. These applications will be further discussed in Chapter 13.

Additionally, this study is important with regard to refinement of paleogeography and paleotectonics of the area. This study indicates that there was significant embayment of the shoreline in northeastern Montana during a Maastrichtian marine transgression. The formation of this incised valley is related here to a fall in relative sea-level but future work could focus on the internal architecture of strata within the incised valley to potentially determine the relative roles of tectonics and eustasy. Differences in stratal architecture from purely tectonic to purely eustatic causes of incised valleys will be discussed further in Chapter 10.

CHAPTER 9

SEQUENCE STRATIGRAPHIC INTPRETATION: BEARPAW AND FOX HILLS FORMATIONS

Depositional Sequence

The Bearpaw and Fox Hills Formations and their associated facies are contained beneath a composite sequence boundary (Se of the Colgate Member), and therefore constitute the earliest depositional sequence of the stratal succession observed in the study area. Only the uppermost part of this sequence was described in the field since it was not the main focus of the study. All of the measured sections begin in this depositional sequence in order to insure that the complete sequence above was described as well as to fully understand the transition between the two.

Systems Tracts

The deposits of the Bearpaw and Fox Hills Formations were deposited in the highstand systems tract during a relative sea-level stillstand and in the lowstand systems tract at start of sea-level fall. The resulting geometry of the Fox Hills and Bearpaw Formations during the stillstand would be either strictly progradational, as shown by the seven clinoforms on the left of Figure 42 or could be aggradational as well as progradational depending on the interplay of accommodation and sediment supply. As sea-level starts to fall at the beginning of the lowstand systems tract, successive shoreface units (Fox Hills Formation) downstep as a forced regression onto offshore units (Bearpaw Formation), reflecting the loss of accommodation. These shoreface to offshore clinoforms create a shingled deposit as relative sea-level continues to fall during the lowstand (Figures 42). The degree of interconnectivity between successive shoreface units depends on the rate of relative sea-level fall, the rate of sediment supply and the slope of the shelf (Posamentier and Allen, 1999).

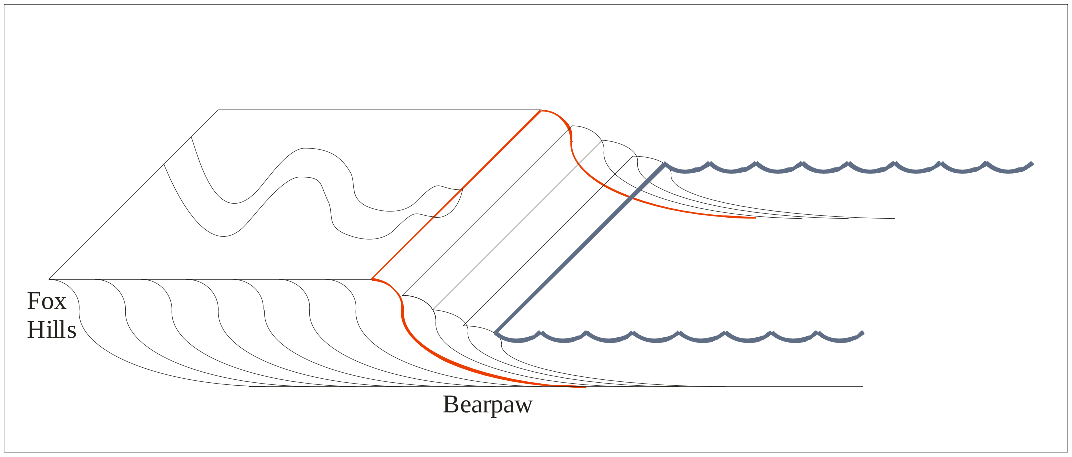


Figure 42: Schematic indicating the highstand geometry of the Fox Hills and Bearpaw Formation clinoforms. Seven clinoforms on the left of the diagram indicate deposition during the highstand systems tract, while the three clinoforms on the right represent deposition during the lowstand systems tract, sometimes referred to as a forced regression. The red line indicates the location of the sequence boundary.

There is currently much debate about what vocabulary to assign to deposits having this geometry, with some authors discriminating a falling stage systems tract from the highstand and lowstand systems tracts, some combining it with the highstand systems tract and others referring to this pattern as a forced regression that is part of the lowstand. Here, the terminology of Van Wagoner (1995) and Posamentier and Allen (1999) will be used. They place this progradational, downstepping geometry in the lowstand systems tract. Figure 43 below highlights the relationship of lowstand, forced regression deposits with the composite sequence boundary that caps the entire downstepping succession. Here that composite sequence boundary is Se of the Colgate Member.

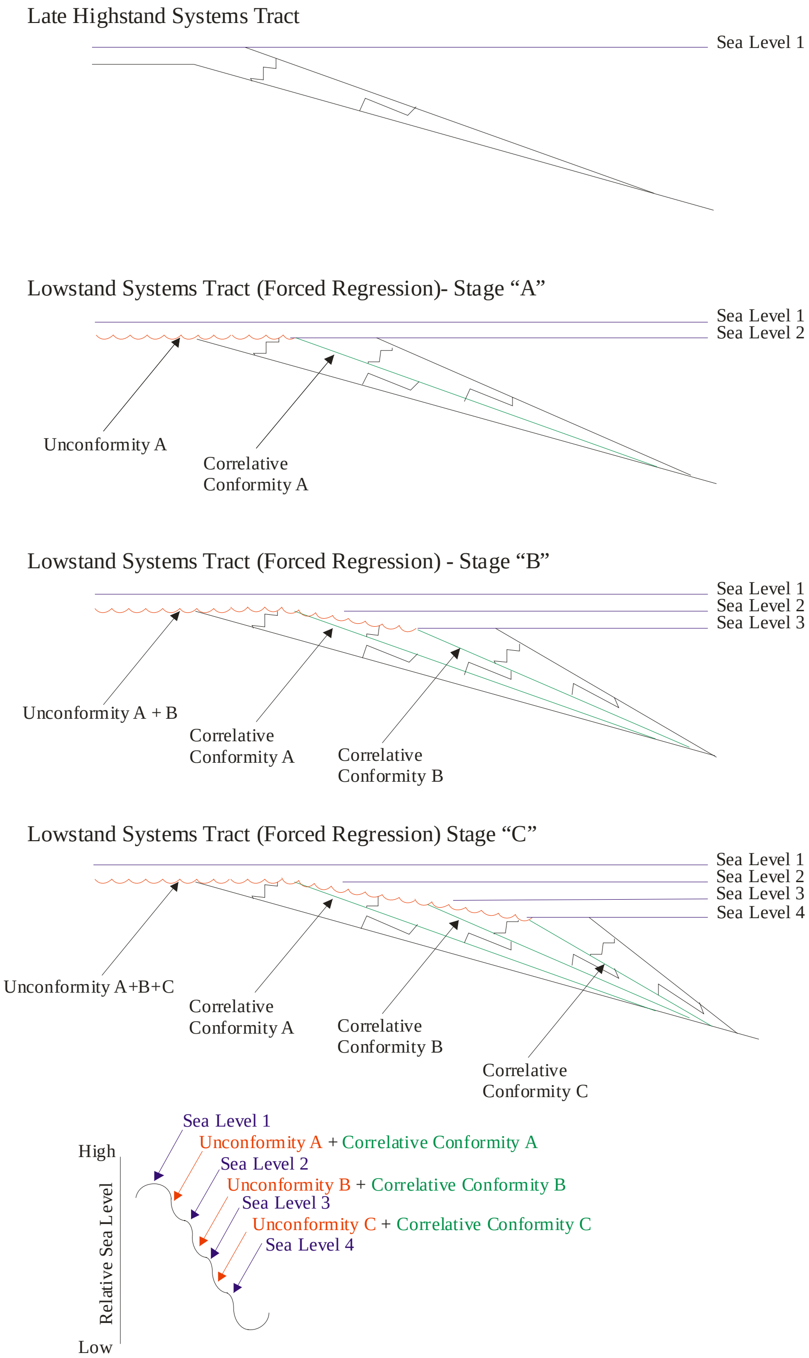


Figure 43: Formation of a forced regression. Figure modified from Shanley and McCabe (1993).

Although the ‘true’ sequence boundary lies beneath the first downstepped clinoform, where it is a correlative conformity to the very first erosional surface, successive progradation in this manner generates a package of lowstand deposits that are floored by a correlative conformity to the initial sequence boundary and capped by a composite sequence boundary that is merged with the initial one. The exact location of the first erosional surface and its correlative conformity was not identified in this study. The parasequences of the downstepping, progradational Fox Hills and Bearpaw Formations are correlative conformities to an erosional surface forming more landward; however, the association of a particular correlative conformity to its respective portion of the composite erosional surface was not readily apparent in outcrop. Only the composite sequence boundary (Se of the Colgate Member) had significant expression in outcrop.

Field evidence for a forced regression, as presented by Posamentier and Allen (1999) includes the sharp transition from offshore units (e.g. Mml facies of the Bearpaw Formation) to upper shoreface (e.g. St and Sl of the Fox Hills Formation). The typical succession, as seen in Figure 44, is from offshore to lower shoreface, a Waltherian shift in facies; however, at Site # 11 there is a direct transition from facies Mml of the Bearpaw Formation to facies St of the Fox Hills Formation. This is the only location where this non-Waltherian facies shift takes place, but it is significant because this section is the farthest east. A similar relationship was also observed by Lepp (1981) farther east than this study, and confirms that pattern is also observed to the east where shallow water facies abruptly overlie offshore deposits.

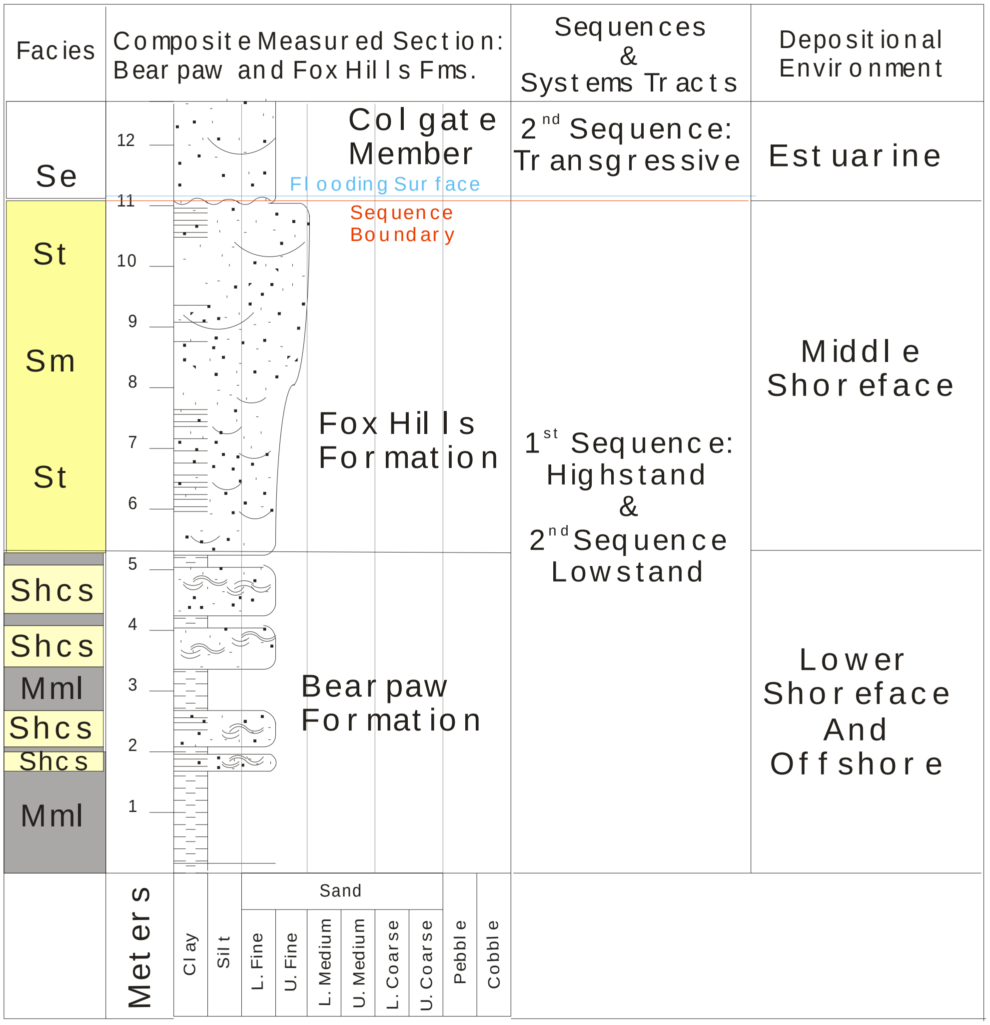


Figure 44: Composite measured section showing facies, significant surfaces and depositional environments of the Bearpaw and Fox Hills Formations.

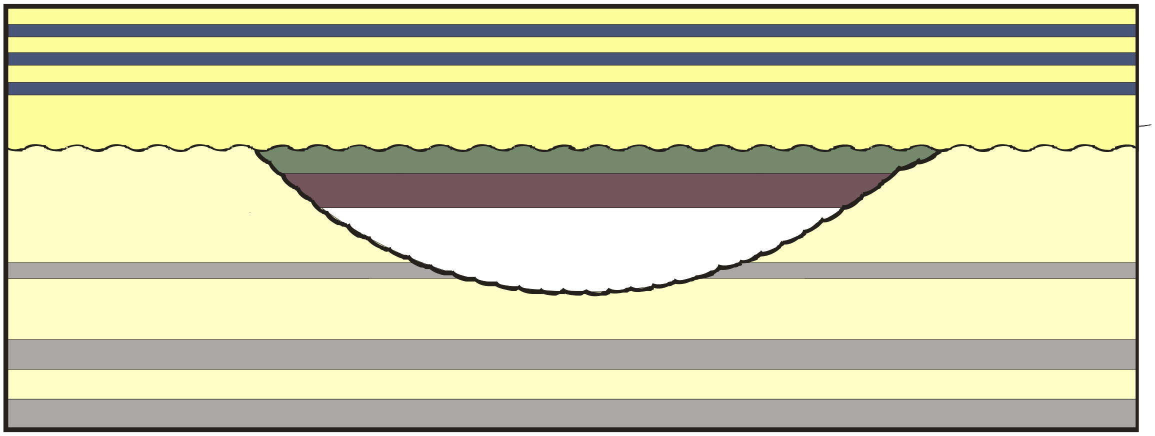
Lepp (1981) investigated Bearpaw through Fort Union Formation strata east of the Fort Peck Reservoir along the Missouri River and concluded that “within the Fox Hills Formation, only distal bar deposits and distributary mouth bar sandstones are present” (Lepp, 1981, p. 33). This conclusion was made based on facies interpretations that placed distal “thinly bedded to interlaminated brown siltstones and dark gray shales” of the lower Fox Hills Formation under the dominant structures of “large scale (up to 3 feet thick), multi-directional, low angle, planar and trough cross-beds" with sparse *Ophiomorpha* burrows (Lepp, 1981, p. 12). This is equivalent to the Mml facies of the Bearpaw Formation being overlain by Sl and St facies of the Fox Hills Formation. This supports the hypothesis that the Fox Hills and Bearpaw Formations were deposited in successively downstepped pattern to the east, as schematically drawn in Figure 42. Lepp (1981) later discusses the offlapping and progradational nature of deposition during the Late Cretaceous through early Tertiary time, although he does not address the geometry of this progradation, or whether he agrees with the downstepped geometry interpreted here.

CHAPTER 10

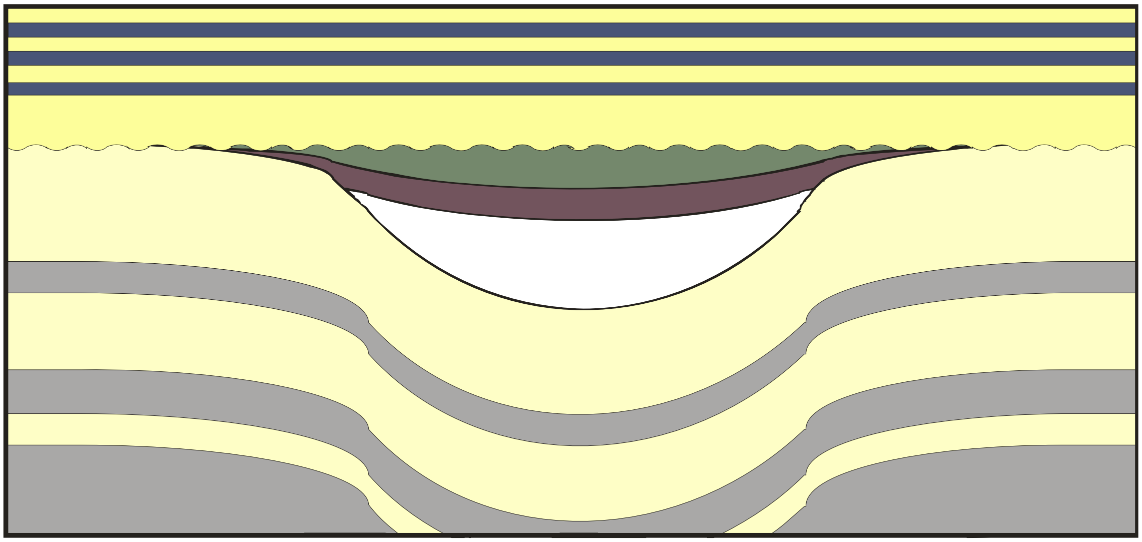
SEQUENCE STRATIGRAPHIC INTERPRETATION: COLGATE MEMBER OF THE FOX HILLS FORMATION

The Colgate Member was deposited at the base of the second depositional sequence present within the field area. It is a depositional remnant, specifically an accommodation remnant (*sensu* Martinsen, 2003), contained within a valley that was either incised into the Fox Hills and Bearpaw Formations below, formed from a region of increased subsidence, or a combination of both (Figure 45). Field evidence from the lower Hell Creek Formation indicates that both subsidence and fluvial incision were responsible for creating the accommodation space filled by the Colgate Member and succeeding strata.

Martinsen (2003) identifies five varieties of depositional remnants (Figure 46). Three of these remnants are accommodational in which different parts of a depositional system are preferentially preserved due to either fault control, local subsidence or localized incision (Figure 46C, D, E, respectively). Geometry of Colgate Member strongly resembles Figure 46E, or a combination of Figures 46D and 46E, where strata are floored by an erosional surface, truncated against the walls of the erosional surface and are erosively overlain by a second surface of the upper Hell Creek Formation. Strata that are preserved are only present within the former topographic lows, created either by incision, subsidence or both. The Colgate Member is therefore interpreted to be a depositional remnant of an incised valley system.



A Fluvially incised valley.



B Tectonically enhanced valley

🟦 Upper Hell Creek Formation Floodplain

🟨 Upper HellCreek Formation Channel

🟩 Upper Hell Creek Formation Channel and Floodplain

🟫 Lower Hell Creek Estuarine

⬜ Colgate Member Estuarine

🟨 Fox Hills Formation Shoreface

▨ Bearpaw Formation Marine

Figure 45: The two end member methods of formation of the valley containing Colgate member strata (*sensu* Martinsen, 2003). A) Fluvial incision which resembles the accommodation remnant of Figure 45E. B) Colgate Member strata preserved in a low created by local subsidence, resembling the accommodation remnant of Figure 45D.

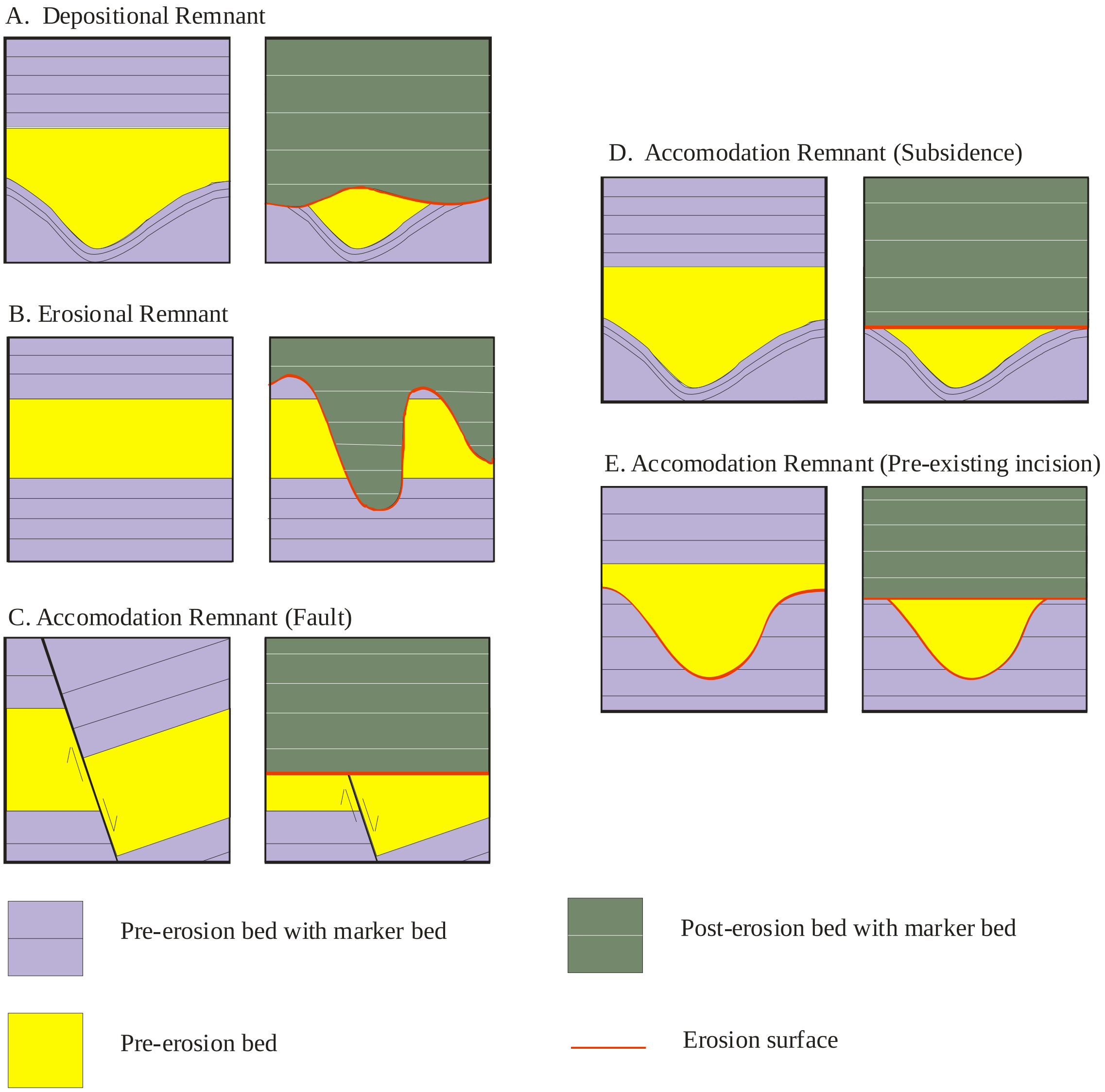


Figure 46: From Martinsen 2003, showing the different kinds of depositional remnants. Diagrams with letters above indicate stratal geometry previous to erosional surface. Diagrams to the right of those with letters indicate the geometry preserved post-erosion. A) Accommodation and subsequent erosion are spatially variable. B) Remnant created by differential erosion. C) Preservation due to post-depositional fault movement. D) Preservation due to localized, syndepositional subsidence. E) Preservation due to deposition in a topographic low.

Depositional Sequence

The Colgate Member is the earliest strata of a depositional sequence comprised entirely of incised valley fill. To establish the existence of an incised valley in which this sequence could be deposited, the defining criteria must be reviewed (piedmont type incised valleys are not included here). The definition of an incised valley is given by Zaitlin et al. (1994, p. 47) as:

> A fluvially eroded, elongate topographic low that is typically larger than a single channel form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base. The fill typically begins to accumulate during the next base-level rise and, and may contain deposits of the following highstand and subsequent sea-level cycles.

As such, the criteria by which they are identified are as follows:

1) **Must be a valley larger than a single channel.** At the time of formation the valley had to be a negative, erosional feature that truncates underlying strata (Dalrymple et al., 1994; Zaitlin et al., 1994; Van Wagoner et al., 1990; Van Wagoner et al., 1988; Zaitlin et al., 1995). Additionally, this valley has to be larger than a single channel in order to distinguish incised valleys from erosion associated with normal, autocyclic fluvial processes.

The lowermost sand (Sm of the Bearpaw Formation) at Sites #13 and #14 is continuous. Between Sm of the Bearpaw Formation and Se of the Colgate Member there is approximately 14 meters of facies Mml at Site #14, but only 8 meters at Site #13. Se eroded at least 6 m of Mml between the two sites. The Colgate Member and the incised portion of the sequence boundary below are not present in all sections because 1) Incised valleys by definition are only locally erosive, and have non-eroded, time equivalent interfluves 2) Se of the Colgate Member is often erosively merged with Se of the upper Hell Creek Formation above, and is therefore removed.

The dimensions of the valley (extent of Se of the Colgate Member) are on the order of tens to hundreds of meters in width and tens of meters in depth. Dalrymple et al. (1994, p. 6 – referencing Van Wagoner et al., 1990; Schumm, 1993) indicate that “erosionally based, fluvial channel deposits that have dimensions of a single channel (10’s to many 100’s of meters wide and up to 10+ meters deep) should not be classified as an incised valley, as they typically result of autocyclic processes such as channel avulsion, stream capture or normal coastal progradation”. By this definition, the interpretation of the Colgate Member as incised valley fill is borderline when based purely on dimensions; however, since the Colgate Member is an accommodation remnant, these dimensions are minimums.

2) **Basal sequence boundary**. The valley must be floored by a sequence boundary which has a time correlative conformity, disconformity or hiatal surface on the valley interfluves (Van Wagoner et al., 1988; Zaitlin et al., 1994; Zaitlin et al., 1995). A Type 1 sequence boundary (Type 2 sequence boundaries will not be discussed here) can be defined by the following criteria: onlap of strata above the sequence boundary on to the sequence boundary (Van Wagoner et al., 1990; Zaitlin et al., 1995); basinward shift in facies (Van Wagoner et al., 1990; Zaitlin et al., 1995); truncation of lower units (Van Wagoner et al., 1990; Zaitlin et al., 1995); presence of the *Glossifungites* ichnofacies (MacEachern et al., 1992; MacEachern and Pemberton, 1994); modification by later transgression (Plint et al., 1992; Van Wagoner et al., 1990); interfluves containing

paleosols (Leckie and Singh, 1991); a pebble lag either from a channel or from a merged sequence boundary / flooding surface in which case the lag is transgressive (Haq, 1991; Van Wagoner et al., 1990). Of these potential criteria, those that are particularly pertinent for defining an incised valley are a non-Waltherian, basinward shift in facies and onlap of valley fill onto the erosional sequence boundary. Other criteria may enhance the interpretation, but both of these characteristics are critical.

There are multiple lines of evidence for the presence of a sequence boundary at the base of the Colgate Member strata. In addition to the erosional nature of the lower boundary, as previously established, there is also a non-Waltherian facies shift across Se of the Colgate Member. Sites #13 and #14 display the most obvious facies shift. At these locales, estuarine Colgate Member facies directly overlie the offshore, fully marine facies of the Bearpaw Formation without any shoreface strata in between. At sites farther east, Colgate Member strata are erosive into the Fox Hills shoreface strata. The facies shift is not as dramatic to the east because of the down-stepping geometry of the shingled shoreface parasequences, as shown schematically in Figures 42 and 43. This results in marine strata being topographically higher in the west than in the east. As incision progressed through this succession, headward erosion began to cut into raised, offshore marine strata to the west while only eroding into shoreface strata in the east.

Onlap of strata on to the valley walls is difficult to observe in the field due to the size of the incised valley relative to the individual outcrops. Figure 47 below illustrates onlapping of Colgate Member strata onto the basal sequence boundary, though superjacent estuarine strata of the lower Hell Creek are eroded before their relationship with the valley walls can be observed.

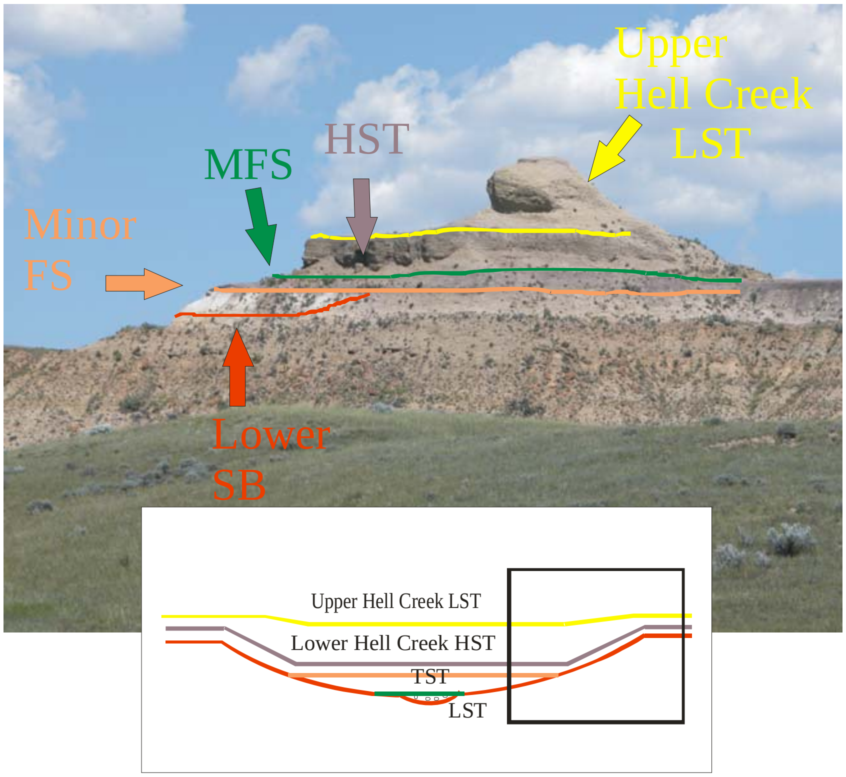


Figure 47: Photo near Site #10 illustrating the onlap of Colgate Member strata (white) onto the sequence boundary (red) which here merges with the transgressive surface beneath lower Hell Creek strata (orange). Relationships are also shown schematically, with portion of schematic shown in photograph outlined.

Se of the Colgate Member also displays evidence of modification by later transgression. As mentioned in the discussion of facies St of the Fox Hills Formation, the uppermost bounding surface of the Fox Hills Formation as well as the upper most bounding surface of the Colgate Member are extensively burrowed and well cemented by iron oxide. These characteristics are similar to those that define a *Glossifungites* surface, however, this surface would form during transgression (where merged with the previous sequence boundary) rather than during initial formation of the erosive surface. Formation of such a transgressive surface has been documented by MacEachern et al. (1992).

Finally, Wheeler (1983) identified the presence of a fluvial lag along the Se surface near Billy Creek. She also documented bioturbation at the base of this lag, though she does not elaborate on the nature of bioturbation. Both of these features are consistent with the formation of a fluvially incised sequence boundary beneath the Colgate Member.

Systems Tracts

Incised valleys are formed in response to a relative sea-level fall (Van Wagoner et al., 1990). There are many factors that can contribute to the relative sea-level fall including eustatic sea-level fall, tectonic uplift, climate change, and stream capture (Schumm and Etheridge, 1994; Thorne, 1994); however, the relative roles of these factors is beyond the scope of this study. Incised valley fill, especially of coastal plain type incised valleys, is simple and comprised of lowstand, transgressive and highstand systems tracts (Zaitlin et al., 1994). The Colgate Member constitutes only the lowstand and transgressive portions of the overall fill.

According to Posamentier and Allen (1999, p. 33), the lowstand “includes all the deposits accumulated after the onset of relative sea-level fall, and as long as shoreline regression continues”. During the early lowstand, fluvial incision causes sediment to bypass the coastal plain. In the late lowstand, relative sea-level stabilizes causing fluvial systems to switch from incision to deposition (Posamentier and Allen, 1999). At this time a normal regression may replace the former forced regression if sediment supply is high relative to rate of increase of accommodation space (Posamentier and Allen, 1999). Landward in the incised valley, fluvial systems aggrade during this late lowstand (Posamentier and Allen, 1999). Typically coarse material is trapped in the fluvial facies tracts of the incised valley systems and finer material is delivered down valley to the estuarine facies tracts (Posamentier and Allen, 1999). As sea-level begins to rise, this coarser fraction is overlain by more distal, basinward deposits, forming the transgressive surface or lower bounding surface of the transgressive systems tract.

Fluvial incision during the lowstand is represented by the Se facies of the Colgate Member, with the erosional surface having been formed in the early lowstand and the actual coarse-grained facies associated with Se having been deposited during the late lowstand (Figure 48). As stated earlier, this coarse-grained fluvial facies was not directly observed by the author. Its presence and fluvial nature was confirmed by Wheeler (1983, 2003) in the area of Billy Creek, south of Site #9.

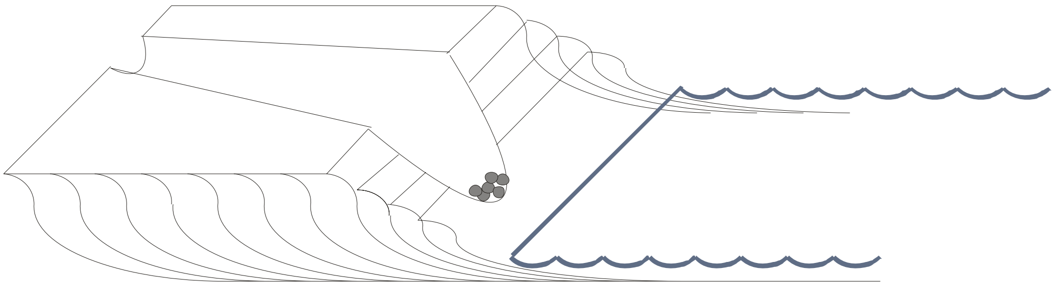


Figure 48: Formation of incised valley into the underlying highstand deposits of the Bearpaw and Fox Hills Formations. Deposition within the incised valley, shown by the coarse lag (Se) above, occurs during the late lowstand.

At the onset of transgression, formerly fluvial regions of the incised valleys are transformed into estuarine environments (Posamentier and Allen, 1999). A transgressive ravinement surface may also be formed at this time, allowing for the formation of a transgressive *Glossifungites* facies that represents a merged flooding surface with sequence boundary from the previous lowstand (MacEachern et al., 1992). Transgression may continue until incised valleys are fully marine in nature; however, in the study area the most distal facies of the Colgate Member are estuarine in nature such that the added complexity of marine transgressive environments is not pertinent to this work.

Within the transgressive systems tract, strata in a vertical succession should display more distal facies from bottom to top. The Colgate Member does not contain readily observable internal flooding surfaces across which retrogradation can be determined. The transgressive nature of the Colgate Member relies on the relationship of all of the upper estuarine facies with the lowermost fluvial Se facies from Wheeler (1983, 2002). Estuarine strata (St, Sm, and Sh) superjacent to fluvial deposits (Se) indicate a marine flooding surface is located above the Se facies (Figure 49). This flooding surface also marks the transition from the late lowstand to the transgressive systems tract, where the majority of the Colgate Member facies were deposited (Figure 50).

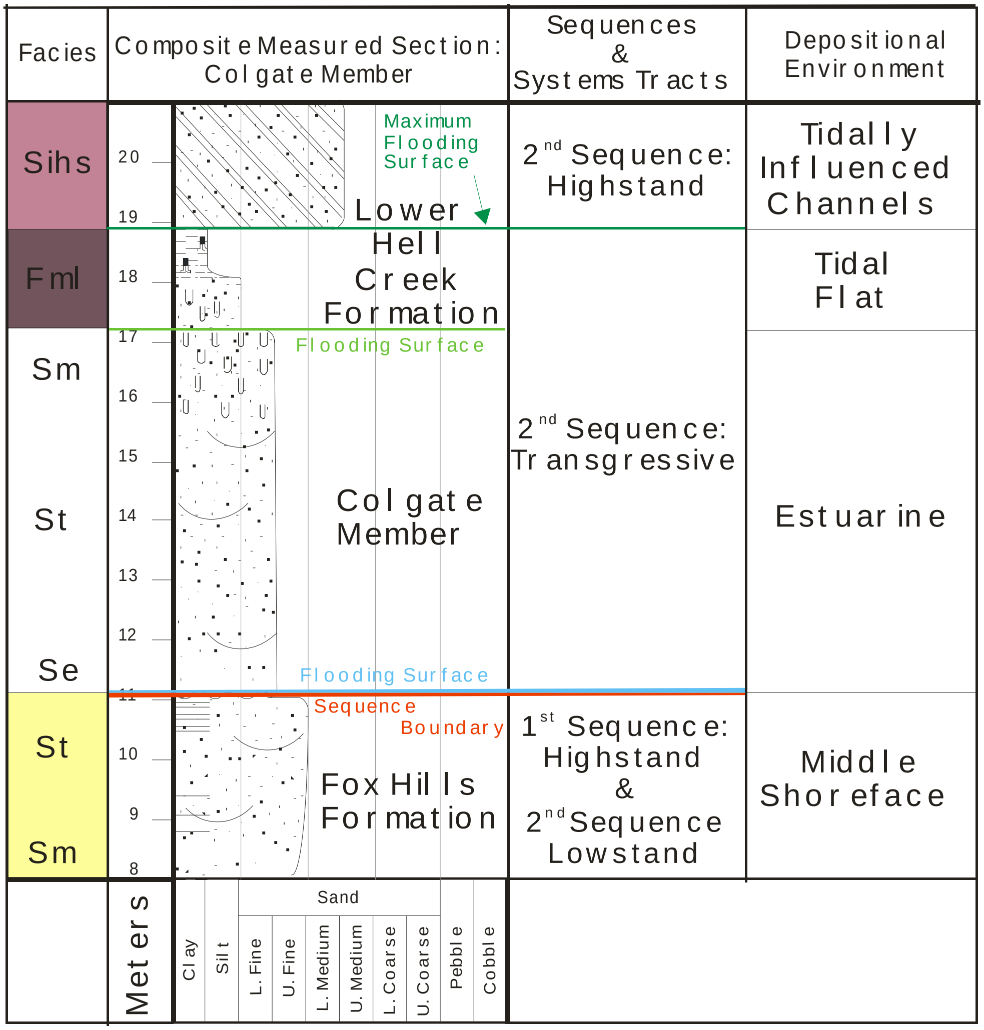


Figure 49: Composite measured section showing facies, significant surfaces and depositional environments of the Colgate Member.

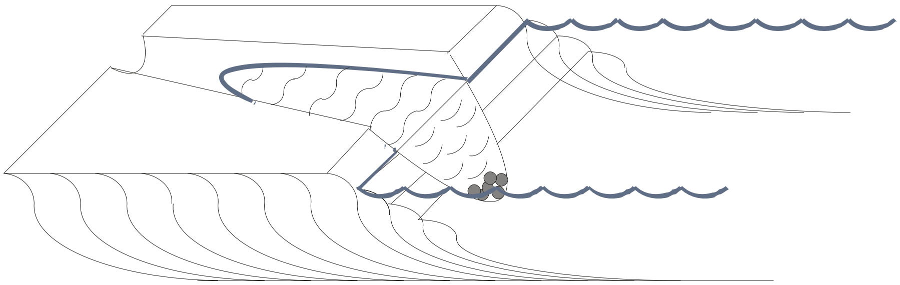


Figure 50: Schematic of estuarine facies of the Colgate Member being deposited over the fluvial facies during a relative sea-level rise.

CHAPTER 11

SEQUENCE STRATIGRAPHIC INTERPRETATION: LOWER HELL CREEK FORMATION

Depositional Sequence

The lower Hell Creek Formation was deposited above the Colgate Member in the second depositional sequence. Like the Colgate Member below, the lower Hell Creek Formation is also a depositional remnant (Figures 39 and 45). Where lower Hell Creek Formation strata are preserved above the Colgate Member, their geometries are sheet-like and resemble both Figure 46A and 46D. Strata onlap the sequence boundary below (Se of the Colgate Member) and are either preserved due to subsidence (an accommodation remnant such as Figure 46D) or due to topography (a depositional remnant such as Figure 46A) on the superjacent sequence boundary (Se of the upper Hell Creek Formation).

Systems Tracts

The lower Hell Creek Formation was deposited during the transgressive and highstand systems tracts of the second depositional sequence. The transgressive portion of the lower Hell Creek Formation consists of facies Fml, the top of which marks the maximum flooding surface (Figure 51). As can be see in the schematic of Figure 52, the transgression floods the interfluves of the former incised valley, forming a co-planar sequence boundary (Se of the Colgate Member) and flooding surface (Fml of the lower Hell Creek) at those locations. In this situation, MacEachern et al., (1992) suggest that a transgressive surface of erosion can scour the interfluve areas and allow for colonization by a firmground suite as transgression progresses. This is what is observed in field relationships of the lower Hell Creek Formation with respect to the Colgate Member and Fox Hills Formation below. Facies Fml is characterized by extensive *Skolithos* burrows and the units beneath (St, Sm, Sh of the Colgate Member) show evidence of colonization by the *Glossifungites* ichnofacies.

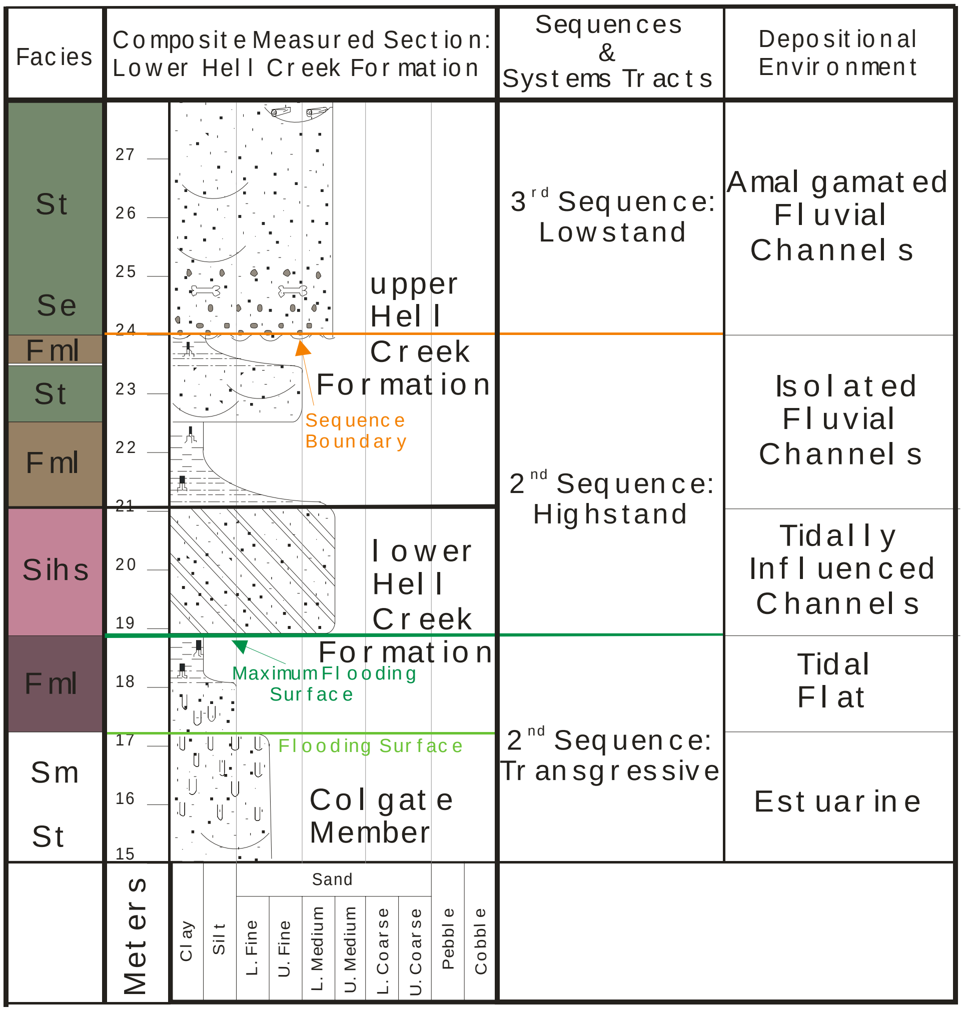


Figure 51: Composite measured section showing facies, significant surfaces and depositional environments of the lower Hell Creek Formation

Near Site #14, evidence of the lower Hell Creek transgression has been completely removed by the lowstand sequence boundary of the upper Hell Creek Formation above. Where the upper Hell Creek Formation erosively overlies the Fox Hills Formation or Colgate Member in this area, there are extensive vertical burrows into the underlying units. These burrows are of the *Skolithos* variety and are interpreted as belonging to the *Glossifungites* ichnofacies. In Figure 52 below, these borings would be located on the flanks of the incised valley at the contact between the black unit that represents the maximum flooding surface and the top of the clinoforms that represent deposition of Fox Hills shoreface strata. In Appendix C, this geometry may be seen in cross section.

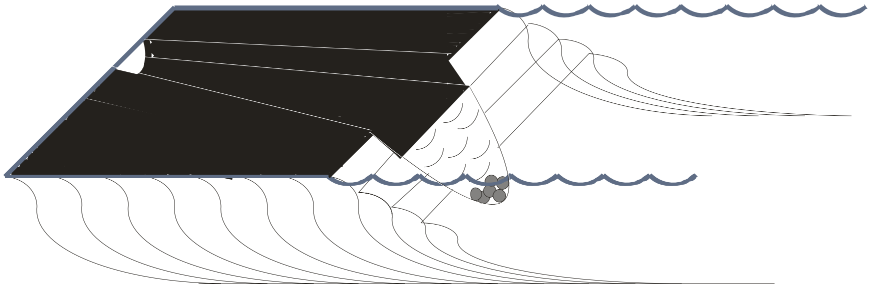


Figure 52: Schematic of maximum flooding surface of the lower Hell Creek Formation being deposited above the transgressive Colgate Member units.

Further evidence that facies Fml is equivalent to a maximum flooding surface is that in non-marine systems, maximum flooding surfaces are recognized by deposition of finer grained and/ or carbonaceous sediment on the floodplains as a result of lowering of fluvial gradients (Cant, 1998). Coal is often an indicator of non-marine flooding surfaces as well (Diessel, 1998). The marginal marine facies (Fml) of the lower Hell Creek is the most carbonaceous facies of this study, and blankets the former interfluves as well as the fill of the incised valley. The regional extent as well as presence of both roots and marine burrows are evidence that Fml was deposited during the maximum transgression of the transgressive systems tract.

The highstand systems tract of the lower Hell Creek Formation consists of estuarine units (Sihs) of a more proximal nature than those of facies Fml below. Sihs blankets Fml (Figure 51), forming both within the incised valley and on the interfluves. Deposition within a tidally influenced channel represents the migration of fluvial systems back across the formerly flooded valleys and interfluves. This progradation suggests that the rate of sediment supply was able to surpass the rate of relative sea-level rise, filling in the available accommodation.

The location of Fml between two estuarine units, the lower transgressive deposits of the Colgate Member and the upper regressive deposits of the lower Hell Creek Formation, is predicted by Zaitlin et al., (1994) in cases where the field area of interest lies within their ‘segment 2’ of an idealized incised valley. In other words, when the field area lies between the maximum landward limit of open marine mudstones and the landward limit of tidal features, the maximum flooding surface will divide two estuarine units. Figure 53 below schematically shows the relationship of the transgressive Colgate Member overlain by the maximum flooding surface of the lower Hell Creek Formation which is then all capped by the regressive deposits of the lower Hell Creek Formation. This relationship can also be observed in the composite measured section of Figure 51 above.

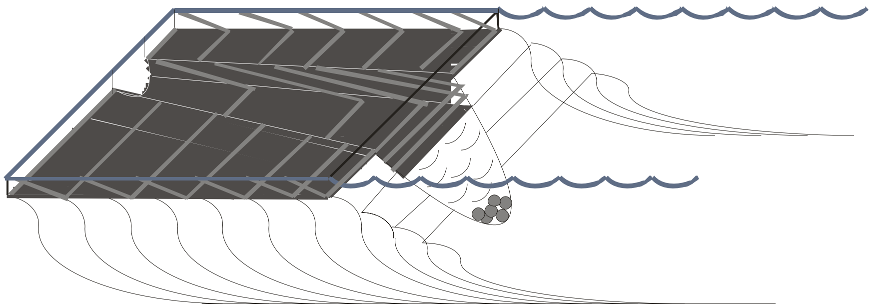


Figure 53: Schematic of the highstand portion of the lower Hell Creek Formation estuarine strata (gray and white inclined units) prograding over the maximum flooding surface (black) and estuarine Colgate strata (white trough cross-stratified valley fill) below.

CHAPTER 12

SEQUENCE STRATIGRAPHIC INTERPRETATION: UPPER HELL CREEK FORMATION

Depositional Sequence

The majority of the upper Hell Creek Formation described here is in the third depositional sequence with minor amounts in the second. This sequence is not described in its entirety because, as with the first depositional sequence, it is not the main focus of this study and was therefore needed only as a boundary for comparison with the middle depositional sequence. This sequence is completely non-marine, displays a sheet-like geometry, and is present in every section within the field area. This sequence was interpreted to a maximum thickness of 30 meters, though the Hell Creek Formation extends for approximately another 70 meters.

The application of sequence stratigraphy to the non-marine realm is somewhat controversial, though it is gaining acceptance. The methodology of sequence stratigraphy was originally designed for marine strata, but can be applied to non-marine strata because alluvial architecture is a function of the rate at which accommodation space is generated, which is in turn related to the rate of base-level change (Shanley and McCabe, 1993). There are several complicating factors with fluvial rocks, such as "the presence of abrupt lateral facies changes, typically poor biostratigraphic resolution and limited absolute age dating, numerous internal erosional surfaces, the absence of through-going marker horizons, and limited outcrops" (Shanley and McCabe, 1993, p. 23) that have lead some authors to claim that “sequence stratigraphy, with all its emphasis on bounding unconformities and marine flooding surfaces, cannot be easily applied to non-marine rocks (if at all)” (Walker, 1990, p. 781). Shanley and McCabe (1993, p. 24), however, have shown at the Kaiparowits Plateau, Utah, that “sediment architecture of both shoreface and alluvial strata varies in a systematic and, therefore, predictable manner depending on position within a depositional sequence”. In that study, as with this one, the presence of tidally influenced fluvial deposits allowed for more confident correlations between the marine and non-marine and assured that base-level changes would in fact be the predominant driving mechanism of stratal architecture (Shanley and McCabe, 1993). In areas that are more proximal (greater than 100-150 km from the coast), climate has a tremendous influence on fluvial architecture and can overwhelm the signal generated by changes in base-level (Shanley and McCabe, 1993).

Systems Tracts

The upper Hell Creek Formation represents deposition during a relative sea-level fall and subsequent relative sea-level rise. Facies of the upper Hell Creek were deposited during both the lowstand, transgressive, and highstand systems tracts. As discussed with the second depositional sequence, the transition from a highstand (lower Hell Creek Formation) to a lowstand (upper Hell Creek Formation) requires the formation of a sequence boundary between the two. A sequence boundary in the non-marine realm is harder to define than those in the marine. Characteristics of fluvial sequence boundaries and the ensuing lowstand deposits are outlined below.

1) Basinward shift in facies. Typically in non-marine successions the basinward shift in facies is not as dramatic as those of the marine and can be especially hard to distinguish from normal, autocyclic stream processes. The evidence used by Shanley and McCabe (1993, p. 43) to define their non-marine sequence boundary in the Kaiparowits Plateau is that "coarse-grained and pebbly, laterally amalgamated fluvial deposits directly overlie finer grained fluvial and alluvial plain strata, carbonaceous shales and, to the east, shoreface strata". Figure 54 below demonstrates the geometry and stacking patterns of a, non-marine lowstand systems tract.

In the upper Hell Creek Formation, amalgamated fluvial channel deposits (St and Sm) above the sequence boundary (Se) erosively overlie estuarine strata of the Colgate Member at Sites #13, #14, #9, and #4, fining upward meandering stream deposits of the upper Hell Creek Formation at Sites # 6, #1, and #10 and shoreface strata of the Fox Hills Formation at Sites #8. #12, #5, #15, #3, #10, and #11. The non-Waltherian facies shift is more prominent basinward (east). The sequence boundary of the upper Hell Creek Formation does not have as much topography as that schematically drawn in Figure 54, however, approximate scale of that figure has significant vertical exaggeration.

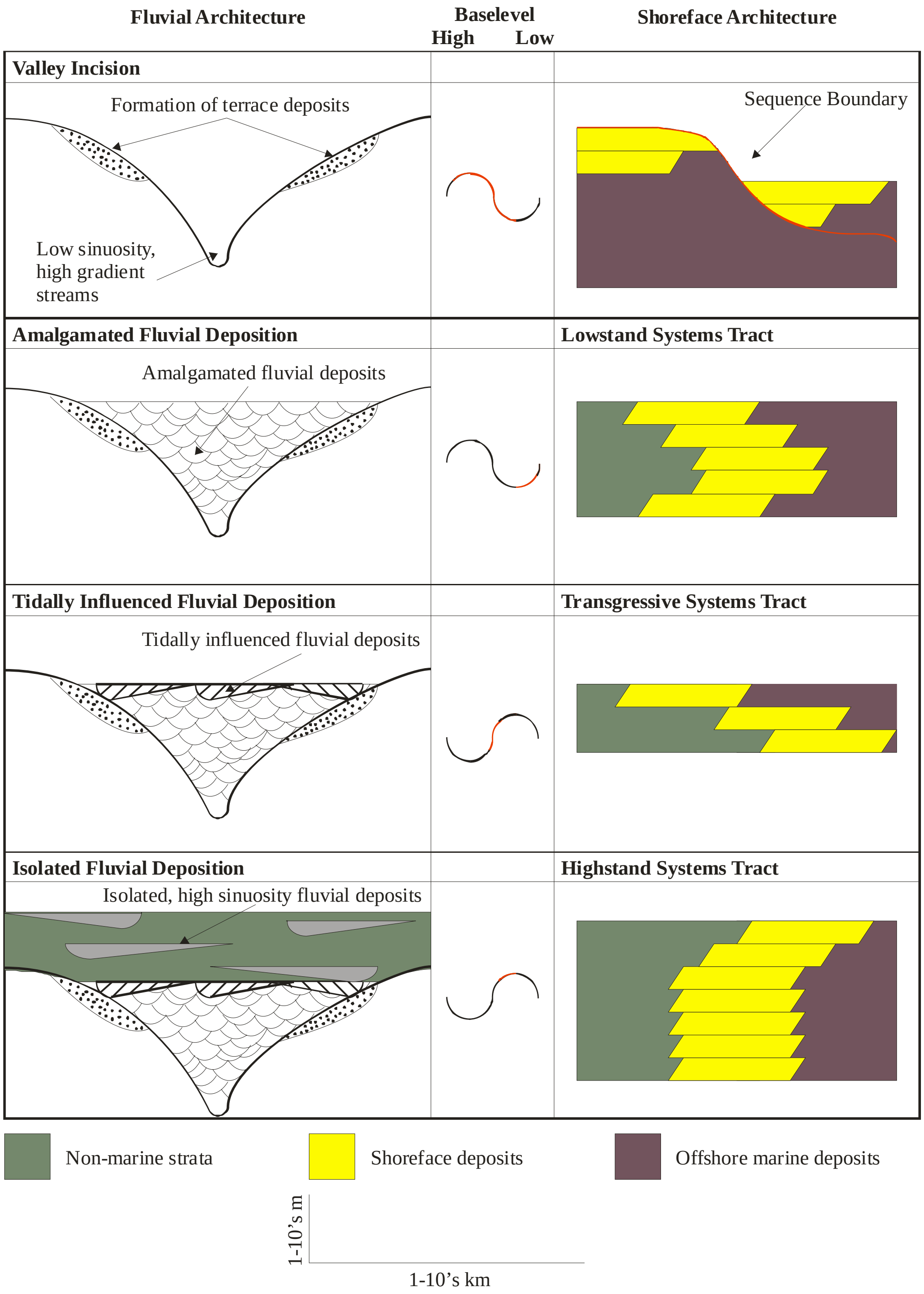


Figure 54: Sequence boundary formation and basinward shift in facies in a non-marine setting. Modified from Shanley and McCabe (1993).

2) Change in fluvial architecture. Above a sequence boundary fluvial sandstones of the lowstand systems tract should be highly amalgamated (Figure 54). In the aforementioned study of Shanley and McCabe (1993) the authors use the truncation of fining upward fluvial deposits, representative of channel sandstones to floodplain deposits, by amalgamated, coarse-grained sandstones to pinpoint a sequence boundary. Changes in stacking pattern are significant because “abrupt changes in composition and degree of amalgamation (or fluvial stacking pattern) across erosional surfaces that have regional extent also suggest a pronounced change in hydraulic character as well as rates of alluvial aggradation and together support the interpretation of sequence-boundary unconformities” (Shanley and McCabe, 1993, p. 43).

Across the sequence boundary of the upper Hell Creek Formation, areas that were previously dominated by small fining upward fluvial deposition (Sites #1, #6, and #10) are erosively capped by thick sandstone bodies of coarser grain size and much larger bedforms. Individual channels do not fine upwards to floodplain deposits, but rather there are several amalgamated channel complexes within this superjacent sand body (Figure 54).

3) Change in sandstone composition. Lawton et al., (2003) use shifts in petrofacies to define sequence boundaries. In their terminology, when two adjacent sandstone bodies are ‘congruent’ both in terms of depositional environment, paleocurrents, and composition, then the division between them is not a significant bounding surface. When two sand bodies are incongruent in, then the division between the two is a significant surface.

In locations where Se overlies significantly different depositional environments, such as estuarine and shoreface strata, changes in petrofacies are not as crucial for the defining a sequence boundary as they are in locations where Se erodes into earlier fluvial deposits of the upper Hell Creek. Paleocurrent data are consistent throughout all of the depositional sequences, with the exception of bimodal paleocurrents in some tidal settings, so direction of transport is not a useful criteria for delineating sequence boundaries here. Petrography of the three sequences was not performed as part of this study.

4) Regionally extensive. The sequence boundary, with the respective characteristics defined above, has to be present on a regional scale and not just in a few locations (Shanley and McCabe, 1993). A small outcrop of coarser sandstone which overlie finer grained floodplain deposits could signify autocyclic processes independent of base-level change. The larger picture must always be kept in mind when dealing with sequence stratigraphy in fluvial environments.

Se of the upper Hell Creek Formation is the most regionally identifiable surface in this study. Almost everywhere that this surface is present it contains a lag of bone and intraclasts, as can be seen from the measured sections and cross section. Figure 55 below schematically displays the relationship of Se and subsequent lowstand deposition of underlying strata. The lowermost units of the upper Hell Creek Formation erosively overlie the Bearpaw Formation, the shoreface portion of the Fox Hills Formation as well as the Colgate Member of the Fox Hills Formation. The basinward shift in facies, regional extent, and its highly amalgamated nature identify it as being deposited in the lowstand systems tract above a sequence boundary.

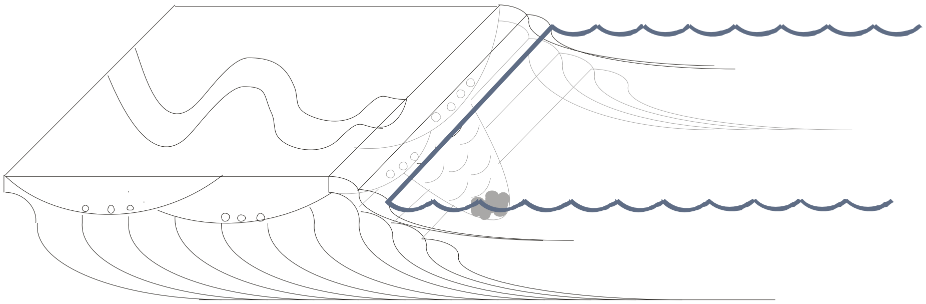


Figure 55: Schematic representation of the lowstand systems tract of the upper Hell Creek Formation.

The final portion of the upper Hell Creek observed for this study is interpreted to represent deposition during the transgressive and highstand systems tracts. In the work of Shanley and McCabe (1991, 1993) non-marine transgressive systems tracts are often identified on the basis of tidal influence. For the Hell Creek Formation there have been marine tongues identified in North Dakota (Seager et al., 1942; Laird and Mitchell, 1942; Frye, 1967, 1969; Hartmann and Kirkland, 2002), at the base of formation, but so far no marine influence from those has been documented in the upper Hell Creek of this study. The interpretation of a transgressive systems tract therefore relies on the absence of an unconformity between the highly amalgamated channels of the lowstand systems tract and the isolated channel sands above which are indicative of a non-marine highstand systems tract. Otherwise, there is not direct evidence in the field area for a transgressive systems tract, at least based on the criteria of Shanley and McCabe (1991).

Following the rapid rise in relative sea-level that is characteristic of the transgressive systems tract, the rate of relative rise slows and allows for sediment supply to meet or exceed the available accommodation space in the highstand systems tract (Schumm et al., 1987; Shanley and McCabe, 1993). This results in aggradation of fluvial environments, and therefore highstand deposition manifests itself as isolated channel sand bodies encased in fine-grained floodplain deposits (Shanley and McCabe, 1991, 1993) as seen in Figure 54. During the late highstand as accommodation decreases even further, isolated sands bodies of the early highstand become more laterally continuous (Shanley and McCabe, 1993).

Above the amalgamated sands of the upper Hell Creek Formation, the ratio of sand to mud drastically decreases. The majority of deposition occurs in floodplain environments (e.g. facies Sm and Fml) and any sand bodies present are smaller, more lenticular, isolated, and finer grained than those of the lowstand systems tract below. No laterally continuous sands were identified, indicating that the portion of the Hell Creek observed in this study was deposited in the early highstand systems tract. Figure 56 shows the facies relationships in a composite measured section of upper Hell Creek strata, and Figure 57 schematically shows the transition from upper Hell Creek lowstand deposition to upper Hell Creek highstand deposition.

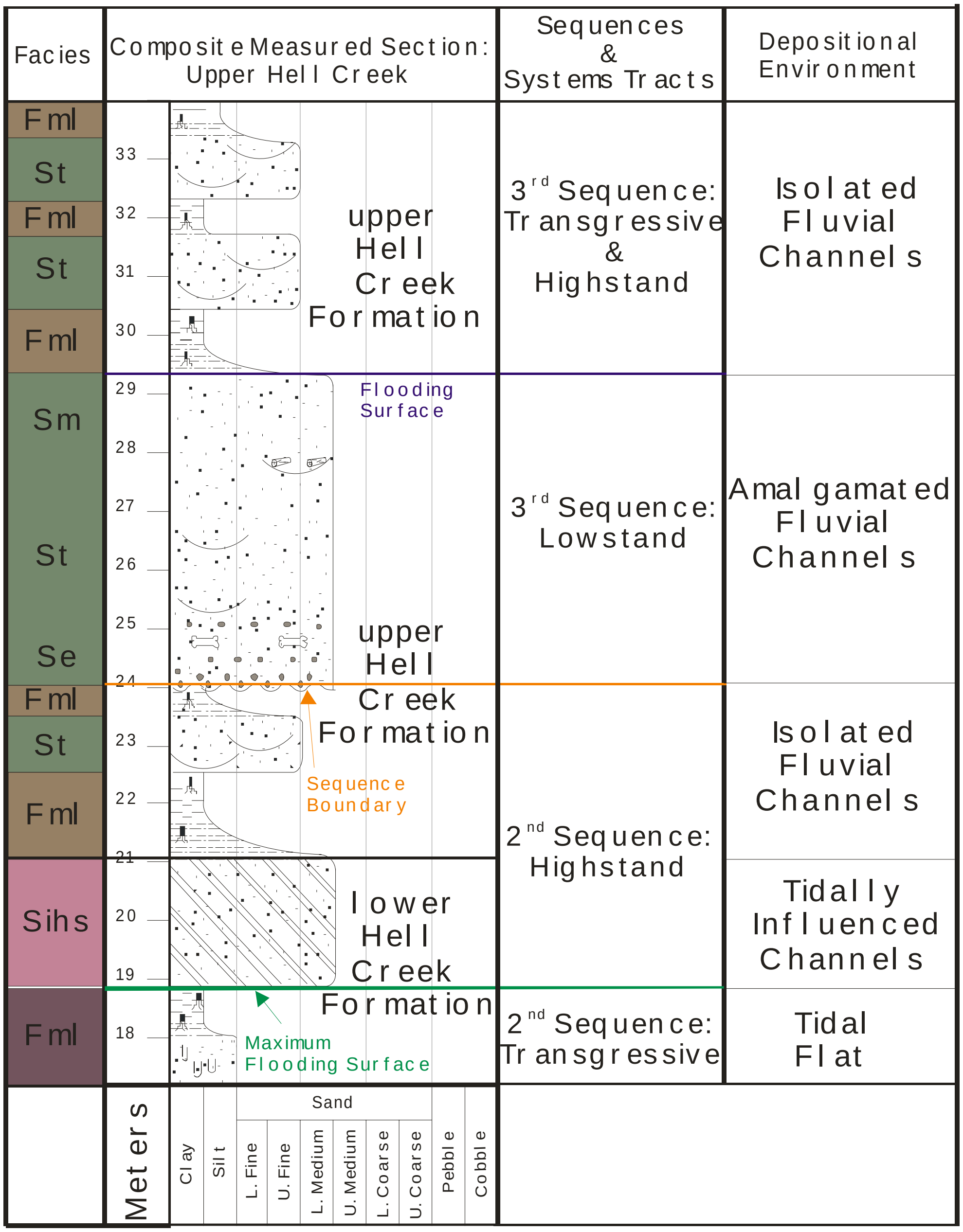


Figure 56: Composite measured section showing facies, significant surfaces and depositional environments of the upper Hell Creek Formation.

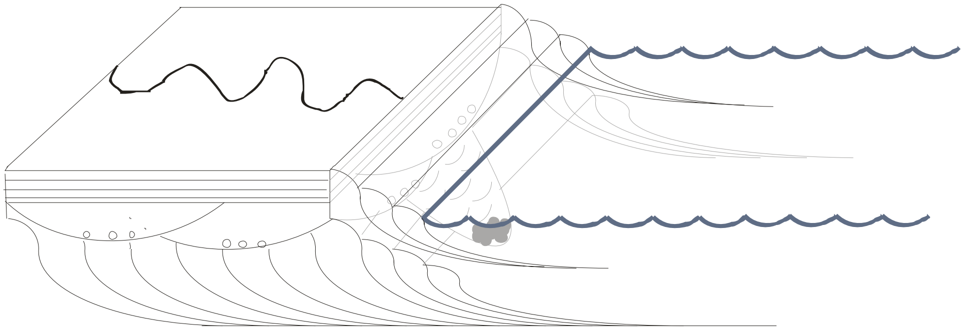


Figure 57: Schematic of the transgressive to highstand systems tracts of the upper Hell Creek Formation.

CHAPTER 13

RELATIONSHIP TO DINOSAUR PALEONTOLOGY

The application of sequence stratigraphy to dinosaur paleontology is quite significant in this area where so few time markers exist. Workers seeking to identify evolutionary changes in various species through time have had a difficult time placing specimens in a chronostratigraphic framework. With the proximity of the Hell Creek formation to the Cretaceous – Tertiary boundary, placing dinosaur sites into relative age groupings is important for questions regarding faunal diversity and population stability through time. To date there has been little success in this endeavor. This study only addresses the lowermost portions of the Hell Creek Formation, where proximity to the coast (as evidenced by tidally influenced deposits) makes sequence stratigraphic interpretation much easier. Further work on fluvial architecture needs to be performed on the entirely non-marine portion in order to fully understand the faunal story of the Hell Creek Formation.

Background

The dinosaurs sites (specifically *Tyrannosaurus rex*) that have measured sections beginning in the Bearpaw or Fox Hills Formations and extend up to the upper Hell Creek are listed in Table 4 below. Shoup (2001) measured each of the sections and placed dinosaur quarry sites in their appropriate stratigraphic position. These sections were then drawn in the same format and scale as the purely geologic sections measured by the author, and are included here as Appendix B. From Shoup's (2001) field description of each unit, each site has been placed into a depositional sequence, systems tract, and facies. Three of the sites were field checked for accuracy of interpretation.

Table 4: Associated specimens with measured sections.

Specimen	Facies	Sequence & Systems Tract
B-Rex	lower Hell Creek-Sihs	2nd Sequence Highstand
C-Rex *	upper Hell Creek - St	3rd Sequence Transgressive & Highstand
G-Rex	upper Hell Creek - Fml	3rd Sequence Transgressive & Highstand
J-Rex	upper Hell Creek - Fml	3rd Sequence Transgressive & Highstand
N-Rex	upper Hell Creek - Fml	3rd Sequence Transgressive & Highstand

* Note: In the measured sections of Appendices B and D, C-Rex appears to be contained within the lowstand systems tract of the third sequence. This placement is believed to be a measurement error in Ben's sections, as C-Rex was found in a lacustrine environment.

Specimens are named based on the identity of the person who discovered it. A 'countable' specimen is classified as three or more bones that can be demonstrated as belonging to an individual. These bones have to display the same degree of wearness (implying similar method and degree of transport) and have to be 'reasonably' close to one another. In other words the bones must demonstrate similar method and degree of transport, as well as be present within a reasonable lateral and vertical range. Bones with similar wearness from outcrops separated by vast differences may not be categorized as associated.

Articulation is not required, and is actually quite rare in the facies identified here, because it requires specific preservational processes and is not absolutely necessary for the identification of one individual. Similarly, the percent completeness of a skeleton is not required for the identification of an individual because the percent completeness as observed today does not necessarily reflect the completeness of the skeleton at the time of burial. Modern erosional processes may remove large percentages of bones that were originally associated with skeleton. In fact, this is the case for almost all of the individuals identified in the Hell Creek area, since most discoveries are made by finding bone weathering out at the surface.

Application of Sequence Stratigraphy

Correlations from this study can answer three important questions about the lower Hell Creek Formation. First, the location and distribution of facies Sihs can be determined. This facies is significant because it contains both the B-Rex (*Tyrannosaurus rex*) and the X-Rex (*Edmontosaurus*). Both of these specimens are extremely well preserved, making this facies an exploration target for future taphonomic studies. From this study, the presence of Sihs can also be pinpointed to one sequence stratigraphic level. All deposits of Sihs are part of the early highstand systems tract of the lower Hell Creek Formation, when the rate of sediment supply was starting to surpass the rate that accommodation was being generated. This facies is chronostratigraphically equivalent everywhere in the field area. Therefore outcrops of Sihs correspond to a single event rather than representing multiple events. This means that individuals found within this facies are roughly time equivalent.

The second question that is addressed by this study is the extent of the upper Hell Creek sequence boundary. This is important because this surface contains an extensive lag of dinosaur bones. Seemingly, the lag on the upper Hell Creek sequence boundary would be useless because it has amalgamated deposits of a wide age range; however, it provides information about diversity. Recent studies have focused upon this lag deposit in order to get a cross section of the fauna that existed around the time of its formation. Because this lag preserves large bones and small bones alike, with no apparent preference, it is a good approximation of the fauna that must have existed during and slightly before formation of the boundary. In a Rogers and Kidwell (2000) study of disassociated vertebrate skeletal concentrations and discontinuity surfaces of the Two Medicine Formation (Campanian) in Montana, the usefulness of this kind of lag decreases with increased depth of incision and / or amount of time or depositional hiatus before incision began. Similarly to Sihs, this sequence boundary formed at one specific time in the history of the upper Hell Creek Formation; therefore, the deposits between it and the transgressive deposits above are all chronostratigraphically equivalent. This information allows current studies to correlate bones that were previously collected as isolated lag deposits across the entire field area. Further work would need to be performed in order to establish the amount of time represented by the included faunal material and whether this amount of time varied across the field area. This study only shows that the surface containing the lag is correlative throughout the field area.

Finally, this study shows a correlation between systems tracts and preservation. In systems tracts of high accommodation, i.e. the transgressive and early highstand systems tracts, dinosaur specimens are associated (note the systems tracts of the ‘named’ dinosaurs from Table 4) and are likely of the same age as the strata in which they are found. In the Rogers and Kidwell (2000) study, tidally influenced fluvial deposits (of the transgressive systems tract) were also found to yield the highest percentage of skeletal material compared to fluvial and shoreface environments. In systems tracts of low accommodation, i.e. the lowstand systems tract, fossil material is disassociated and is more likely to represent older, reworked fauna from subjacent strata (Rogers and Kidwell, 2000).

CHAPTER 14

SUMMARY AND CONCLUSIONS

The Bearpaw through Hell Creek Formations represent deposition during the last major regressive cycle of the Western Interior Cretaceous Seaway. There are three depositional sequences present from the top of the Bearpaw Formation through the lowermost units of the Hell Creek Formation, representing higher order, higher frequency changes in relative sea-level. These sequences were interpreted based on the presence of key surfaces within the field area and are significant in terms of providing relative age control for faunal studies.

The lowermost sequence is composed of Fox Hills Formation shoreface facies and Bearpaw Formation offshore facies. This shoreface to offshore transition is present in several individual parasequences that shingle strata upon one another due to a forced regression process. These formations are considered to be part of the highstand and subsequent lowstand systems tracts which are separated by a correlative conformity from the amalgamated sequence boundary represented by Se of the Colgate Member.

The middle sequence is composed of the Colgate Member fluvial and estuarine facies and the lower Hell Creek Formation estuarine and tidally influenced fluvial facies. The Colgate Member is interpreted to have formed during the lowstand and transgressive systems tracts while the lower Hell Creek represents maximum transgression and early highstand deposition. This early highstand of this sequence contains B-Rex, the best preserved *Tyrannosaurus rex* specimen from the field area and X-Rex, an articulated, well preserved *Edmontosaurus* that contains skin impressions. Both are present in facies Sihs which has been identified here as a tidally influenced meandering stream present only in the early highstand of this second depositional sequence. This sequence is capped by Se of the upper Hell Creek Formation.

The uppermost sequence is composed of the upper Hell Creek Formation fluvial facies. It is interpreted to have formed during a complete cycle of lowstand, transgressive and highstand deposition. This sequence contains the majority of dinosaur specimens extracted from the Hell Creek Formation. Depositional environments of these specimens are varied and spatially unpredictable. In the lowstand systems tract, the bone lag on the regionally extensive lower sequence boundary (Se), provides important information about the faunal population present just at and previous to the formation of the incision, even though no single individuals can be identified.

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