THE GEOMETRY, GENESIS, AND STRATIGRAPHIC FRAMEWORK OF THE COLGATE SANDSTONE MEMBER OF THE FOX HILLS FORMATION, NORTHEASTERN MONTANA

by

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

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

December, 2008

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ABSTRACT

The Upper Cretaceous Colgate Sandstone Member of the Fox Hills Formation near the Fort Peck Reservoir, eastern Montana is of particular scientific interest. These rocks record the last major regression of the Western Cretaceous Seaway. The detailed interpretation of these stratigraphic units yields greater insight into the causes and dynamics of this important geologic event.

The purposes of this research were to: (1) map the extent of the Colgate Sandstone Member in the study area, (2) describe and interpret the facies comprising the Colgate Sandstone Member, (3) determine the facies architecture, and sequence stratigraphic framework of the Colgate Sandstone Member, and (4) to interpret the depositional system active to deposit the Colgate Sandstone Member and those factors that influenced its distribution.

Twenty-four stratigraphic sections were measured near Devilôs Creek area, approximately 65 km (40 miles) NNW of Jordan, MT. Additionally, a series of isopach and structure maps were generated using data from geophysical wireline well logs from nearby boreholes to determine tectonic influences on Colgate Sandstone deposition.

The Colgate Sandstone Member of the Fox Hills Formation is part of an incised valley system that formed in response to a relative sea level drop of the Western Interior Seaway during the Maastrichtian stage in northeastern Montana and western North Dakota. The valley fulfills the criterion set forth by Zaitlin (1994, 1995) to characterize a depositional system as an incised valley-fill. The valley-fill strata onlaps the unconformity forming the valley floor and sides and demonstrates an abrupt basinward shift of facies relative to those of the eroded substrate (Van Wagoner et al., 1988). Further, these lowstand and transgressive system tract valley fill strata are deposited during a 3rd order relative sea level cycle that correlate to Haq et. al.ôs (1987) UZA-4.5 depositional sequence. This sequence lasted approximately 1 Ma, and is considered the last sequence of the Zuni transgression. There is also sub-surface and field evidence that regional subsidence (the Blood Creek Syncline) and local subsidence along the Plum Creek lineament were significant in determining the location of the valley system and potentially increasing accommodation beyond that created by fluvial incision alone.

CHAPTER 1

INTRODUCTION

This study characterizes the stratigraphy and process sedimentology of the Upper Cretaceous Colgate Sandstone Member of the Fox Hills Formation in northeast Montana. The purposes of this research are to: 1) map the extent of the Colgate Sandstone Member in the study area; 2) describe and interpret the facies comprising the Colgate Sandstone Member; 3) determine the facies architecture and sequence stratigraphic framework of the Colgate Sandstone Member; 4) to interpret the depositional system active to deposit the Colgate Sandstone Member and those factors that influenced its distribution.

The study area is a part of in the Northern Great Plains physiographic province of eastern Montana (Fenneman, 1931). It encompasses the western margin of the Williston Basin and lies east of the Little Rocky Mountains and northeast of the northwest trending Cat Creek anticline. Sedimentary rock units that are the focus of this study are exposed along the Missouri River and its tributaries northwest of Jordan, Montana. Most field work was completed between Hell Creek and Devilôs Creek on the south shore of Fort Peck Reservoir on the Charles M. Russell Wildlife Refuge (Figure 1).

Sedimentary rocks in the area range in age from Late Cretaceous to Early Paleogene. From oldest to youngest, formations cropping out in the area are the Cretaceous Bearpaw Shale, Cretaceous Fox Hills Sandstone (of which the Colgate Sandstone is a member), Cretaceous Hell Creek Formation, and Paleocene Fort Union Formation .

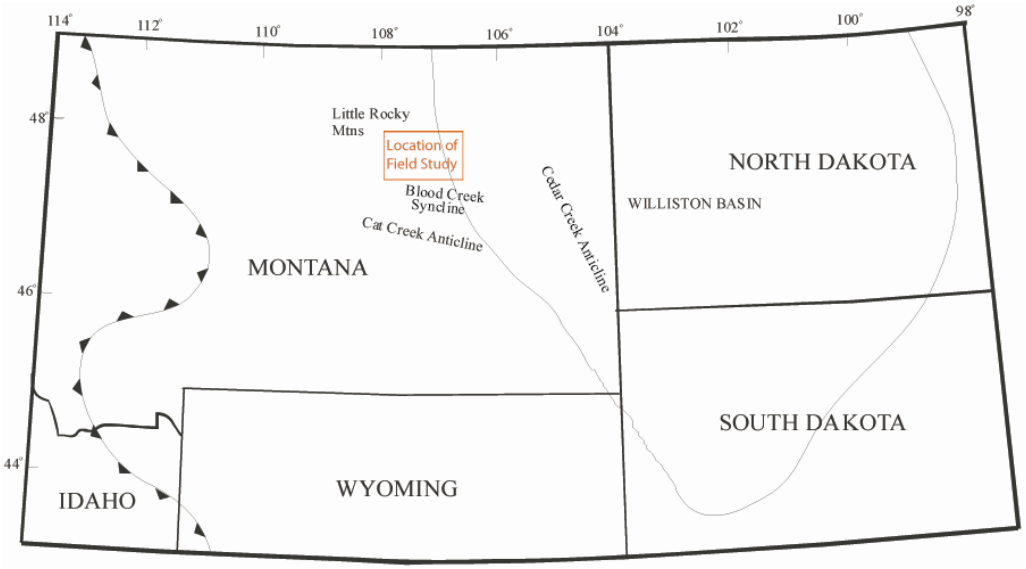

Figure 1: Location of field study in respect to nearby prominent geologic features.

These units are well-exposed along the Missouri River and its tributaries due to erosion following the last Pleistocene glacial retreat. High discharge during retreat of continental ice sheets scoured this area to depths in excess of 100 meters (330 feet) (Fullerton, 2004). These exposures provide excellent outcrops for study of the upper Cretaceous and Paleogene stratigraphy of this region (Flight, 2004). This is especially true in the Devilôs Creek area where the Colgate Sandstone Member of the Fox Hills Sandstone is well-exposed.

The Colgate Sandstone Member of the Fox Hills is of particular scientific interest. It rests unconformably on lower units within the Fox Hills Formation and at times rests directly upon the Bearpaw Shale (Flight, 2004). Recent work has suggested that the Colgate Sandstone Member of the Fox Hills Sandstone is an incised valley fill system (Flight et al., 2004). If the Colgate Sandstone Member is part of an incised valley fill

system, then a predictable fill within the valley should be present (Zaitlin et al., 1994; Zaitlin et al., 1995). Incised valley systems are significant components of siliciclastic sequence stratigraphic models and can be important for interpreting the relative sea level history of a region. The Bearpaw Shale to Fox Hills Sandstone to Hell Creek Formation succession is significant in that it marks the last major regression of the Western Interior Cretaceous Seaway. Incised valley fill strata within the Fox Hills Sandstone or Hell Creek Formation may contain beds that document high frequency, relative sea level changes that occurred during this major regression. The interpretation of this stratigraphic unit may yield greater insight into the causes and dynamics of this important geologic event.

Also, the Colgate Sandstone Member of the Fox Hills Sandstone is used as an important marker horizon in the region of Fort Peck Reservoir by vertebrate paleontologists excavating numerous specimens from Hell Creek Formation. Understanding the distribution, thickness, and sedimentologic character of the Colgate Sandstone Member is important in order to use it as a reference for other sedimentary rock units. Finally, incised valley-fill systems are economically important as hydrocarbon reservoirs (Bowen et al., 1993; Dalrymple et al., 1994). Characterization of the Colgate Sandstone Member of the Fox Hills Sandstone may give insight into the geometry and compartmentalization of analogous oil and gas reservoirs. Additionally, time equivalent rocks are significant oil and gas reservoirs throughout the Western Interior Basin of North America (Bois et al., 1982).

CHAPTER 2

GEOLOGIC OVERVIEW OF NORTHEASTERN MONTANA

Geologic Setting

Mesozoic time in the western United States and Canada is characterized by mountain building associated with subduction of the oceanic Farallon Plate beneath the continental North American Plate (Engebretson et al., 1984; Van Der Pluijm and Marshak, 2004). The locus of deformation spread eastward with development of the Sevier fold and thrust belt during Early Cretaceous through the middle Cretaceous time followed by the Laramide Orogeny characterized by basement cored foreland uplifts that formed during Late Cretaceous through Early Paleogene time further east in central to eastern Montana, Wyoming and Colorado (Snoke, 1993; Van Der Pluijm and Marshak, 2004).

Sediments sourced from these uplifts were deposited in an eastward migrating foreland basin. During Cretaceous time, the foreland basin was largely covered by the shallow, epeirogenic, north-south trending Western Interior Cretaceous Seaway (Figure 2). This seaway spanned the continent from the Arctic Ocean to the Gulf of Mexico during maximum highstand periods (Hancock and Kauffman, 1979). Tectonic loading induced rapid subsidence at the western margin of the basin. This, coupled with high sediment inputs from adjacent mountains, led to the development of thick foredeep and foreland basin strata during the Cretaceous, reaching thicknesses of up to 10,000 meters

(33,000 feet) in the western parts of the basin and tapering in thickness to the east (Beaumont, 1981).

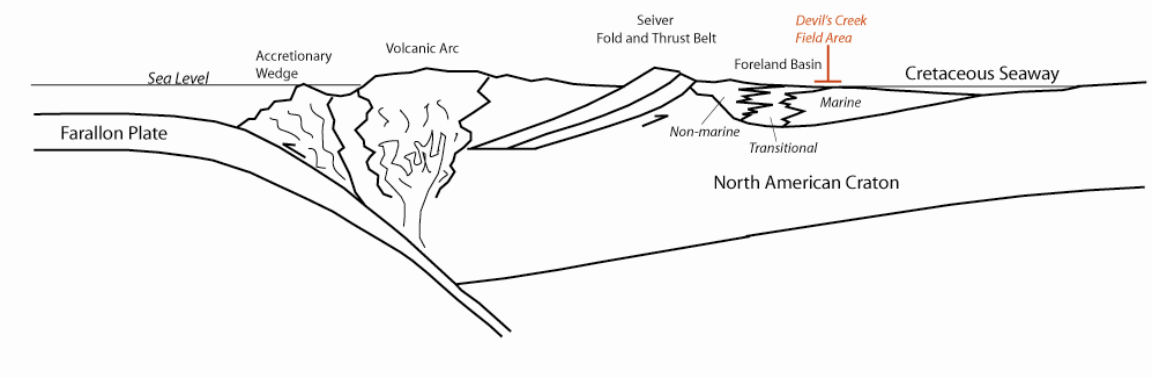

Figure 2. Cross section showing paleogeographic setting of the Devil's Creek field area during the late Mesozoic. Figure modified from Snoke (1993).

Four major transgressive-regressive sedimentary wedges comprise this basin fill (Hancock and Kauffman, 1979). These wedges are named for the transgressive formations that punctuate each cycle (Cobban and Reeside, 1952; Weimer, 1960; Cross and Pilger, 1978; Hancock and Kauffman, 1979). Starting with the oldest, these four cycles are named Greenhorn, Niobrara, Claggett and Bearpaw (Figure 3). Each of these cycles deposited sand further to the east suggesting that they might represent higher ordered, tectonically controlled depositional packages related to variations in subsidence and sedimentation rates. These depositional packages were controlled by orogenesis to the west, overprinted on a lower order eustatic sea level fall (Weimer, 1960; Crowder, 1983; Weimer et al., 1983; Figure 3).

The upper part of the Bearpaw Sequence contains the strata deposited from a relative lowering of sea level that occurred during Maastrichtian time (Weimer, 1960). Locally, intense uplift along the axes of the Laramide ranges, along with extensive

volcanism in western Montana and western Alberta, affected a retreat of the Cretaceous Seaway from Montana (Gill and Cobban, 1973; Zaleha, 1988). This regression is termed the Fox Hills regression (Gill and Cobban, 1973; Cross and Pilger, 1978). The Colgate Sandstone Member represents a higher-frequency cycle super-posed on this Fox Hills regressive event (Flight et al., 2004).

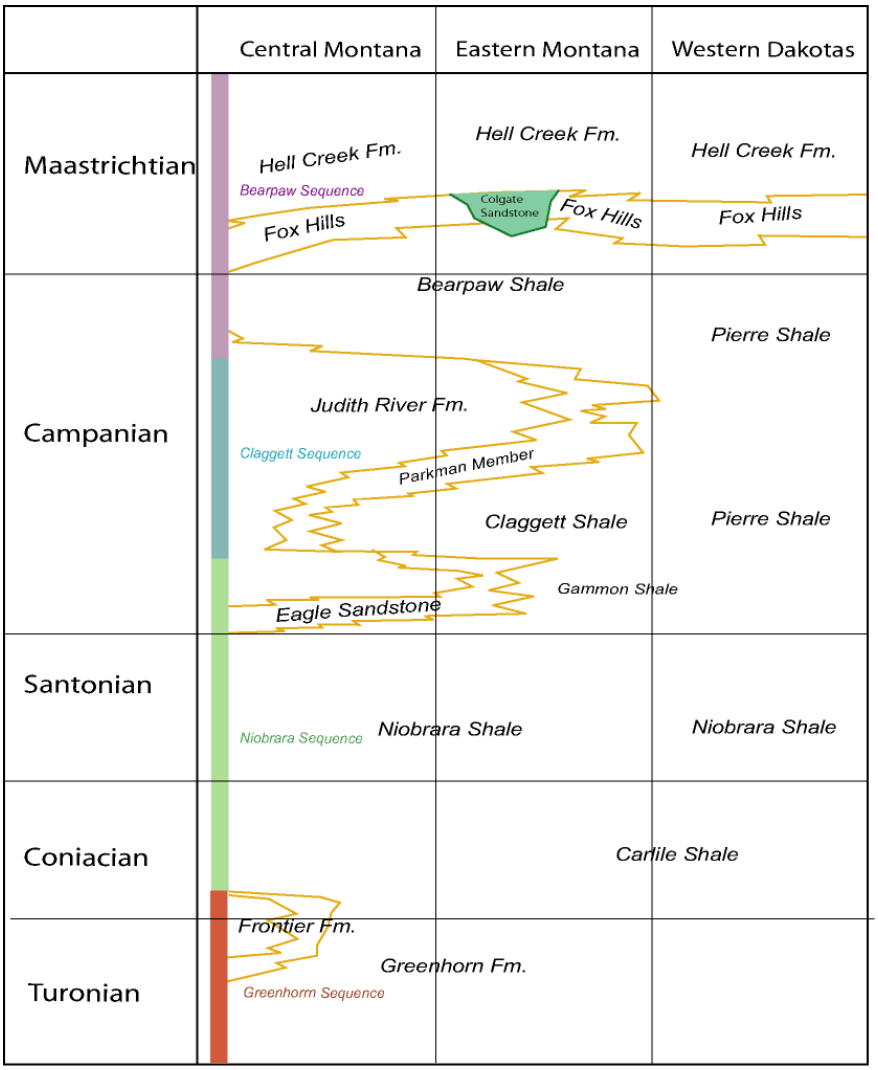

Figure 3. Regional cross section of eastern Montana stratigraphy showing the three upper sequences described for Upper Cretaceous rocks in the Western Interior Seaway. The strata described in this work are members of the Bearpaw sequence. Figure modified from Gill and Cobban (1973).

Generally, the provenance of the sediments deposited along the western margin of the Cretaceous Seaway is from the Cordilleran orogen to the west (Gill and Cobban, 1973; Butler, 1980; Dickenson et al., 1983). However, the specific provenance in any given location or sequence is less determinate. Some researchers have attributed the sole source of sediment for the Bearpaw Sequence to be the Elkhorn Mountain Volcanics from the west (Butler, 1980; Crowder, 1983). This volcanic field was active from 83 to 70 Ma and is one of the most proximal sources to explain the high occurrence of immature and sometimes heavily altered volcanic lithic grains in sandstones of the Bearpaw sequence (Gill and Cobban, 1973; Butler, 1980; Crowder, 1983; Wheeler, 1983). However, citing mainly paleoflow and mineralogic inconsistencies, Zaleha (1988) argued the interpretation of a single volcanic source to be overly simplistic. Maastrichtian aged sedimentary rocks on the Cedar Creek anticline, he measured paleoflow directions in the strata and also interpreted suites of minerals to result from mixing of constituents derived from sedimentary and volcanic rocks located to the northwest. He argues the provenance of the rocks were likely Albertaôs Sevier Cordillera, Montanaôs Elkhorn and/or Adel Volcanic Fields (Zaleha, 1988). He also interpreted the drainage patterns in eastern Montana to be consistent throughout the deposition of Fox Hills and Hell Creek (Zaleha, 1988).

All the major structures in eastern Montana have had recurrent activity since the Proterozoic (Hoffman, 1988). These basement features resulted from the collision of the Wyoming Craton with the Hearne Craton along the Great Falls Tectonic Zone (OôNeill and Lopez, 1985) and subsequently the Wyoming-Hearne Craton with the Superior

Craton along the Tran-Hudson Orogeny (Anna, 1986; Maughan and Perry, 1986; Shurr and Rice, 1986; Shurr, 1989). These basement structural elements comprise a basement block ñmosaicò documented to have influenced deposition throughout the Paleozoic (Brown, 1978; Thomas, 1983) and Mesozoic (Anna, 1986; Clement, 1986; Shurr and Rice, 1986; Shurr, 1989). The Blood Creek syncline (Clement, 1986), Cat Creek anticline and Cedar Creek anticline (Shurr, 1989) are prominent examples of these inherited basement structures that were reactivated during Laramide deformation and influenced concurrent deposition.

Stratigraphic Overview

The Upper Cretaceous strata in the Cretaceous Western Interior Basin comprise four depositional sequences related to major relative sea-level cycles (Crowder, 1983; Weimer et al., 1983; Anna, 1986). The rocks in the study area are part of the Bearpaw sequence, (the youngest of these four sequences) and represent deposition during the last major regression of the Cretaceous Seaway. The Bearpaw sequence includes the Bearpaw Shale, Fox Hills Sandstone (containing the Colgate Sandstone Member), and Hell Creek Formation.

The Bearpaw Shale was named from its exposure in the Bearpaw Mountains by Stanton et al. (1905). Its age is estimated to be from 73.5 Ma to 69 Ma (Macauley, 1964; Zaleha, 1988). The Bearpaw Shale is dark clay shale with a westward thinning geometry that represents the beginning of the Bearpaw transgression. It is interpreted to have been deposited in an open marine environment with normal marine fauna (Weimer, 1960

Balster, 1972; Wheeler, 1983). The Bearpaw Shale conformably overlies the Judith River Formation (Weimer, 1960), deposited during the regression that deposited the upper part of the Clagget sequence (Crowder, 1983). The Bearpaw Shale attains thicknesses as great as 340 meters (1100 ft) and is correlative to the Pierre Shale in North Dakota and northeastern Wyoming, (Weimer, 1960) and the Lewis Shale of southeastern Wyoming (Crowder, 1983; Figure 4).

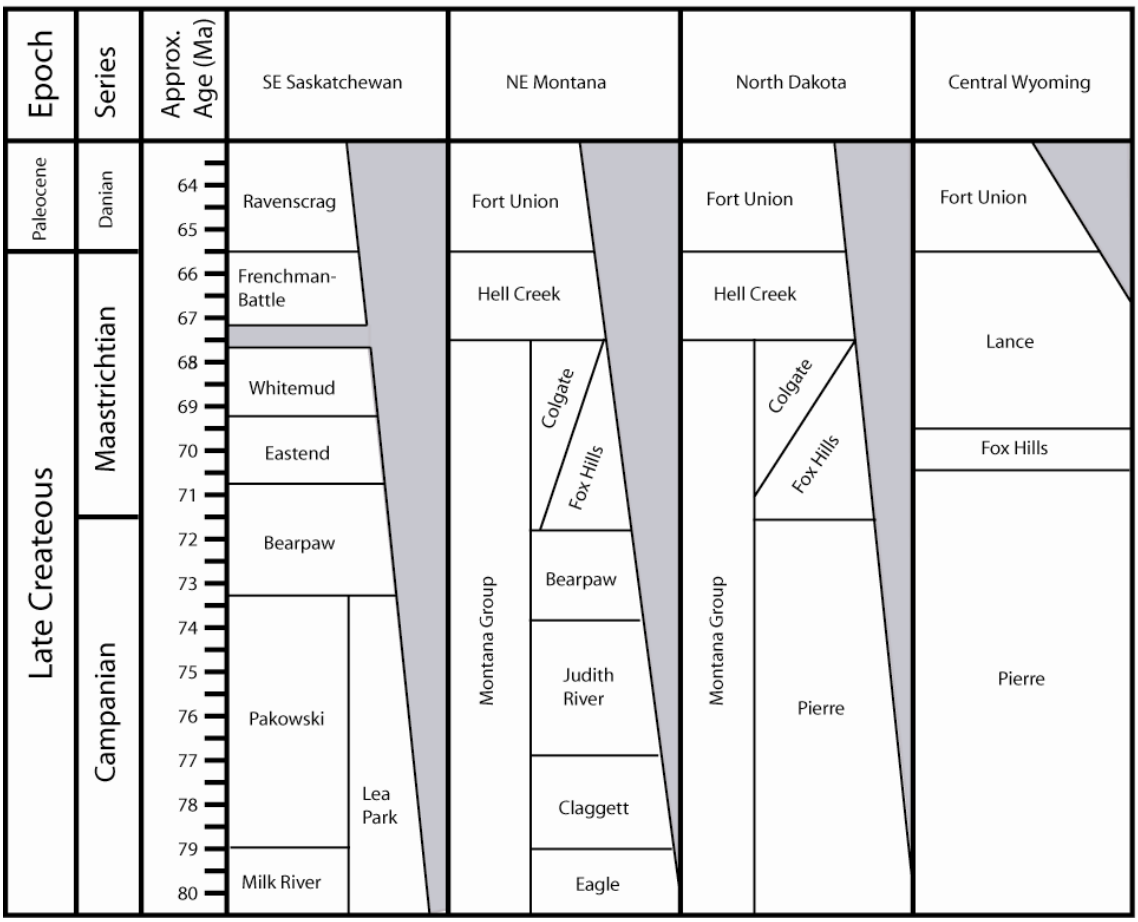

Figure 4. Regional stratigraphic column modified from Macauley (1964) and Roberts (1972).

The Fox Hills Sandstone was named for its exposure at Fox Ridge in South Dakota by Meek and Hayden (1862). Its age in eastern Montana is estimated to be between 69.5 Ma to 67.5 Ma (Macauley, 1964; Zaleha, 1988), and becoming younger to the east (Figure 3). It is a yellowish grey to white, fine- to medium-grained sandstone, and is interpreted to have been deposited in a shoreface environment that marked the final regression of the Cretaceous Seaway. It inter-tongues with the underlying Bearpaw Formation (Flight, 2004) and is either unconformably overlain by the Colgate Sandstone Member of the Fox Hills Sandstone or the Hell Creek Formation (Flight, 2004). Except when completely removed by erosion, the thickness of the Fox Hills Formation ranges from 5 to 152 meters (16 to 500 ft). It is correlative to the Lennep Formation of central Montana and the Eastend Formation of south-central Canada (Macauley, 1964; Figure 4).

The Colgate Sandstone Member was named for its exposure at Colgate Station near Glendive, Montana by Calvert (1912). Its age is not accurately known but estimates are bracketed by the upper age of Fox Hills Sandstone, 67.5 Ma (Macauley, 1964) and the lower age of Hell Creek, 67 Ma (Macauley, 1964). It is described as a white to grayish green, volcanic sandstone that forms dramatic white cliffs at its type locality (Wagge, 1968). Where present, it lies unconformably on either the Fox Hills Sandstone or Bearpaw Shale. The upper contact of the Colgate is either gradational or unconformable with the overlying Hell Creek Formation. The geometry of the Colgate Sandstone is ribbon-like (width-to-thickness ratio of approximately 1:300), and is not present in many parts of the Missouri River outcrop belt (Flight, 2004). The depositional environment of the Colgate Member has been interpreted as a paleosol (Hamblin, 2004),

marine, lagoonal, back-barrier beach (Feldman, 1972; Wheeler, 1983), shallow-subtidal or intertidal (Waage, 1968) and non-marine fluvial (Frasier et al.,1935; Butler, 1980). Most recently, Flight (2004) hypothesized the Colgate Sandstone Member to include non-marine fluvial strata and tidally influenced estuarine deposits. Its thickness is highly variable, but has a maximum observed thickness of 16 meters (50 feet) thinning to zero at its margins. It is in the same stratigraphic position and has been correlated with the Whitemud Formation in south-central Canada (Byers, 1969; Figure 4).

The Hell Creek Formation was named for its exposures near the Hell Creek tributary to the Missouri River north of Jordan, Montana by Brown (1907). It is interpreted to have been deposited between 67.5 Ma and 65.5 Ma in eastern Montana (Macauley, 1964). It represents the youngest Cretaceous unit in the study area. It is described as laterally discontinuous sandstones, shales and lignites deposited in meandering stream environments (Hartman, 2002) and tidally influenced estuaries (Flight, 2004). It is stratigraphically correlative to the Lance Formation of Wyoming as well as the Frenchman, Battle, and Willow Creek Formations of south-central Canada (Figure 4).

CHAPTER 3

RESEARCH METHODS

This project is a stratigraphic field study. It encompasses a detailed field area within a larger reconnaissance area of study. Twenty-four stratigraphic sections were measured in the Devilôs Creek field area, approximately 65 kilometers (40 miles) NNW of Jordan, MT (Figure 5; Figure 6). The Colgate Sandstone Member of the Fox Hills Sandstone is best exposed in this region of the study area. The sections were measured using a Brunton compass with a 1.5 meter Jacob staff graduated in decimeter increments and a 20 meter rope graduated to the same accuracy. Some parts of sections were badly weathered and had developed a modern soil layer, necessitating trenching with a trench tool and/or rock hammer to access fresh rock for description. The location and frequency of sections measured in the detailed area were primarily controlled by outcrop exposure. However, an attempt was made to space measured sections approximately 750 meters (2461 feet) apart. In the larger area of study, Billie Creek, Hell Creek, Seven Blackfoot and Snow Creek, occurrence of Colgate Sandstone was noted and its thickness tallied, but not described in detail due to time constraints. These points were called ólocationsô. The sections and locations were plotted using a Magellan SportTrack GPS unit (North American Datum 1984). All described measured sections are included in Appendix A.

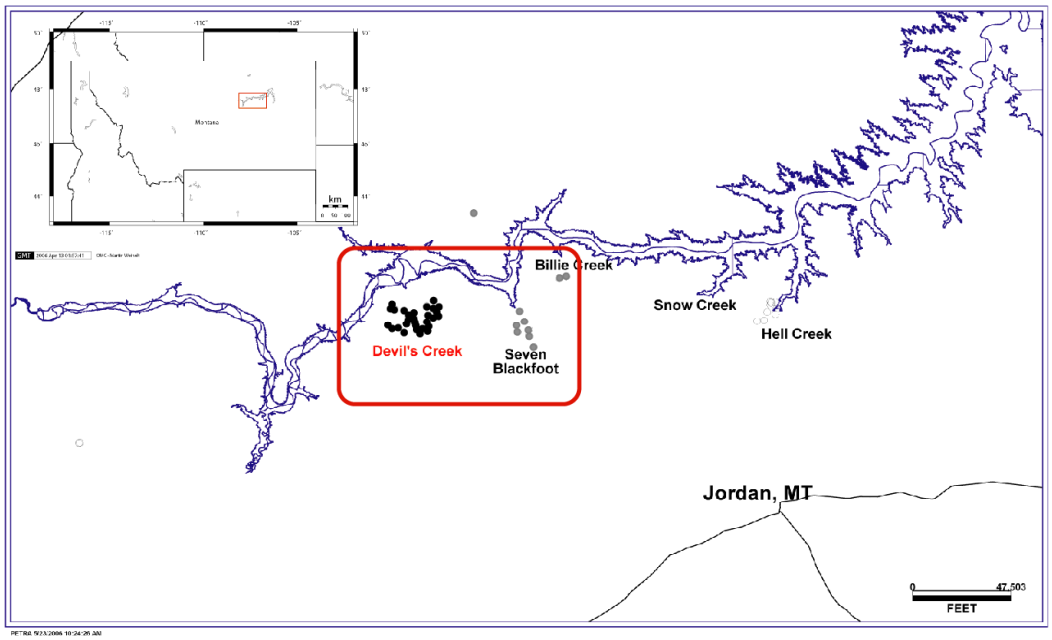

Figure 5. Location of field area on the south side of Fort Peck Reservoir. Black circles indicate the location of measured and described sections or "Sites". Grey circles represent measured sections or "Loc's".

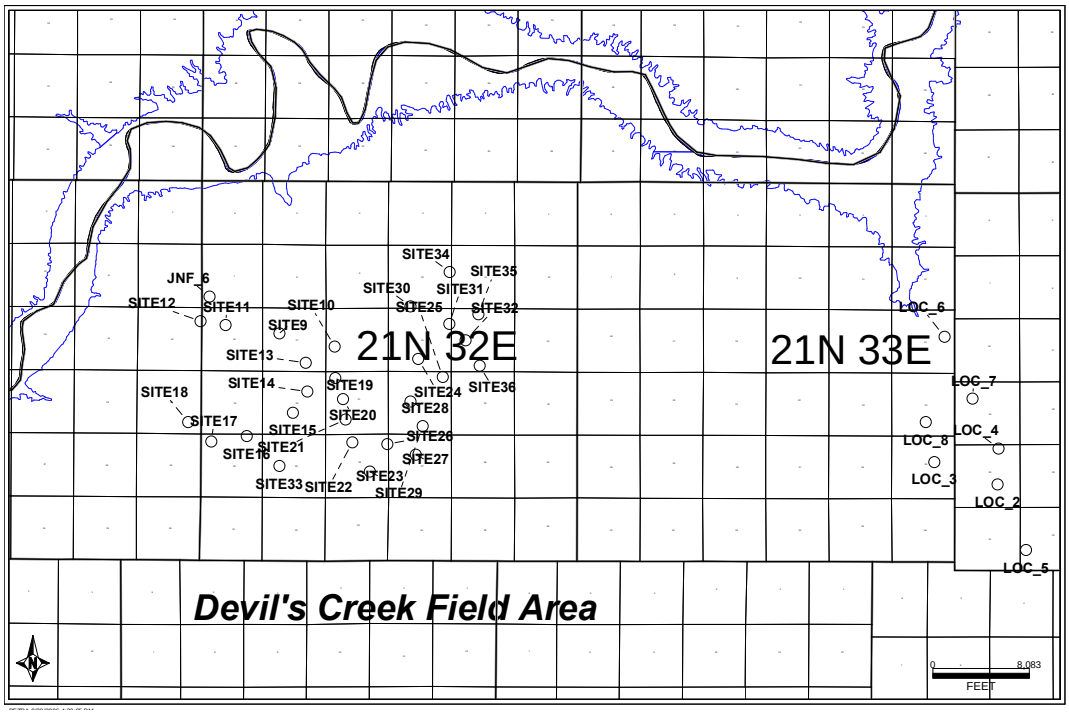

Figure 6. Location map of the detailed study area showing Devil's Creek field area made up of 24 "Sites" and to the east measured "locations" can be seen.

Methods used to collect data in the field were developed from Tucker (2003) and are as follows: 1) determine lithology or the composition and/or mineralogy of the sediment; 2) determine the texture or the features and arrangements of the grains in the sediment, most importantly grain size; 3) ascertain if there are any sedimentary structures on bedding surfaces and within beds, some of which may reveal paleocurrents indicators; 4) determine the color of the sediments; 5) note the geometry and relationships of the beds or rock units and their vertical and lateral changes; 6) and, determine the nature and distribution of fossils contained within the rocks. Properties of the grains were described in the field using a visual comparator and 10X magnification hand lens, and later in the lab using a binocular microscope on numerous samples collected. Sedimentary structures were identified using Table 5.1 Tucker (2003, p. 84), which includes all known sedimentary structures with references to drawn or pictured examples. Sedimentary structures were then measured, photographed and described. Biogenic structures were drawn, photographed and identified using drawings and descriptions from Boggs (2001) and Tucker (2003). Color of fresh rock surface was described according to templates found within Munsell Soil Color Charts (1994). Paleocurrents from trough-cross bedding were measured using a Brunton compass corrected with a fourteen degree declination to the east using techniques described by DeCelles et al. (1983) as measurable trough axes were rare. DeCelles et al. (1983) describes a method to measure paleocurrent without available trough axes by measuring trough limb measurements and plotting and averaging them with use of a stereoplot. Finally, appropriate lithofacies were identified and described modifying nomenclature set forth by Miall (1978). Miallôs (1978)

nomenclature involves using the first letter of the lithology (i.e. S=sand) and coupling it with the first letter of major descriptive constituents of the facies (i.e. t=trough cross bedding) (i.e. St = through cross bedded sandstone).

Photographs were taken of sedimentary structures, biogenic structures, bedding contacts, and entire outcrops. Outcrop scale photographs were used for the construction of photo mosaics to aid in large scale outcrop description and in documenting their lateral variation.

To determine tectonic influences on Colgate Sandstone deposition, a series of isopach and structure maps were generated using data from geophysical wireline well logs from nearby oil and gas boreholes at a density of 1 to 3 well logs per township, depending on drilling density. The depths to formation tops were determined using microfiche of geophysical logs of wells that penetrated at least to the top of the Eagle Formation. These depths were organized into a database using Petra® software where they were mapped and contoured.

CHAPTER 4

LITHOFACIES DESCRIPTIONS AND HYDRODYNAMIC INTERPRETATIONS

In the study area eleven lithofacies were observed and described based on data collected in the field including: lithology, grain properties, fabric, sedimentary structures, biogenic structures, thickness, degree of induration, color on fresh surfaces, natures of contacts, and lateral continuity of these characteristics. These lithofacies were grouped into three lithofacies associations according to their common occurrence.

Laminated Muddy Siltstone to Silty Mudstone (Fml)

Description

Lithofacies Fml is characterized by massive to laminated, poorly indurated, medium grey (N5) to dark grey (N3), well sorted, loamy to gritty, silty mudstone. Zones of oxidized planar, horizontal, laminated, silty mudstone occur randomly at the centimeter scale. Where laminations are visible, bounding surfaces are marked by color and grain size changes from silty mud to muddy silt. Oxidized silty mudstone layers appear as orangish-red lamina, whereas muddy siltstone appears lighter grey (Figure 7, Figure 8). No bioturbation in this facies was observed in the field.

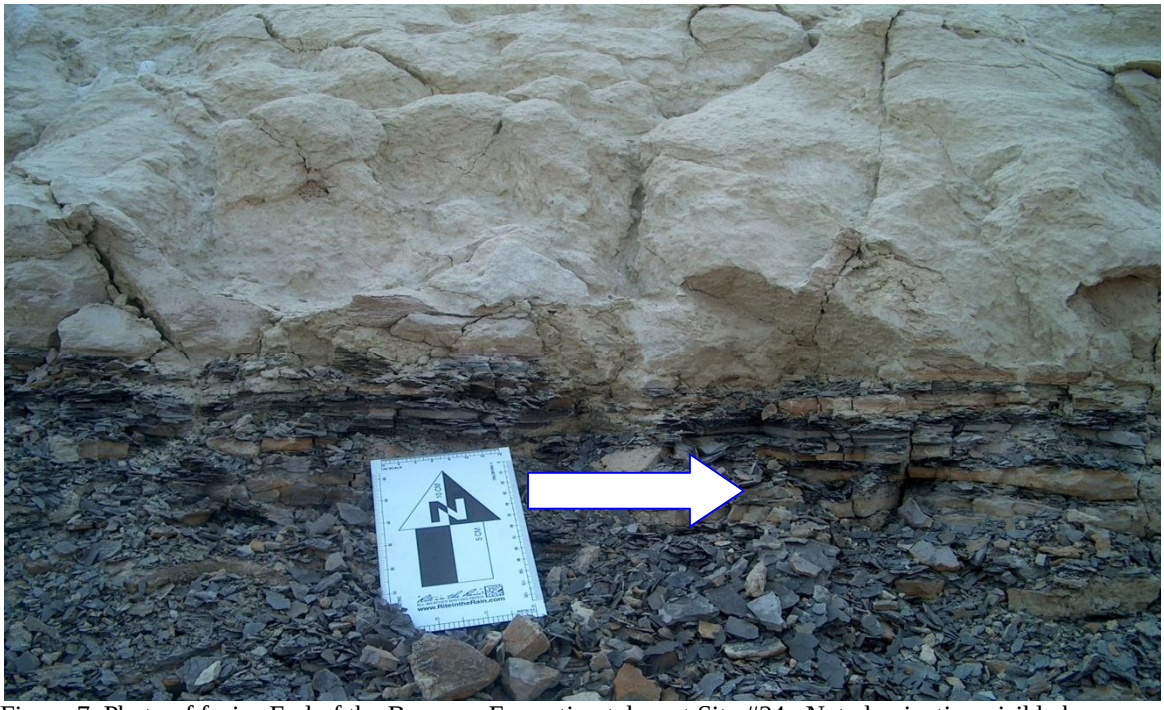

Figure 7. Photo of facies Fml of the Bearpaw Formation taken at Site #24. Note lamination visible by alteration of dark grey and reddish brown colorations.

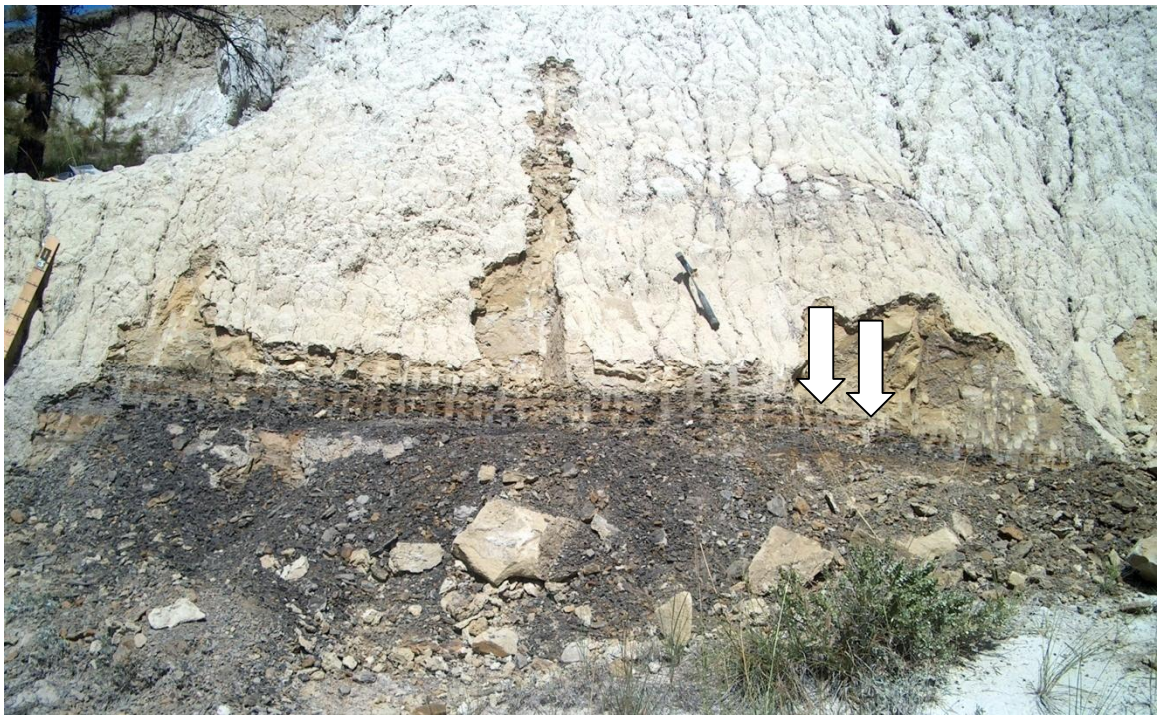

Figure 8. Erosive contact of facies Fml (Bearpaw Formation) and Se (Colgate Sandstone Member) at Site #11. Note the truncation of reddish colored mud layers of the Bearpaw Formation by the buff colored Colgate Sandstone Member. See rock hammer for scale.

Hydrodynamic Interpretation

Facies Fml represents deposition from suspension and/or very low traction currents where fine sediment is abundant (Boggs, 2001; Miall, 1996). Traction currents can produce a viscous subflow that in turn creates depositional sorting of clays and silts (Ghibaudo, 1992) that produce laminations frequently seen in the field.

Massive Sandstone with Clay Inclusions (Se)

Description

This facies occurs as massive, dusky yellow (5Y 6/4) to white (N9), micaceous, clay-rich, moderately sorted, sub-angular to sub-rounded, very fine- to medium-grained sandstone with clay intraclasts. These dark gray, mudstone intraclasts are common throughout this facies and can be as large as 5 centimeters (2 inches) in diameter. These intraclasts are observed most frequently to be discoidal and sometimes equant or well-rounded (Figure 9). This facies is widespread throughout the field area.

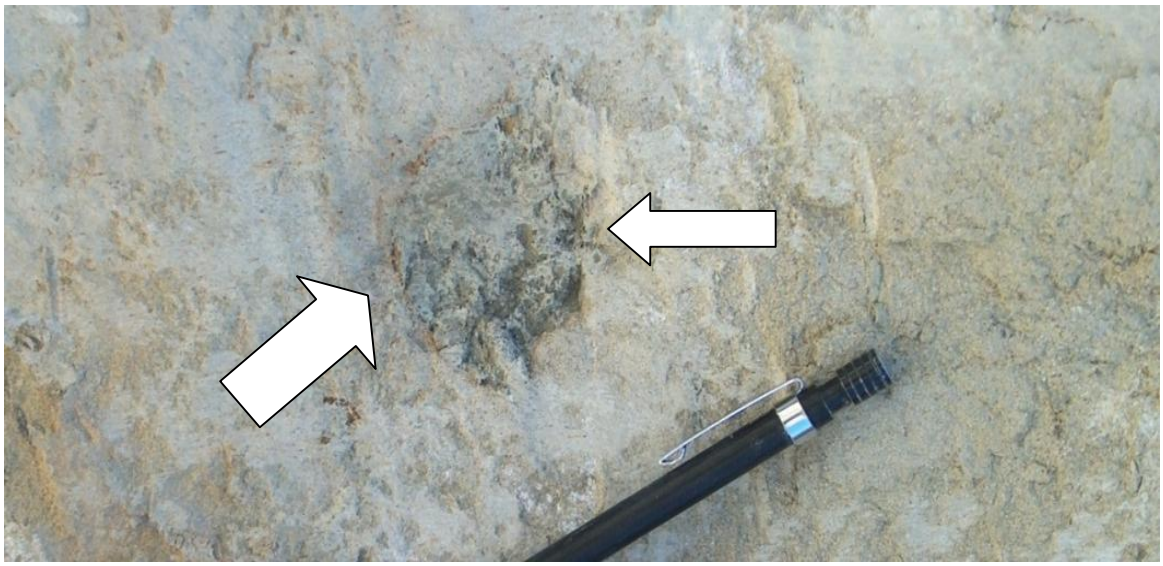

Figure 9. Photo of rounded mud intraclast within massive sandstone. Photo taken at Site #12 note pen for scale.

Hydrodynamic Interpretation

The erosional contact and presence of clay rip-ups lithologically identical to the underlying mudstone of the Bearpaw Formation are indicative of erosive unidirectional currents (Boggs, 2001; Miall, 1996). The horizontally stratified sands that occur at times within this facies support the unidirectional current interpretation. Furthermore, flume studies find that the attrition of mudclasts in unidirectional flow proceeds quickly; therefore the intraclasts were probably ripped up from a location on the order of 10ôs to 100ôs of meters (33 to 328 feet) from the site of deposition (Smith, 1971).

Planar Horizontally Stratified Sandstone (Sh)

Description

Facies Sh is a moderate light olive brown (5Y 5/2) to white (N9), micaceous, clay-rich, moderately sorted, sub-angular to sub-rounded, very fine- to medium-grained sandstone that is ubiquitous in the Devilôs Creek field area. Facies Sh can be up to 2.5 meters (8 feet) thick with horizontal lamina to bedding usually 0.3 centimeters to 1.5 centimeters (0.1 to 0.5 inches) thick (Figure 10). Sh also can be observed, due to preferential Fe-staining, interbedded with Sm at decimeter scale with the same lamina thickness. Sh facies is laterally persistent at the outcrop scale, 10s to 100s of meters (33 to 328 feet). *Skolithos* burrows occasionally occur in this facies and display preferential iron oxide cementation of the burrow structures.



Figure 10. An example of facies Sh, horizontal parallel laminations, near the base of the Colgate Sandstone Member. Picture taken at Site #21.

Hydrodynamic Interpretation

Plane beds occur in both upper and lower flow regimes. However, lower flow regimes can be disregarded because lower flow plane beds rarely occur in nature and never form in the fine- to medium-grained sediment found in the Colgate Member (Miall, 1996). Upper flow regime plane beds are interpreted to form and best be preserved when the viscous sub-layer exceeds the diameter of the grains making up the beds (Allen and Leeder, 1980). They are also interpreted to form (Harms, 1975) and be preserved (Boggs, 2001) with rapid rates of sedimentation and changing flow conditions. However, rapid deposition can subdue bed forms more apt to form under this given flow condition making paleohydrodynamic flow interpretations problematic (Harms, 1975).

Massive Sandstone (Sm)

Description

Facies Sm is a massive, dusky yellow (5Y 6/4) to white (N9), micaceous, clay-rich, moderately-sorted, sub-angular to sub-rounded, fine- to medium-grained sandstone that occurs in all Colgate measured sections in the Devilôs Creek area. Bioturbation in the form of *Skolithos* and root cast are sometimes seen in the massive sandstone facies. No grading within massive beds is apparent.

Hydrodynamic Interpretation

Primary massive bedding can be generated by a continuously high sedimentation rate (Boggs, 2001; Simpson et. al, 2002; Baas, 2004), narrow grain-size distribution (Simpson et. al, 2002; Baas, 2004) or ñen masseò freezing of hyperconcetrated flows (Simpson et. al, 2002). However, more frequently massive bedding is created post-depositionally by liquefaction, bioturbation and/or erosion (Boggs, 2001; Baas, 2004). Also, digenesis of the Colgateôs volcanic grain constituents has been pervasive. This change from volcanic rock fragments to montmorillonite (Blinda and Vasu Nambudiri, 1991) and/or kaolin (Hudson, 1987) also could have lead to the present day massive appearance of the sandstone. Further, statistical analysis of massive sandstones using x-ray radiography has concluded that 97% of massive bedding had internal structure not seen megascopically (Hamblin, 1965). A secondary genesis of the apparent massive bedding seen in the Colgate Sandstone by way of digenesis of volcanolithics and/or bioturbation is most likely.

Ripple Cross-Laminated Sandstone (Sr)

Description

Facies Sr is a ripple laminated, white (N9), micaceous, clay-rich, moderately sorted, sub-angular to sub-rounded, fine- to medium-grained sandstone that only occurs in one section (Site #30) in the Devilôs Creek field area. The ripple length is 15 centimeters (6 inches) and its height is 4 centimeters (1.5 inches) with asymmetric climbing ripple geometries. Laminations that are visible from color changes due to oxidation make this bed form discernable laterally for 0.5 meters (1.6 feet) after which it appears massive (Figure 11).

Hydrodynamic Interpretation

Asymmetric ripples form in silt and fine-grained sand under unidirectional lower flow regime conditions (Harms, 1975; Ricci-Lucchi, 1995). The observed climbing geometry results from sediment being added more quickly than the ripple crest could migrate (Harms, 1975); therefore this bedform and resulting cross-stratified geometry indicate a relative abundance of sediment. However, the rate of migration of the crest has great variability (Reineck and Singh, 1973).

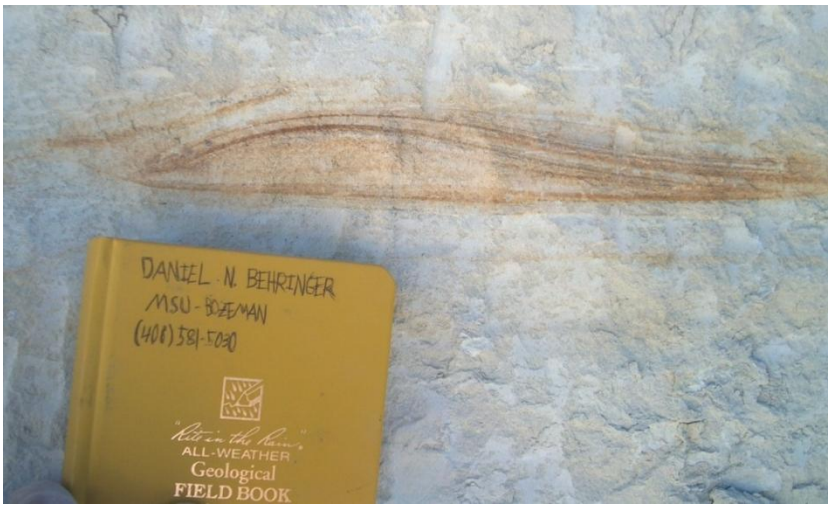

Figure 11. Photo of facies Sr taken looking west at Site #30. This sole occurrence of facies Sr in the Devil's Creek Field area reveals an asymmetric aggradational ripple geometry caused by unidirectional flow with paleoflow roughly to the south.

Trough Cross Stratified Sandstone (St)

Description

The trough cross-bedded light grey (N7) to white (N9), micaceous, clay-rich, moderately sorted, sub-angular to sub-rounded, fine- to medium-grained sandstone was observed in all but three outcrops in the Devilôs Creek field area (Figure 12). Gently curving, concave-up erosional bounding surfaces define 0.1 to 0.5 meters (.33 to 1.6 feet) thick sets of typically low angle (5° to 20°) tangential forsets that can be traced laterally up to 5 meters (16.5 feet). Individual forsets are usually defined by 0.2 to 0.5 centimeter (.08 to .2 inch) laminations, but are also found to be thickly bedded at Site #33. Bioturbation of the *Skolithos* variety is frequently observed in the trough cross-stratified facies (Figure 13).



Figure 12. Example of trough cross-stratification of facies St. Photograph taken at Site #24, note pen for scale.



Figure 13. Photograph of vertical *Skolithos* burrow taken near the top of the Colgate Member at Site #27 within facies Sm. The preference for iron oxidation within the burrow (as seen here) along with burrows filled with a dark carbonaceous material was seen extensively within facies St, Si, and Fm towards the top of the Colgate Member.

Hydrodynamic Interpretation

Trough cross-bedding is the result of the migration of three dimensional dunes in fine- to course-grained sands (Harms, 1975; Miall, 1977). Dunes form and migrate in moderate to rapid unidirectional currents of greater than a few decimeters (5 to 10 inches) deep (Miall, 1977). Minimum flow depths of currents depositing this facies can be determined by doubling the thickness of trough cross beds (Harms, 1975). Using this method the minimum flow depth for the Colgate St facies can be determined to be 0.75 to 3.0 meters (2.5 to 10 feet).

Laminated Mudstone (Ml)

Description

Facies Ml is thickly to thinly laminated, poorly consolidated, medium grey (N5) to dark grey (N7), well sorted, gritty mudstone that occurs interbedded with Sh, St, and Sm in many of the measured sections in the Devilôs Creek field area. This facies never exceeds 5 centimeters (2 inches) in thickness and is most commonly less than 0.5 centimeters (0.2 inches) (Figure 14). Iron oxidation can be present along lamina surfaces, but is not common. In weathered outcrop this facies produces characteristic planar horizontal protrusions that commonly exist through the extent of the entire outcrop.

Hydrodynamic Interpretation

Facies Ml represents deposition from low velocity traction currents in quiet water where fine sediment is abundant (Boggs, 2001; Miall, 1996). Laminations can be formed by slight changes in current velocities (Sanders, 1965). Traction currents can produce a

viscous subflow that in turn causes depositional sorting of clays that also produce laminations (Ghibaudo, 1992).

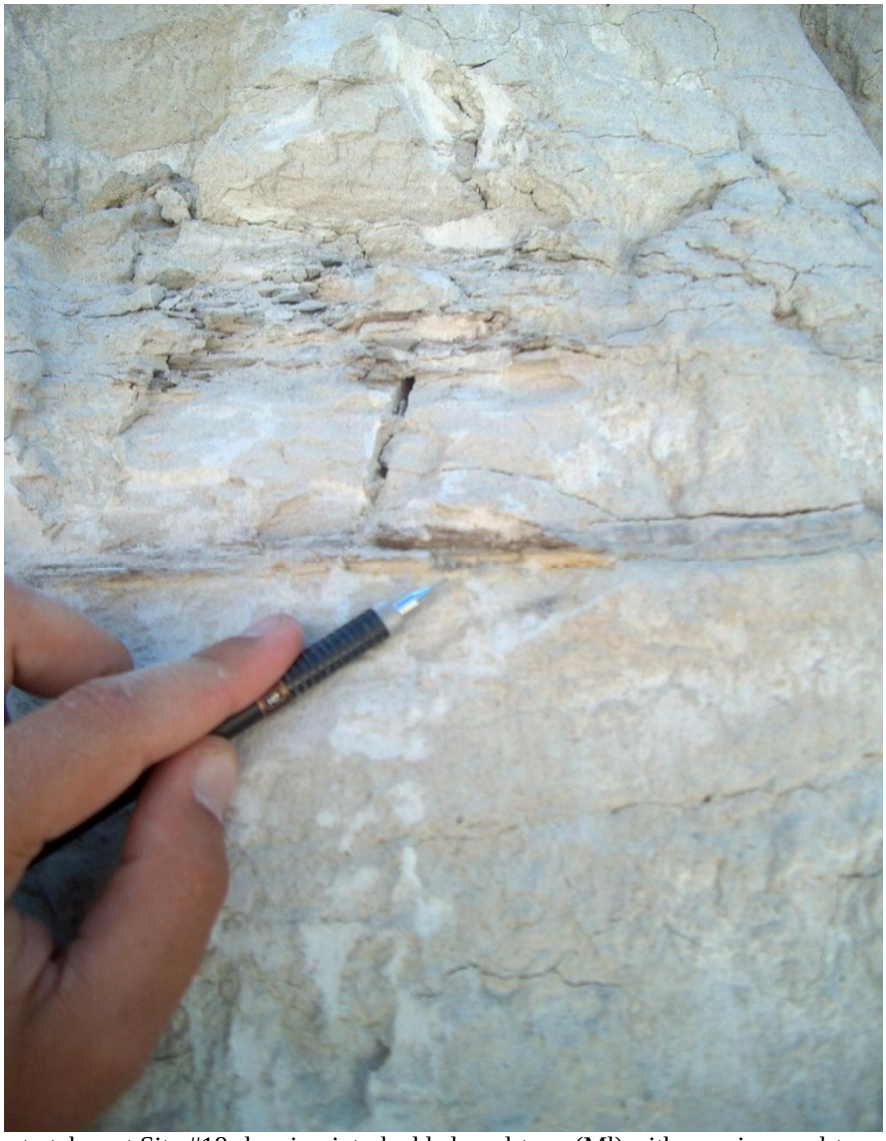

Figure 14. Photo taken at Site #19 showing interbedded mudstone (Ml) with massive sandstone in the Colgate Sandstone Member. Black line represents approximately 1.0 centimeters (0.4 inches).

Inclined Heterolithic Stratification (Si)

Description

Lithofacies Si is characterized by its inclined interbedded sandstones, mudstones and siltstones with shallowly dipping beds that exhibit planar, convolute to rippled sedimentary structures (Figure 15). The dip direction of the beds are largely to the south and east (Figure 15). Approximately 98% of this facies is sandstone. The sandstones are very light grey (N8) to grayish purple (5PB 3/3), sub-angular to rounded, moderate to well sorted, lower-fine to upper-medium with small clasts of charcoal (Figure 16), leafy organic material and mud intraclasts. Thin lamina, less than 5 millimeters (0.1 inch), of laterally continuous mud to silt is occasionally present and found at the same angle as major bedding planes. Internal reactivation surfaces (Figure 17) are seen at angles less than that of the major bedding surfaces. Above these reactivation surfaces is commonly planar bedded sandstone for 1 to 10 centimeters (0.4 to 4 inches). Facies Si that also exhibits abundant bioturbation by *Skolithos* can be frequently seen truncated by scours (Figure 17). Secondary iron concretions were observed at Site #16 ranging in diameter from 3 to 7 centimeters (1 to 3 inches). This facies is only observed on the southwest side of the Devilôs Creek field area and forms a distinctive purplish ledge in outcrop that varies from 0.5 to 2 meters (1.5 to 7 feet) in thickness (Figure 24).

Hydrodynamic Interpretation

Most inclined strata form as a result of the lateral growth of active, large-scale bedforms such as point or estuarine bars (Thomas et al., 1987). The association with quiet water deposition of facies Fsm and Fm above indicates that Si was formed under

higher energy. The presence of mud lamina drapes of facies Ml and reactivation surfaces indicates more oscillatory conditions than that of St found below. Cyclic flows that could be responsible for such stratification include seasonal flows, tidal cycles, and periodic floods (Todd, 1996). The origin of the frequently observed convolute bedding is still not thoroughly understood (Boggs, 2001). Rheologically, convoluted bedding is thought to arise from plastic deformation of a sediment and water slurry. Mass movements of sediment after deposition, or slumping, has also been attributed to the creation of convoluted bedding (Holland, 1959).



Figure 15. Photo taken looking roughly to the west at Site #14 showing the inclined bedding of facies Si dipping seven degrees to the north. See rock hammer for scale.

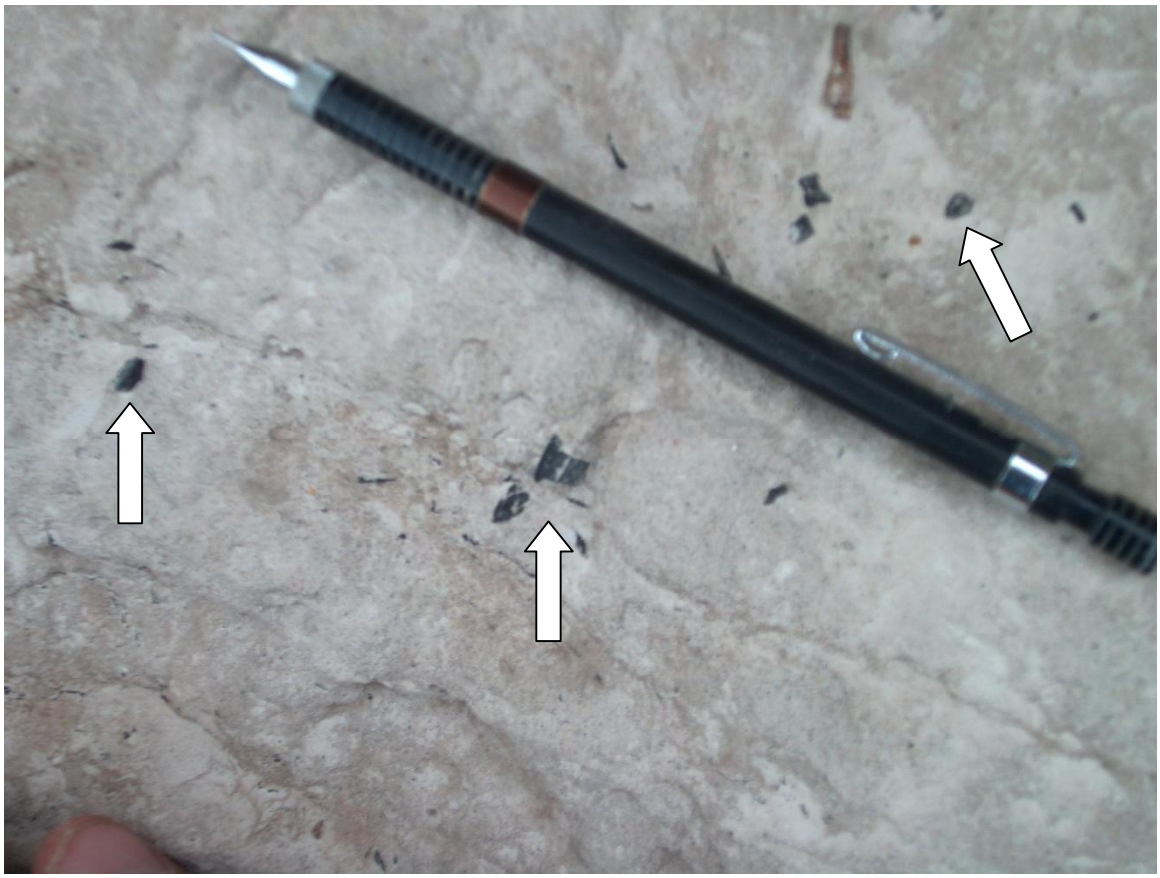

Figure 16. Photograph of charcoal found within inclined sandstone (Si) taken at Site #14. Note pen for scale.



Figure 17. Photograph taken at Site #18 of facies Si. Notice the truncation of biogenic structures, presumably eroded to a plane by a scour and fill contact.

Fine Grained Paleosol (Fpm)

Description

Facies Fpm is a pale purple (5P 6/2) to moderate reddish brown (10R 4/6), very well indurated, well sorted, massive, Fe-stained, siltstone to fine-grained sandstone that is only described in one measured section (Site #35) in the Devilôs Creek area. However, this facies was noted with frequency in the Billie Creek and Hell Creek areas (Figure 5). This facies is laterally persistent on the outcrop scale 10s to 100s meters (33 to 330 feet) varying in thickness from about 0.5 to 0.7 meters (1.6 to 2.3 feet). This facies has a very high occurrence of anabranching root casts that are filled with dark brown to black organic matter (Figure 18).



Figure 18. Picture taken at Site #34 showing a rooted redish paleosol (facies Fpm) at the top of the Fox Hills Formation underlying facies Fm of the lower Hell Creek Formation where the Colgate Sandstone Member is absent.

Interpretation

Facies Fpm is interpreted to be a subaerially exposed pedogenically altered horizon masking original sedimentary structures and has an abundance of root casts and pervasive Fe-staining and cementation. Soil profiles composed of fine sandstone with Fe-cemented horizons are termed Ferric Paleosols (Mack, 1993). The presence of paleosols in the upper Fox Hills strata indicates that sedimentation within the basin

ceased long enough for colonization by terrestrial flora and mineral alteration of weaker minerals such as kaonlinite and volcanic lithics (Buol et al., 1997).

Massive Siltstone (Fsm)

Description

Facies Fsm is a massive, dark grey (N3) to medium grey (N5), normally graded, infrequently laminated, moderately indurated, moderately well-sorted siltstone that occurs in most measured sections. Facies thicknesses do not exceed 2.0 meters (6.5 feet) and are approximately seen to be about 1.0 meter (3.3 feet) thick (Figure 19). This facies is extensively bioturbated with root cast and *Skolithos*. Fsm is laterally persistent throughout the field area with the exception of where it has been eroded (Figure 20).

Hydrodynamic Interpretation

The presence of normally graded siltstone indicated deposition from continually decelerating currents (Bose et al., 1997). The massive nature of this facies can either be caused by consistent grain size or biogenic reworking (Ghibaudo, 1992; Ricci-Lucchi, 1995). Considering the normally graded nature and abundant occurrence of trace fossils the later interpretation is more likely.

Massive Mudstone (Fm)

Description

Facies Fm is a massive, infrequently laminated, moderately indurated, brownish black (5YR 2/1) to black (N1), organic-rich, moderately well sorted, carbonaceous

mudstone that occurs in most measured sections in the Devilôs Creek field area. Facies thickness does not exceed 1.5 meters (5 feet) and is usually seen to be about 0.75 meters (2.5 feet) thick (Figure 19). The organic material is made up mainly of plant material, namely stems and leaves. Facies Fm has lateral extent throughout the field area aside from four sections where contacts suggest it has been eroded (Figure 20).

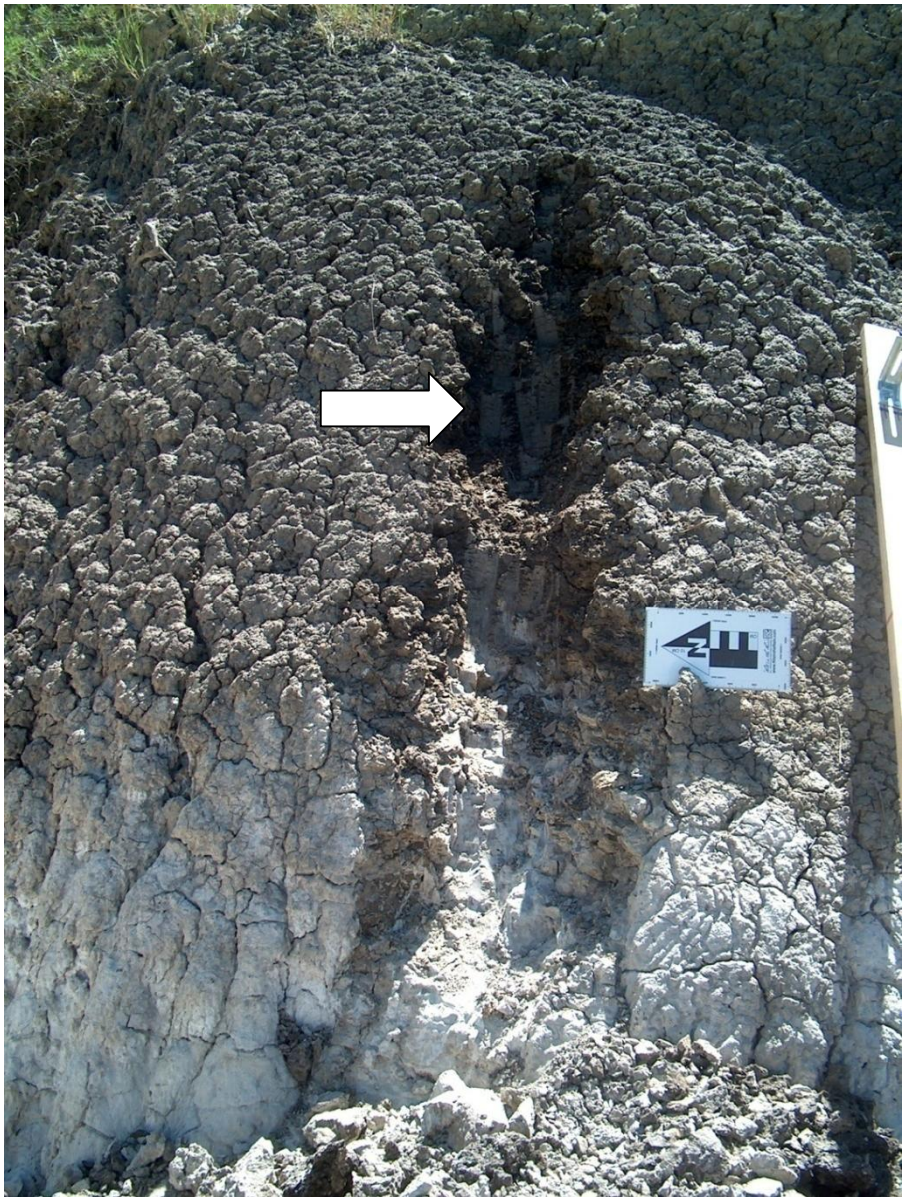

Figure 19. Photograph of typical graded contact between the Colgate Sandstone Member and Fm of Lower Hell Creek taken at Site #9. Note black facies Fm at the top of the trench. This unit is seen at the same stratigraphic level throughout the greater field area.



Figure 20. Picture of erosional contact between the Colgate Sandstone Member and Upper Hell Creek taken at Location #4 near Seven Blackfoot Creek. Note clasts of white sandstone of Colgate within Upper Hell Creek sands.

Hydrodynamic Interpretation

The fine-grained nature of facies Fm indicates deposition by suspension in quiet water (Boggs, 2001; Miall, 1996). The massive nature of this facies can either be caused by consistent grain size or biogenic reworking (Ghibaudo, 1992; Ricci-Lucchi, 1995). Considering the occurrence of trace fossils and moderate well sorting the latter interpretation is more likely.

CHAPTER 5

FACIES ASSOCIATIONS, DEPOSITIONAL PROCESS AND INTERPRETATION

Facies Associations

Eleven lithofacies were described in the Devilôs Creek field area. These different facies are grouped into four facies associations that are grouped by hydrodynamic regimes or flow patterns from which the facies were deposited.

Pelagic to Hemi-pelagic Facies Associations

Fml facies within the Bearpaw Formation have an abrupt erosional upper contact with either facies Sm or facies Se; the latter is the predominant association (Figure 21). Where Fml lamina are visible at this contact they are often truncated and on-lapped by Se of the Colgate Sandstone Member (Figure 8). This erosive contact shows up to 2 meters (7 feet) of relief at the outcrop scale in the Devilôs Creek area (Figure 8).

The deposition of Facies Fml likely formed as a result of pelagic to hemi-pelagic sedimentation in a low energy environment. Fmlôs relationship with facies Se of the Colgate Member or St of the Fox Hills Formation is hydrodynamically unrelated. These contacts represent a substantial change in sedimentary process and basinward shift of facies tracts. Lithofacies Fml of the Bearpaw Shale represents low energy deposition whereas lithofacies St of the Fox Hills Formation and lithofacies Se at the base of the Colgate Formation represent a higher energy environment of deposition (Figure 21). Further, the truncation of Fml lamina, on-lapping of Se lamina and described relief of the

abrupt Fml/Se contact (Figure 8) all suggest that an unconformity separates these two lithofacies.

Flight (2004) noted a biogenically bored surface along the erosional contact that was interpreted to be a *Glossifungites* ichnofacies also indicating an unconformity although not observed in this research,

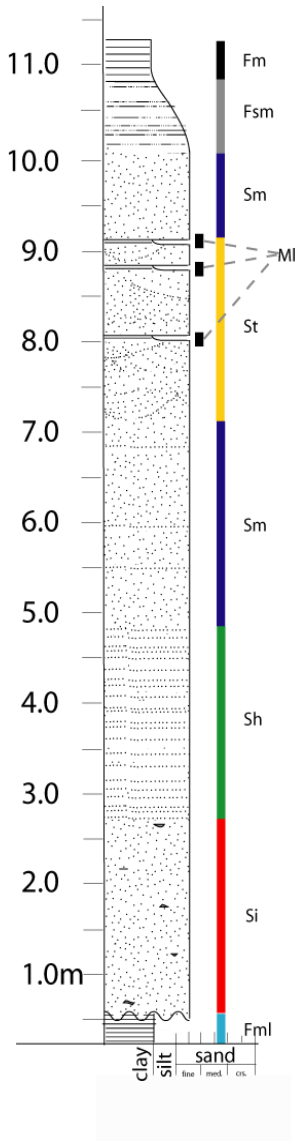

Figure 21. Composite stratigraphic column of the Colgate Sandstone Member as described in the Devil's Creek field area, Garfield County, Montana.

Glossifungites ichnofacies is a substrate controlled assemblage of trace fossils that excavate into semiconsolidated (firmground) substrates (MacEachern et al., 1992). The occurrence of this type of surface corresponds to a depositional hiatus between an erosional event and sedimentation of the overlying unit (MacEachern et al., 1992). Also, *Glossifungites* assemblages overwhelmingly reflect marine or marginal marine positions quickly following erosion related to relative sea level lowstand conditions in either subaerial or submarine conditions. These assemblages have been noted to occur frequently on the surfaces of erosion associated with the seaward margins of incised valley fills (MacEachern et al., 1992).

Unidirectional Flow Facies Associations

Facies Se represents a dramatic change into a higher energy depositional environment from the erosional contact with Fml. Rip-ups that are lithologically identical to facies Fml found within facies Se are commonly attributed to high energy currents. Also supporting high energy currents are the occurrence of planar bedding seen within facies Se and the overall transition into facies Sh (Figure 21). Sh in fine grained sediment, as described in this rock, likely represents upper flow regime in shallow waters or rapid sedimentation that drowns out other likely hydrodynamic structures (Harms, 1975).

Above facies Sh there is a gradational transition to Sm (Figure 21). The transitions into and from facies Sm is widely variable and largely dependent on the weathering of the outcrop and therefore likely does not represent conditions at deposition. For example, fluted weathering affords the best sedimentary structure recognition better

suited to retain original sedimentary structures, whereas broad cliffs almost always appear massive after weathered mantle is removed.

X-ray work done by Hamblin (1965) concluded 95% of observed massive rock has traces of sedimentary structures. Therefore, it is predictable that there are unobserved sedimentary structures in many of the Devilôs Creek area measured sections within facies Sm. With Hamblinôs (1965) findings , the presence of sedimentary structure óghostsô and lateral grading into and out of Sm on a decimeter scale, the predicted transition for the Colgate Sandstone Member is facies Sh gradually changing to facies St (Figure 21).

Facies St represents a transition to lower flow regime (Boggs, 2001) and the migration of three dimensional dunes in a water depth at least twice the height of observed trough-cross dune sets (1 to 2 meters (3 to 7 feet) for the Colgate). It is interpreted that the transition from Sh to St represents a slowing and or deepening of fluid flow or possibly, a decrease in sedimentation rate, as high rates of sedimentation also favor horizontal bed forms as seen in facies Sh (Harms, 1975).

At Site #30 (Appendix A), the observed transition is from facies Sm to facies Sr back to facies Sm. Although this massive facies also has facies Sh structural óghostô and it laterally grades into a better exposed facies Sh. Applying the x-ray findings of Hamblin (1965), an interpretation can be made that facies Sm is actually unrecognizable facies Sh. The resultant transition becomes facies Sh to facies Sr back to facies Sh. This relationship, only described once in the field, could be from normal autogenic stream behavior as the flow decreases from an upper stage flow regime (facies Sh) to lower stage flow regime (facies Sr) and back to upper stage. Also, there is evidence of relatively high sedimentation rates as climbing ripples are observed (Figure 11). It is noted that faceis Sr

is only seen in the Devilôs Creek field area by the preservation of a few lamina that represent only minutes to days of actual deposition (Wagner et al., 1990; Miall, 1996). However, this relationship is most likely underrepresented in outcrop as many inconclusive óghostsô of facies Sr were necessarily described as facies Sm.

Cyclic Energy Facies Associations

Above these lower Colgate transitions and largely within St lithofacies, there is the repeated occurrence of facies Ml, a result of slack or tractional water deposition (Figure 21). The ubiquitous gradational lower contact of facies Ml (primarily with facies St or Sm) observed in the field represents waning flows that allows finer and finer sediment to fall out of suspension. The upper contact is also usually abrupt with St or Sm (Figure 21) and occasionally erosional. This represents a return to higher energy flows. The repetition of the interbedded Ml facies suggesting a cyclic process is responsible for this pattern. The preserved interbedded Ml is primarily found towards the top of the Colgate (Figure 21) indicating a deepening or creation of slack water deposits that is only seen occurring during the late stages of the Colgate deposition .

Also in the upper portions of the Colgate Sandstone Member is the facies Si (Figure 22). It is on the same stratigraphic level as much of the St and Ml facies previously discussed. The lower contact of Si facies is abrupt and sometimes with irregular relief as it overlies St, Sm or Sh. The facies it overlies depends on the thickness of the Si. The thicker the unit the more apt it is to overlie Sh and the thinner it is, the more often it overlies St. The wavy contact sometimes observed is likely the result of infilling of a rippled (Sr) topography or soft sediment deformation. Within Si, bedding is primarily massive to convolute with only the major inclined beds being recognizable

(Figure 15; Figure 22). This bedding may be the result of slumping and intense biogenic reworking as *Skolithos* is again abundant in this facies

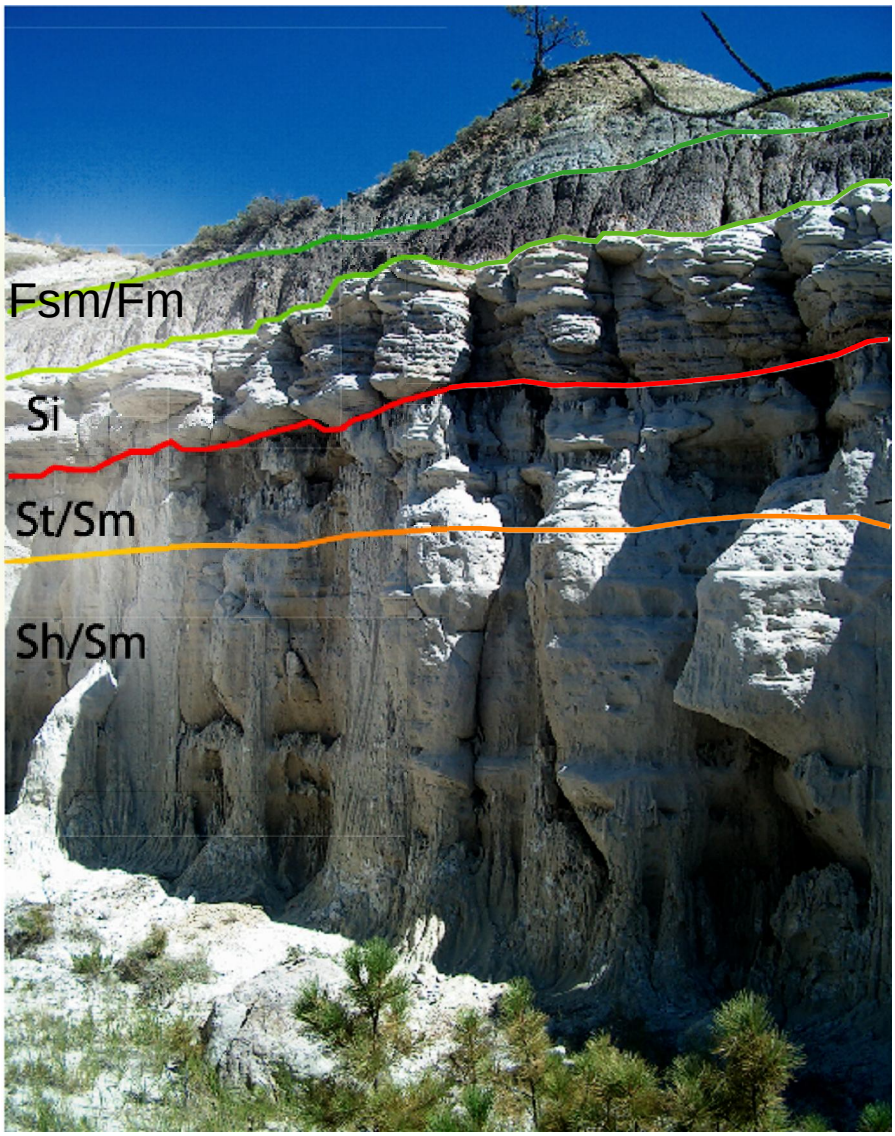

Figure 22. Picture of Site #21 showing typical outcrop of the Colgate Sandstone Member with facies Si.

Associated with the Si facies, there is a paucity of mud laminations as compared with the interbedded facies Sm, Ml and St at the same stratigraphic level. However, there is evidence that the record of cyclic deposition is underrepresented in the Si facies. The mudclasts within the Si facies (not seen in stratigraphic equivalents) may owe their origin

to cyclic slack water deposits that have been reworked by high energy flows (Ranger and Pemberton, 1992) or mass movement of sand beds themselves (Tillman, 1996). These erosive contacts within facies Si are demonstrated in the field by the truncation of biogenic *Skolithos* trace fossils to a planar surface (Figure 17).

Waning Energy Facies Associations

Facies Fsm overlies Sm, St, and Si abruptly to gradationally. When the contact is abrupt, it sometimes demonstrates irregular relief of a wavy nature and could be the result of soft sediment deformation or infilling of relict topography of underlying facies Sr. Root casts and *Skolithos* are observed to go through gradational and abrupt contacts into the lower Colgate Member facies. The upper contact of facies Fsm is exclusively with facies Fm and is gradational (Figure 19). There is no evidence of erosion at the lower or upper contacts. The rare root casts and *Skolithos* that are observed in facies Fm penetrate through the gradational contact with facies Fsm. The upper contact of facies Fm was not documented.

Facies Fsm always underlies facies Fm in the Devilôs Creek field area. The general relationship of St or Si grading into Fsm grading into Fm represents an overall fining upward sequence of sediments. Hydrodynamically, a continual waning of energy formed these two facies until in the time of deposition of facies Fm there was low-energy deposition by stagnation or deepened waters.

Geometry and Description of Rock Bodies

Pelagic to Hemi-Pelagic and Unidirectional Facies Associations

In previous sections it has been shown that there is major change in depositional energy between the pelagic to hemi-pelagic facies associations and the unidirectional current facies association and that this change, along with the observed *Glossifungites* surface, represents an unconformity. However, the same changes are not observed basin wide but rather only within the shoestring geometry that typify the Colgate Sandstone Member. In areas not encompassed in the shoestring geometry, facies Fpm occurs. This relationship of facies Fsm overlying facies Fpm is described in Site #34 and is noted in several areas in the wider field of reconnaissance. Facies Fpm represents a paleosol or an indication of non-deposition. Therefore, in areas where the Colgate is not found there is a depositional hiatus on a correlative unconformable surface that makes up the erosional transition from pelagic to hemi-pelagic facies to unidirectional flow facies.

Also, paleoflow data gathered within facies Sr and the lower part (below the appearance of facies Ml or *Skolithos* ichnofacies) of the facies St show a relatively consistent ESE trend (Figure 23). The relationship and geometry of the rock bodies and paleoflow data both support channelized entrenchment and unidirectional flow interpretation for the early stage of the Colgate Sandstone Memberôs deposition.

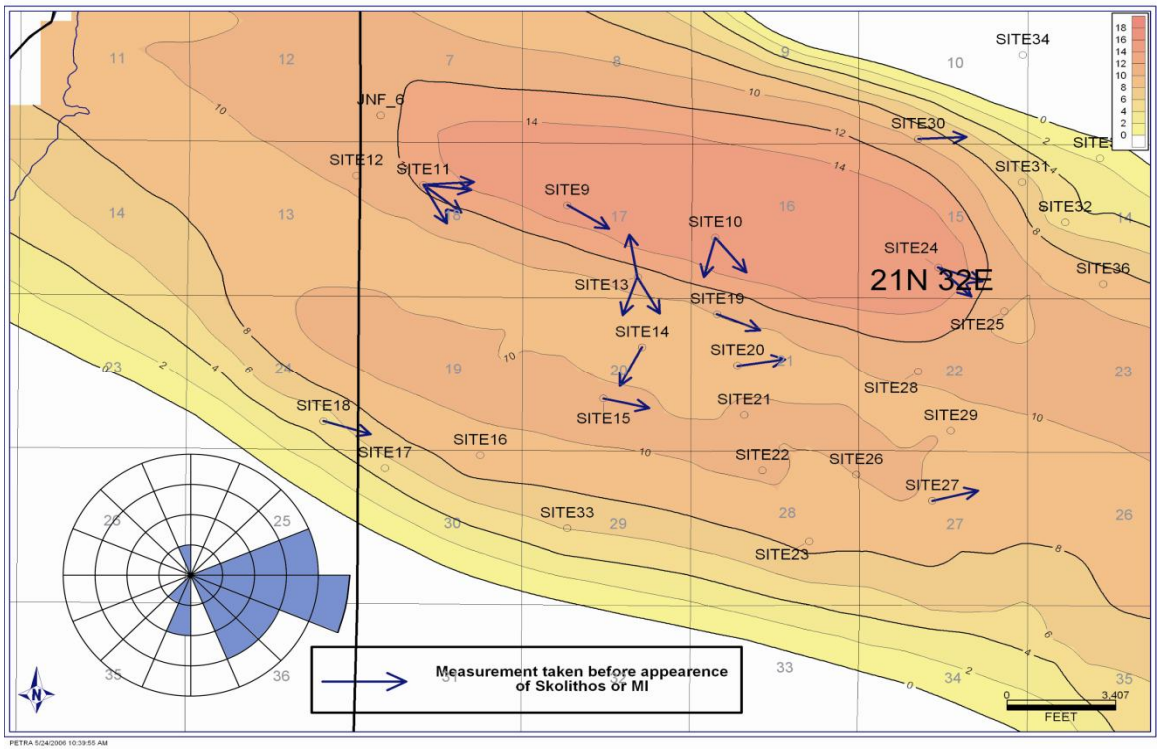

Figure 23. Map of the Devil's Creek field area showing isopach of the Colgate Sandstone Member with direction of paleoflow measurements from measured sections before the occurrence of Facies Ml or *Skolithos* ichnofauna.

Cyclic Flow Facies Associations

The preserved interbedded Ml is primarily found towards the top of the Colgate Sandstone or within the cyclic flow facies association (Figure 21) and indicates a deepening or creation of slack water deposits. Above, and sometimes interbedded with the slack or tractional facies Ml and towards the top of the facies St, paleoflow indicators becomes more variable and bimodal (Figure 24) from the dominantly ESE trend observed in the lower parts of the Colgate Sandstone (Figure 23).

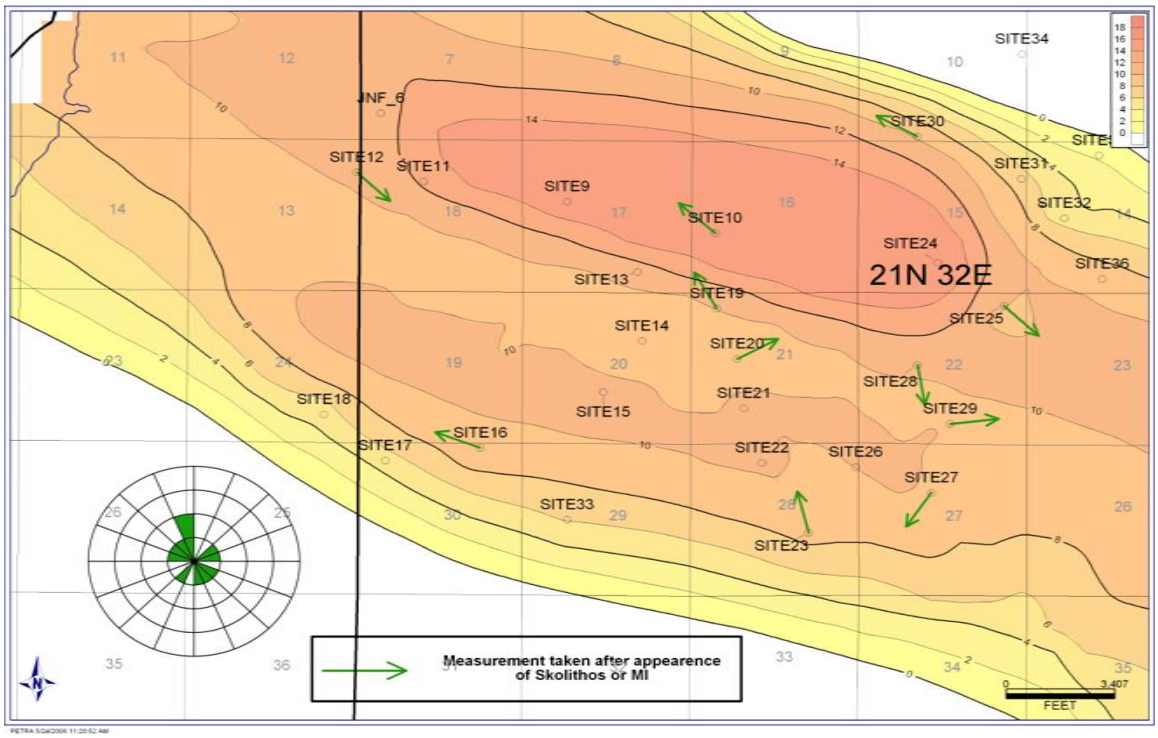

Figure 24. Map of the Devil's Creek field area showing isopach of the Colgate Sandstone Member with direction of paleoflow measurements from measured sections after the occurrence of Facies Ml or *skolithos* ichnofauna.

Coincident with the change to bimodal paleoflow is the appearance of *Skolithos* ichnofossils, a high energy burrow often found in foreshore and sometimes estuarine environments. Organisms that create *Skolithos* inchnofacies construct deep burrows to protect against temperature or salinity changes and as a means to escape the changing substrate of the surface (Boggs, 2001; MacEachern and Pemberton, 1992; Pemberton and Wightman, 1992). The more scattered to increasingly westward measured paleoflows (Figure 24), coupled with this marine to estuarine ichnofossil, could suggest salt-water incursions that reversed flow direction and provided enough opportunity for a primarily marine suspension-feeding organism and a condition favorable for the deposition of facies Ml.

Found at the same stratigraphic level as the interbedded St and Ml facies, is facies Si. This facies is only found in the southwest corner of the Devilôs Creek field area (Figure 25). The inclined beds of facies Si are dipping 2° to 10° primarily in the ESE direction (Figure 22; Figure 25). The *Skolithos* ichnofossil is once again frequent in this facies as it is in its stratigraphic equivalence within the Colgate Sandstone Member.

Waning Flow Associations

Facies Fsm overlies Sm, St, and Si of the Colgate Sandstone Member abruptly to gradationally, it also overlies facies Fpm of the Fox Hills Formation. The waning flow facies association is found everywhere in the Devilôs Creek field area and almost everywhere in the wider reconnaissance area. It is not seen in the Seven Blackfoot Coulee (Figure 8) area as it has been eroded by the environments in the above Hell Creek Formation (Figure 20).

Depositional Interpretation

The facies succession Se, Sh, St, Ml, Si, Fsm to Fm reveals a changing depositional environment likely brought on by a change in base level. Two major depositional environments interpreted from this facies succession are fluvial and estuarine (Figure 26).

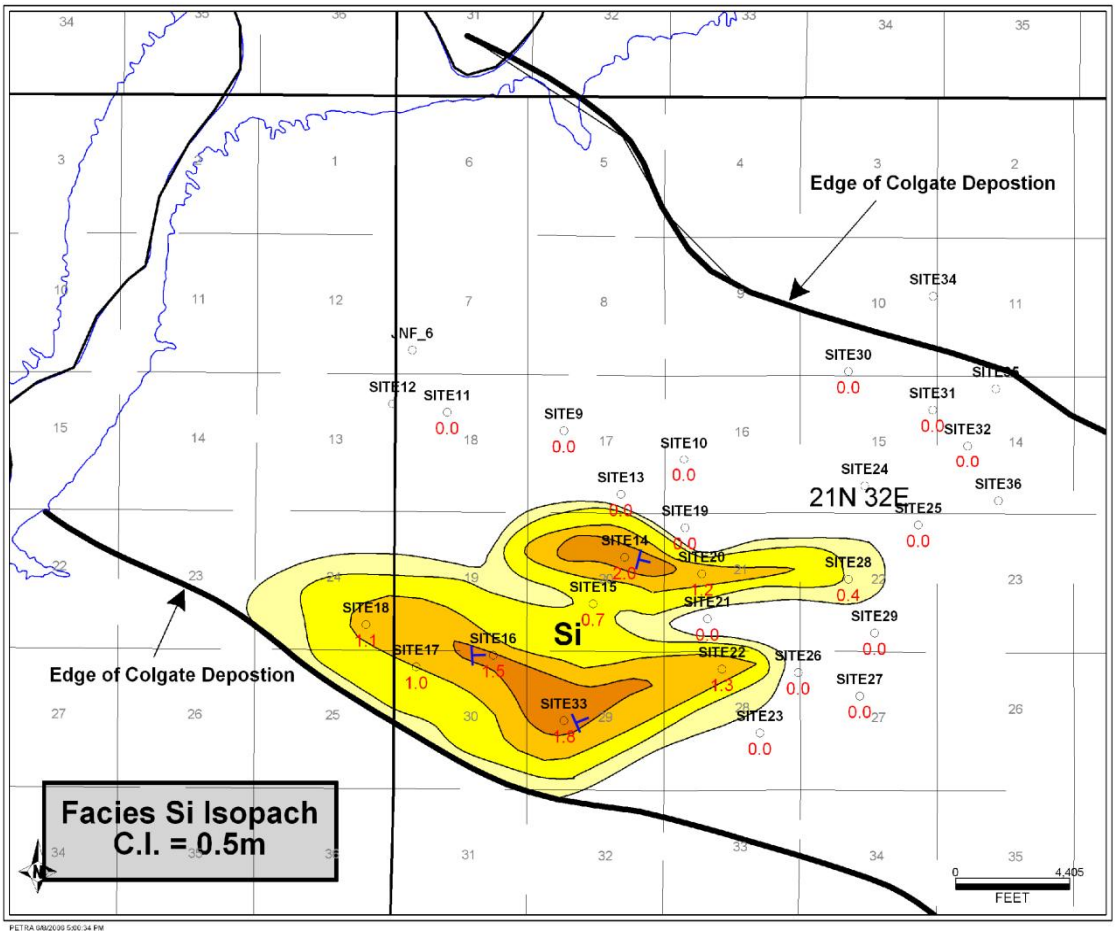

Figure 25. Isopach of facies Si in the Devil's Creek field area. Also shown is the dip direction of facies Si bedding on three measured sections (seen in blue).

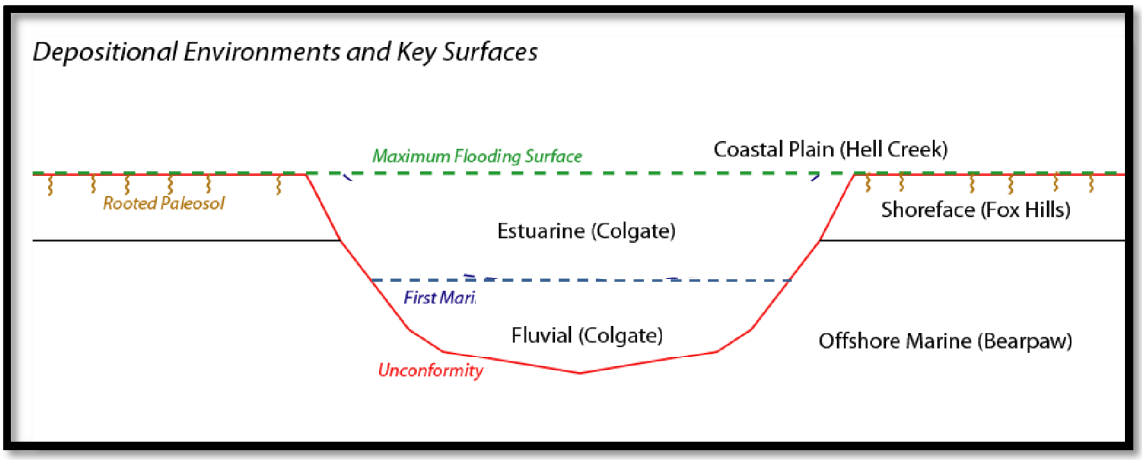

Figure 26. Cross-section showing the Bearpaw Sequence Formations and their depositional interpretations along with the geometry and key surfaces of the Colgate Sandstone Member.

Fluvial Facies Interpretation

The relationship of Si, Sh, St and Sr is consistent with the vertical relationship of a sandy low-sinuosity meandering river facies as described by Boggs (2001). A sand dominated meandering river can have very little vertical change in grain size and commonly contains few interbeds of mud (Darby, 1990; Figure 27). Both characteristics are commonly observed in the field. The abundance of horizontal laminated sands near the lowest part of the Colgate suggests flashy flow and rapid deposition, both characteristics of modern braided rivers (Cant, 1982). However, also present in the lower facies are amorphous mudclasts suggesting that banks were not stable as would be expected in a braided system. The textural inversion of these deposits (larger, amorphous mudclast with smaller more rounded fine- to medium- grained sand) likely represents slumps and rip-ups from the actively eroded Bearpaw Formation that have not experienced much transport prior to deposition (Schmitt pers. comm., 2003). Slumping, rip-ups and general bank instability are common features to meandering systems (Boggs, 2001).

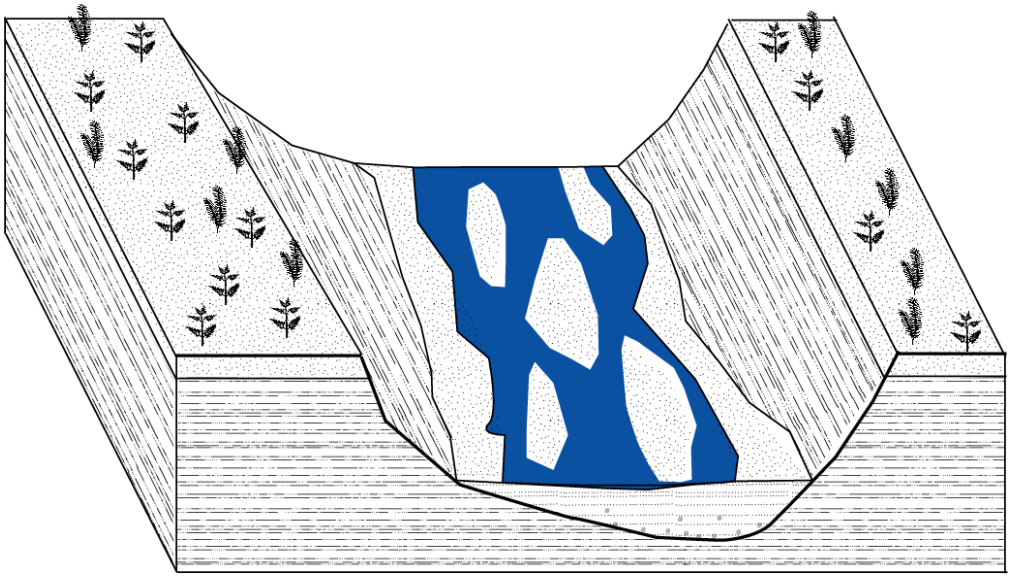

Figure 27. Block diagram showing the depositional environment of the Colgate Sandstone Member during the earliest stages of infilling, primarily facies Sh.

Higher in the Colgate Sandstone, section Sh is largely replaced by St hydrodynamically indicating that the current velocity must have gradually slowed as trough cross-bedding forms under lower flow conditions (Harms, 1975; Figure 28). This transition also means discharge became less flashy and more consistent as the rocks show evidence of the stream being at least 1 to 2 meters (3 to 7 feet) deep throughout the deposition of St. A relative rise in base level could cause an overall change in stream profile that could cause it to slow, deepen and vertically aggrade (Posamentier and Allen, 1999). Meandering river deposits can originate from either lateral deposits or vertical accretion deposits. The lack of lateral accretionary deposits and the low variance of the paleoflow measurements (Figure 25) indicate this was most likely a low sinuosity system. A study by Levey (1978) on the Congaree River in South Carolina serves as an example of a low sinuosity meandering river. It shows that straight to sinuous crested dunes were

the predominate bedforms in the lower sinuosity stretches and lateral deposits were largely absent.

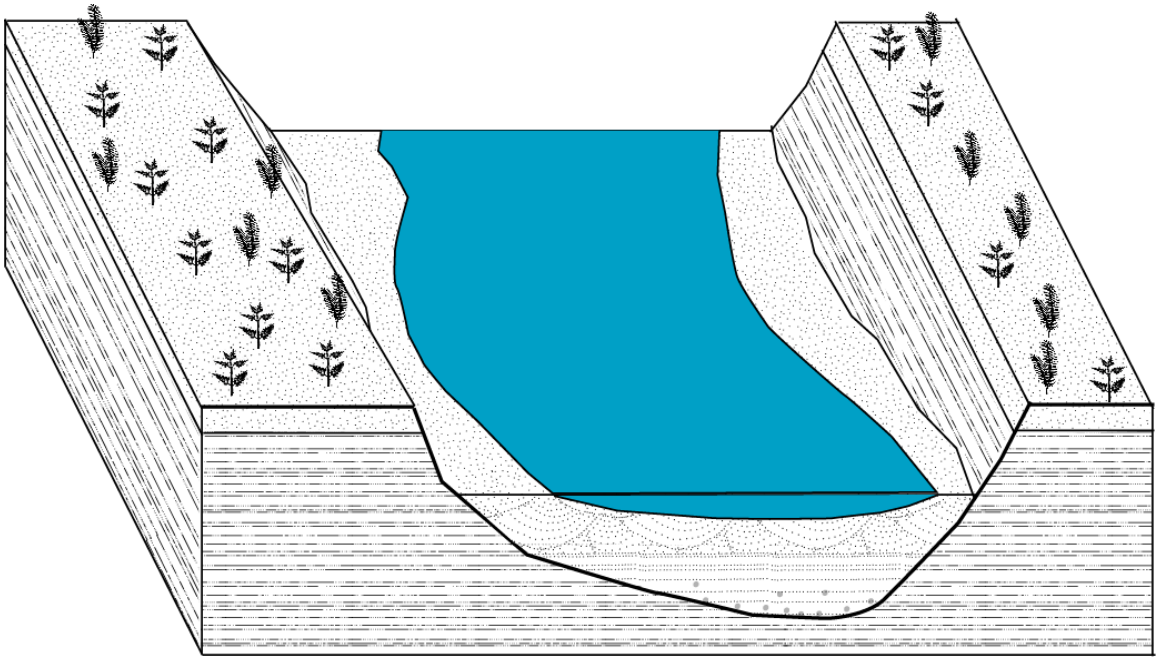

Figure 28. Block diagram showing the depositional environment during the middle stages of the infilling of the Colgate valley, primarily facies St.

Estuarine Facies Interpretation

During the deposition of the upper Colgate Sandstone there is evidence of estuarine deposition (Figure 29). First, *Skolithos* ichnofacies, primarily found in the shoreface environment but also found in tidally influenced environments (MacEachern et al., 1992), becomes abundant. *Skolithos*, or more generally simple burrows, can be a strong indicator of brackish or tidally influenced deposition as organisms that tend to live in these conditions are ñtrophic generalist whose activities result in morphologically simple burrowsò (Pemberton and Wightman, 1992, pg. 15). Also, the fact that *Skolithos* is the only trace fossil found also points to brackish conditions, as diversity in such

settings is reduced but high individual densities can be maintained (Pemberton and Wightman, 1992).

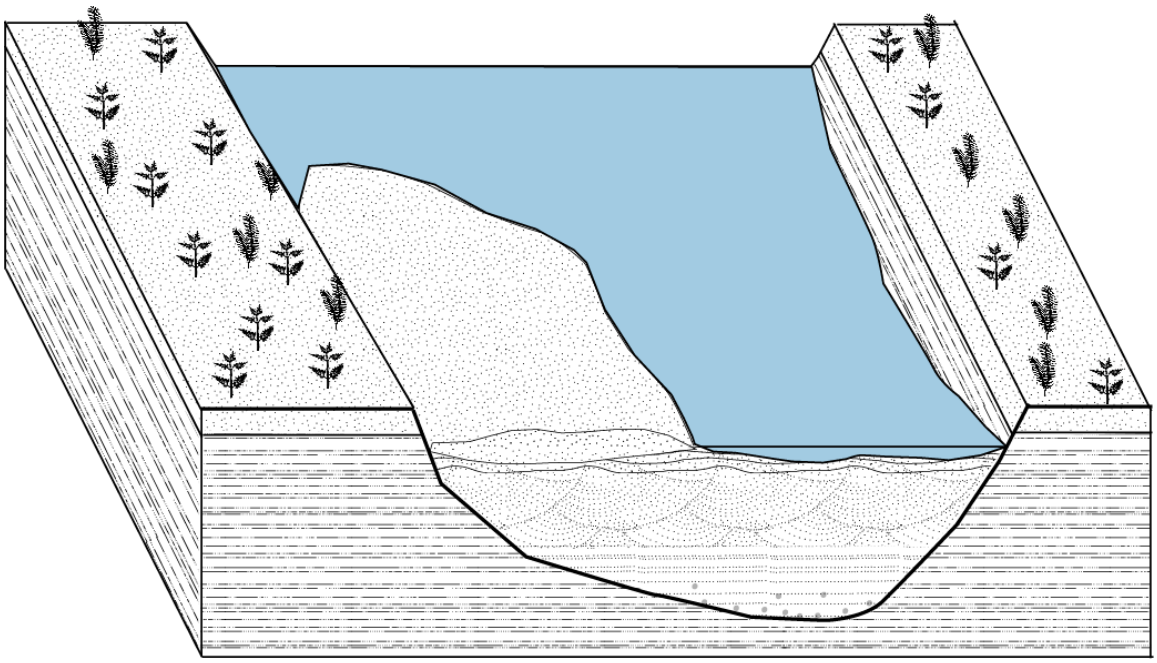

Figure 29. Block diagram showing the estuarine depositional environment, that includes occurrence of interbedded Ml facies, a large estuarine tidal bar, bi-modal paleoflow measurements (not depicted) and abundant *Skolithos* ichnofacies (not depicted).

A second reason for an estuarine interpretation is the paleoflow measurement data. Measurements become bimodal and scattered with the strongest trends in northwesterly directions (Figure 24). The variable to bimodal paleocurrent directions could be due to a reversal of flow direction within the channel as a result of flood tide deposition in an estuarine environment.

A third reason for an estuarine interpretation is the cyclic deposition suggested by the interbedding of Ml and St that only occurs in the upper half of the Colgate deposition. There are two possibilities in which this cyclic environment could arise. Either fluvial systems having seasonal changes in stream flow (Miall, 1996) or secondly, tidally

influenced slack water deposition (Tillman pers. comm. 2005; Todd, 1996). The interbedded Mlôs occurrence with *Skolithos* and Stôs bimodal paleoflow measurements favor a tidally influenced interpretation.

Finally, the tidally influenced estuarine interpretation is also supported by what is interpreted to be a tidal accretion sandbar (facies Si) in the southwest part of the Devilôs Creek field area (Figure 25; Figure 29). Bedding in tidal-accretion bars generally have dips between 2° and 30° in a predominantly downstream direction (Tillman, pers. comm., 2005; Figure 25). As seen on the Si isopach map (Figure 25) the feature is a large bar that has bedding dipping in a largely downstream or orthogonal to downstream direction and contains bedding surfaces that dip at 10° to the ESE. Internally, the massive, convoluted to planar horizontal nature may owe its existence to slumping and extensive bioturbation. As the sandbar becomes subaerially exposed during low neap tides there is a greater potential for critical shear stress being exceeded and a slump, made up of a slurry of water and sand, can be created that generates the observed massive to convoluted bedding (Tillman, 1996). Also, tidal slack water deposits (mud drapes) that would normally be found in association with a tidal sandbar can be reworked by the process of slumping and found as angular mudclasts with plant roots and other carbonaceous material at random orientations in a seemingly massive slurry (Tillman, 1996). In tidal accretion bars when slumping occurs, many times only the slumped slip face bedding would be preserved as original sedimentary structures are destroyed during the process.

Also explaining a paucity of mud drapes in facies Si is the occurrence of scour surfaces and horizontal laminations (Ranger and Pemberton, 1992). With the onset of

high energy tidal currents, reactivation surfaces scour the top of tidal sand bars and can completely remove slack water mud (Ranger and Pemberton, 1992). Evidence of this scouring or reactivation surface in facies Si can be seen in Figure 17.

In the Colgate Sandstone Member, lower deposits are characterized by unidirectional, downstream oriented paleocurrents while upper deposits are bimodal; lower deposits are not burrowed while upper deposits are burrowed by *Skolithos* ichnofauna; lower deposits are dominated by sand while \ upper deposits are often interbedded with mud. These differences are distinguishing features of a fluvial environment that is transitional to an estuarine environment (Reineck and Singh, 1980). When these above observations are coupled with the occurrence of a large tidal-accretion sandbar during the latter stages of the Colgateôs deposition, it is the interpretation that the Colgate Sandstone Member was initially deposited by a unidirectional non-marine fluvial system that became progressively influenced by bidirectional tidal processes in an estuarine setting. Finally, capping the Colgateôs estuarine environment is a gradation from silts to carbonaceous mud (Figure 30) that represents either rapid flooding of the area or the former ebb and flood currents becoming stagnant. Both cases would cause deposition from suspension.

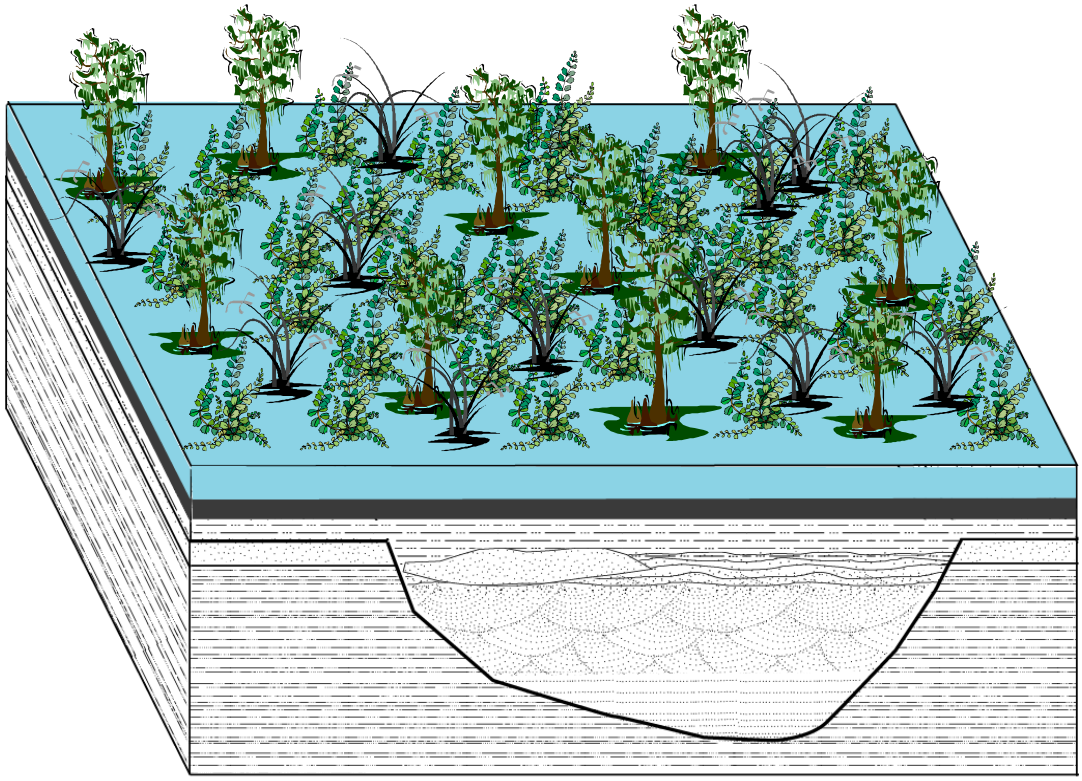

Figure 30. Block diagram showing deepened and stagnated water responsible for depositing facies Fm and Fsm in the latest stages of valley infilling

CHAPTER 6

INCISED VALLEY SYSTEMS

General Description of Incised Valleys

An incised valley system is defined as a fluvially-eroded, shoestring topographic low that is larger than a single channel form and is characterized by an abrupt seaward shift of depositional facies across a sequence boundary at its base, which is mappable regionally onto the interfluve. The fill usually begins to accumulate during the next base level rise, and may contain deposits of the following highstand and subsequent sea-level cycles (Zaitlin et al., 1994). The two basic elements or stages needed for an incised valley system are an incised valley and incised valley depositional fill. The incision is a result of erosion and sediment bypass caused by relative lowering of sea-level and the fill is in response to a relative rise in sea-level (Van Wagoner et al., 1990). Intense research into the sedimentology and stratigraphy of these systems for the last 20 to 25 years has revealed many complexities and specific competencies of these systems (Possamenteir and Allen, 1999).

Evolution of Incised Valley System Model

Work leading to the recognition and development of an incised valley system model has been described to have four phases by Zaitlin et al. (1995). First is the rudimentary observation of unconformities in the rock record and attempts to quantify rates of valley incision by pioneering naturalists such as Lyell and Dana in the 1800s to provide fodder to scientifically debunk biblical claims of a young earth. Second, as the

idea of the unconformity matured, workers began to compile data to help in their recognition. During this stage, in the first half of the 1900s, many incised valley systems were recognized and studied. They were described by workers engaged in regional mapping projects to more efficiently locate hydrocarbons. Next was the wide recognition that these features were of high economic importance. Hence understanding the three-dimensional geometry of these óshoestringô channel sands was the focus of research. The depositional environment and facies associations of the valley-fill became the focal point in the fourth stage during the early 1980s largely due to developments in seismic stratigraphy and the importance placed on unconformities and associated incised valley-fill deposits. Today incised valley systems are one of the most actively pursued and prolific hydrocarbon plays (Bowen et al., 1993; Zaitlin et al., 1994). Incised valley systems (and related sequence boundaries) are also a key component of sequence stratigraphic models. With present-day global warming and a scientific focus of climate change research, the effects of past sea-level rises can be studied within the fill of incised valleys (Zaitlin et al., 1994; Zaitlin et al., 1995).

Criteria for the Recognition of an Incised Valley System

In the Maastrichtian Fox Hills and Hell Creek Formations, recent work has hypothesized the presence of an incised valley-fill system including the Colgate Sandstone Member of the Fox Hills Sandstone (Flight et al., 2004). To test this hypothesis a series of criteria need to be met. Zaitlin et al., (1994) and subsequently a revision by Zaitlin et al., (1995) put forth such a list to create a standard for incised valley-fill recognition and to facilitate communication between workers in such a rapidly

emerging field. These criteria will be listed and applied to test the hypothesis of the Colgate Sandstone Member being an incised valley-fill within the Fox Hills Sandstone Formation.

Significant Valley Incision

First, as stated by Zaitlin et al. (1994; 1995), an incision marks the beginning stage of an incised valley systemôs development and is recognized as a negative paleotopographic feature where the surface making up the valley walls and floor truncates underlying strata (Figure 31). It is also paramount that the width of this negative surface be more than a single channel. This helps to exclude smaller, far more abundant and less significant cut and fill amalgamated channels that have no regional significance.

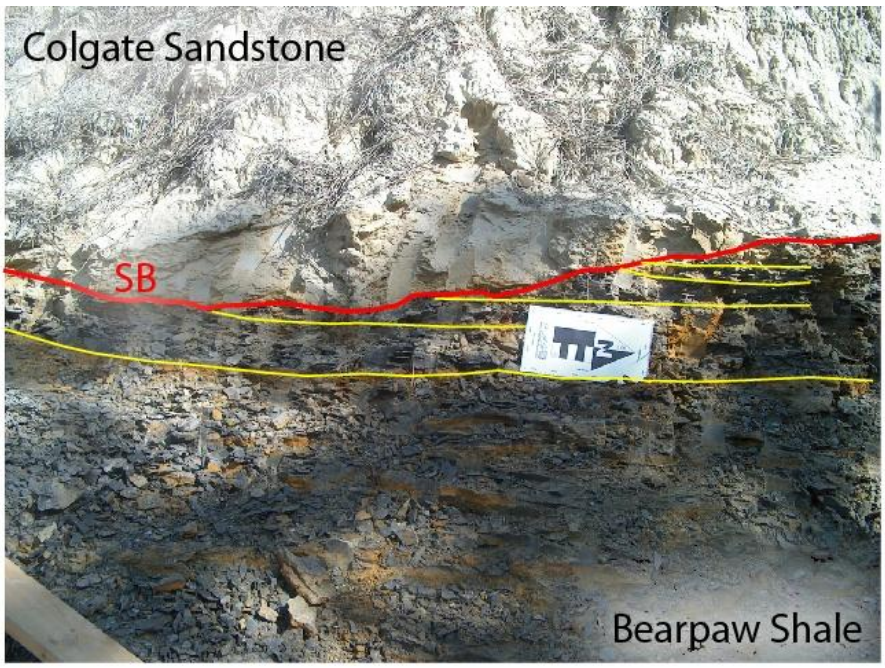

Figure 31. A picture at Site #24 showing the truncation of facies Ml of the Bearpaw Formation by facies Se of the Colgate Formation.

Within the Devilôs Creek field area, truncation of underlying strata can be demonstrated at the outcrop scale (Figure 32). This incision is indicated in places by the absence of reddish brown to light grey, well-sorted, sheet sandstones and siltstones of the Fox Hills Formation. The Fox Hills Sandstone has been interpreted as being a shoreface deposit (Anna, 1986; Bartram, 1937; Flight, 2004) and, as a result, the Fox Hills Formation meets the standard of having a regional sheet geometry and thus serves as a ñregional stratigraphic markerò (Zaitlin et al., 1995, pg.17) that, when removed, verifies valley truncation. In almost all measured sections in the Devilôs Creek field area, the Fox Hills Formation has been completely removed and the Se facies of the Colgate Sandstone Member unconformably overlies the Bearpaw Formation. The truncation pictured in Figure 31 and Figure 32, coupled with the regional absence of the Fox Hills stratigraphic marker, confirms a negative paleotopograhic feature truncating underlying strata.

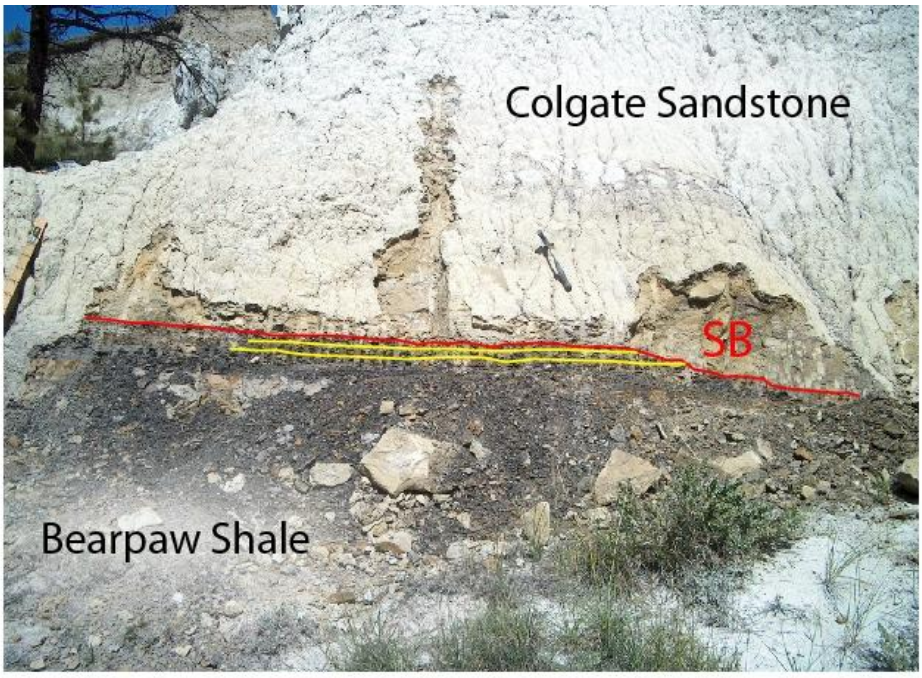

Figure 32. Picture at Site #21 depicting the facies Se of the Colgate Member's erosional surface downcutting into Facies Ml of the Bearpaw Formation. SB=Sequence Boundary and yellow lines represent highlighted laminations.

Correlative Unconformity on Interfluves

Another criterion for the recognition of an incised valley system is that the erosional surface that makes up the base of the valley is correlative to an erosional surface outside the valley that is present across interfluve regions. This surface may be modified by subsequent transgression and therefore be a combined erosional and transgressive surface (Plint et al., 1992). Also, the sequence boundary under the incised valley-fill and extended to the interfluves may have a pebble lag, *Glossifungites* ichnofacies (MacEachern and Pemberton, 1994; MacEachern et al., 1992), and/or a rooted soil horizon (Aiken and Flint, 1994; Leckie et al., 1989).

In the Devilôs Creek field area where the Colgate Sandstone Member is not present gradationally below facies Fsm of the lower Hell Creek, facies Fpm, a rooted, red, well indurated sandstone is often present (see Appendix A; Site #34 and Figure 18). This facies therefore is interpreted as a rooted paleosol. This same facies is ubiquitous in the Hell Creek area and represents soil development on interfluves during the drop in base level that caused valley incision. In previous work, a biogenically bored surface was observed on the sequence boundary approximately 10 kilometers (6 miles) to the northeast of the Devilôs Creek field area and was interpreted to be a *Glossifungites* ichnofacies within facies Fpm (Flight, 2004).

The above observations indicate a sequence boundary as the lower bounding surface of the Colgate Member and the upper bounding surface of the Fox Hills Formation just below the maximum flooding surface. These observations can be made beyond the detailed Devilôs Creek field area and regionally correlated with previous work

(Crowder, 1983; Flight, 2004; Wheeler, 1983) and therefore meets another criterion for an incised valley as set forth by Zaitlin et al. (1995).

Non-Waltharian Facies Relationship

A third geologically based criterion that must be satisfied in order to interpret an erosive based channel-form geometry as an incised-valley system is the need to have more proximal facies above the valley floor surface sequence boundary and more distal facies below it (Zaitlin et al., 1994; Zaitlin et al., 1995). This is to ensure that the sediments above and below the boundary are not in a continuous ñWaltharianò succession and to ensure a depositional lapse substantial enough to produce these juxtaposed facies. Normally, what is seen in incised valley-fill systems is a valley cut during lowstands of sea level and filled during relative rises in sea level. This would place highstand shoreface or marine sediments beneath late lowstand and early transgressive systems tracts strata (Van Wagoner et al., 1990; Zaitlin et al., 1995).

This relationship is seen in the field. In the Devilôs Creek field area open marine sediments of the Bearpaw Formation underlie the sequence boundary defining the valley floor, whereas fluvial and estuarine sediments of the Colgate Member are found above (Figure 31; Figure 32). The Bearpaw Formation is interpreted to be deposited in a marine depositional environment and within the late transgressive systems tract to highstand systems tract of a previous sequence, whereas the lower sediments of the Colgate Member are interpreted to be deposited in fluvial depositional environments that were active during deposition of the late lowstand and early transgressive systems tracts. The absence of the usually omnipresent prograding highstand shoreface environment of the Fox Hills is the result of erosion during relative sea level lowstand. The incised valley

often completely removed the Fox Hills. The missing Fox Hills is due to erosion and is not a result of a hiatus or non-deposition because outside of the valley, at the same stratigraphic level, the Fox Hills Sandstone is present.

Valley Wall On-lap

The final criterion offered by Zaitlan et al. (1995) is the need for depositional markers within the incised valley-fill to on-lap against the valley walls. This regional relationship is easily observed from the subsurface when seismic data is used to image incised valley-fill but is very difficult to observe in outcrop as a function of scale. In the Devilôs Creek field area this is the case. Because of the very low angle of the valley walls, all truncation and on-lap geometries observed are at the base of the formation. Also, due to the massive bedding at the base of the valley-fill, facies Sm and Si, it is difficult to observe on-lapping relationships.

The criteria discussed support the interpretation the Colgate Member of the Fox Hills Formation as part of an incised-valley system.

CHAPTER 7

SEQUENCE STRATIGRAPHY OF THE COLGATE MEMBER AND ADJACENT STRATA

Sequence stratigraphy is ñthe analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for them to accumulateò (Posamentier and Allen, 1999, Page 21). Figure 33 has been included showing patterns, geometries and terms frequently used in sequence stratigraphic analysis.

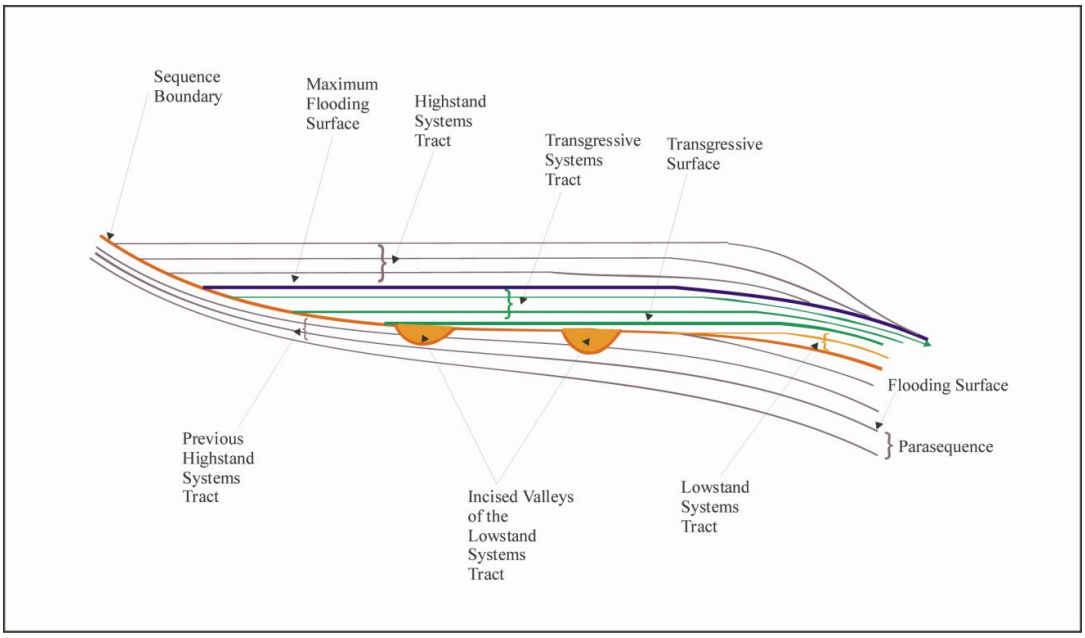

Figure 33. Figure showing the strata patterns, geometries and frequently used terms of a sequence stratigraphic depositional system. Figure modified from Van Wagoner et al. (1990).

Sequence Stratigraphic Framework of Adjacent Strata

The upper Bearpaw through Hell Creek Formations represent deposition during the last major regressive cycle of the Western Interior Cretaceous Seaway (Hancock and

Kauffman, 1979). Flight (2004), in her development of a sequence stratigraphic framework, identified three depositional sequences present from the top of the late Maastrichtian Bearpaw Formation through the lowermost units of the latest Maastrichtian Hell Creek Formation (Figure 34). These represent higher 4th order, higher frequency changes in relative sea-level during the lower 3rd order, lower frequency Bearpaw sequence.

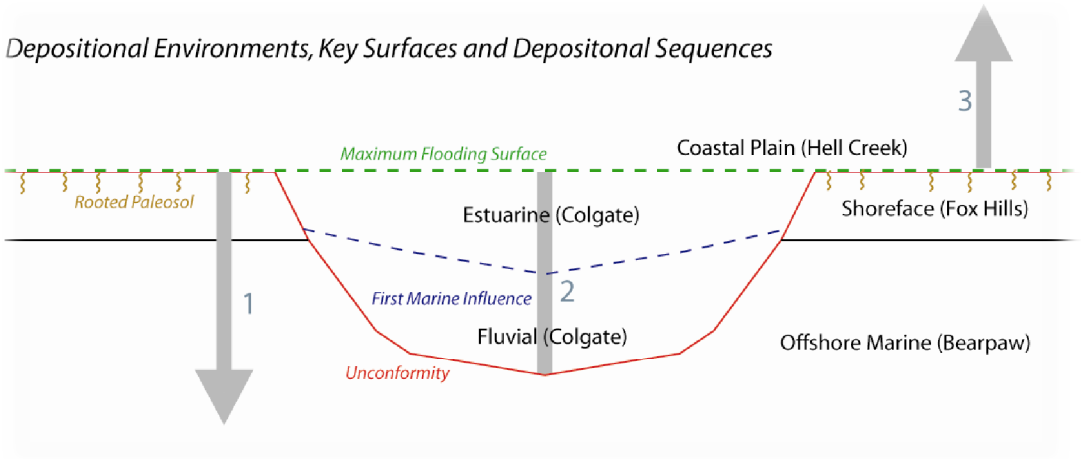

Figure 34. Illustration showing a schematic cross section through the three depositional sequences. Modified from Flight (2004).

A depositional sequence is defined as ña relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformitiesò (Mitchum et al., 1977; Van Wagoner et al., 1990, pg.7). Depositional sequences are made up of three systems tracts; the lowstand systems tract is deposited between the lowermost sequence boundary and first flooding surface, the transgressive systems tract is deposited between the first flooding surface and the maximum flooding surface and lastly, the highstand system s tract is deposited between the maximum flooding surface and the next sequence boundary (Figure 35).

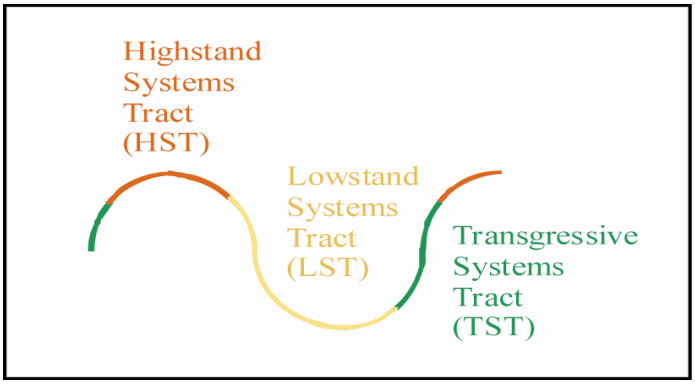

Figure 35. The three different systems tracts placed along a relative sea-level curve (given a constant sediment supply). Modified from Posamentier and Allen (1999).

The lowermost depositional sequence within the lower order Bearpaw composite sequence is made up of Fox Hills and Bearpaw Formations (Figure 34). These units 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 the erosional base of the Colgate Member and associated interfluves (Flight, 2004).

Concerning the middle sequence or sequence 2 (Figure 34), the focus of this study, Flight (2004) concluded that it is composed of the Colgate Member and the lower Hell Creek Formation. She interprets the Colgate to include the lowstand and transgressive systems tracts and the lower Hell Creek to represent maximum transgression and early highstand deposition. Finally, the uppermost sequence is made up entirely of the fluvial upper Hell Creek Formation.

Sequence Stratigraphy of the Colgate Sandstone Member

One goal of this study is to test and, if needed, modify the sequence stratigraphic framework created by Flight (2004), with a focus on the middle sequence (Colgate

Member and lower Hell Creek Formation). Incised valley systems, such as the Colgate Member of the Fox Hills Sandstone, are especially sensitive to changes in base level. Detailed work concerning this incised valley-fill affords a higher resolution record of tectonic influences, eustatic sea-level, and sediment delivery.

Following are a series of six block diagrams that depict the depositional environment of the Colgate incised valley system at different stages during its development. Also accompanying the block diagrams is a relative sea-level curve created using sequence stratigraphic concepts and their relationships to the interpreted depositional environments.

Incised valleys are formed in response to a relative sea-level fall (Posamentier and Allen, 1999). There are several factors that can be responsible for a relative sea-level fall including eustatic sea-level fall, increased sediment supply, tectonic uplift, stream capture, and climate change (Posamentier and Allen, 1999; Schumm and Ethridge, 1994). Incised valley fills can be simple or compound. Simple fill records environments of one relative sea-level cycle whereas compound fills record two or more cycles (Zaitlin et al., 1994; Zaitlin et al., 1995). As noted by Flight (2004) and delineated by the depositional mapping of this study, the Colgate incised valley system is shown to contain the fluvial lowstand system track and estuarine transgressive system tracks within the valley. This makes it a simple valley fill.

The lowstand systems tract includes all the strata deposited after the onset of relative sea-level fall and prior to a transgressive surface where rate of accommodation is greater than rate of sedimentation (Posamentier and Allen, 1999). Figure 36, Figure 37 and Figure 38 all show the act of incision that was concurrent to the beginning of relative

sea-level fall. Also illustrated in the three figures is that with continued downcutting in the Devilôs Creek field area, deposits of the Fox Hills Sandstone were completely removed and erosion continued into the subjacent Bearpaw Formation. During this time it would be expected that the interfluves were stable and hence soil horizon and vegetation began to develop as they were subaerially exposed (Figure 38).

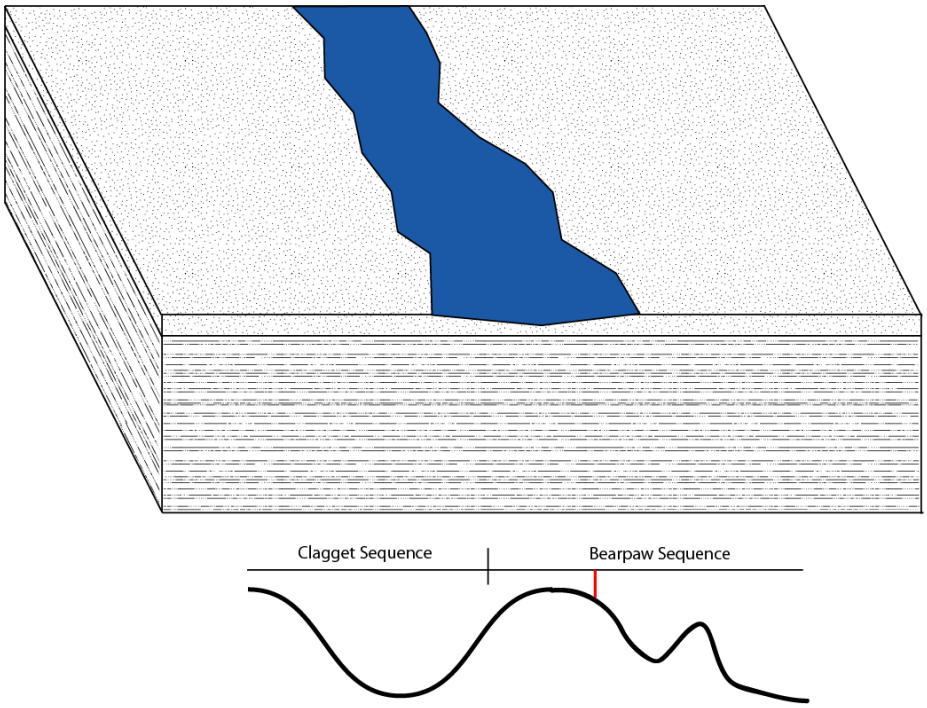

Figure 36. Block 1; Incipient stages of relative sea-level fall as shown by relative sea-level curve and the beginning of fluvial downcutting into the Fox Hills Formation.

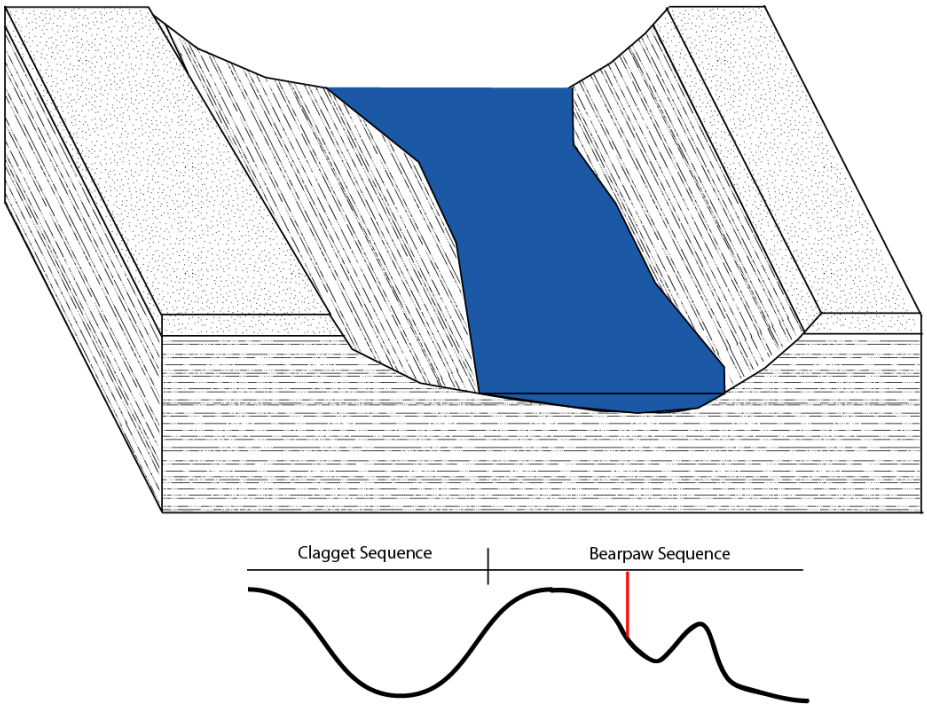

Figure 37. Block 2; Relative sea-level fall accelerates and downcutting completely erodes through sandstone (Fox Hills).

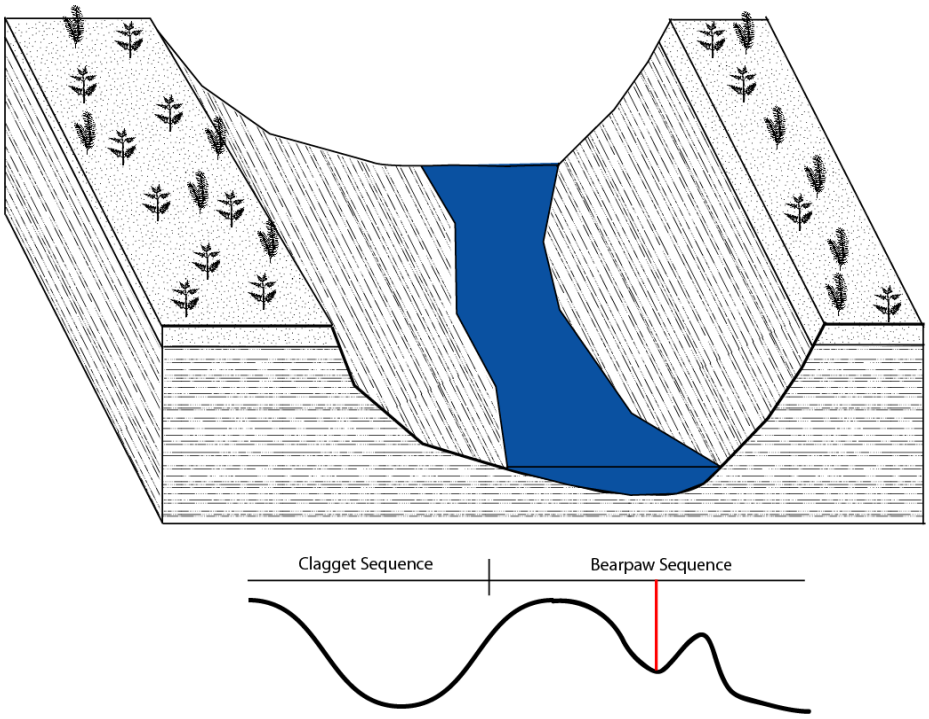

Figure 38. Block 3; End of relative sea-level fall, Colgate system incision ceases. Note stable interfluves host pedogenic processes and vegetation.

Incision continued until relative sea level began to rise. As relative sea level rose, the fluvial system changed from a net erosive system to an aggrading system (Posamentier and Allen, 1999; Figure 39). However, regression could continue because the rate of sediment supply could overwhelm accommodation such that the shoreline continued to migrate in a seaward direction even though relative sea level was rising. In the case of the Colgate Sandstone, a regression driven by the rate of sediment supply greater than accommodation is distinctly possible as there are clues from the field that point to a high sediment rate at the beginning of the deposition of the Colgate (i.e. Facies Sh (Harms, 1975) and the climbing ripple geometery of facies Sr). Sediment in incised valley-fills began to accumulate late in the development of the lowstand systems tract as early lowstand sediment was bypassed to the marine environment (Posamentier and Allen, 1999).

Channelized unidirectional deposition continued during the deposition of facies St as the lower portions of facies St exhibited unidirectional paleocurrent vectors (Figure 23). There is also evidence that the unidirectional flow deepened and slowed as there is a transition from upper flow regimes responsible for the deposition of facies Sh and Sr to the lower flow regimes of facies St. This increase in accommodation is interpreted to result from an increased rate of sea-level rise and also a lowering of the gradient of the stream profile (Posamentier and Allen, 1999; Figure 40).

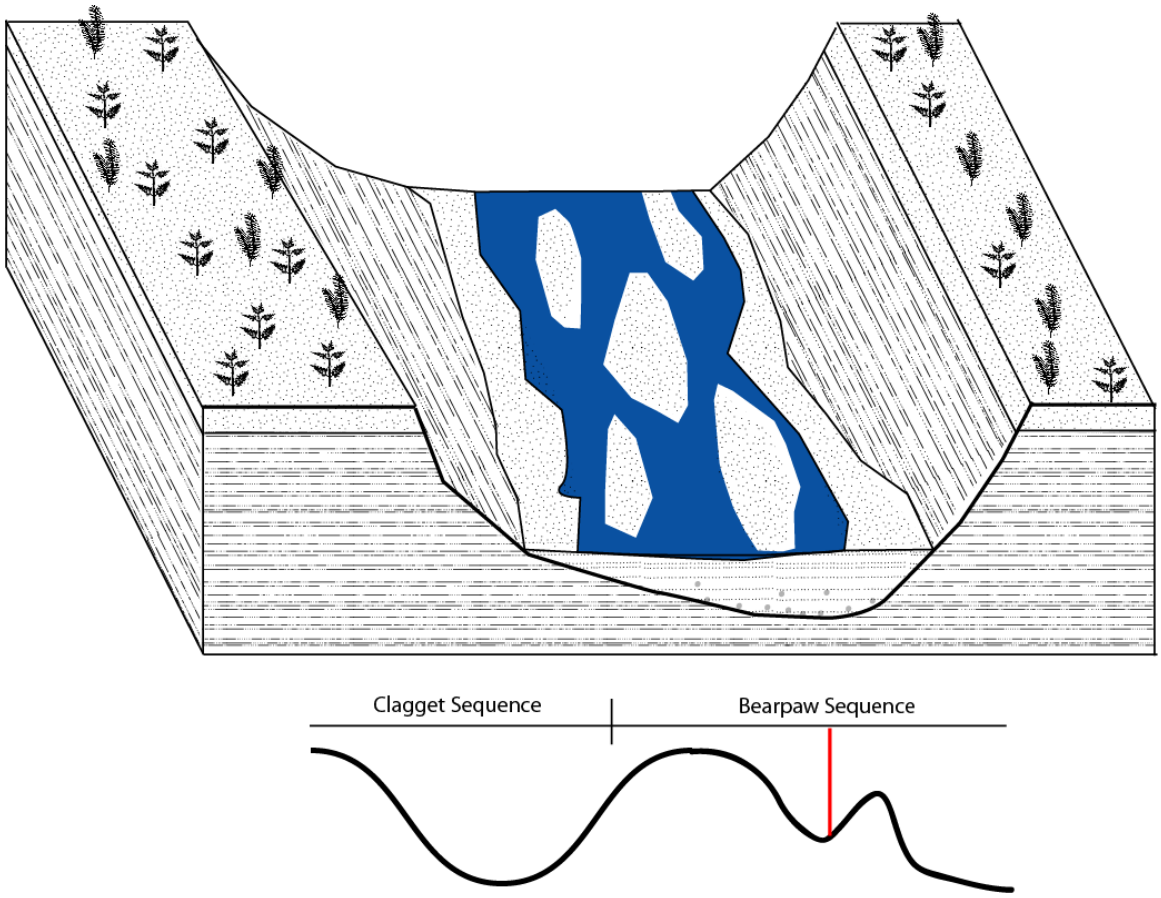

Figure 39. Block 4; Relative sea-level rise begins and infilling (with facies Sh) of the newly created valley commences. Note grey mudclasts, representative of the unstable nature of bank deposits.

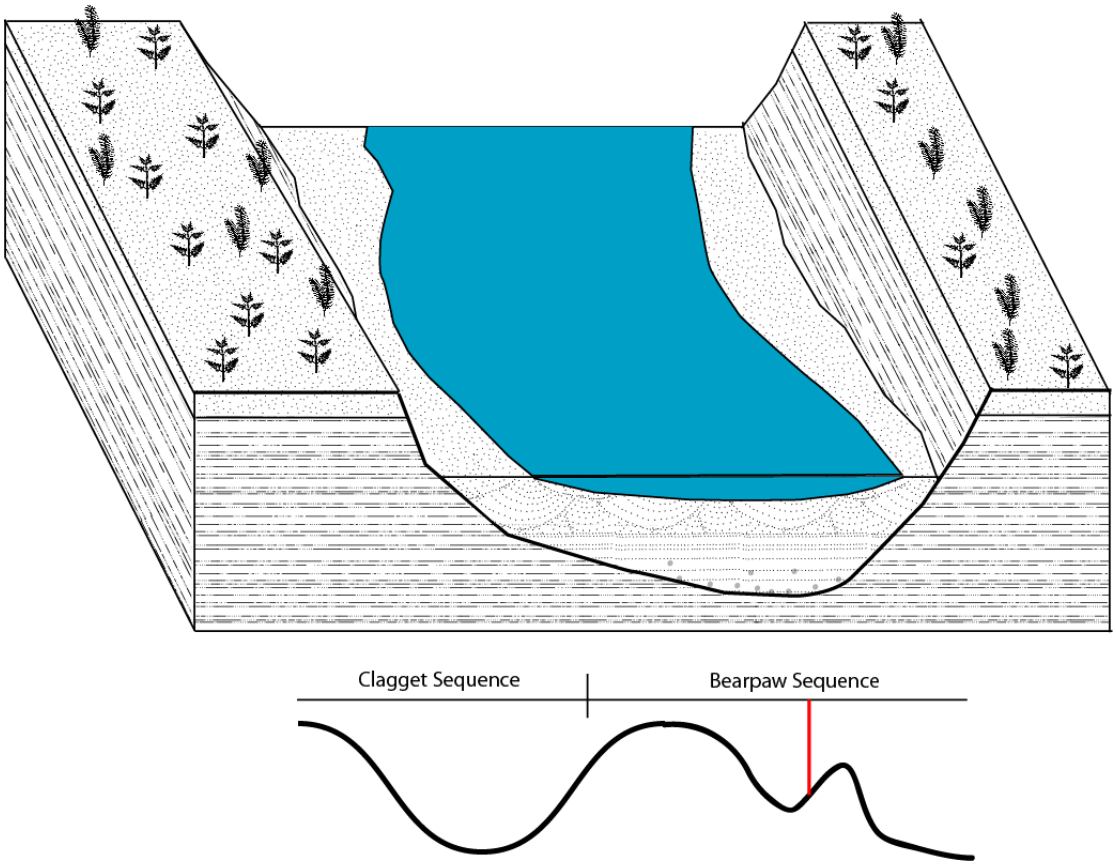

Figure 40. Block 5; Relative sea-level rise accelerates as deposition of St continues to fill the valley depression.

With the onset of transgression, fluvial environments transitioned to estuarine environments (Posamentier and Allen, 1999). The change in environment is shown in Figure 41. As relative sea level continued to rise, the finer sediment began to get trapped up-dip as the valley system was filled with brackish water and became a bay. At the seismic scale, within the valley, parasequences are often observed that give indication of the backstepping nature of the transgressive systems tract. At the outcrop scale, without the benefit of vertical exaggeration, such surfaces are difficult to identify. This is the case for the Colgate Member. However, the observed facies tract relationships indicate the overall backstepping in the transgressive systems tract. Also, as Flight (2004) and Wheeler (1983) noted, a change from fluvial deposits to estuarine deposits necessitates a

marine flooding surface. This key surface delineates strata below of the lowstand systems tract from strata above of the transgressive systems tract. The cross sections in Appendix B show the marine flooding surfaceôs location within the Colgate Member, placing it at the base of the first indication of marine influence and the estuarine environment.

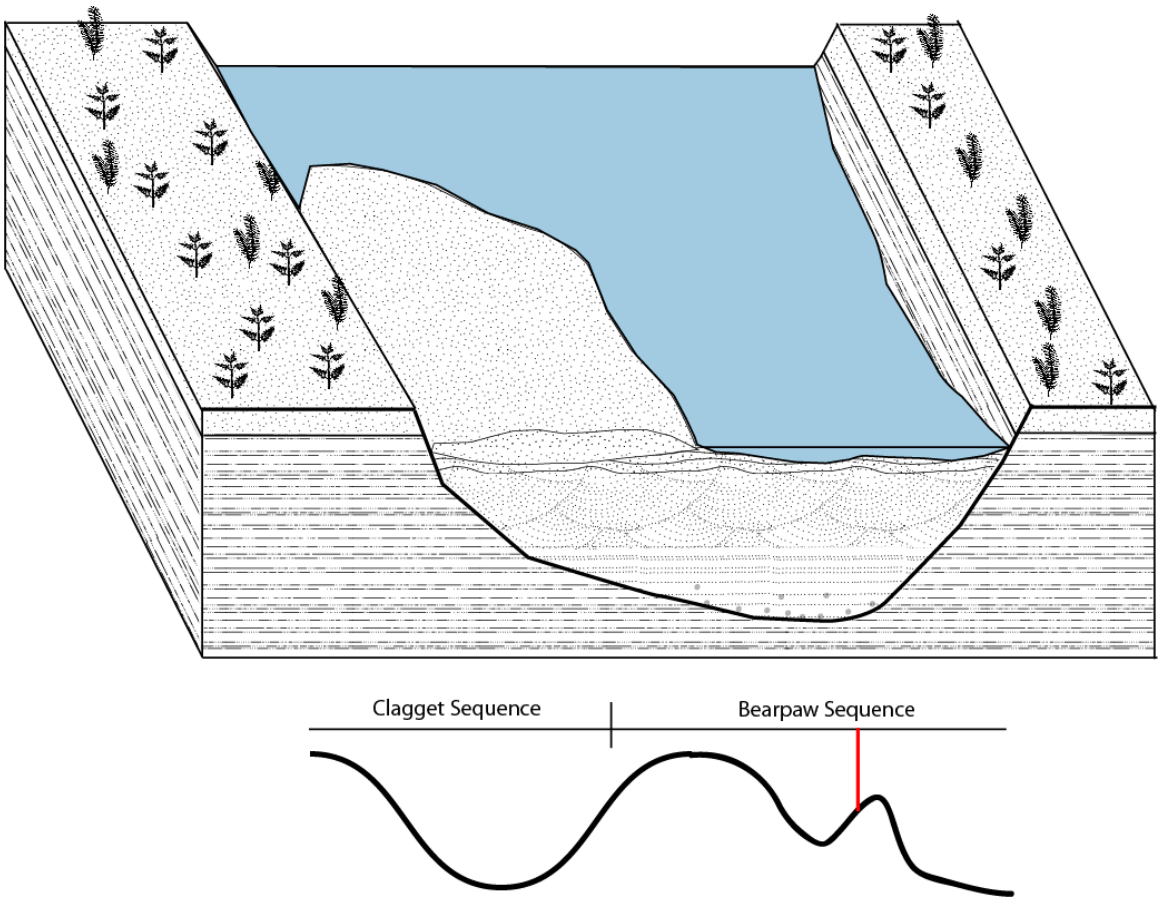

Figure 41. Block 6; Relative sea-level rise continues and the first signs of marine water appear with the onset estuarine facies associations.

As the transgression continues, sediment deposited in the estuary begins to fine. Facies Fpm and Fm of the lower Hell Creek Formation are the results of this upward fining grain size and lower depositional energy (Figure 42). The uppermost contact of facies Fm represents the maximum flooding surface in agreement with the interpretation

of Flight (2004). This represents the maximum landward incursion of marine sediment during this depositional cycle as flooding occurred across the interfluves. Sediments above the maximum flooding surface are part of the highstand systems tract.

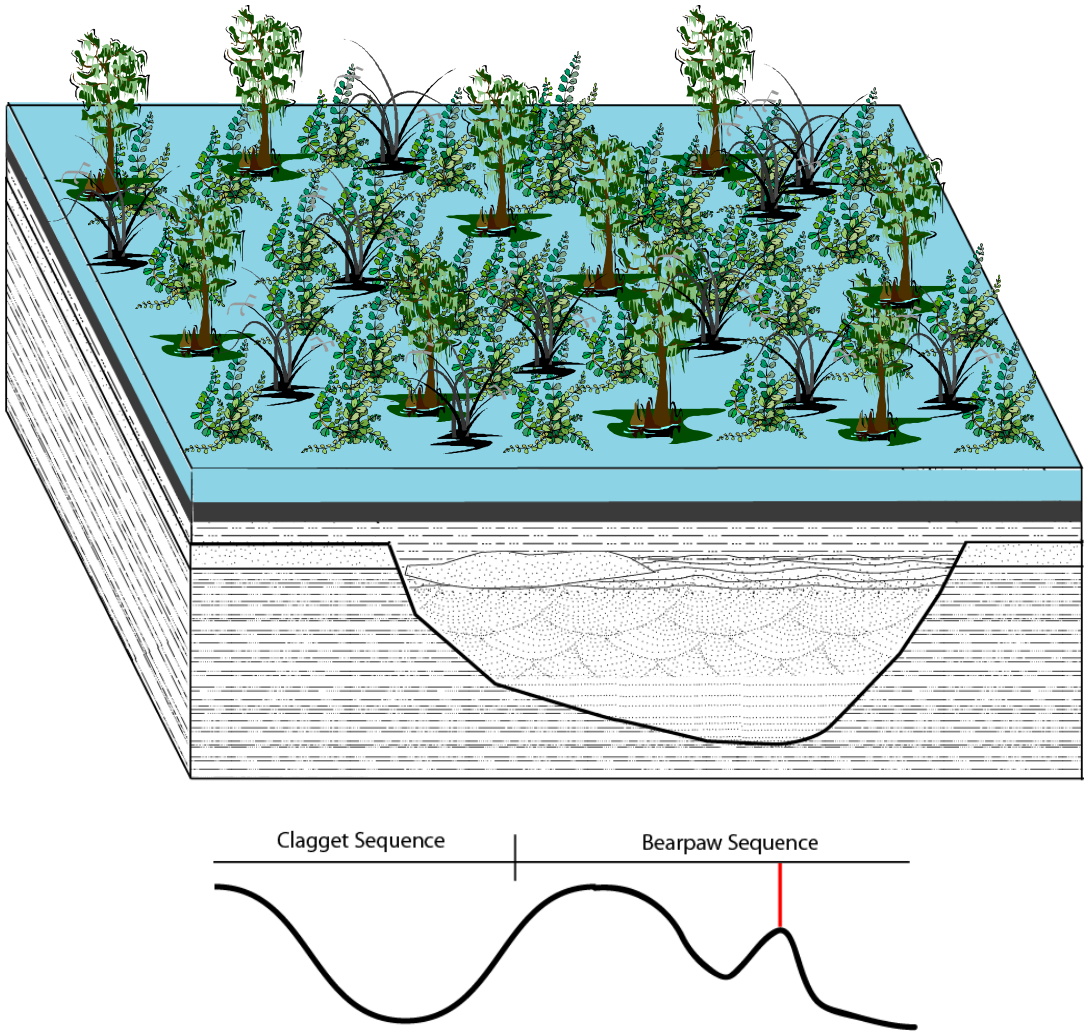

Figure 42. Block 8; Maximum flooding surface is created at the most landward transgression of the sea, depicted here with the deposition of facies Fm.

CHAPTER 8

CONTROLS ON THE COLGATE SANDSTONE MEMBER INCISED VALLEY SYSTEM

Controls on Valley Incision

Erosion or deposition in a fluvial system depends on sediment load and average sediment size, gradient and stream discharge (Miall, 1977). A change in the balance of these variables leads to erosion or to aggradation. During the formation of an incised valley system, fluvial conditions are such that erosion dominates for a relatively long period of time. This can be achieved in several ways. First, there can be a eustatic drop in sea level that in turn increases the fluvial systemôs profile or slope. A eustatic drop in sea level can be caused by storage of glacial ice at the poles, decrease in rates of seafloor spreading, cooling and contraction of oceanic water and the shape of the geoid (Donovan and Jones, 1979). Other potential reasons for an increased gradient of a fluvial profile include glacio-eustatic rebound, continental collision, epeirogeny, and an increased rate of subsidence down-gradient. Unrelated to relative sea level, increased precipitation or stream capture can promote incision by increasing discharge or a reduction in sediment supply can cause erosion as there would be excess capacity or energy in the fluvial system. Factors leading to a fluvial aggradation or erosion are well depicted by Laneôs Balance (Figure 43).

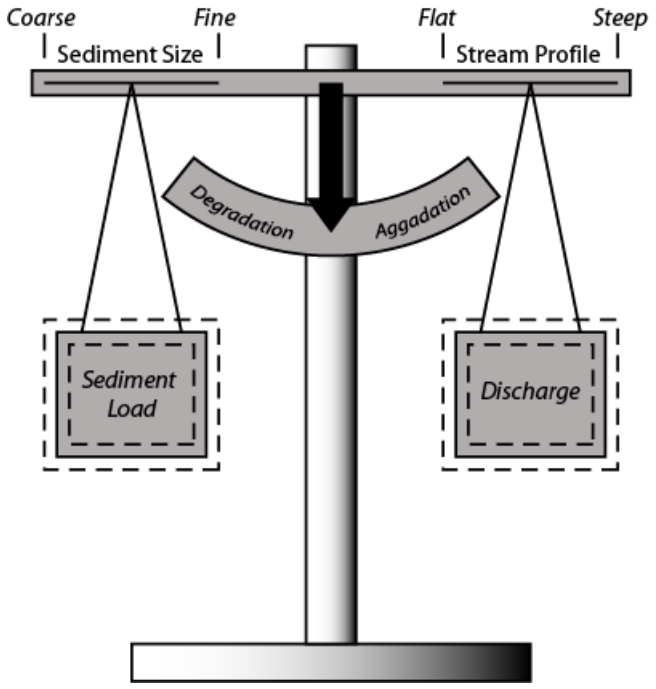

Figure 43. Diagram of Lane's Balance depicting the four variables that control whether a stream is aggradational or degradational. Modified from Lane (1955).

It is rare that only one of the above factors is responsible for the formation of an incised valley. In the Colgate incised valley-fill system, as with most systems, it is likely that a combination of factors lead to erosion for the extended amount of time needed. It is well documented that the Fox Hills and Hell Creek Formations record the last regression of the Western Cretaceous Seaway and falling eustatic sea levels (Weimer, 1960). However, markedly different strata patterns are described overprinting the Fox Hills regression in different locals. For example, Pylesô (2004) work in central Wyoming concluded there were high frequency (4th Order) depositional sequences recorded within a lower order transgressive systems tract and subsequent highstand systems tract. He asserts there are ten high frequency cycles that average 110 ka in duration each with identifiable lowstand systems tract deposits. Further, the regressive phase of the

highstand systems tract was influenced by the Lost Solder anticline, a Laramide uplift to the north of his study area. This example illustrates the complexities local tectonism can have on a sequence stratigraphic model. Some examples of local mechanisms that can bring about a relative sea-level fall include tectonic uplift inland (Pyles, 2004), subsidence, increased discharge or decreased sediment load (Dalrymple et al., 1994). While it is often difficult to determine the relative importance that eustatic sea level, sediment delivery and tectonic influences have on base-level change, (Zaitlin et al., 1995) a goal of this work is to determine if there was a tectonic influence as hypothesized by Flight (2004) during the formation and deposition of the Colgate incised valley-fill. Also, an interpretation of the relative importance of eustatic and tectonic influences on deposition of the Colgate Sandstone Member system will be made.

Tectonic Setting

During Mesozoic time in the western United States and Canada, mountains were rising on the western cratonic margin marking the beginning of subduction of the oceanic Farallon plate under the continental North American plate (DeCelles, 2004). With subduction, profound orogenic events began in the Late Jurassic beginningwith the Nevadan Orogeny in present day California and Nevada (DeCelles, 2004). The locus of deformation spread eastward with the Sevier fold-and-thrust belt during the mid-Cretaceous. This was then followed by uplift of Laramide basement-cored foreland uplifts during the Late Cretaceous to Early Paleogene extending further to the east in central to eastern Montana, Wyoming and Colorado (Snoke, 1993; DeCelles, 2004).

In eastern Montana, structures are controlled or underlain by zones of Proterozoic weakness that have had recurrent activity throughout the Phanerozoic (Hoffman, 1988). These basement features likely resulted from a series of major tectonic events, starting in the early Proterozoic with the collision of the Wyoming Craton with the Hearn Craton along the Great Falls Tectonic Zone in present day eastern Idaho and western Montana (OôNeill and Lopez, 1985). Then in the middle Proterozoic the Wyoming-Hearn Craton collided with the Superior Craton along the Tran-Hudson Orogeny (Anna, 1986; Maughan and Perry, 1986; Shurr and Rice, 1986, Shurr, 1989, Ansdell, 1995). This newly formed part of Laurentia subsequently underwent a period of major extension in the middle Proterozoic (Winston, 1986). These three major events provided and inherited basement fabrics that are expressed at the surface today as lineaments.

Lineaments that help define a basement block ñmosaicò are of special interest for this research because they have been documented to have been active and influencing deposition throughout the Paleozoic (Brown, 1978; Slack, 1981; Thomas, 1983) and Mesozoic (Anna, 1986; Clement, 1986; Shurr, 1989; Shurr and Rice, 1986). Even though the locus of deformation during the Laramide is often hundereds of miles away, a far field tectonism can create a stress regime to influence zones or plans of weakness preexisting in the basement fabric (Kluth, 2005). The Blood Creek syncline (Clement, 1986) and the Cat Creek and Cedar Creek anticlines (Shurr, 1989) are prominent examples of movements on these basement features that have influenced the deposition and surface expression of sediments during Laramide deformation proximal to the Devilôs Creek area of study. Not only are these features proximal to the area of study,

they are documented to have been active during the time of the Colgate Sandstoneôs deposition.

Eastern Montana Basement Block Mosaic

Basement block control on deposition and on structures in the eastern half of Montana was first suggested by Thom (1923) and later linked to Laramide structures by Sonnenberg (1956). More regional studies in the 1960ôs described lineamentï bound basement blocks subjected to horizontal compression (Sales, 1968; Smith, 1965; Stone, 1969). Basement blocks have been defined on the basis of isopach patterns, air and satellite images, geophysical data and geologic maps (Shurr, 1989). Thomas (1972) used air photos to map a lineament system then related that system to stratigraphic patterns in Paleozoic and Mesozoic rocks (Figure 44). Satellite images, geophysical data, geologic maps, and Cretaceous stratigraphic patterns were the methods used by Shurr and Rice (1986) to create a basis for interpreting a basement block mosaic. Maughan and Perry (1986), Anna (1986) and Winston (1986), interpreted basement block expression by use of stratigraphic patterns. The synthesis of this work strengthens the hypothesis that a basement block mosaic does exist and that it influences the structural development and sedimentation on the Montana plains. What is not widely agreed upon is the stress field in which these blocks are activated and the sense of displacement on the deep seated faults (Shurr, 1989)

Structural Control on Other Incised Valley Systems

Several examples from the literature demonstrate underlying basement structure controlling the paleo-drainage of fluvial systems and incised valley systems. These

examples are used to represent how other workers have interpreted these tectonic influence and document common recognizable features.

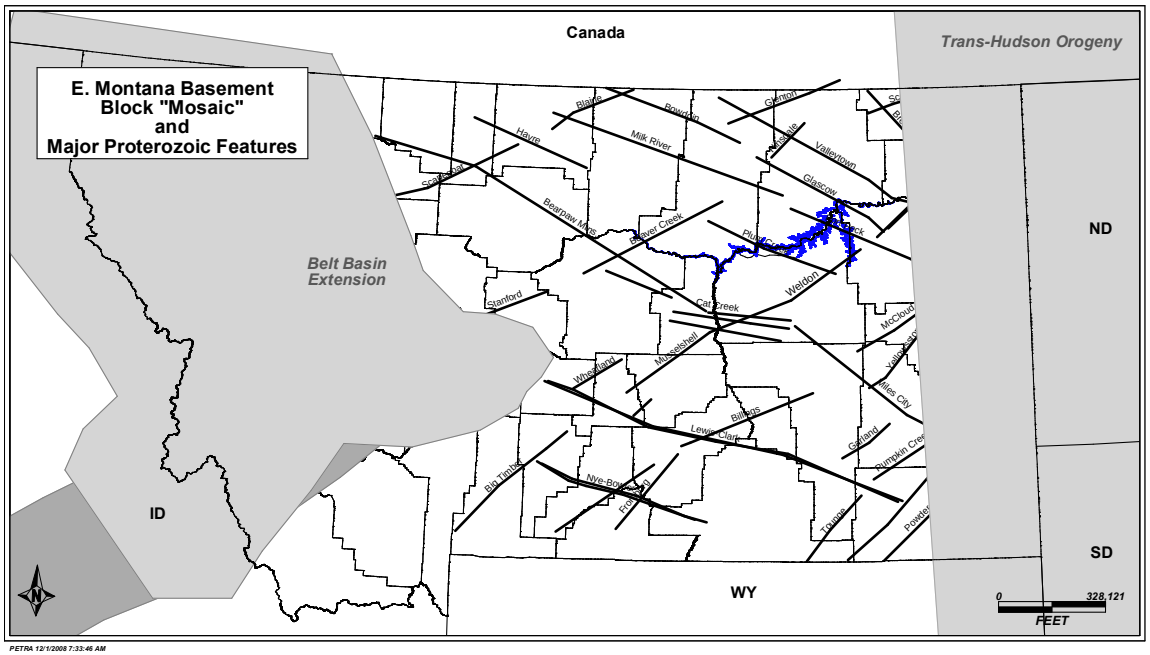

Figure 44. Map showing named lineaments mapped by Thomas (1972) with use of air-photo. These lineaments are thought to reveal zones of basement weakness created in Proterozoic continental collisions and extension that have subsequently influenced depositional patterns of Phanerozoic sediments.

Work done on the Tonganoxie Sandstone (Upper Pennsylvanian) incised valley system by Beaty et al. (1999) in northeast Kansas was analyzed using isopach maps and lineament maps. The isopach maps were used to detect subtle changes in local topography caused by structural movement. They found that persistent linear thicknesses correspond closely to trends of mapped lineaments, suggesting that basement reactivation influenced the location of the paleovalley development.

Another example of basement control on an incised valley system comes from the lower Cretaceous of southeast Montana (Lopez, 2000). The Greybull Sandstone Member of the upper Kootenai shows a close association with the Nye-Bowler fault zone. Lopez and others (2000) measured and described outcrop and subsurface data to create isopach

maps to conclude the Nye-Bowler and Fromburg fault zones were active during the time of incision and/or deposition and dictated the location of the Greybull incised valley system.

A final example comes from the Powder River Basin in Wyoming. Slack (1981) correlated hydrocarbon accumulation to paleotectonic features. His work demonstrated that productive Minnelusa, Dakota and Muddy reservoirs lie along the downthrown fault blocks that form the Belle Fourche Arch. Of particular interest is the Muddy incised valley-fill system. Slack (1981) states that Muddy incised valley-fill systems follow subtle synclinal troughs of the fracture zones and that these troughs are a result of subtle tectonic movement after the deposition of the underlying Skull Creek Formation and prior to valley incision.

Tectonic Influence on the Colgate System

Flight (2004) hypothesized that the Colgate member ñis a depositional remnant, specifically an accommodation remnant (*sensu* Martinsen, 2003), contained within a valley that was incised into the Fox Hills and Bearpaw Formations below, formed from a region of increased subsidence, or a combination of both (2004, p. 108).ò She goes on to say that field evidence indicated that a combination of incision and subsidence were responsible for creating the accommodation filled by the Colgate Member.

Martinsen (2003) describes five styles of depositional remnants, two of which resemble possible geometries for the Colgate incised valley system are pictured in Figure 45. Figure 45A depicts accommodation being created solely by localized, syndepositional subsidence likely caused by faulting. The bottom (Figure 45B) depicts preservation of strata due to deposition in a topographic low such as would be casued by

fluvial incision. Flightôs (2004) conclusion that a combination of these factors led to the creation and preservation of the Colgate Sandstone utilized field evidence to support subsidence. This evidence would be sediment inside the valley geometry on-lapping sediments originally part of the interfluve (Figure 46 B and C). This relationship was not observed in the Devilôs Creek field area or in the wider area of reconnaissance by the author, but previous work reports the equivalent of facies Fm on-lapping the equivalent of facies Fpm (Flight, 2004).

To further test Flightôs (2004) interpretation that the Colgate incised valley system was structurally influenced, a more regional subsurface analysis was performed. A series of isopach and structure maps were generated using geophysical wireline logs from nearby oil and gas boreholes. Figure 44 (B and C) shows that if there was structural influence or enhancement of this valley system certain diagnostic features should be present. First, there would be a structural depression in the formations below making a mappable syncline under the valley system (Figure 46 B and C). Second, to determine a history of subsidence in this localized area, overthickened strata would develop as more accommodation would be available not only for Colgate sediments but for those sediments below (Figure 46 C). These results are also compared to lineaments mapped by Thomas (1978) to see if observed structural trends are caused by basement zones of weakness.

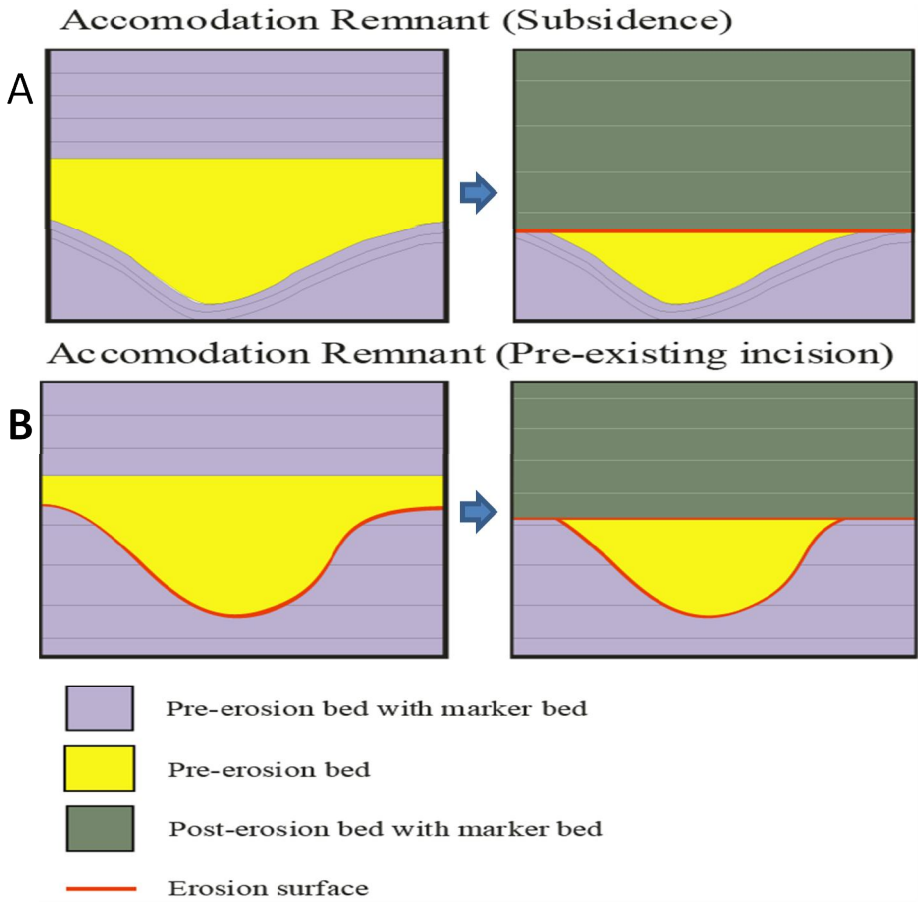

Figure 45. From Martinsen (2003), showing two different types of depositional remnants. A) Preservation due to localized, syndepostional subsidence likely caused by faulting. B) Preservation due to deposition in a pre-existing topographic low.

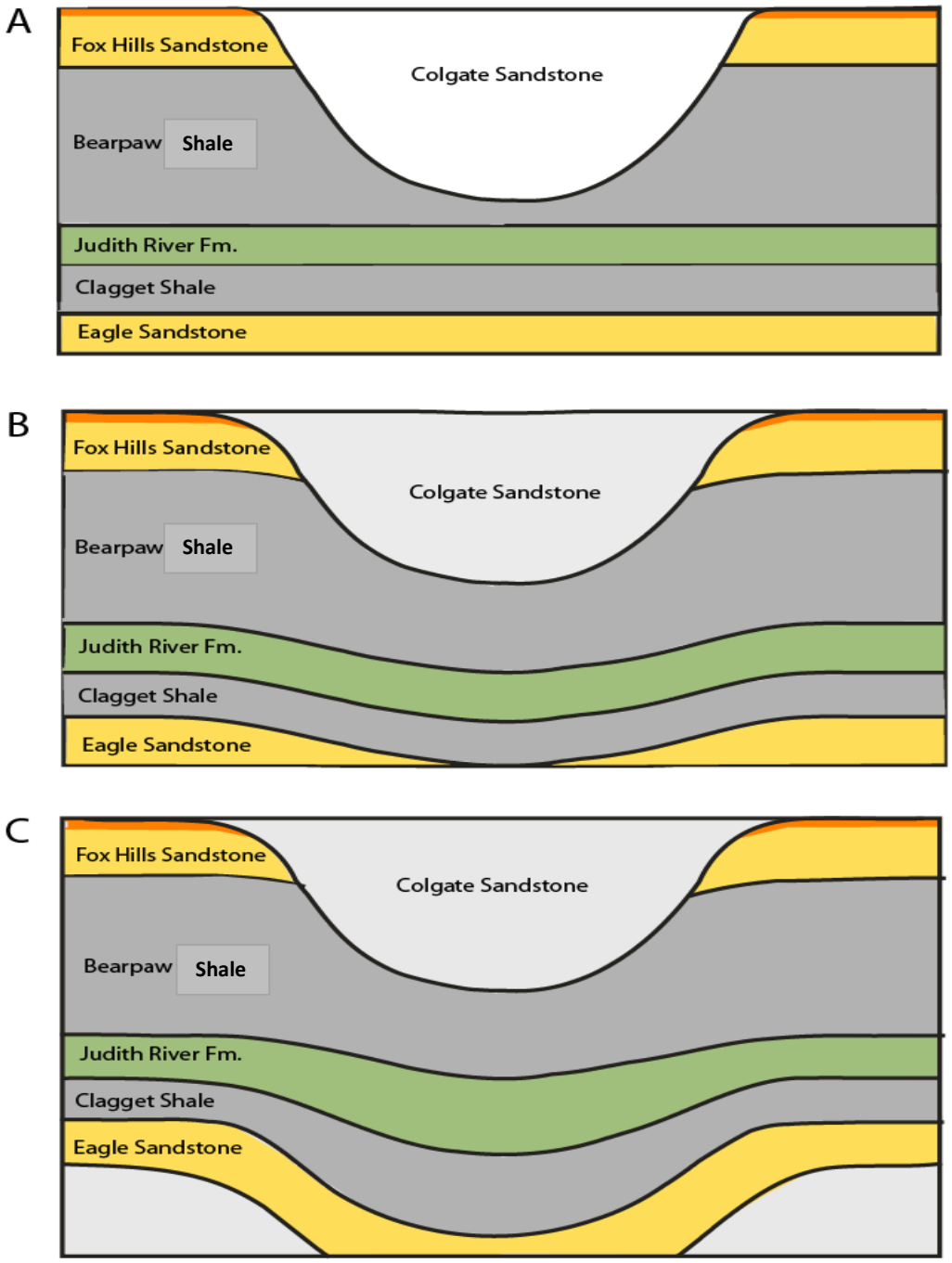

Figure 46. Three possible stratigraphic geometries for the Colgate Formation and the underlying strata. A) Fluvial incision which resembles Martinsen (2003) accommodation remnant Figure 45B. B) Colgate Member strata preserved in a low created by syndepositional local subsidence, resembling the accommodation remnant of Figure 45A. Note synclinal shapes of underlying strata. C) The result of syndepostional and predepostional subsidence, this shows a history of movement in this localized area. Note the overthickened strata below the Colgate Member, this can mean this area is historically prone to subside. Note-highly diagrammatic not to scale.

Sub-Surface Bearpaw Maps: The Bearpaw Formation was deposited from approximately 73.5 Ma to 69 Ma (Maculey, 1964) or about 1.5 Ma before the Colgate Sandstone. Of the three formations analyzed in the subsurface the Bearpaw Formation is the youngest as the Fox Hills Formation is not deep enough in the subsurface to be registered on enough logs to allow mapping. The Bearpaw Formation is regionally a westward thinning marine formation that marks the beginning of the Bearpaw Sequence (Weimer, 1960; Figure 3). The structure map (Figure 47) of the Bearpaw Shale shows basinward dip and possible influence from the Blood Creek syncline and Cat Creek anticline to the south of the Devilôs Creek field area. However, there is no evidence of synformal structure below the mapped Colgate occurrence.

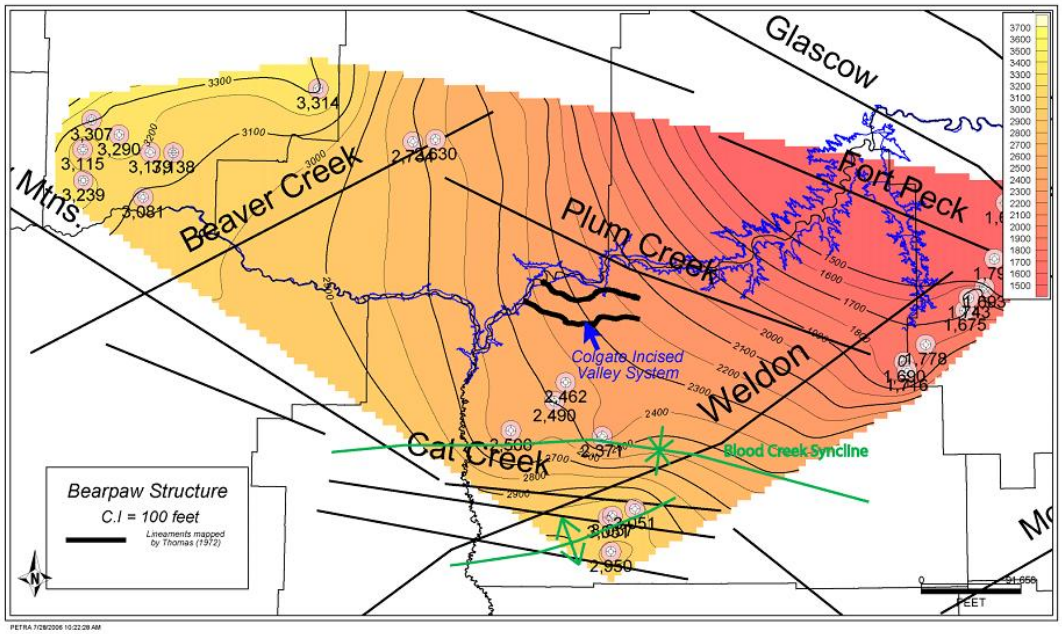

Figure 47. Structure Map of the Bearpaw Formation. Notice structural influence from the Blood Creek Syncline (green) and Cat Creek Anticline (green) to the south of Devil's Creek Field Area.

The Bearpaw Formation isopach map is measuring the thickness of the shale formation and it shows thickening to the south (Figure 48). As the strandline during the Bearpaw was striking largely to the NNE it can be inferred that the seemingly unusual tectonic thickening to south is due to the active subsidence of the Blood Creek Syncline. There is little to no evidence of tectonic thickening under the mapped Colgate incised valley system. However, it should be noted that data is limited in the region of the study area because the top of the Bearpaw Formation outcrops in the vicinity of the Devilôs Creek Field area.

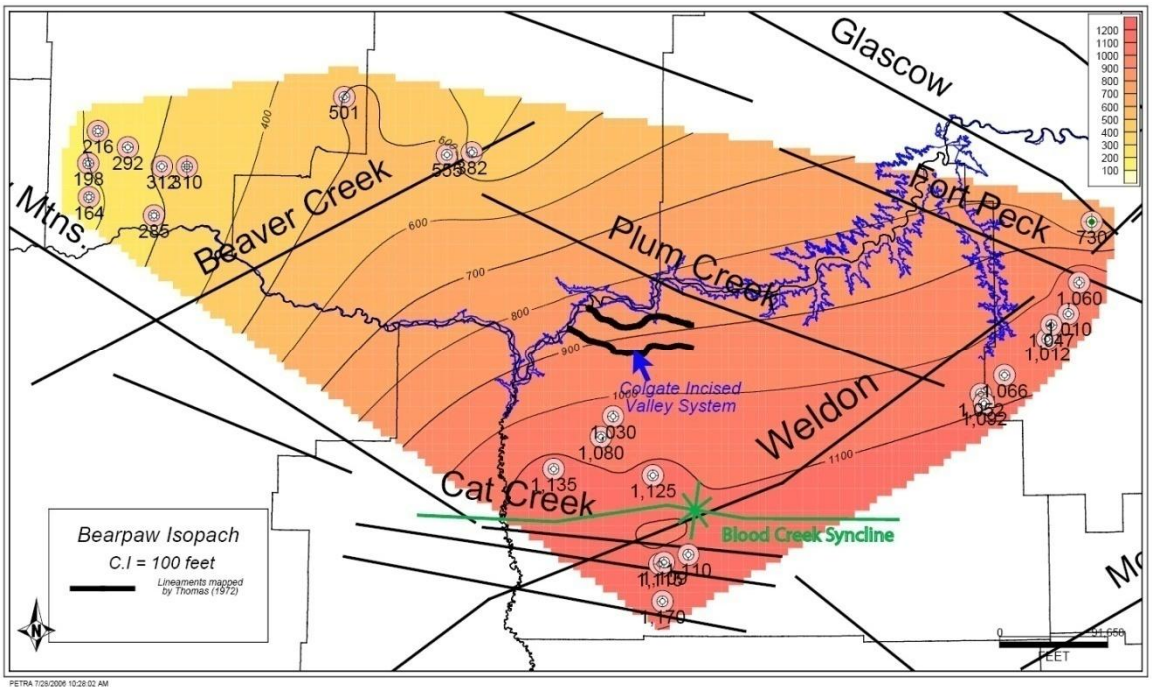

Figure 48. Map of Bearpaw thickness in the Eastern Montana Fort Peck area. Notice depositional thickening possibly associated with the Blood Creek Syncline (green).

Sub-Surface Judith River Maps: The next oldest strata are the Judith River Formation. The Judith River represents the progradation of the Claggett Sequence shoreline from the west. It was deposited approximately 73 Ma (Macauley, 1964) and, therefore, predates the time of Colgate deposition by approximately 6 Ma. The structure map of the Judith River shows the location of the Blood Creek Syncline to the south (Figure 49). This feature is adjacent to the mapped Colgate incised valley system, but is not proximal enough to validate a structural influence for the Colgate trend. Also observed is the structural high of the Cat Creek Anticline to the south of the Blood Creek Syncline.

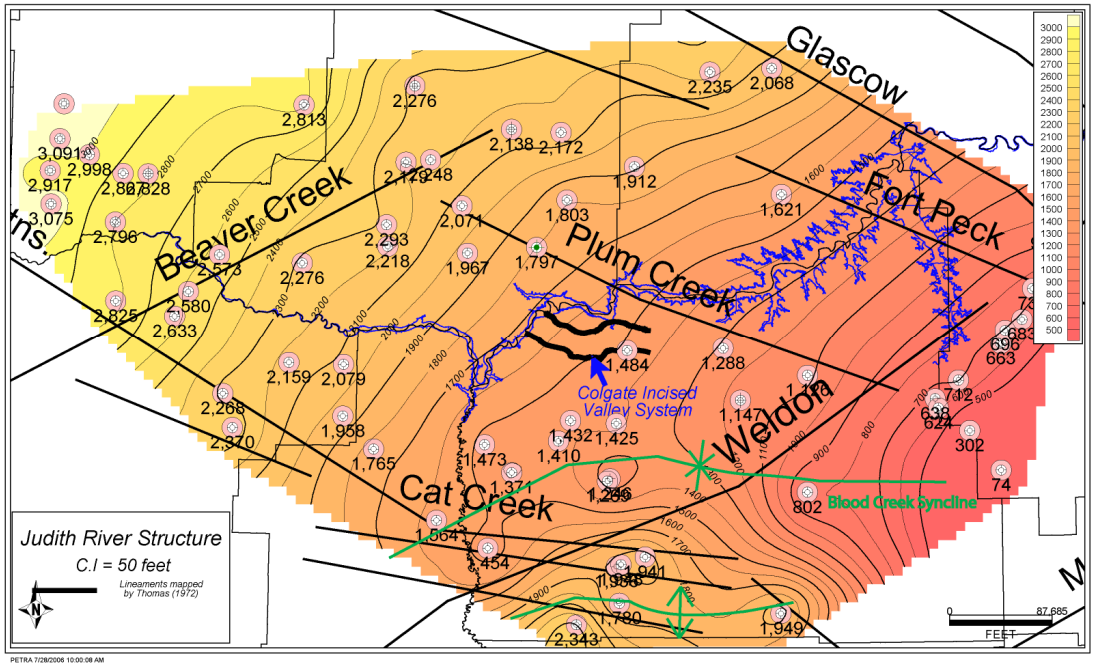

Figure 49. Map of the Judith River Formation structure in the eastern Montana Fort Peck area. Notice the Blood Creek syncline and Cat Creek anticline (both green) to the south of the Devil's Creek field area.

The Judith River isopach map shows an interesting relationship with the Judith River Structure Map (Figure 49 and 50). Where the Blood Creek syncline appears in the structure map, there is no tectonic thickening of the Judith River strata; this could mean

that the Blood Creek syncline at the time of the deposition of the Judith River was quiescent or not even in existence. Depositional thickening appears to have developed right under the mapped Colgate trend on the south side of Thomasô(1973) Plum Creek lineament.

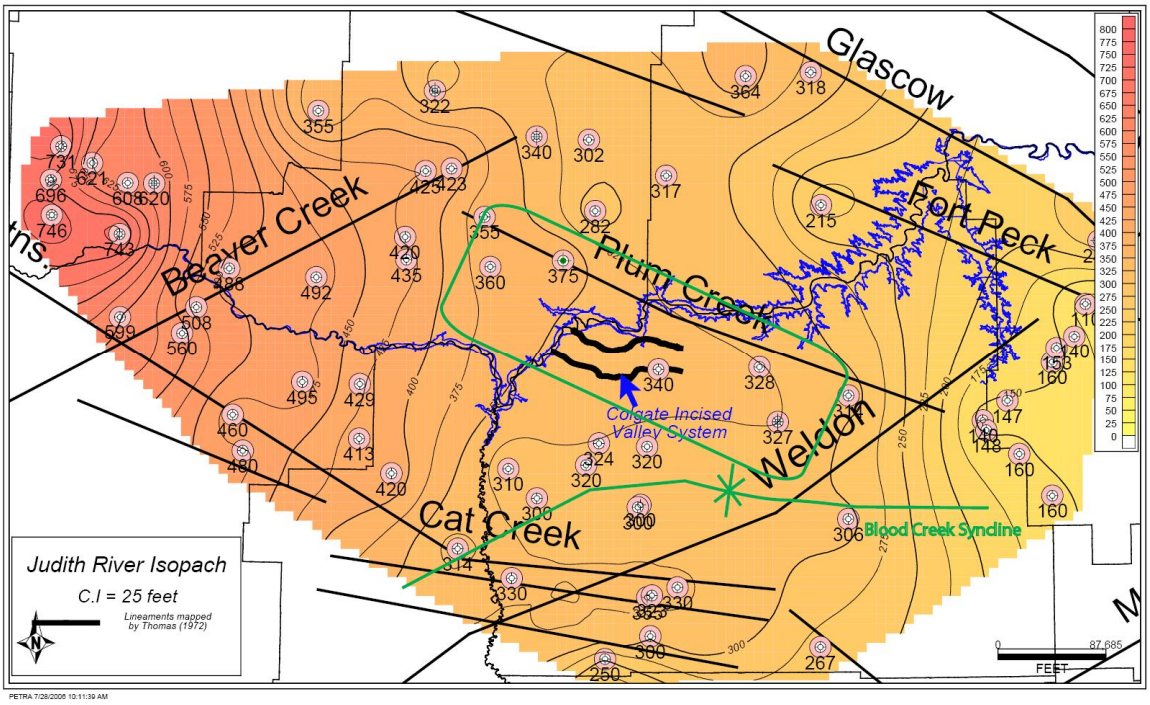

Figure 50. Map of the thickness of the Judith River Formation in the eastern Montana Fort Peck area. Notice the depositional thickening on the south flank of the Plum Creek lineament that closely coincides with the Colgate incised valley system location (highlighted by green box).

Sub-Surface Claggett Shale Maps: The Claggett Shale represents the beginning of the Claggett transgression and in the Devilôs Creek field area thins depositionally to the east. It was deposited approximately 76Ma (Macualey, 1964) in the Campanian or approximately 9 million years before the deposition of the Colgate. The Claggett Shale structure map depicts the Blood Creek syncline to the south and, even further to the south, the Cat Creek anticline (Figure 51). There is some evidence of a synformal

structure along the northwest flank of the Plum Creek lineament; it is likely that this feature is significant to the formation the Colgate incised valley system.

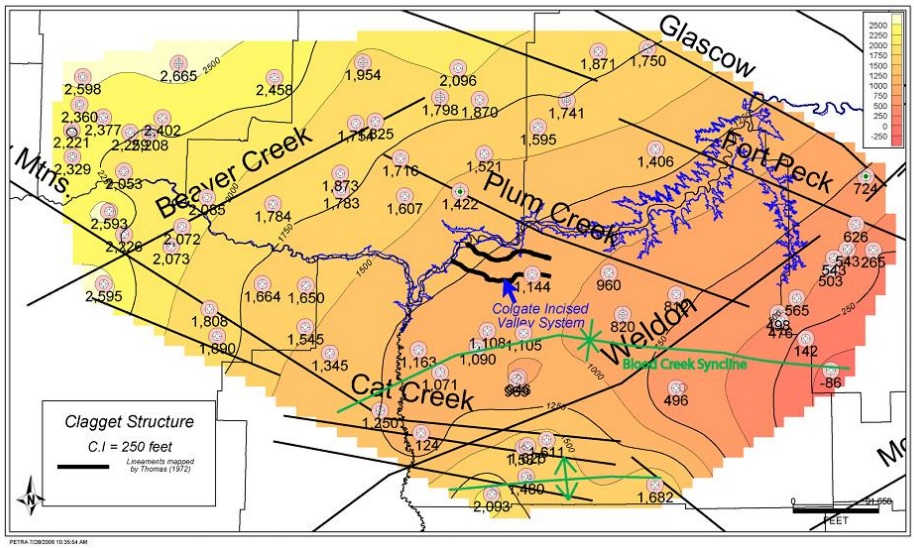

Figure 51. Map of the Claggett Shale Structure in the eastern Montana Fort Peck area. Cat Creek anticline and Blood Creek syncline both can be seen south of Devil's Creek field area (both marked in green).

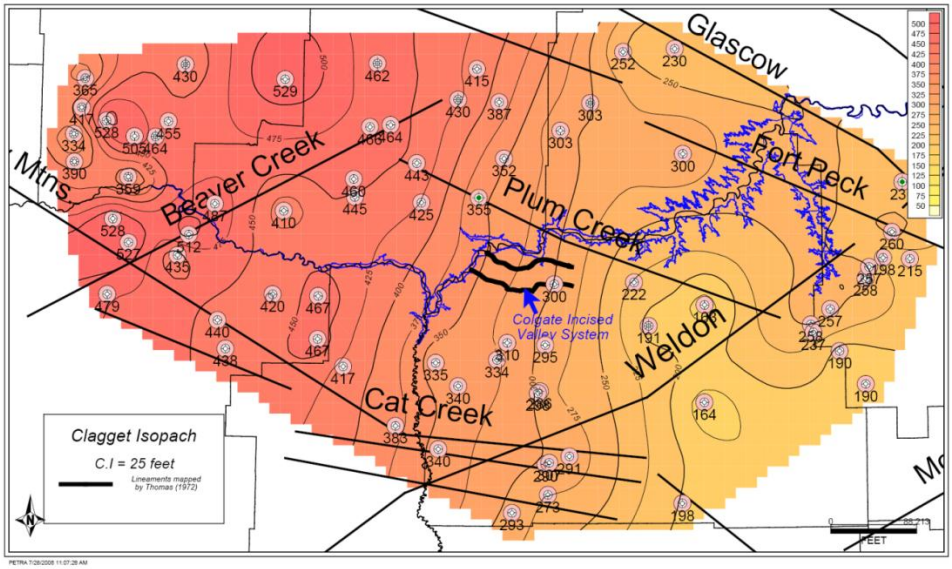

Figure 52. Map of the thickness of the Claggett Shale in the eastern Montana Fort Peck area. Isopach shows west to east formational thinning with no significant variance along depositional strike.

The Claggett isopach map (Figure 52) in the Devilôs Creek field area shows west to east formational thinning, with no significant variances in thickness along depositional strike.

Composite Isopach Maps: As can be seen in the isopach combining the Bearpaw, Judith River and the Claggett Formations (Figure 53), the Bearpaw Formation, overthickens and potentially drowns out any signature that would be needed to make a determination on the role that tectonics played on the deposition and preservation of the Colgate Member. Therefore, taking away the Bearpaw Formation from the isopach should reveal depositional trends that were potentially overshadowed by the formation of the Blood Creek syncline. As can be seen on the isopach map that includes the thicknesses of the Judith River and Claggett Formations (Figure 54), there is depositional thickening along the south flank of the Plum Creek lineament.

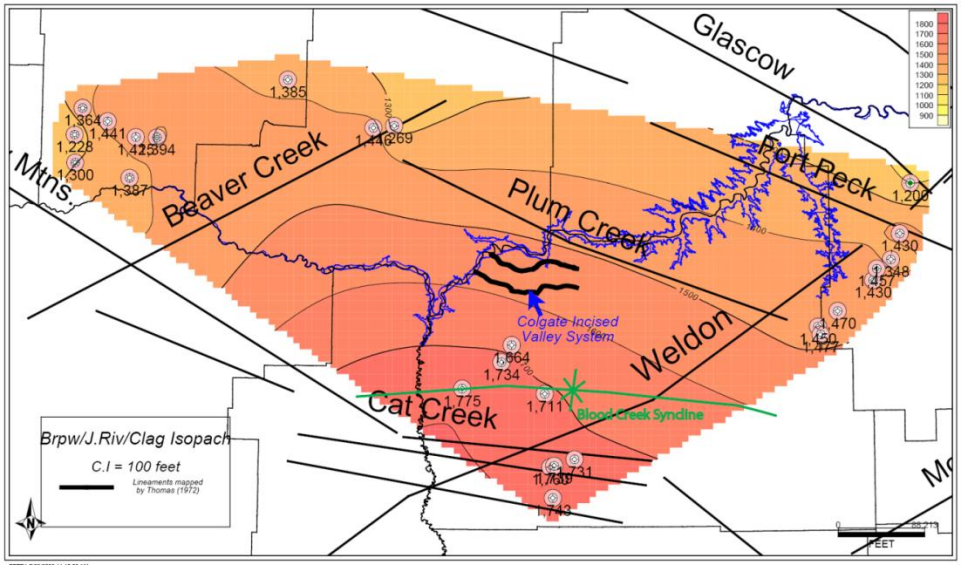

Figure 53. Map of the combined thicknesses of the Bearpaw, Judith River and Claggett Formations in the eastern Montana Fort Peck area. Depositional thickening caused by the Blood Creek syncline (green) mostly during Bearpaw deposition can be seen as the intervals isopach increases to the south.

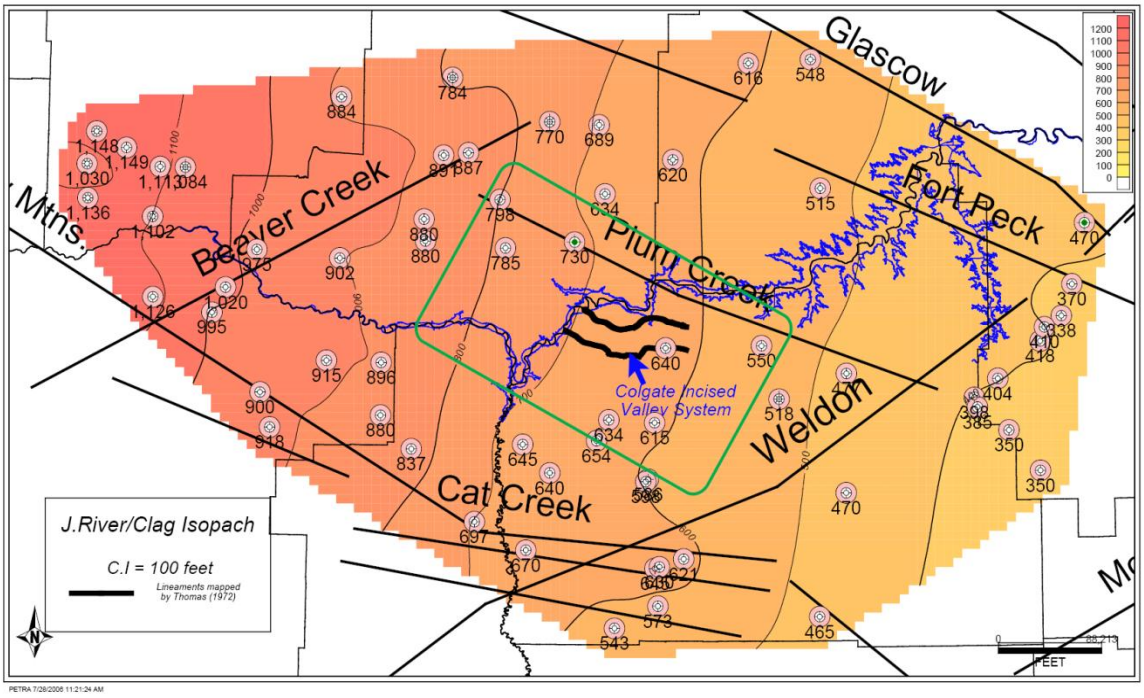

Figure 54. Map of the combined thickness of the Judith River and Claggett Formations in the eastern Montana Fort Peck area. Highlighted by the green box is formational thickening along depositional strike likely a result of movement of the basement feature associated with the Plum Creek lineament.

The purpose of going back 6 Ma from the approximate time of deposition of the Colgate Sandstone Member to the time that the Eagle Sandstone was being deposited to create these maps is to show patterns through time. These maps attempt to verify a link to deposition to these surface features as that are reactivated through time. The subsurface data, aerial photographic data and field evidence create enough support to interpret that there was structural influence on the Colgate incised valley system regionally with the onset of the Blood Creek syncline's subsidence (initiated in Bearpaw Formation time) and locally along the south flank of the Plum Creek lineament that shows evidence of reactivation during Judith River time.

Eustatic Sea Level

Haq et al. (1987) published eustatic and coastal on-lap curves for the Mesozoic and Cenozoic. These curves integrate magneto-, chrono-, and biostratigraphic data with sequences noted in the subsurface and outcrop sections from different sedimentary basins. The ñHaq et al. curvesò have been the subject of spirited debate as it is seen by some to not take into proper account adequate corrections for local and regional subsidence (Haq et al., 1987). However, it can be a very useful tool in developing a chronostratigraphic framework and to integrate depositional sequences documented in outcrops from any basin in the world.

Figure 54 takes the published absolute ages (Macauley, 1964; Zaleha, 1988) of deposition of the Bearpaw sequence formations (Bearpaw, Fox Hills and Hell Creek) and compares it to the global eustatic sea-level curve prepared by Haq et al. (1987). The Colgate Member is not included in Figure 54 because no absolute date has been obtained for this unit. However, it can be bracketed by the Fox Hills Formation and Hell Creek Formation absolute ages. Figure 55 demonstrates a close match to Flightôs (2004) regional sequence stratigraphic interpretation for the Bearpaw sequence stratigraphy. The Bearpaw Shale was deposited 73 to 69.5 Ma (Macauley, 1964) and is considered to be of the transgressive systems tract and highstand systems tract in the first of her recognized sequences. In Figure 53, the Bearpaw Shale fits along the Haq et al. curve where the interpreted systems tracts occur. The Fox Hills Formation was deposited from 69.5 Ma to 68 Ma (Macauley, 1964; Zaleha, 1986) and was interpreted by Flight (2004) to be a continuation of the highstand systems tract of the lower sequence. Again, this interpretation fits the Haq et al. eustatic sea-level curve. Lastly, Hell Creek Formation

deposition occurred from 67 Ma to the end of the Cretaceous at 65.5 Ma (Macauley, 1964). The Haq et al. (1987) curve has a eustatic sea level drop, depositional sequence UZA-4.5, that fits the gap in deposition from 68 to 67 Ma that is also enough time for the creation of the Colgate incised valley system (interpreted to be a 4th order depositional sequence).

The generic relative sea-level curve (Figure 56) was created through the synthesis of field results from Flight (2004) and this research. The processes and depositional environments that were observed in the field were placed on a hypothetical generalized relative sea-level curve with each red line correlating to a specific time of incision or deposition represented by the seven block diagrams (Figures 38-44). The curvesô inflections were created using significant surfaces and depositional environment interpretation (Figure 56).

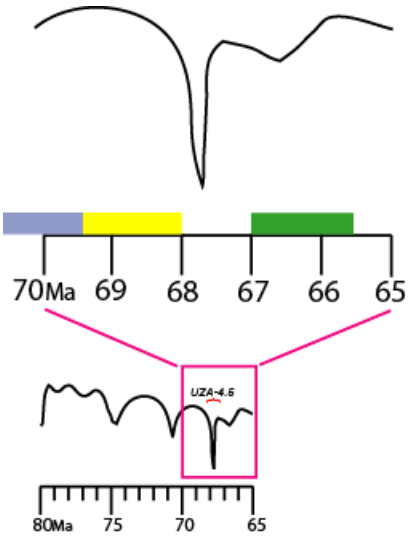

Figure 55. Diagram comparing the eustatic sea-level curve prepared by Haq et al. (1987) compared to the absolute ages of deposition for the deposition of Bearpaw sequence sediments in eastern Montana (Macauley, 1964; Zaleha, 1986). Bearpaw Formation is represented by the grey color, Fox Hills Formation is yellow and Hell Creek Formation is green. The gap in deposition from 68 to 67 Ma is enough time for the creation Colgate incised valley system (interpreted to be a 4th order depositional sequence).

When the generic relative sea-level curve is compared to the Haq et al (1987) eustatic sea-level curve there is another correlation (Figure 56). The UZA-4.5 sequence of Haq et al. (1987) has similar features to the generalized relative sea-level curve. This correlation and the absolute timing correlation made above is significant because if the generic relative sea-level curve and the Haq et al. (1987) absolute eustatic sea-level curve match well, it can be inferred that eustatic sea-level, and more specifically Haq et al.ôs (1987) UZA-4.5 played a large part in the relative sea-level fluctuation responsible for the creation and deposition of the Colgate Sandstone Member.

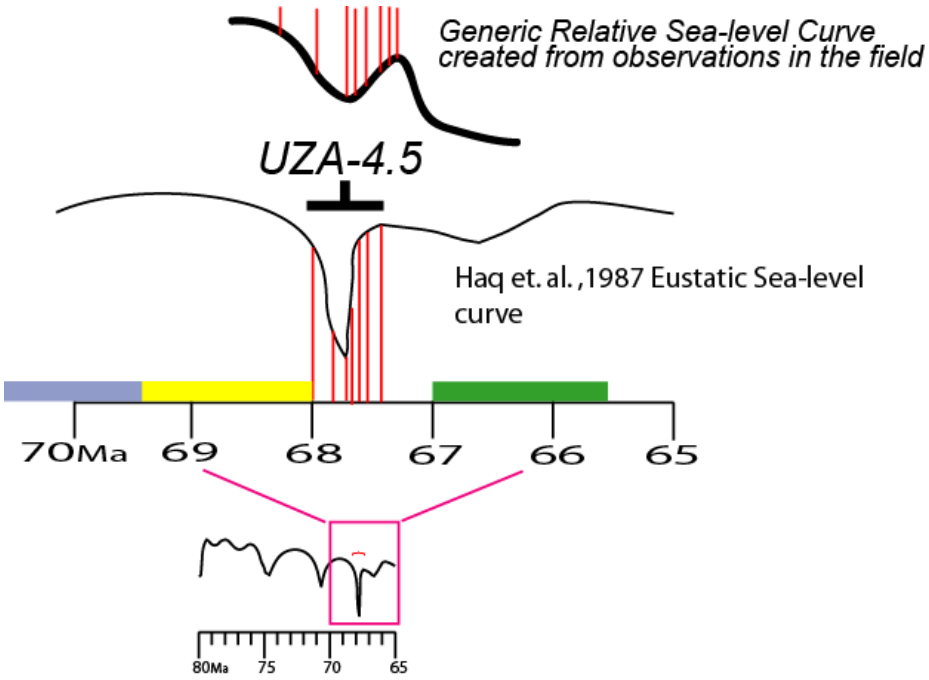

Figure 56. Diagram showing Haq et al (1987) eustatic sea-level curve, a curve created by field observations and absolute ages ascribed to the Bearpaw Fox Hills and Hell Creek Formations (Macauley, 1964; Zaleha, 1986). Each red line on the generic relative sea-level curve and Haq et al. (1987) eustatic sea-level curve represent a block diagram or a specific time of deposition seen in Figures 36 to 42. As can be seen there is a good fit between general relative sea level created from field observation and interpretation and the absolute eustatic sea-level curve created by Haq et al. (1987)

CHAPTER 9

SUMMARY AND CONCLUSION

The Colgate Sandstone Member of the Fox Hills Formation is part of an incised valley system that formed in response to a relative sea-level drop of the Western Interior Seaway during the Maastricchtian stage in northeastern Montana and western North Dakota. The valley fulfills the criterion set forth by Zaitlin (1994, 1995) to characterize a depositional system as an incised valley-fill. The valley-fill strata onlaps the unconformity forming the valley floor and sides and demonstrates an abrupt basinward shift of facies relative to those of the eroded substrate (Van Wagoner et al., 1988). As mapped in the Devilôs Creek field area, the Colgate incised valley system is up to 6 kilometers (3.5 miles) wide, 16 meters (55 feet) deep and generally trends in an ESE direction. Isopach maps and stratigraphic evidence indicate that the location of the valley-fill in the region of study may be influenced by recurrent movement along the Plum Creek lineament.

Work on the detailed internal architecture of the strata comprising the Colgate Sandstone has defined a lower fluvial facies that contains planar horizontal, rippled and trough cross-stratified sedimentary structures in well-sorted, fine- grained sandstone that formed during a lowstand systems tract. The lowstand fluvial facies gradually transitions to transgressive estuarine and tidally influenced facies that were recognized by the occurrence of marine ichnofauna, bimodal paleocurrent measurements, tidal accreationary sandbar units and strata containing abundant mud laminations. This is capped by facies (Fm) and (Fsm) of the lower Hell Creek Formation that represent rapid

marine flooding of the valley and interfluves and the occurrence of the maximum flooding surface.

These lowstand and transgressive systems tract valley-fill strata are deposited during a 3rd order relative sea-level cycle that correlate to Haq et al.ôs (1987) UZA-4.5 depositional sequence lasting approximately 1 Ma, coincidently considered the last sequence of the Zuni transgression. There is also sub-surface and field evidence that regional subsidence (the Blood Creek syncline) and local subsidence along the Plum Creek lineament were significant in determining the location of the valley system and potentially increasing accommodation beyond that created by fluvial incision alone.

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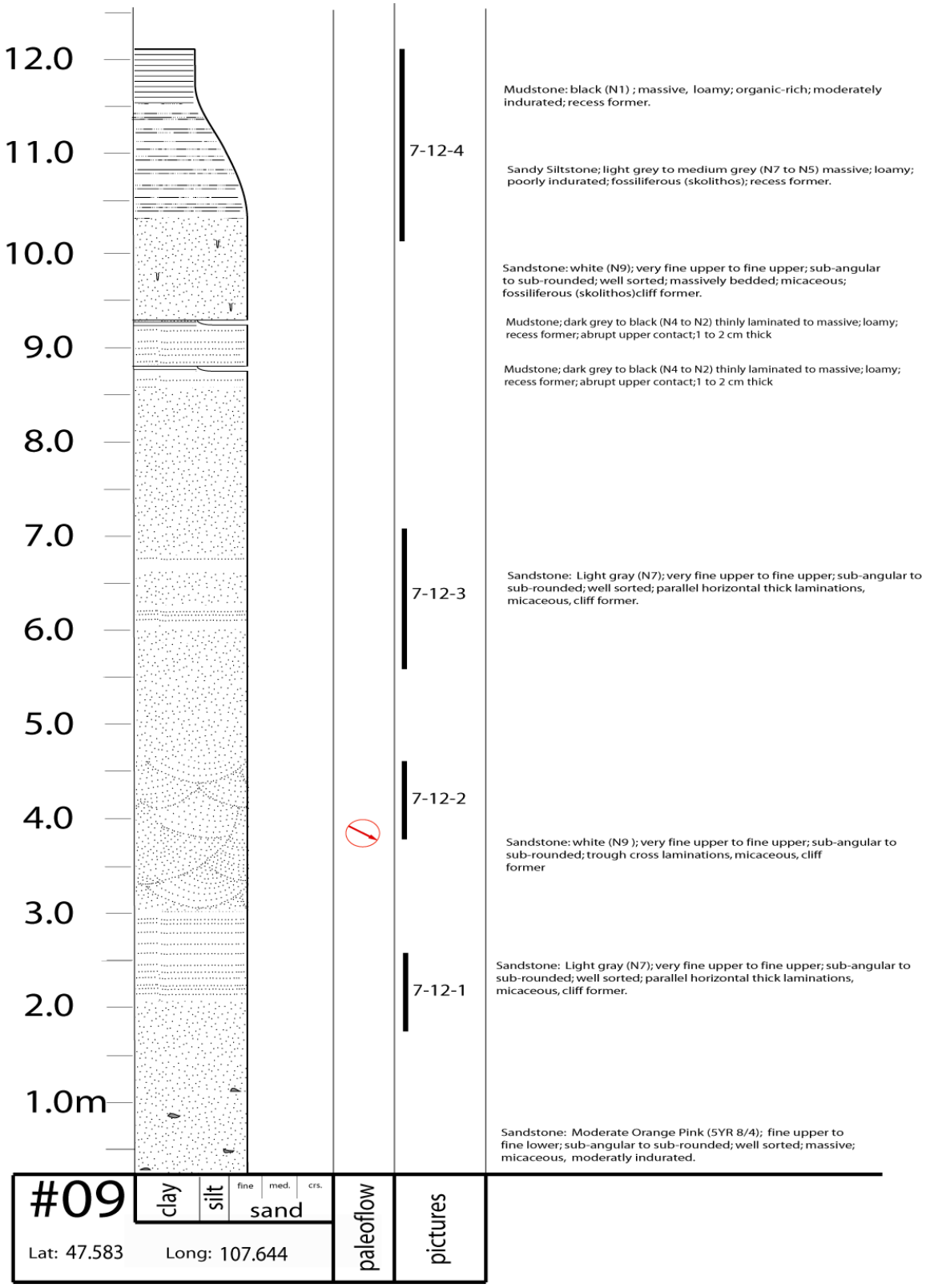
APPENDICES

APPENDIX A

STRATIGRAPHIC MEASURED SECTIONS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Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; fossiliferous (skolithos); recess former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded; micaceous; fossiliferous (skolithos)cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Sandstone: Light gray (N7); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; parallel horizontal thick laminations, micaceous, cliff former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former
Sandstone: Light gray (N7); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; parallel horizontal thick laminations, micaceous, cliff former.
Sandstone: Moderate Orange Pink (5YR 8/4); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive; micaceous, moderatly indurated.
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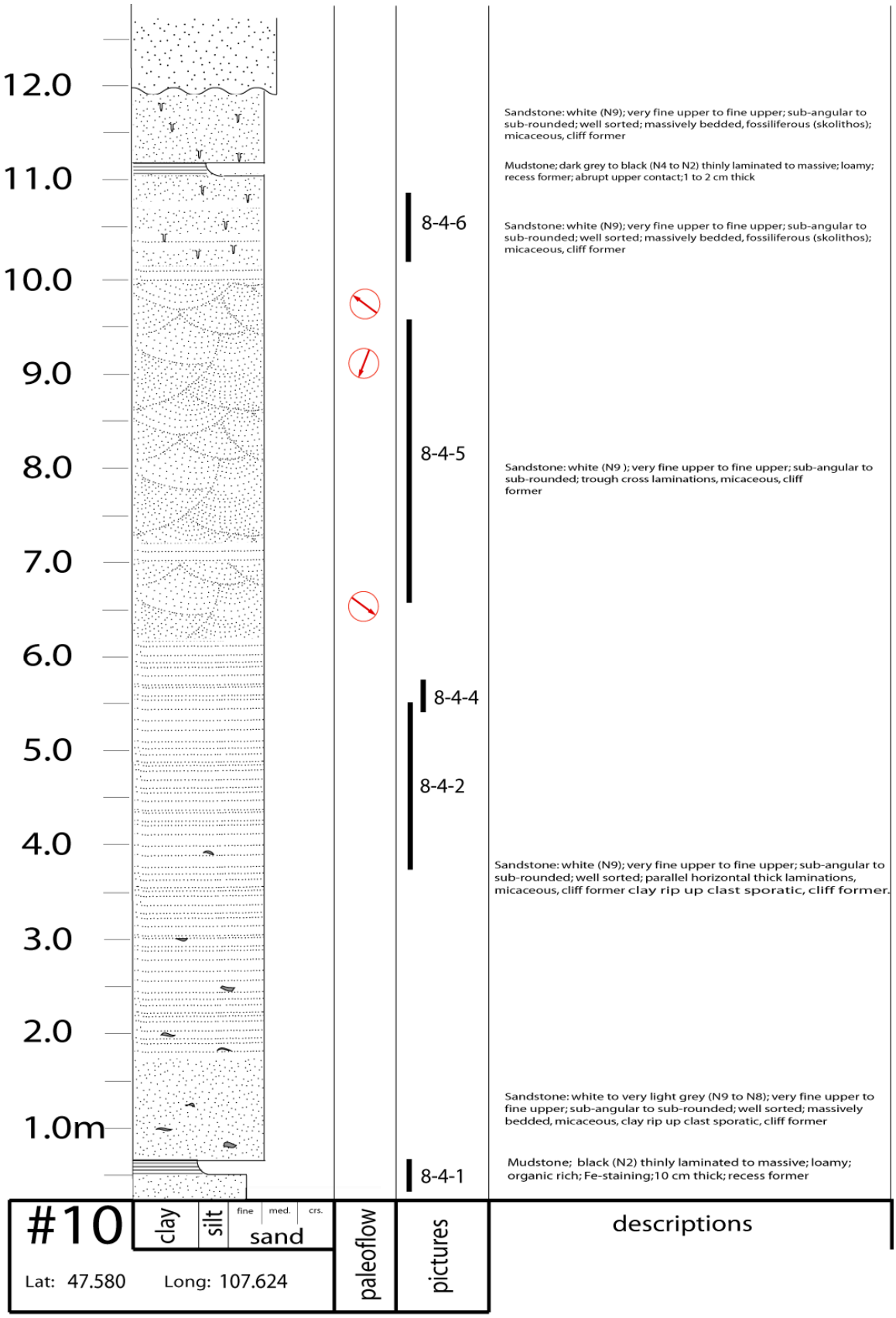
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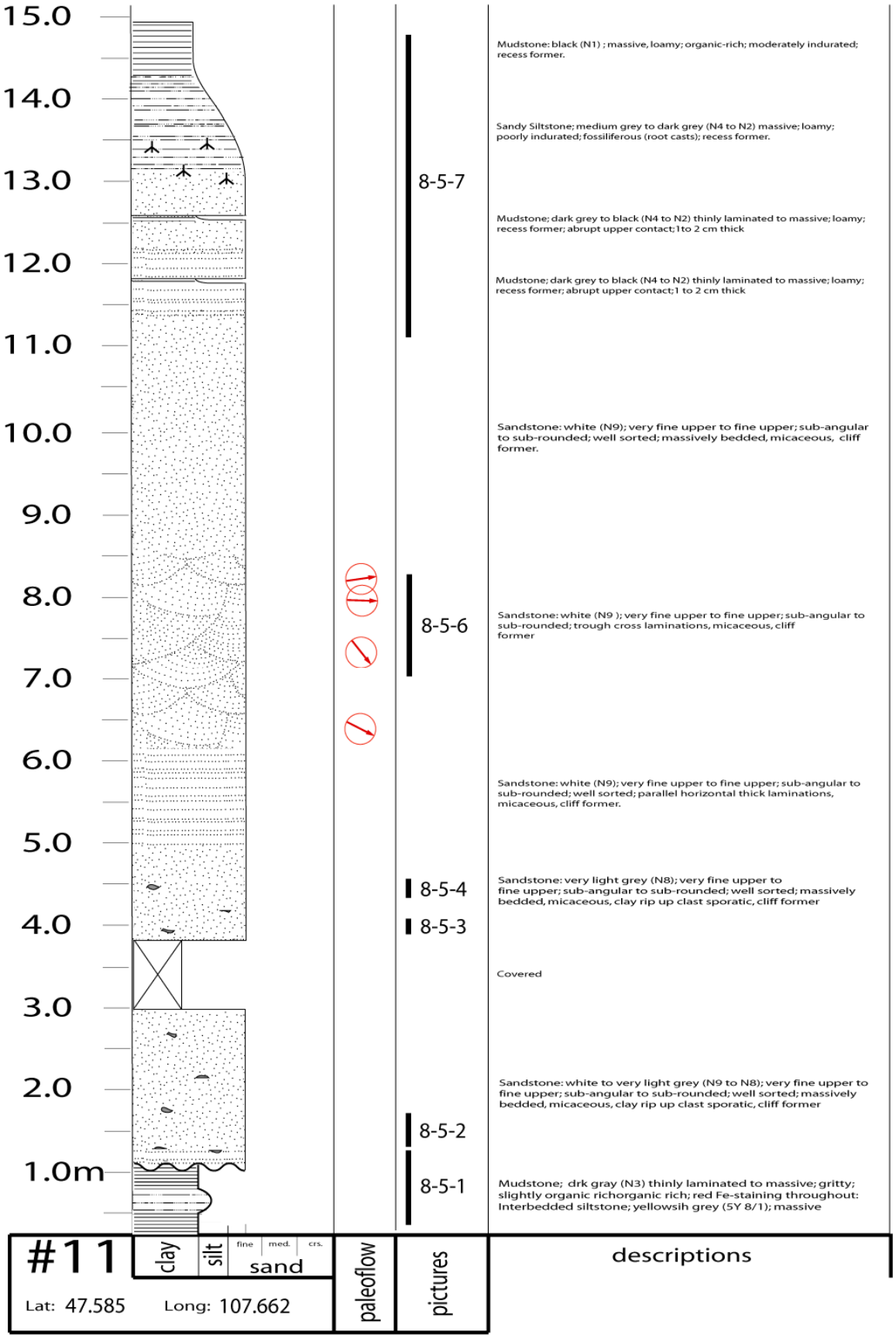
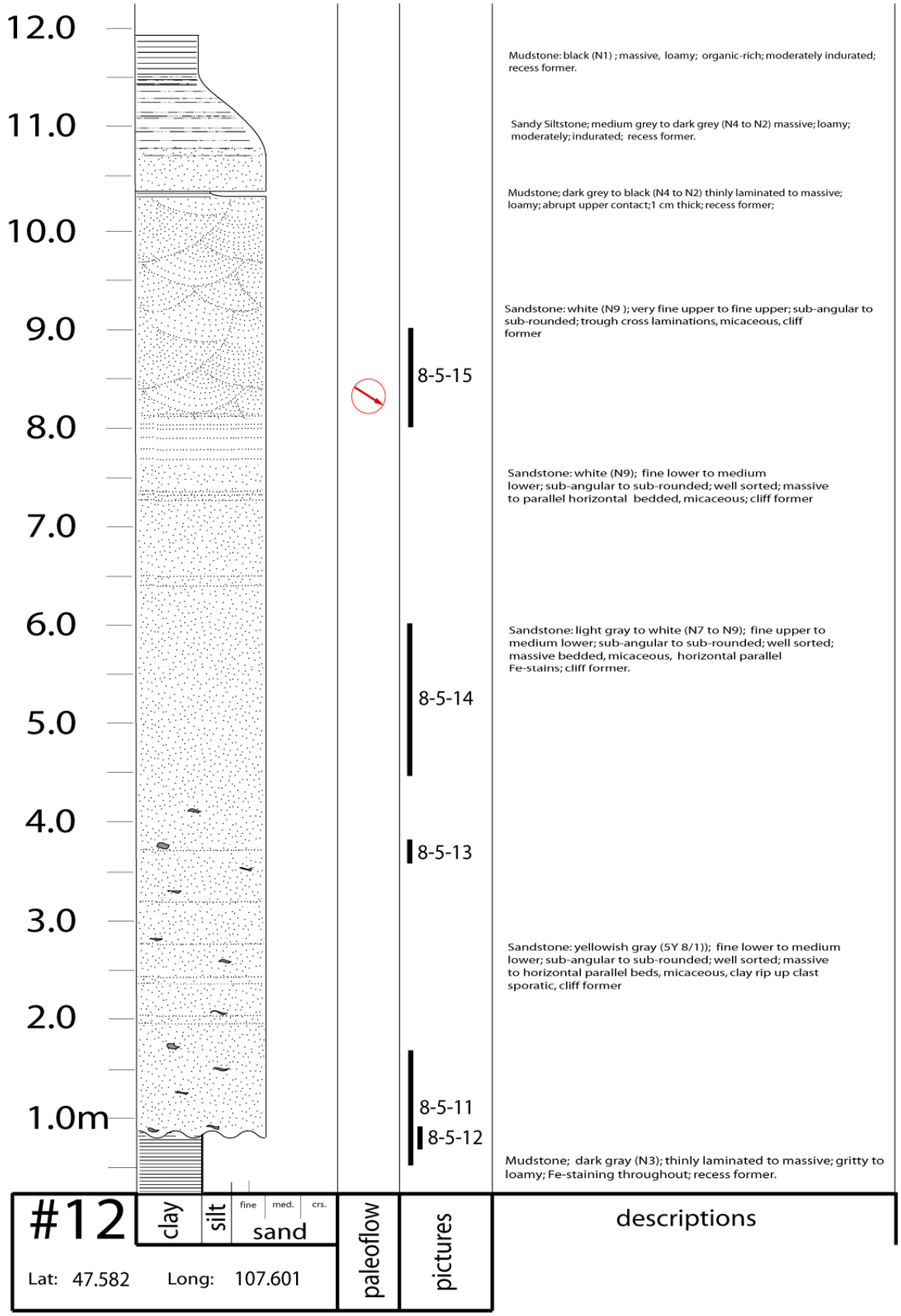
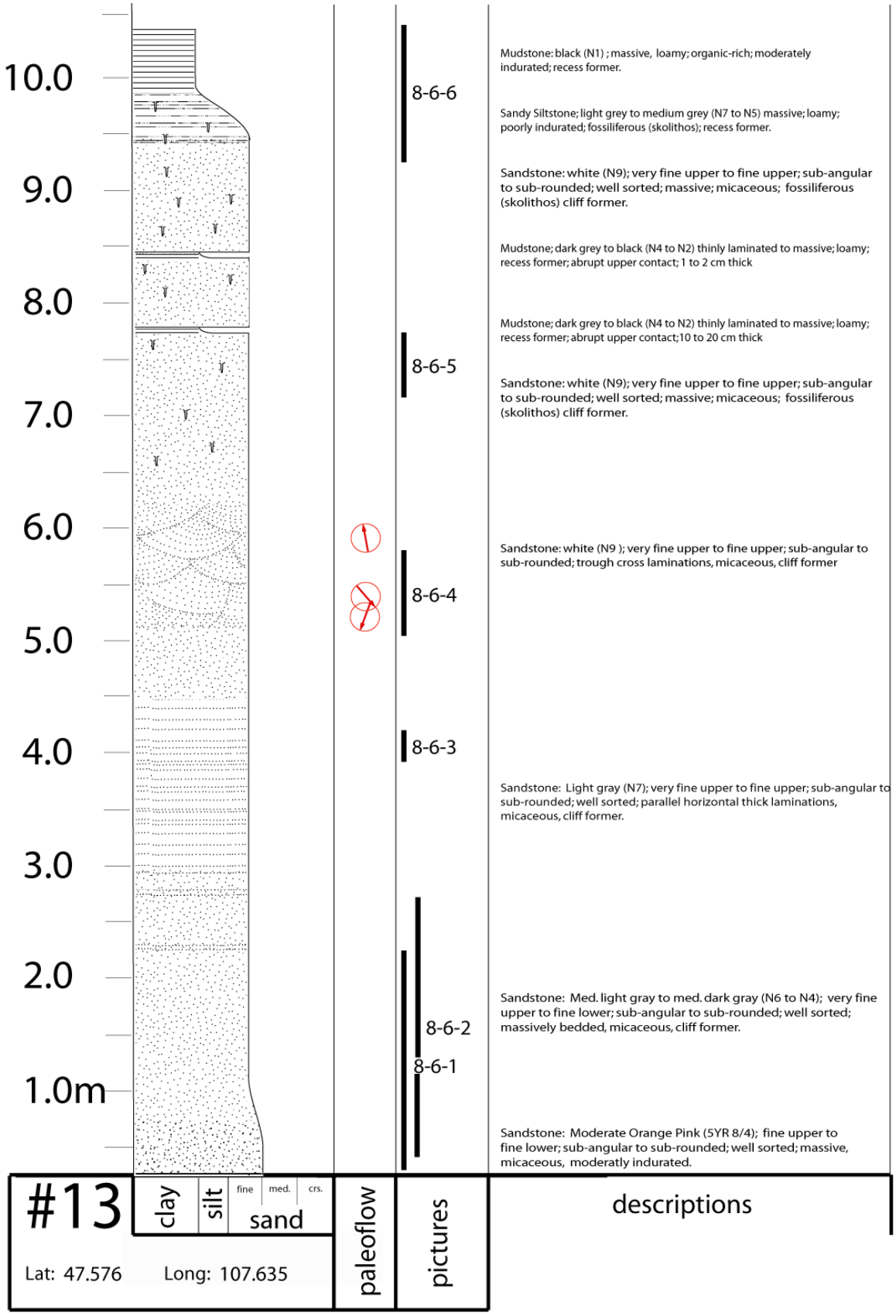
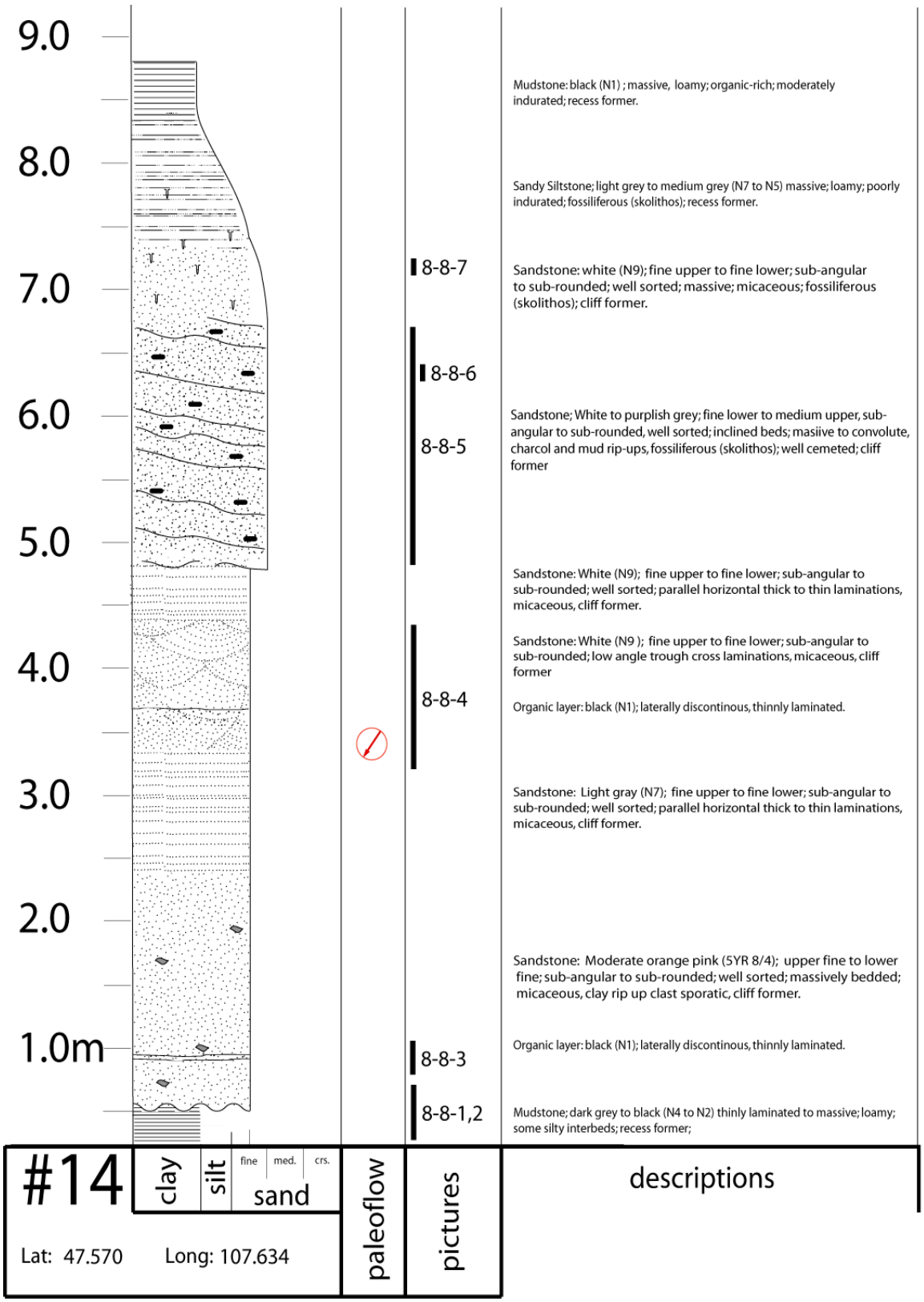
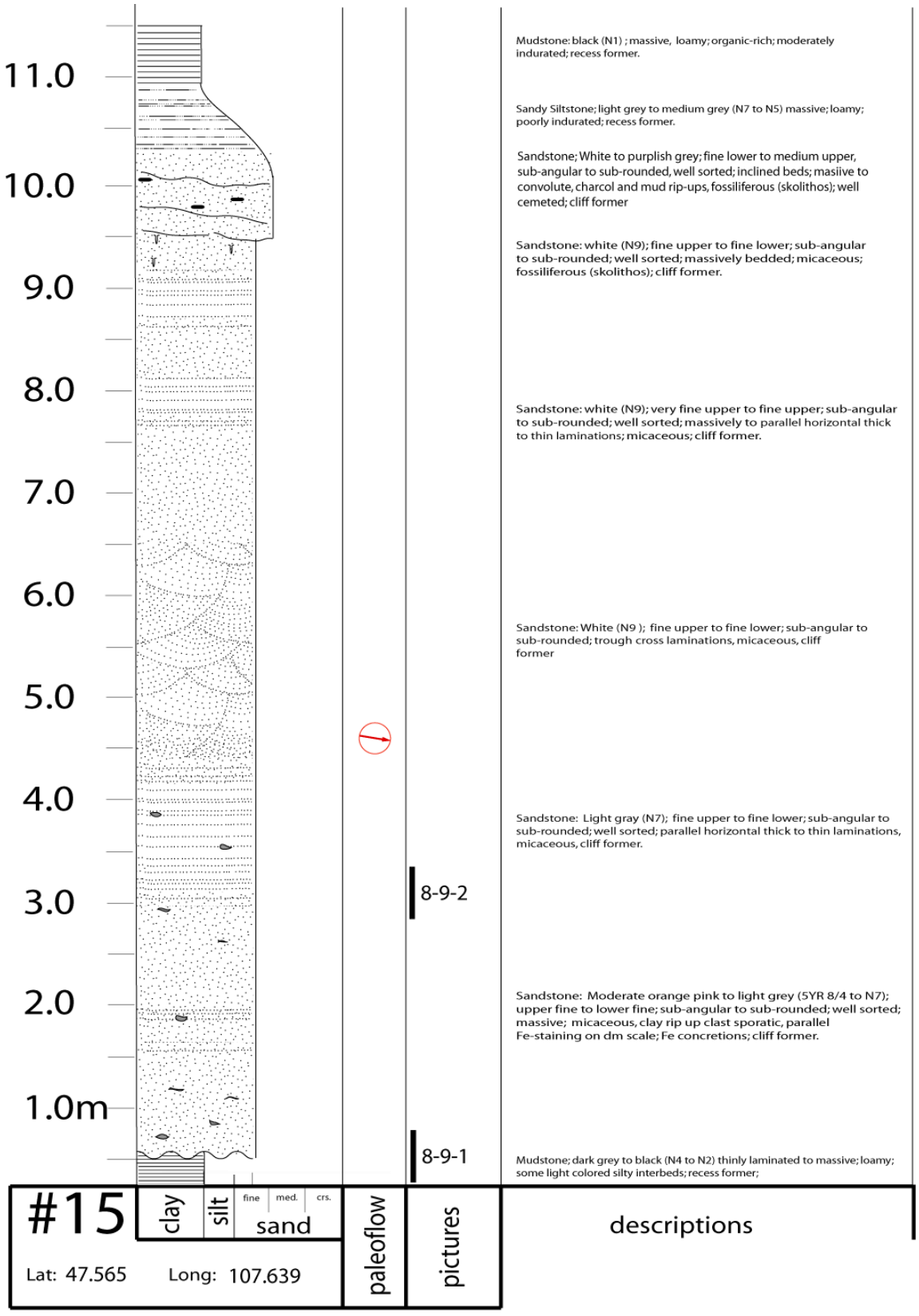
8-4-4
8-4-2
8-4-1
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded, fossiliferous (skolithos); micaceous, cliff former
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded, fossiliferous (skolithos); micaceous, cliff former
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; parallel horizontal thick laminations, micaceous, cliff former clay rip up clast sporatic, cliff former.
Sandstone: white to very light grey (N9 to N8); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded, micaceous, clay rip up clast sporatic, cliff former
Mudstone; black (N2) thinly laminated to massive; loamy; organic rich; Fe-staining;10 cm thick; recess former
#10
clay
silt
fine
med.
crs.
sand
Lat: 47.580
Long: 107.624
paleoflow
pictures
descriptions

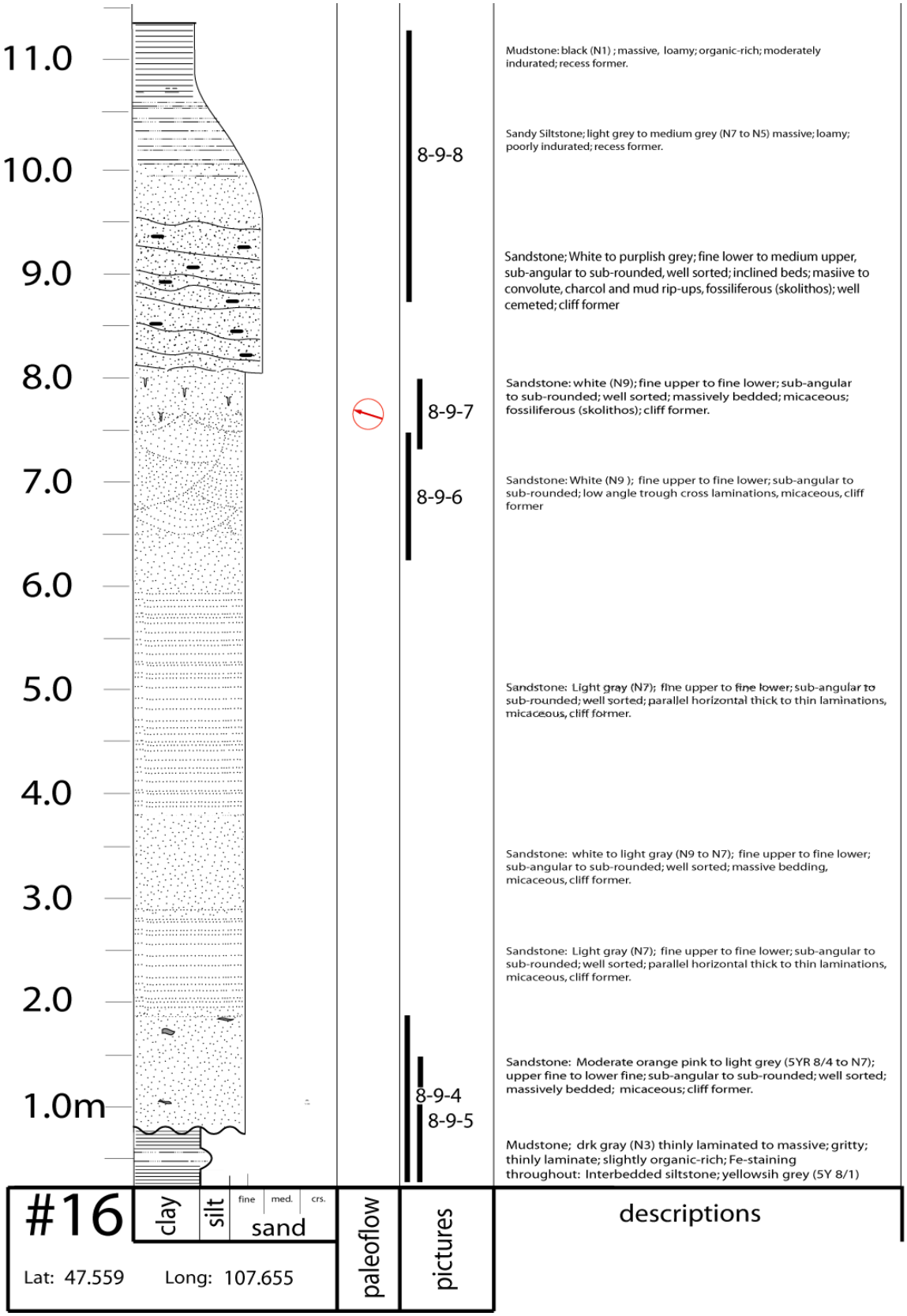

15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#11
clay
silt
fine
med.
crs.
sand
Lat: 47.585
Long: 107.662
paleoflow
pictures
descriptions
8-5-7
8-5-6
8-5-4
8-5-3
8-5-2
8-5-1
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; poorly indurated; fossiliferous (root casts); recess former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1to 2 cm thick
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded, micaceous, cliff former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; parallel horizontal thick laminations, micaceous, cliff former.
Sandstone: very light grey (N8); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded, micaceous, clay rip up clast sporatic, cliff former
Covered
Sandstone: white to very light grey (N9 to N8); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively bedded, micaceous, clay rip up clast sporatic, cliff former
Mudstone; drk gray (N3) thinly laminated to massive; gritty; slightly organic richorganic rich; red Fe-staining throughout: Interbedded siltstone; yellowsih grey (5Y 8/1); massive

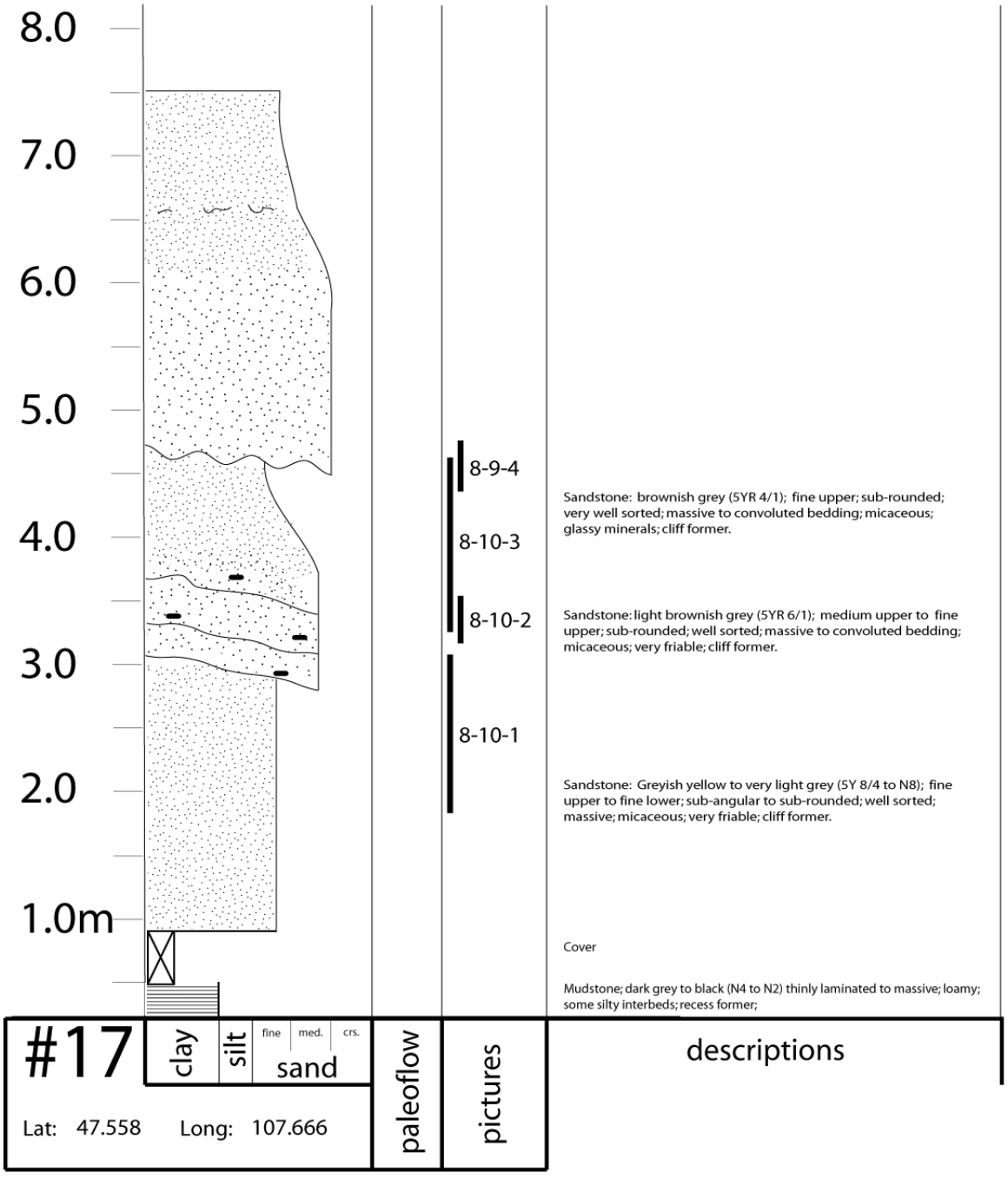

12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-5-15
8-5-14
8-5-13
8-5-11
8-5-12
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately; indurated; recess former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; abrupt upper contact;1 cm thick; recess former;
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former
Sandstone: white (N9); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to parallel horizontal bedded, micaceous; cliff former
Sandstone: light gray to white (N7 to N9); fine upper to medium lower; sub-angular to sub-rounded; well sorted; massive bedded, micaceous, horizontal parallel Fe-stains; cliff former.
Sandstone: yellowish gray (5Y 8/1)); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel beds, micaceous, clay rip up clast sporatic, cliff former
Mudstone; dark gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.
#12
clay
silt
fine
med.
crs.
sand
Lat: 47.582
Long: 107.601
paleoflow
pictures
descriptions

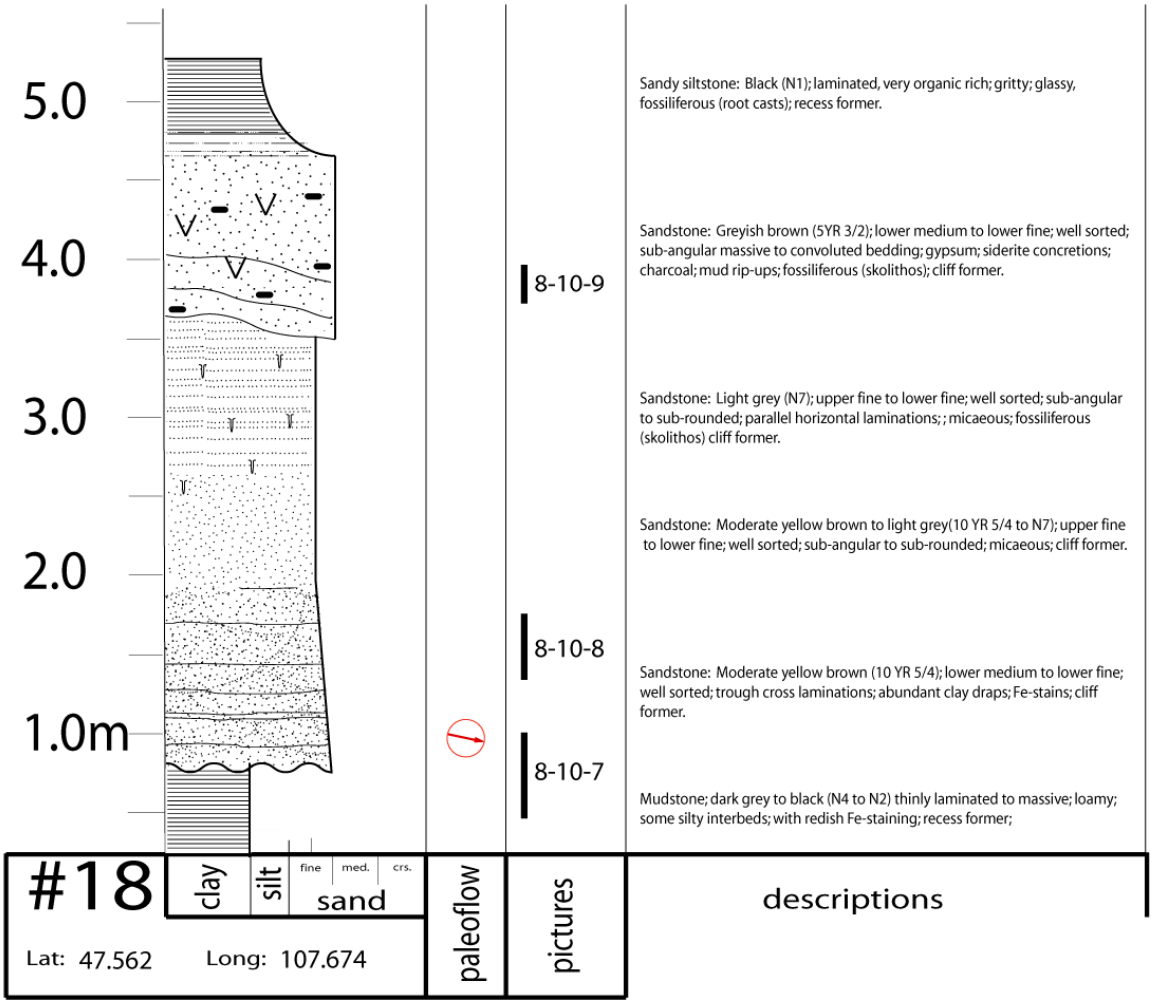

10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-6-6
8-6-5
8-6-4
8-6-3
8-6-2
8-6-1
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; fossiliferous (skolithos); recess former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massive; micaceous; fossiliferous (skolithos) cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact; 1 to 2 cm thick
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;10 to 20 cm thick
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massive; micaceous; fossiliferous (skolithos) cliff former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former
Sandstone: Light gray (N7); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; parallel horizontal thick laminations, micaceous, cliff former.
Sandstone: Med. light gray to med. dark gray (N6 to N4); very fine upper to fine lower; sub-angular to sub-rounded; well sorted; massively bedded, micaceous, cliff former.
Sandstone: Moderate Orange Pink (5YR 8/4); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive, micaceous, moderatly indurated.
#13
clay
silt
fine
med.
crs.
sand
Lat: 47.576
Long: 107.635
paleoflow
pictures
descriptions

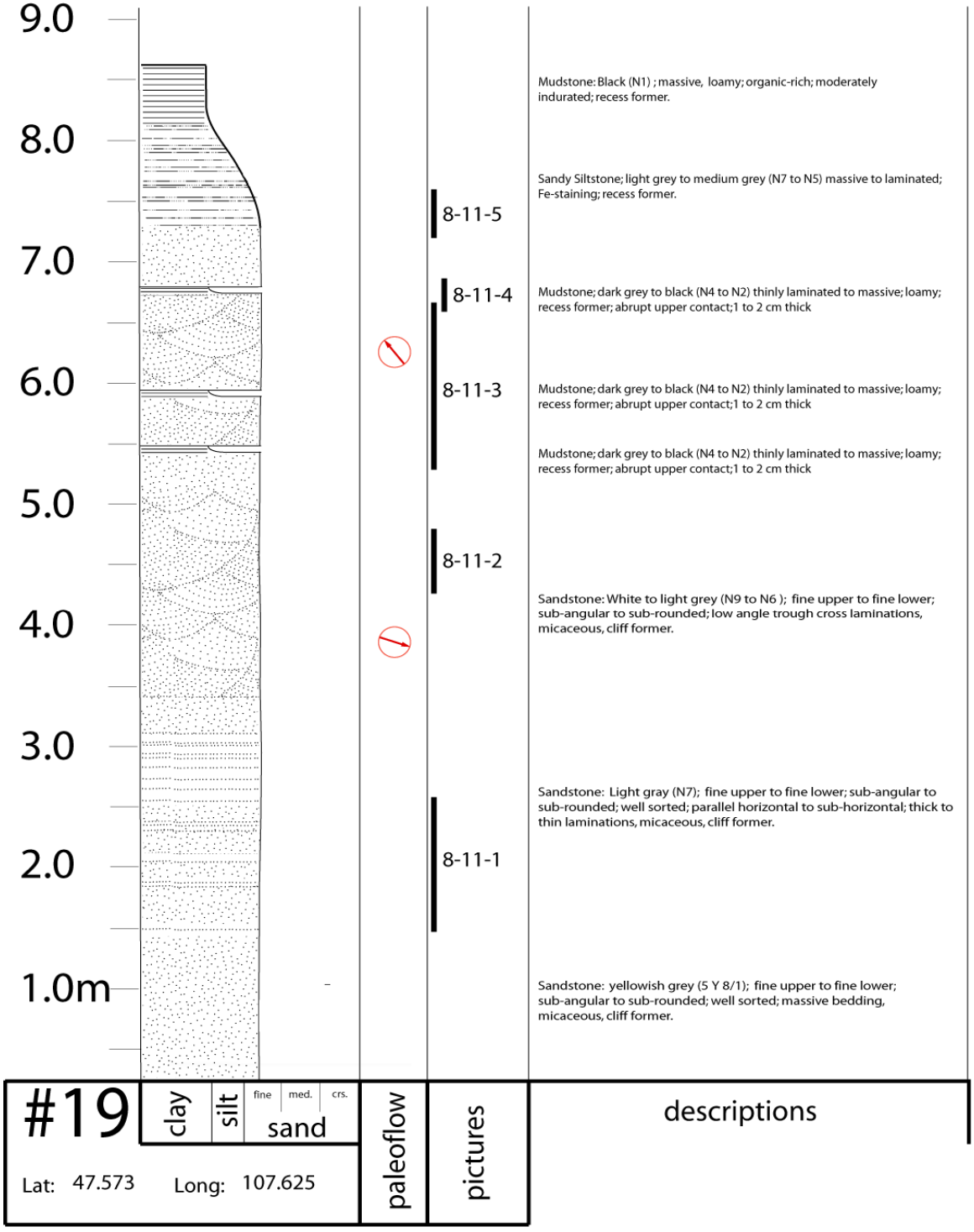

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#14
clay
silt
fine
med.
crs.
sand
Lat: 47.570
Long: 107.634
paleoflow
pictures
descriptions
8-8-7
8-8-6
8-8-5
8-8-4
8-8-3
8-8-1,2
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; fossiliferous (skolithos); recess former.
Sandstone: white (N9); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive; micaceous; fossiliferous (skolithos); cliff former.
Sandstone; White to purplish grey; fine lower to medium upper, sub-angular to sub-rounded, well sorted; inclined beds; masiive to convolute, charcol and mud rip-ups, fossiliferous (skolithos); well cemeted; cliff former
Sandstone: White (N9); fine upper to fine lower; sub-angular to sub-rounded; well sorted; parallel horizontal thick to thin laminations, micaceous, cliff former.
Sandstone: White (N9); fine upper to fine lower; sub-angular to sub-rounded; low angle trough cross laminations, micaceous, cliff former
Organic layer: black (N1); laterally discontinous, thinnly laminated.
Sandstone: Light gray (N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; parallel horizontal thick to thin laminations, micaceous, cliff former.
Sandstone: Moderate orange pink (5YR 8/4); upper fine to lower fine; sub-angular to sub-rounded; well sorted; massively bedded; micaceous, clay rip up clast sporatic, cliff former.
Organic layer: black (N1); laterally discontinous, thinnly laminated.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; some silty interbeds; recess former;

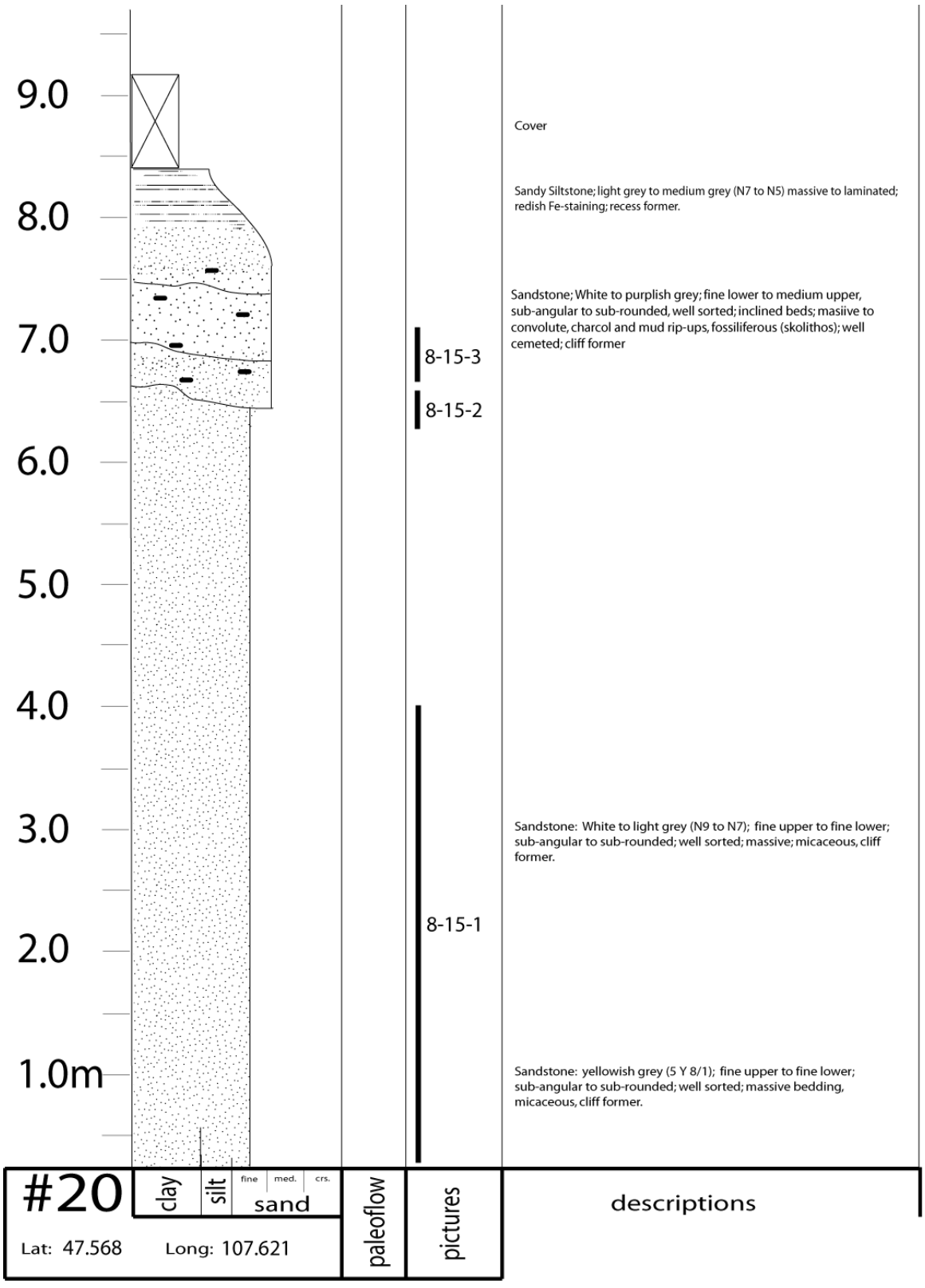

11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-9-2
8-9-1
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; recess former.
Sandstone; White to purplish grey; fine lower to medium upper, sub-angular to sub-rounded, well sorted; inclined beds; masiive to convolute, charcol and mud rip-ups, fossiliferous (skolithos); well cemeted; cliff former
Sandstone: white (N9); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massively bedded; micaceous; fossiliferous (skolithos); cliff former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; massively to parallel horizontal thick to thin laminations; micaceous; cliff former.
Sandstone: White (N9); fine upper to fine lower; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former
Sandstone: Light gray (N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; parallel horizontal thick to thin laminations, micaceous, cliff former.
Sandstone: Moderate orange pink to light grey (5YR 8/4 to N7); upper fine to lower fine; sub-angular to sub-rounded; well sorted; massive; micaceous, clay rip up clast sporatic, parallel Fe-staining on dm scale; Fe concretions; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; some light colored silty interbeds; recess former;
#15
clay
silt
fine
med.
crs.
sand
Lat: 47.565
Long: 107.639
paleoflow
pictures
descriptions

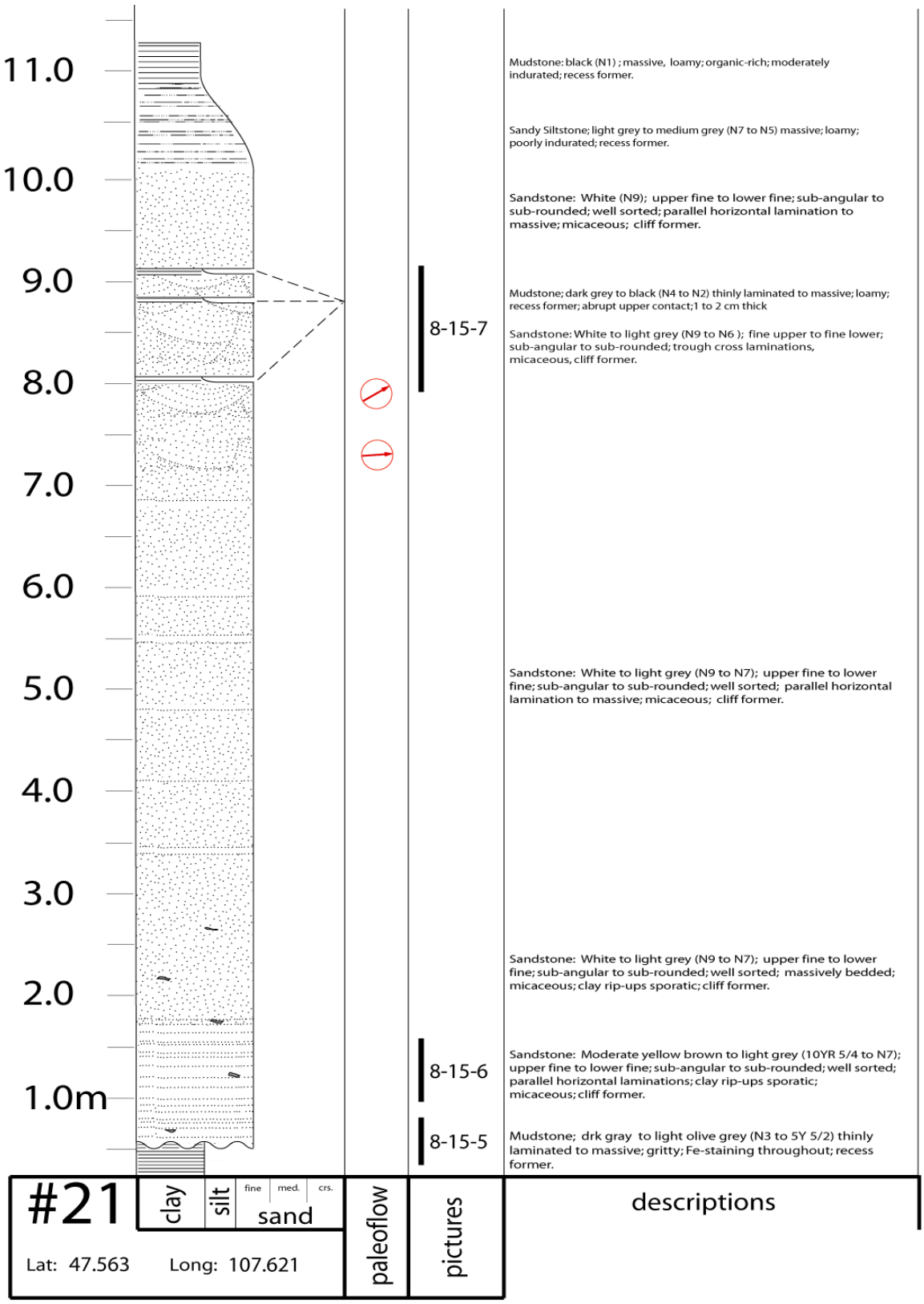

11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-9-8
8-9-7
8-9-6
8-9-4
8-9-5
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; recess former.
Sandstone; White to purplish grey; fine lower to medium upper, sub-angular to sub-rounded, well sorted; inclined beds; masiive to convolute, charcol and mud rip-ups, fossiliferous (skolithos); well cemeted; cliff former
Sandstone: white (N9); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massively bedded; micaceous; fossiliferous (skolithos); cliff former.
Sandstone: White (N9); fine upper to fine lower; sub-angular to sub-rounded; low angle trough cross laminations, micaceous, cliff former
Sandstone: Light gray (N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; parallel horizontal thick to thin laminations, micaceous, cliff former.
Sandstone: white to light gray (N9 to N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive bedding, micaceous, cliff former.
Sandstone: Light gray (N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; parallel horizontal thick to thin laminations, micaceous, cliff former.
Sandstone: Moderate orange pink to light grey (5YR 8/4 to N7); upper fine to lower fine; sub-angular to sub-rounded; well sorted; massively bedded; micaceous; cliff former.
Mudstone; drk gray (N3) thinly laminated to massive; gritty; thinly laminate; slightly organic-rich; Fe-staining throughout: Interbedded siltstone; yellowsih grey (5Y 8/1)
#16
clay
silt
fine
med.
crs.
sand
Lat: 47.559
Long: 107.655
paleoflow
pictures
descriptions

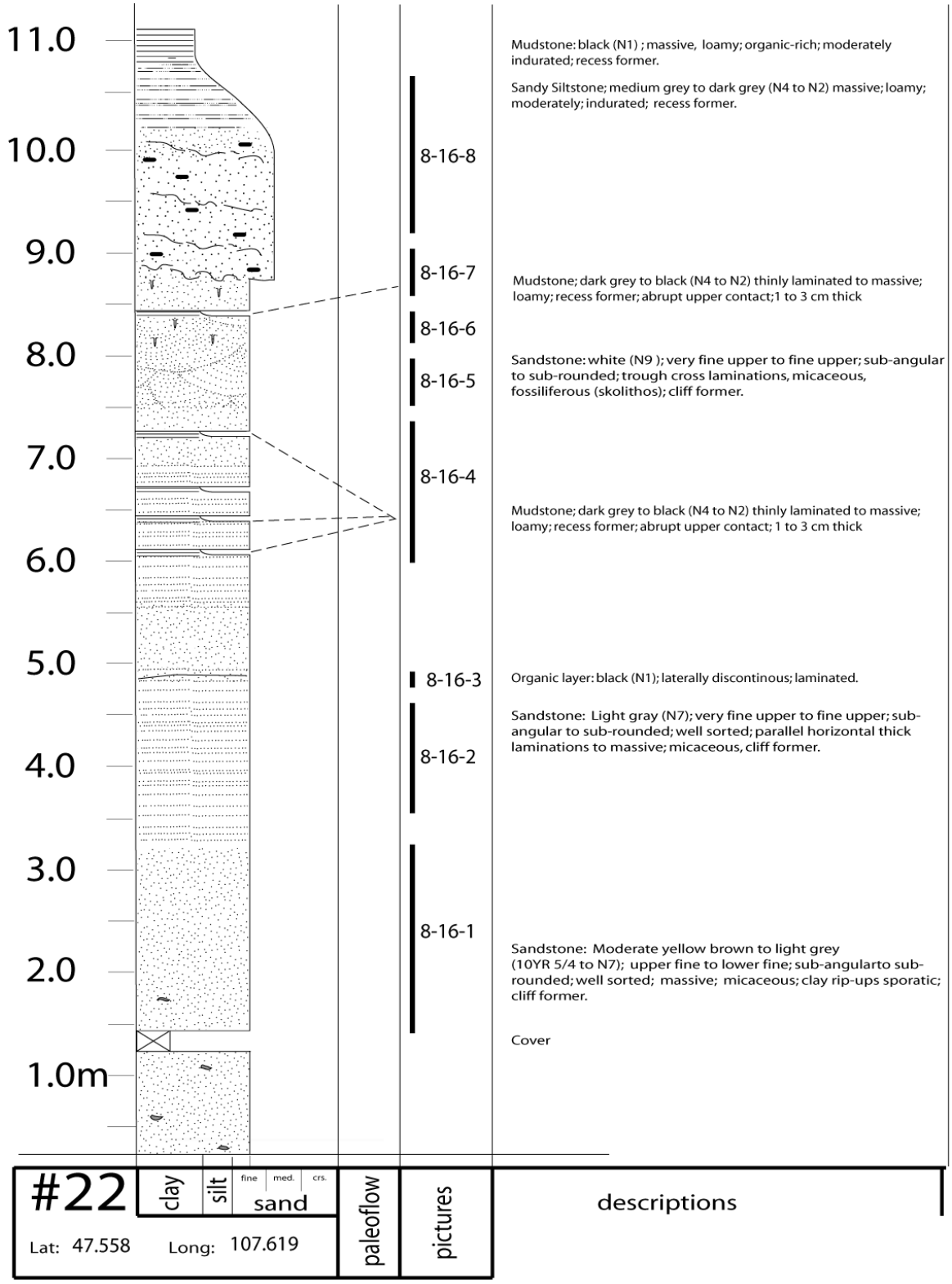

8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-9-4
8-10-3
8-10-2
8-10-1
Sandstone: brownish grey (5YR 4/1); fine upper; sub-rounded; very well sorted; massive to convoluted bedding; micaceous; glassy minerals; cliff former.
Sandstone: light brownish grey (5YR 6/1); medium upper to fine upper; sub-rounded; well sorted; massive to convoluted bedding; micaceous; very friable; cliff former.
Sandstone: Greyish yellow to very light grey (5Y 8/4 to N8); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive; micaceous; very friable; cliff former.
Cover
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; some silty interbeds; recess former;
#17
clay
silt
fine
med.
crs.
sand
Lat: 47.558
Long: 107.666
paleoflow
pictures
descriptions

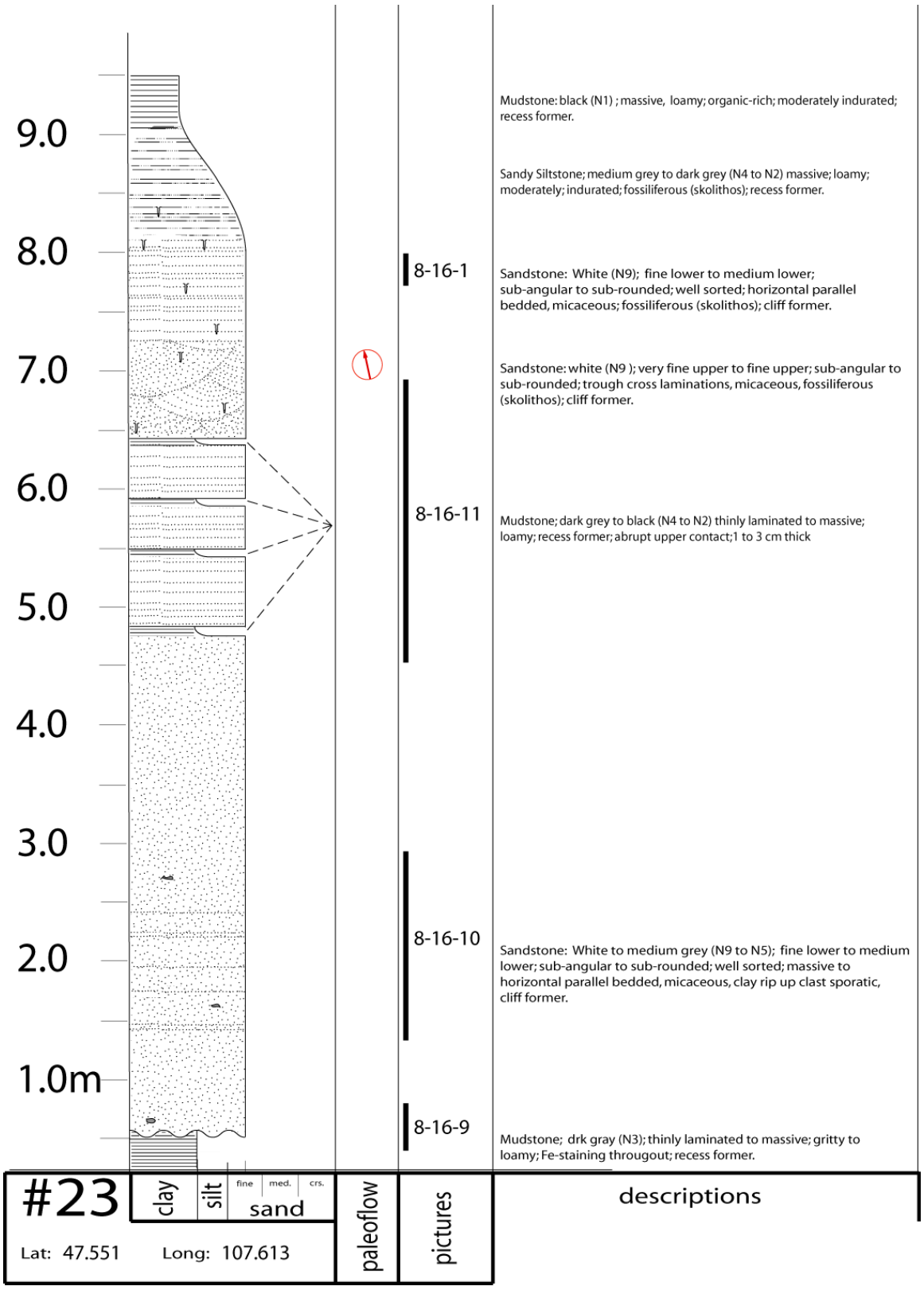

5.0
4.0
3.0
2.0
1.0m
#18
clay
silt
fine
med.
crs.
sand
Lat: 47.562
Long: 107.674
paleoflow
pictures
descriptions
8-10-9
8-10-8
8-10-7
Sandy siltstone: Black (N1); laminated, very organic rich; gritty; glassy, fossiliferous (root casts); recess former.
Sandstone: Greyish brown (5YR 3/2); lower medium to lower fine; well sorted; sub-angular massive to convoluted bedding; gypsum; siderite concretions; charcoal; mud rip-ups; fossiliferous (skolithos); cliff former.
Sandstone: Light grey (N7); upper fine to lower fine; well sorted; sub-angular to sub-rounded; parallel horizontal laminations; ; micaeous; fossiliferous (skolithos) cliff former.
Sandstone: Moderate yellow brown to light grey(10 YR 5/4 to N7); upper fine to lower fine; well sorted; sub-angular to sub-rounded; micaeous; cliff former.
Sandstone: Moderate yellow brown (10 YR 5/4); lower medium to lower fine; well sorted; trough cross laminations; abundant clay draps; Fe-stains; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; some silty interbeds; with redish Fe-staining; recess former;

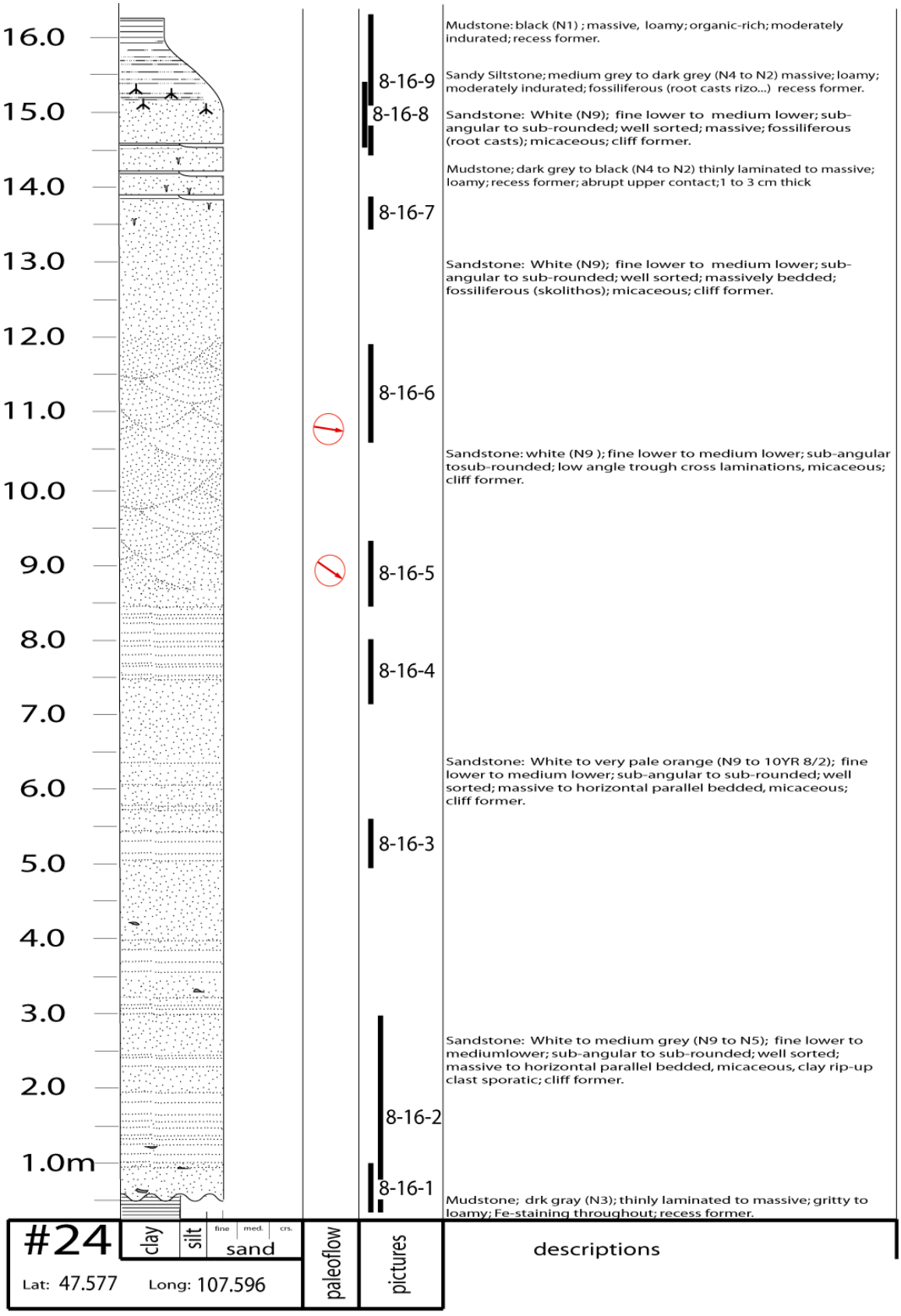

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#19
clay
silt
fine
med.
crs.
sand
Lat: 47.573
Long: 107.625
paleoflow
pictures
descriptions
8-11-5
8-11-4
8-11-3
8-11-2
8-11-1
Mudstone: Black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive to laminated; Fe-staining; recess former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Sandstone: White to light grey (N9 to N6); fine upper to fine lower; sub-angular to sub-rounded; low angle trough cross laminations, micaceous, cliff former.
Sandstone: Light gray (N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; parallel horizontal to sub-horizontal; thick to thin laminations, micaceous, cliff former.
Sandstone: yellowish grey (5 Y 8/1); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive bedding, micaceous, cliff former.

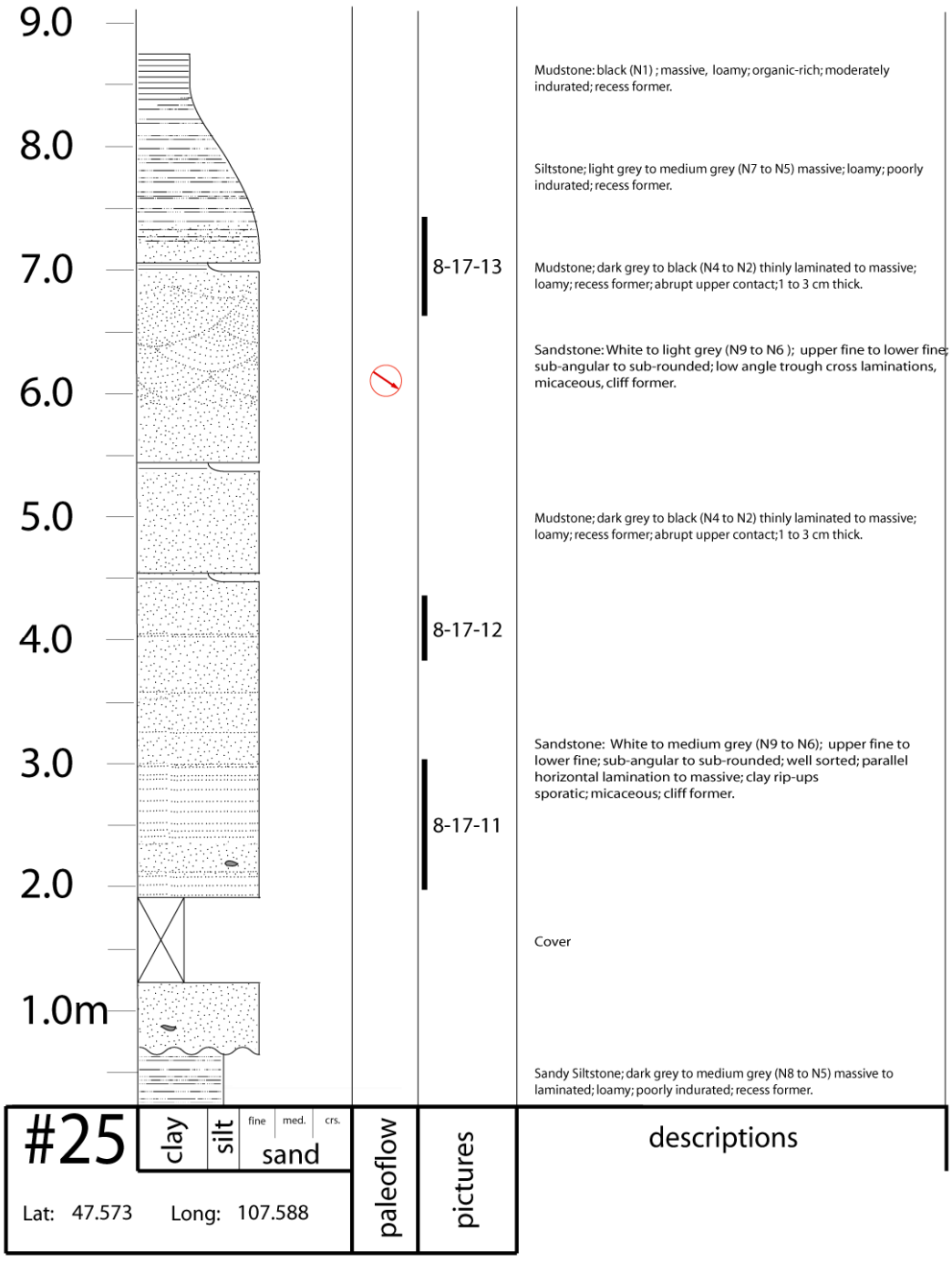

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-15-3
8-15-2
8-15-1
Cover
Sandy Siltstone; light grey to medium grey (N7 to N5) massive to laminated; redish Fe-staining; recess former.
Sandstone; White to purplish grey; fine lower to medium upper, sub-angular to sub-rounded, well sorted; inclined beds; masiive to convolute, charcol and mud rip-ups, fossiliferous (skolithos); well cemeted; cliff former
Sandstone: White to light grey (N9 to N7); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive; micaceous, cliff former.
Sandstone: yellowish grey (5 Y 8/1); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive bedding, micaceous, cliff former.
#20
clay
silt
fine
med.
crs.
sand
Lat: 47.568
Long: 107.621
paleoflow
pictures
descriptions

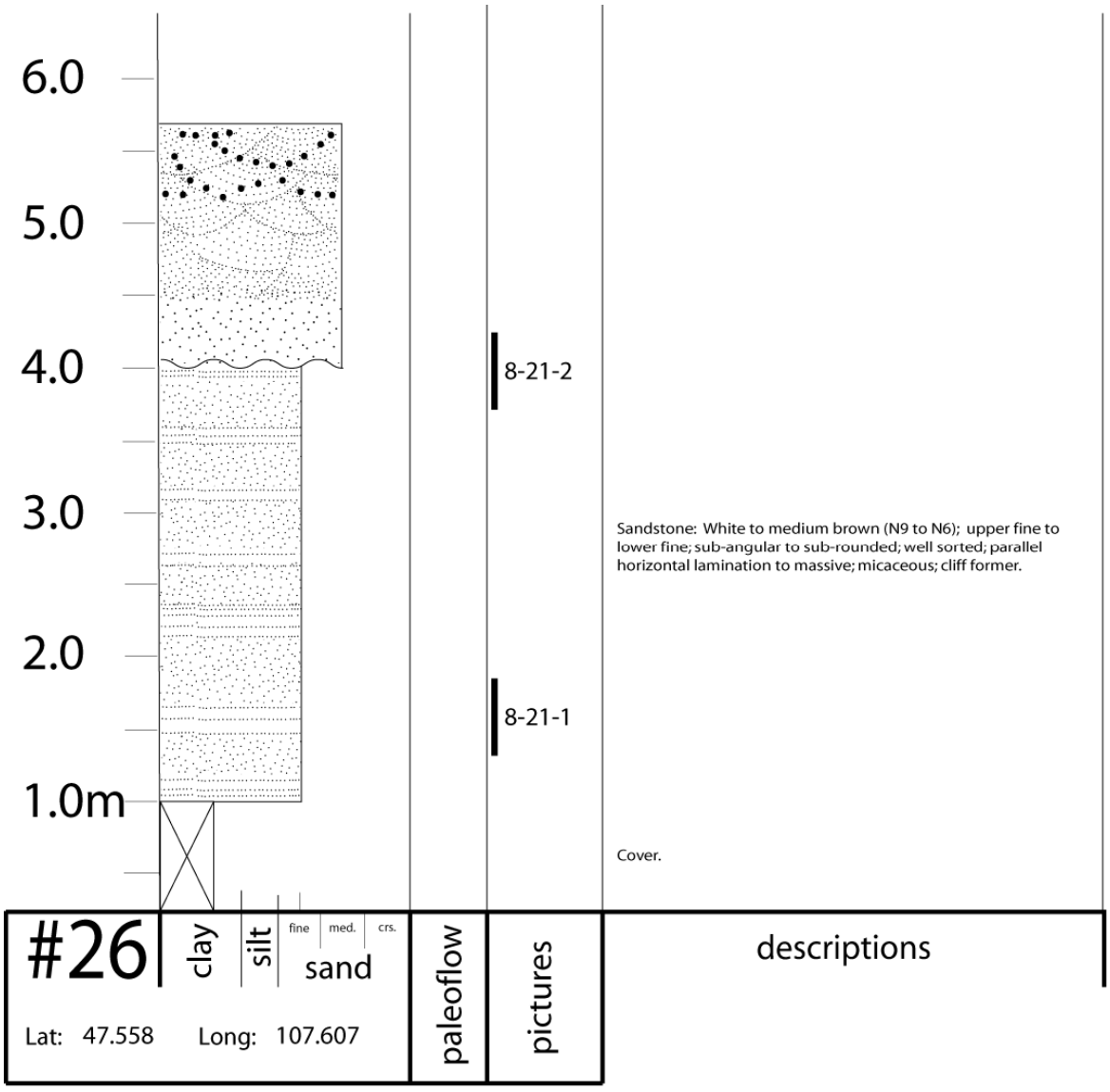

11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#21
clay
silt
fine
med.
crs.
sand
Lat: 47.563
Long: 107.621
paleoflow
pictures
descriptions
8-15-7
8-15-6
8-15-5
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; recess former.
Sandstone: White (N9); upper fine to lower fine; sub-angular to sub-rounded; well sorted; parallel horizontal lamination to massive; micaceous; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 2 cm thick
Sandstone: White to light grey (N9 to N6); fine upper to fine lower; sub-angular to sub-rounded; trough cross laminations, micaceous, cliff former.
Sandstone: White to light grey (N9 to N7); upper fine to lower fine; sub-angular to sub-rounded; well sorted; parallel horizontal lamination to massive; micaceous; cliff former.
Sandstone: White to light grey (N9 to N7); upper fine to lower fine; sub-angular to sub-rounded; well sorted; massively bedded; micaceous; clay rip-ups sporatic; cliff former.
Sandstone: Moderate yellow brown to light grey (10YR 5/4 to N7); upper fine to lower fine; sub-angular to sub-rounded; well sorted; parallel horizontal laminations; clay rip-ups sporatic; micaceous; cliff former.
Mudstone; drk gray to light olive grey (N3 to 5Y 5/2) thinly laminated to massive; gritty; Fe-staining throughout; recess former.

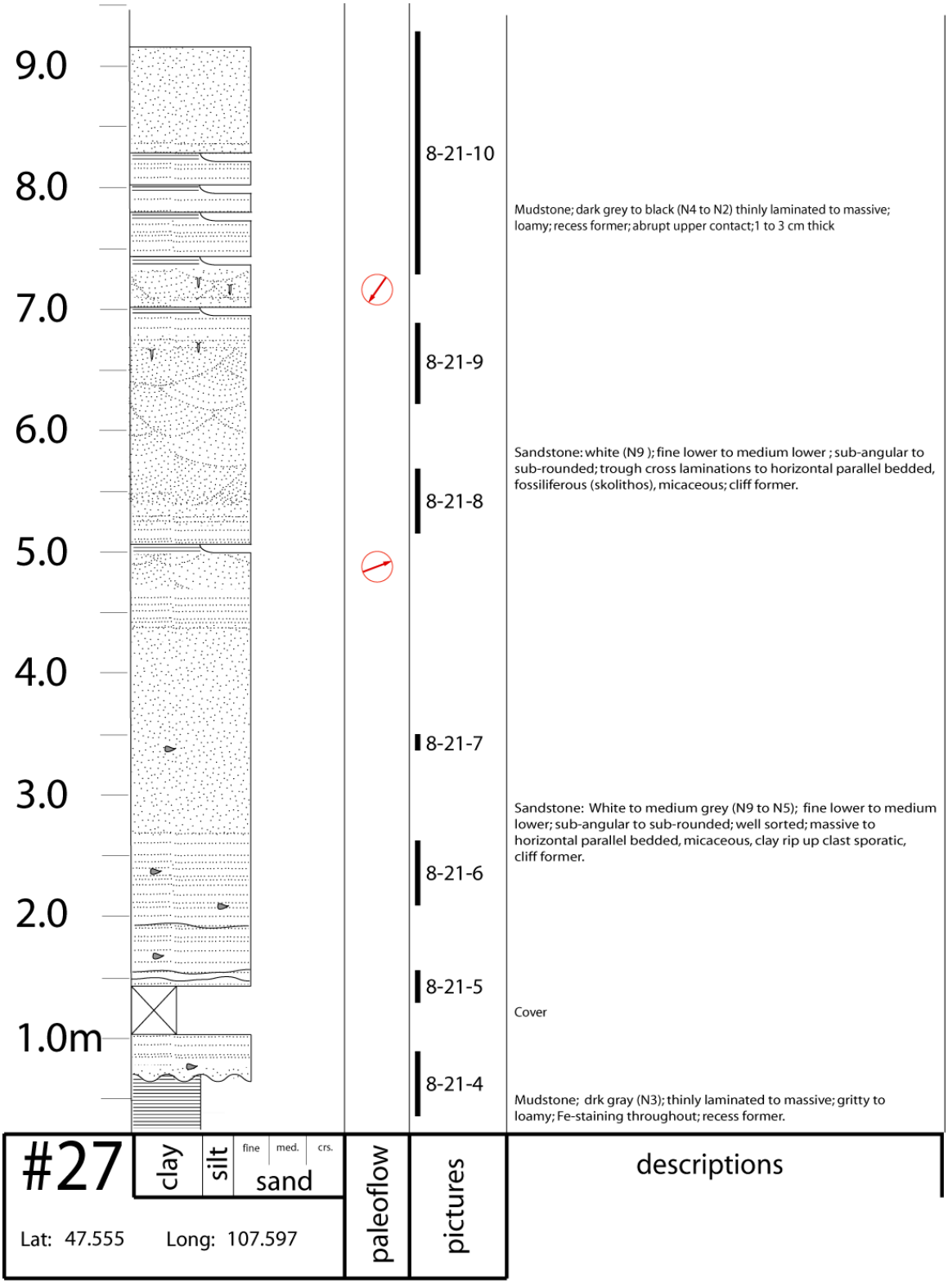

11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-16-8
8-16-7
8-16-6
8-16-5
8-16-4
8-16-3
8-16-2
8-16-1
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately; indurated; recess former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, fossiliferous (skolithos); cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact; 1 to 3 cm thick
Organic layer: black (N1); laterally discontinous; laminated.
Sandstone: Light gray (N7); very fine upper to fine upper; sub-angular to sub-rounded; well sorted; parallel horizontal thick laminations to massive; micaceous, cliff former.
Sandstone: Moderate yellow brown to light grey (10YR 5/4 to N7); upper fine to lower fine; sub-angularto sub-rounded; well sorted; massive; micaceous; clay rip-ups sporatic; cliff former.
Cover
#22
Lat: 47.558
Long: 107.619
clay
silt
fine
med.
crs.
sand
paleoflow
pictures
descriptions

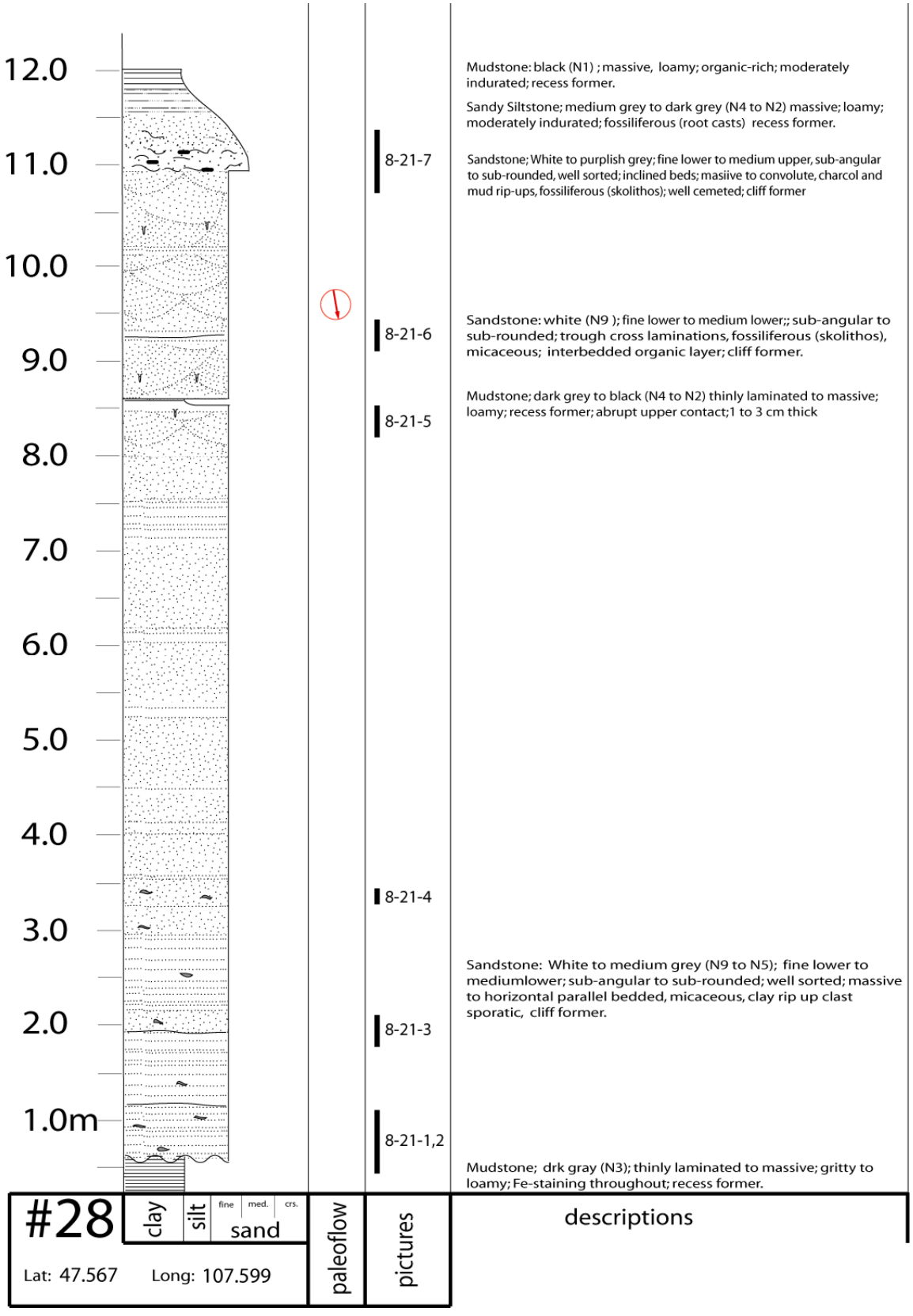

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#23
clay
silt
fine
med.
crs.
sand
Lat: 47.551
Long: 107.613
paleoflow
pictures
descriptions
8-16-1
8-16-11
8-16-10
8-16-9
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately; indurated; fossiliferous (skolithos); recess former.
Sandstone: White (N9); fine lower to medium lower; sub-angular to sub-rounded; well sorted; horizontal parallel bedded, micaceous; fossiliferous (skolithos); cliff former.
Sandstone: white (N9); very fine upper to fine upper; sub-angular to sub-rounded; trough cross laminations, micaceous, fossiliferous (skolithos); cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: White to medium grey (N9 to N5); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip up clast sporatic, cliff former.
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining througout; recess former.

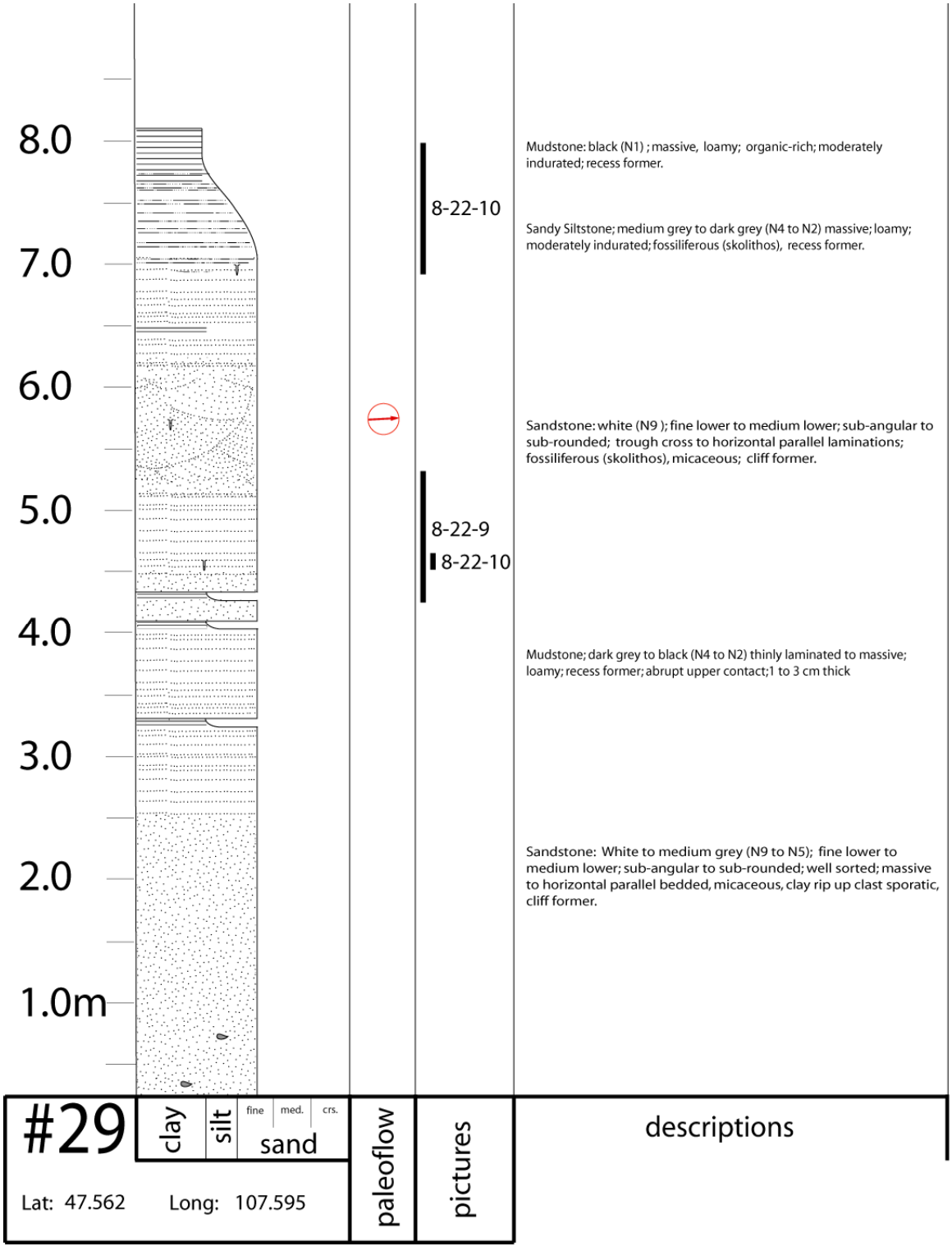

16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-16-9
8-16-8
8-16-7
8-16-6
8-16-5
8-16-4
8-16-3
8-16-2
8-16-1
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (root casts rizo...) recess former.
Sandstone: White (N9); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive; fossiliferous (root casts); micaceous; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: White (N9); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massively bedded; fossiliferous (skolithos); micaceous; cliff former.
Sandstone: white (N9); fine lower to medium lower; sub-angular tosub-rounded; low angle trough cross laminations, micaceous; cliff former.
Sandstone: White to very pale orange (N9 to 10YR 8/2); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous; cliff former.
Sandstone: White to medium grey (N9 to N5); fine lower to mediumlower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip-up clast sporatic; cliff former.
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.
#24
clay
silt
fine
med.
crs.
sand
Lat: 47.577
Long: 107.596
paleoflow
pictures
descriptions

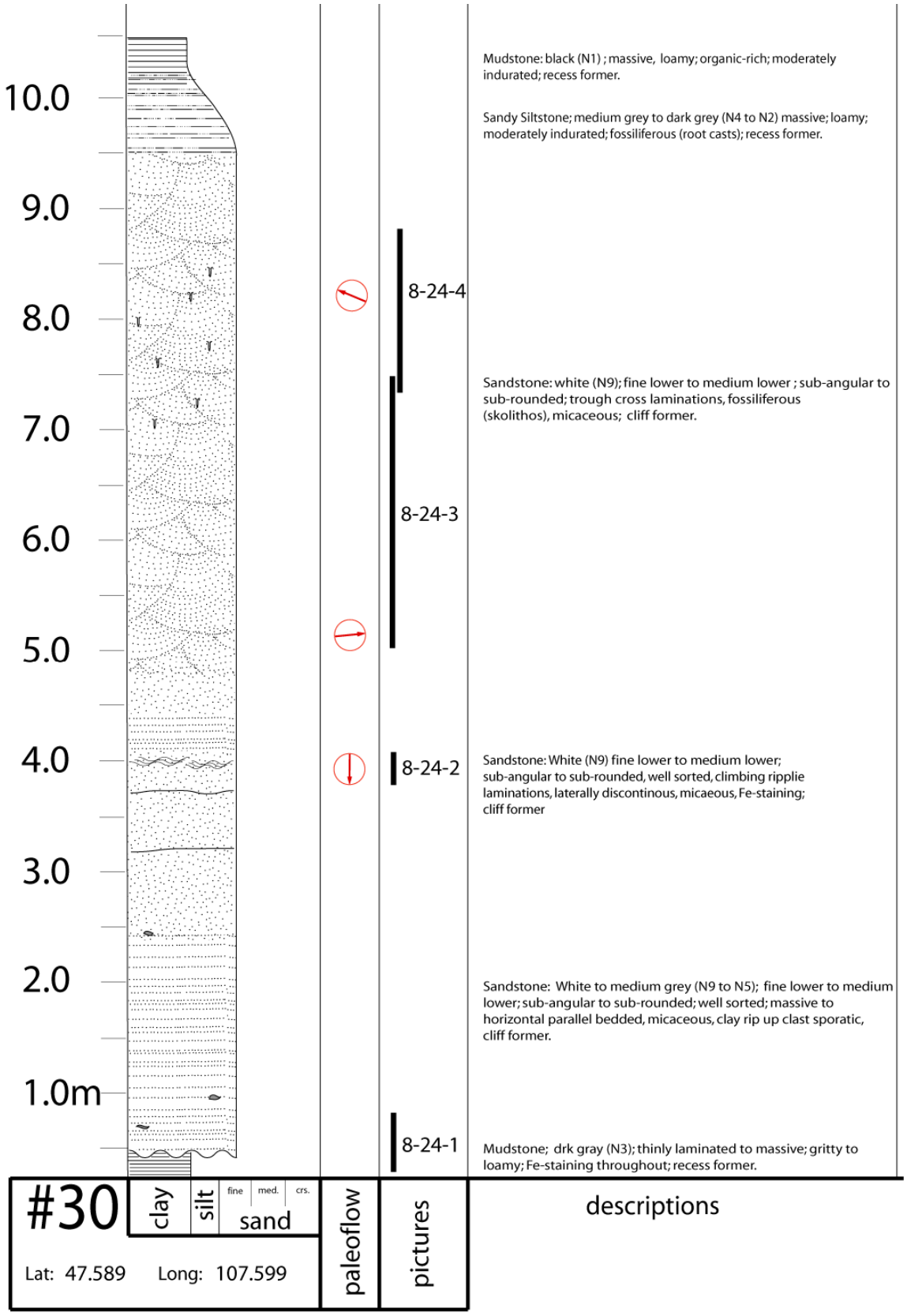

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-17-13
8-17-12
8-17-11
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Siltstone; light grey to medium grey (N7 to N5) massive; loamy; poorly indurated; recess former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick.
Sandstone: White to light grey (N9 to N6); upper fine to lower fine; sub-angular to sub-rounded; low angle trough cross laminations, micaceous, cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick.
Sandstone: White to medium grey (N9 to N6); upper fine to lower fine; sub-angular to sub-rounded; well sorted; parallel horizontal lamination to massive; clay rip-ups sporatic; micaceous; cliff former.
Cover
Sandy Siltstone; dark grey to medium grey (N8 to N5) massive to laminated; loamy; poorly indurated; recess former.
#25
clay
silt
fine
med.
crs.
sand
Lat: 47.573
Long: 107.588
paleoflow
pictures
descriptions

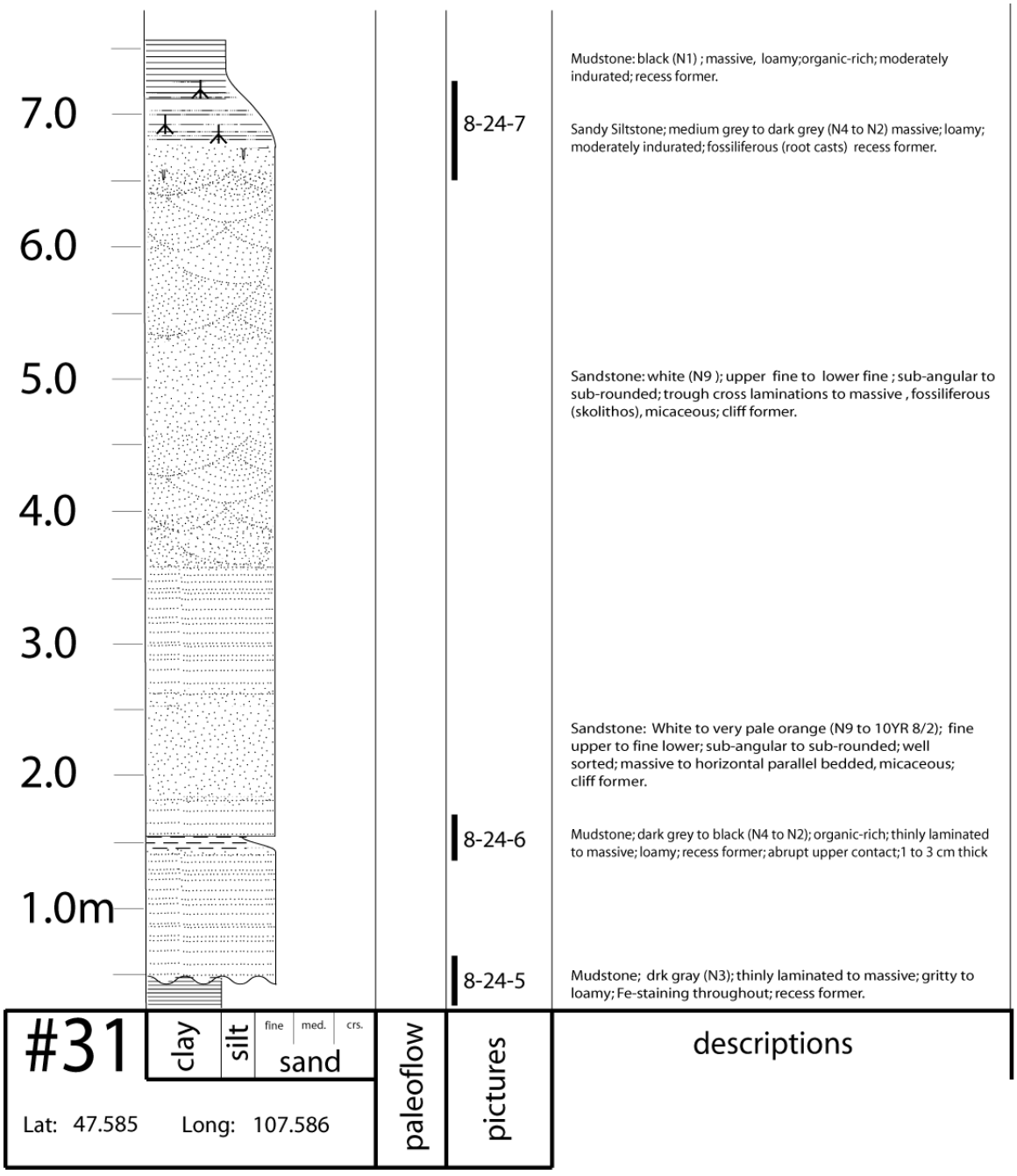

6.0
5.0
4.0
3.0
2.0
1.0m
8-21-2
8-21-1
Sandstone: White to medium brown (N9 to N6); upper fine to lower fine; sub-angular to sub-rounded; well sorted; parallel horizontal lamination to massive; micaceous; cliff former.
Cover.
#26
clay
silt
fine
med.
crs.
sand
Lat: 47.558
Long: 107.607
paleoflow
pictures
descriptions

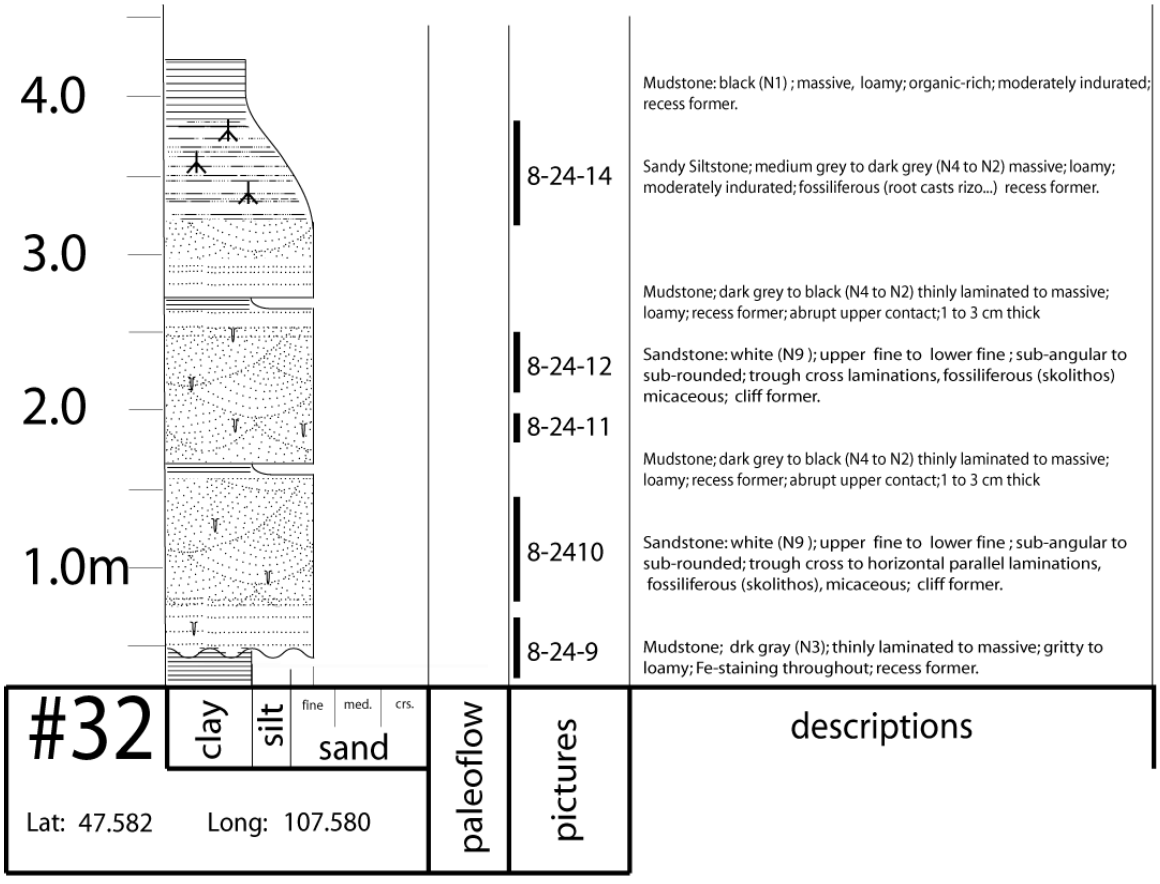

9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-21-10
8-21-9
8-21-8
8-21-7
8-21-6
8-21-5
8-21-4
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: white (N9); fine lower to medium lower ; sub-angular to sub-rounded; trough cross laminations to horizontal parallel bedded, fossiliferous (skolithos), micaceous; cliff former.
Sandstone: White to medium grey (N9 to N5); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip up clast sporatic, cliff former.
Cover
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.
#27
clay
silt
fine
med.
crs.
sand
Lat: 47.555
Long: 107.597
paleoflow
pictures
descriptions

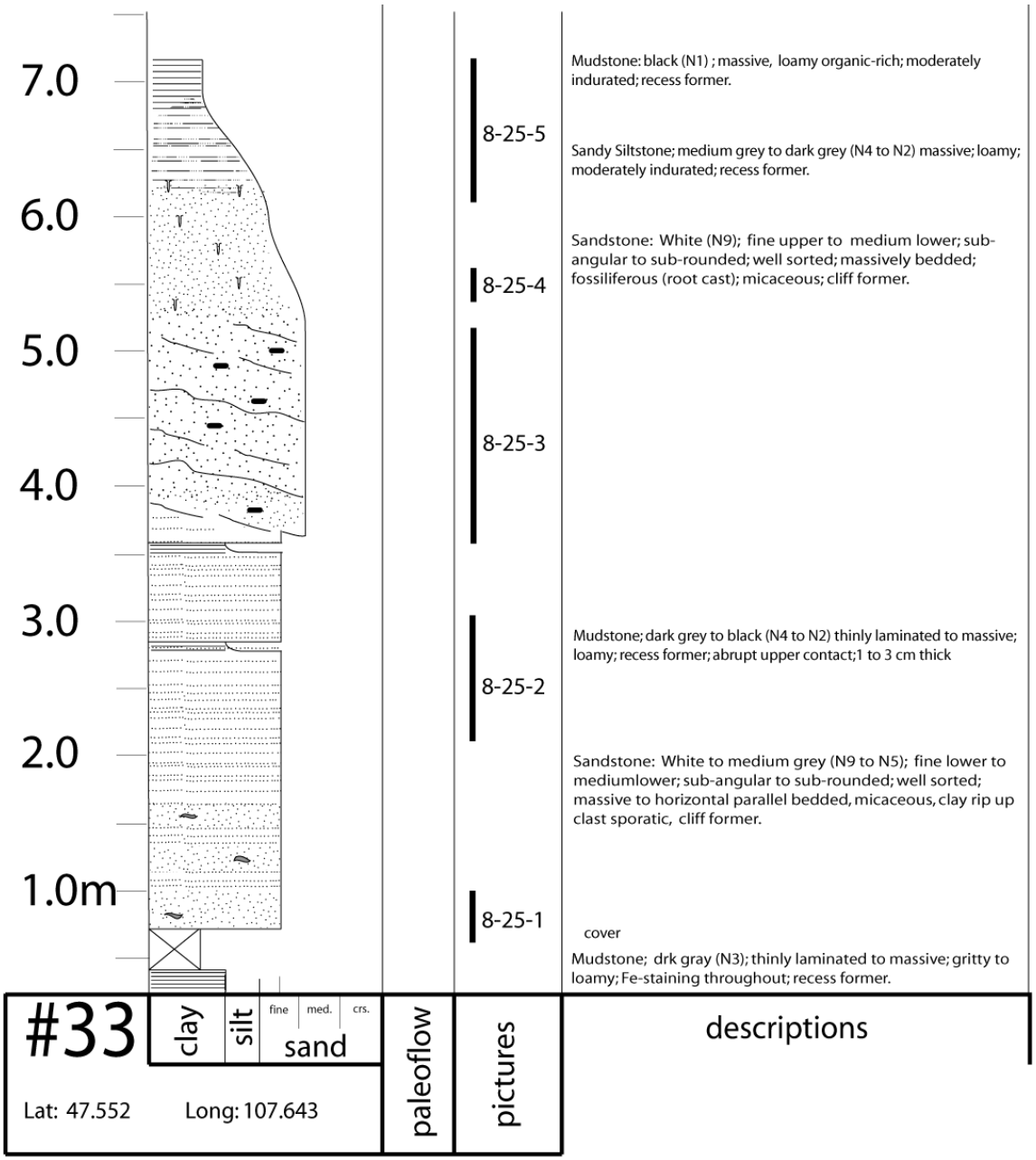

12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#28
clay
silt
fine
med.
crs.
sand
Lat: 47.567
Long: 107.599
paleoflow
pictures
descriptions
8-21-7
8-21-6
8-21-5
8-21-4
8-21-3
8-21-1,2
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (root casts) recess former.
Sandstone; White to purplish grey; fine lower to medium upper, sub-angular to sub-rounded, well sorted; inclined beds; masiive to convolute, charcol and mud rip-ups, fossiliferous (skolithos); well cemeted; cliff former
Sandstone: white (N9); fine lower to medium lower;; sub-angular to sub-rounded; trough cross laminations, fossiliferous (skolithos), micaceous; interbedded organic layer; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: White to medium grey (N9 to N5); fine lower to mediumlower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip up clast sporatic, cliff former.
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.

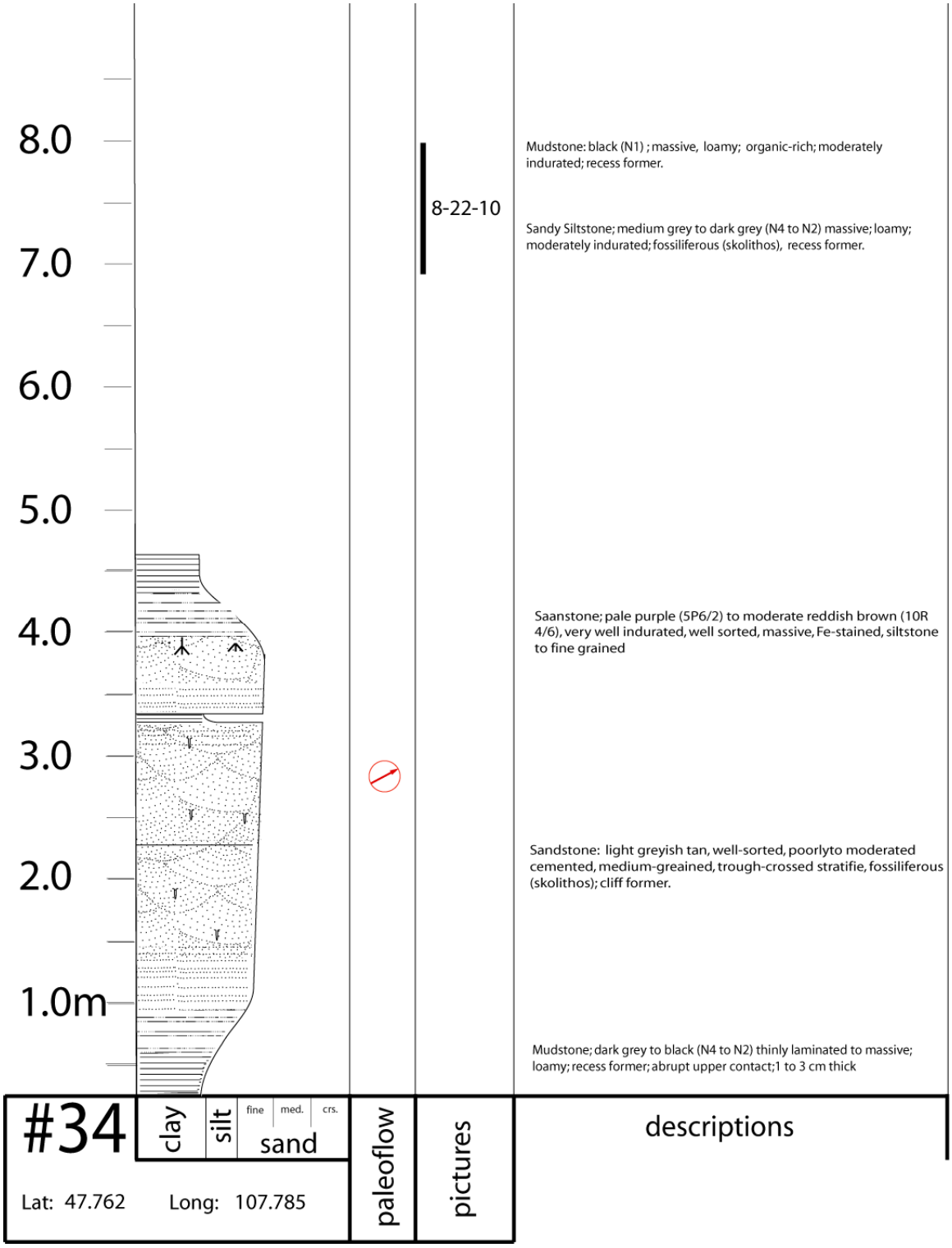

8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-22-10
8-22-9
8-22-10
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (skolithos), recess former.
Sandstone: white (N9); fine lower to medium lower; sub-angular to sub-rounded; trough cross to horizontal parallel laminations; fossiliferous (skolithos), micaceous; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: White to medium grey (N9 to N5); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip up clast sporatic, cliff former.
#29
clay
silt
fine
med.
crs.
sand
Lat: 47.562
Long: 107.595
paleoflow
pictures
descriptions


10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#30
clay
silt
fine
med.
crs.
sand
Lat: 47.589
Long: 107.599
paleoflow
pictures
descriptions
8-24-4
8-24-3
8-24-2
8-24-1
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (root casts); recess former.
Sandstone: white (N9); fine lower to medium lower ; sub-angular to sub-rounded; trough cross laminations, fossiliferous (skolithos), micaceous; cliff former.
Sandstone: White (N9) fine lower to medium lower; sub-angular to sub-rounded, well sorted, climbing ripplie laminations, laterally discontinous, micaeous, Fe-staining; cliff former
Sandstone: White to medium grey (N9 to N5); fine lower to medium lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip up clast sporatic, cliff former.
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.


7.0
6.0
5.0
4.0
3.0
2.0
1.0m
#31
clay
silt
fine
med.
crs.
sand
Lat: 47.585
Long: 107.586
paleoflow
pictures
descriptions
8-24-7
8-24-6
8-24-5
Mudstone: black (N1) ; massive, loamy;organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (root casts) recess former.
Sandstone: white (N9); upper fine to lower fine ; sub-angular to sub-rounded; trough cross laminations to massive , fossiliferous (skolithos), micaceous; cliff former.
Sandstone: White to very pale orange (N9 to 10YR 8/2); fine upper to fine lower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous; cliff former.
Mudstone; dark grey to black (N4 to N2); organic-rich; thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.

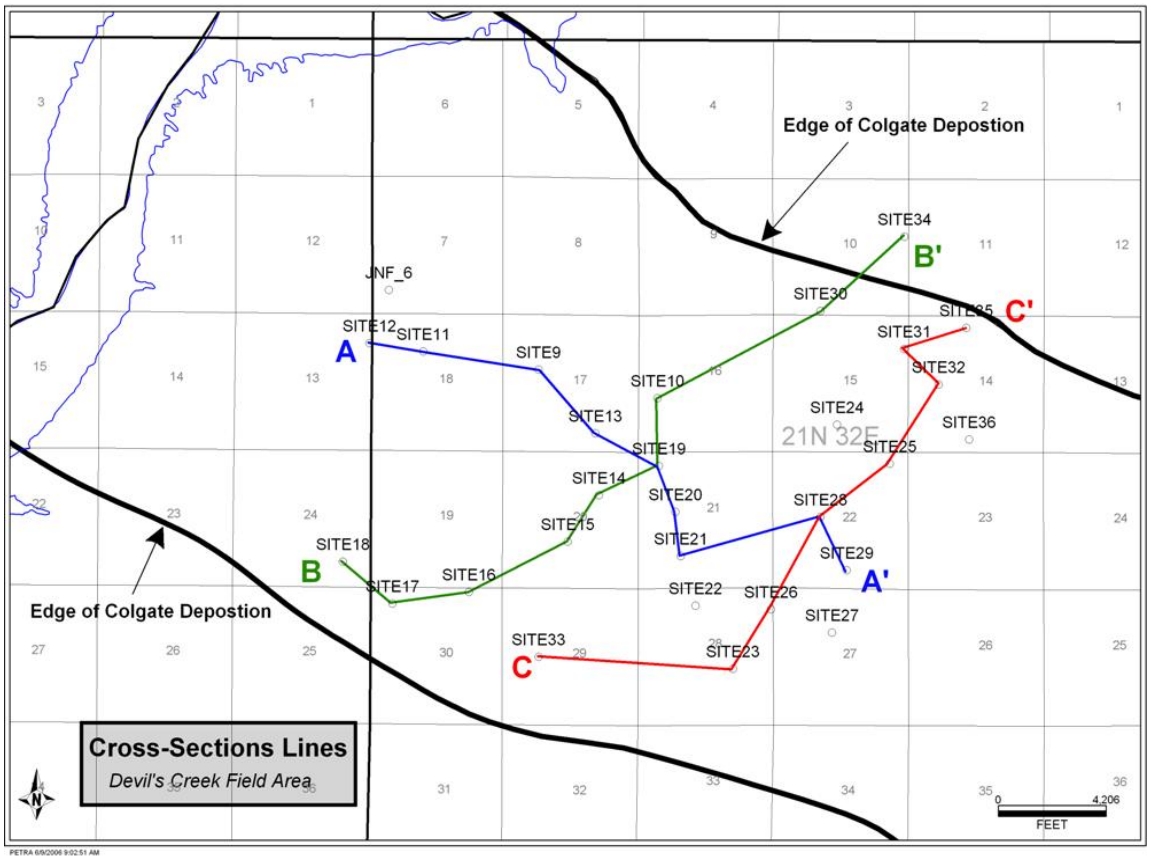

4.0
3.0
2.0
1.0m
#32
clay
silt
fine
med.
crs.
sand
Lat: 47.582
Long: 107.580
paleoflow
pictures
descriptions
8-24-14
8-24-12
8-24-11
8-2410
8-24-9
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (root casts rizo...) recess former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: white (N9); upper fine to lower fine ; sub-angular to sub-rounded; trough cross laminations, fossiliferous (skolithos) micaceous; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: white (N9); upper fine to lower fine ; sub-angular to sub-rounded; trough cross to horizontal parallel laminations, fossiliferous (skolithos), micaceous; cliff former.
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.


7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-25-5
8-25-4
8-25-3
8-25-2
8-25-1
Mudstone: black (N1) ; massive, loamy organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; recess former.
Sandstone: White (N9); fine upper to medium lower; sub-angular to sub-rounded; well sorted; massively bedded; fossiliferous (root cast); micaceous; cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
Sandstone: White to medium grey (N9 to N5); fine lower to mediumlower; sub-angular to sub-rounded; well sorted; massive to horizontal parallel bedded, micaceous, clay rip up clast sporatic, cliff former.
cover
Mudstone; drk gray (N3); thinly laminated to massive; gritty to loamy; Fe-staining throughout; recess former.
#33
clay
silt
fine
med.
crs.
sand
Lat: 47.552
Long: 107.643
paleoflow
pictures
descriptions

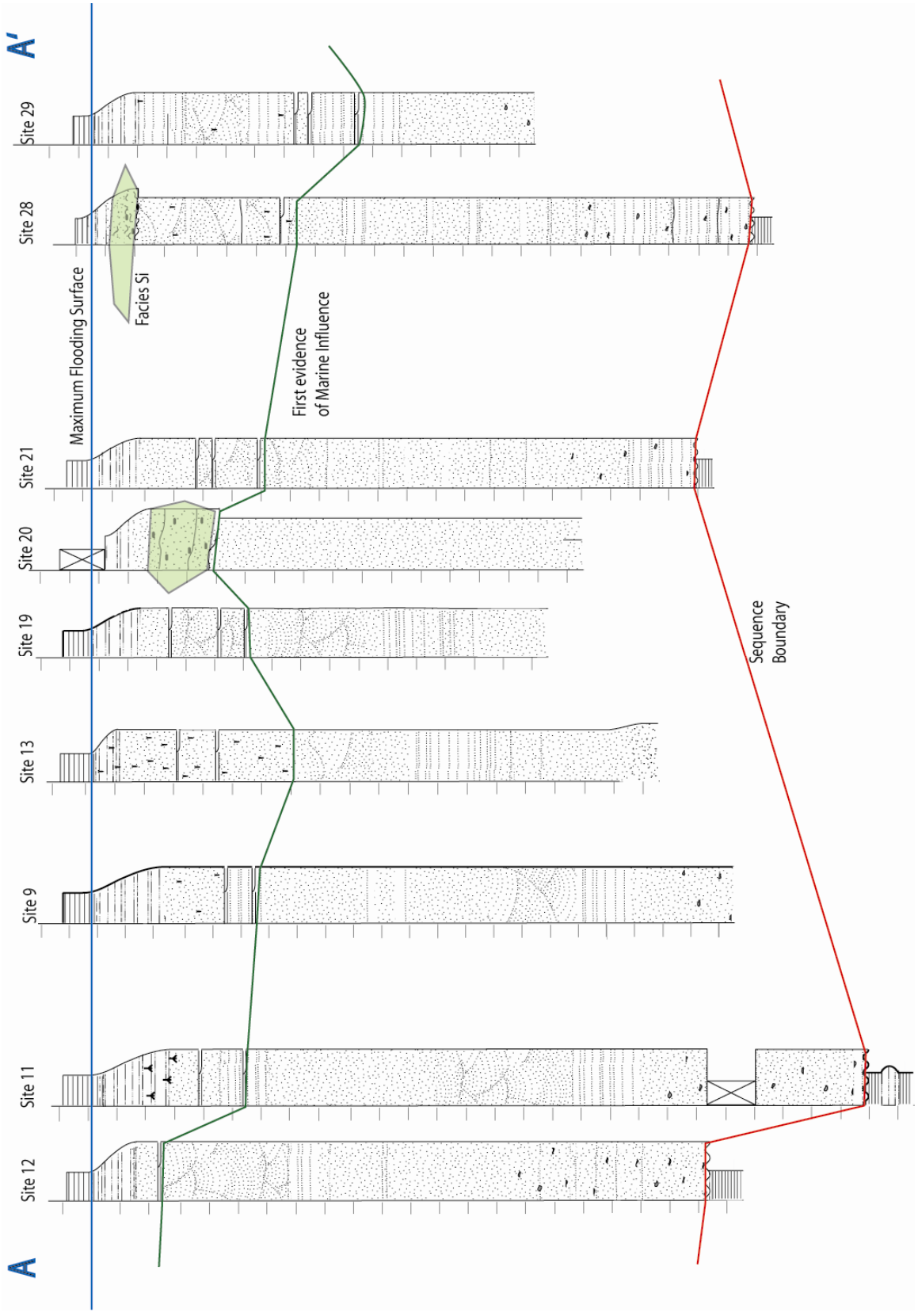

8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0m
8-22-10
Mudstone: black (N1) ; massive, loamy; organic-rich; moderately indurated; recess former.
Sandy Siltstone; medium grey to dark grey (N4 to N2) massive; loamy; moderately indurated; fossiliferous (skolithos), recess former.
Saanstone; pale purple (5P6/2) to moderate reddish brown (10R 4/6), very well indurated, well sorted, massive, Fe-stained, siltstone to fine grained
Sandstone: light greyish tan, well-sorted, poorlyto moderated cemented, medium-greained, trough-crossed stratifie, fossiliferous (skolithos); cliff former.
Mudstone; dark grey to black (N4 to N2) thinly laminated to massive; loamy; recess former; abrupt upper contact;1 to 3 cm thick
#34
clay
silt
fine
med.
crs.
sand
Lat: 47.762
Long: 107.785
paleoflow
pictures
descriptions

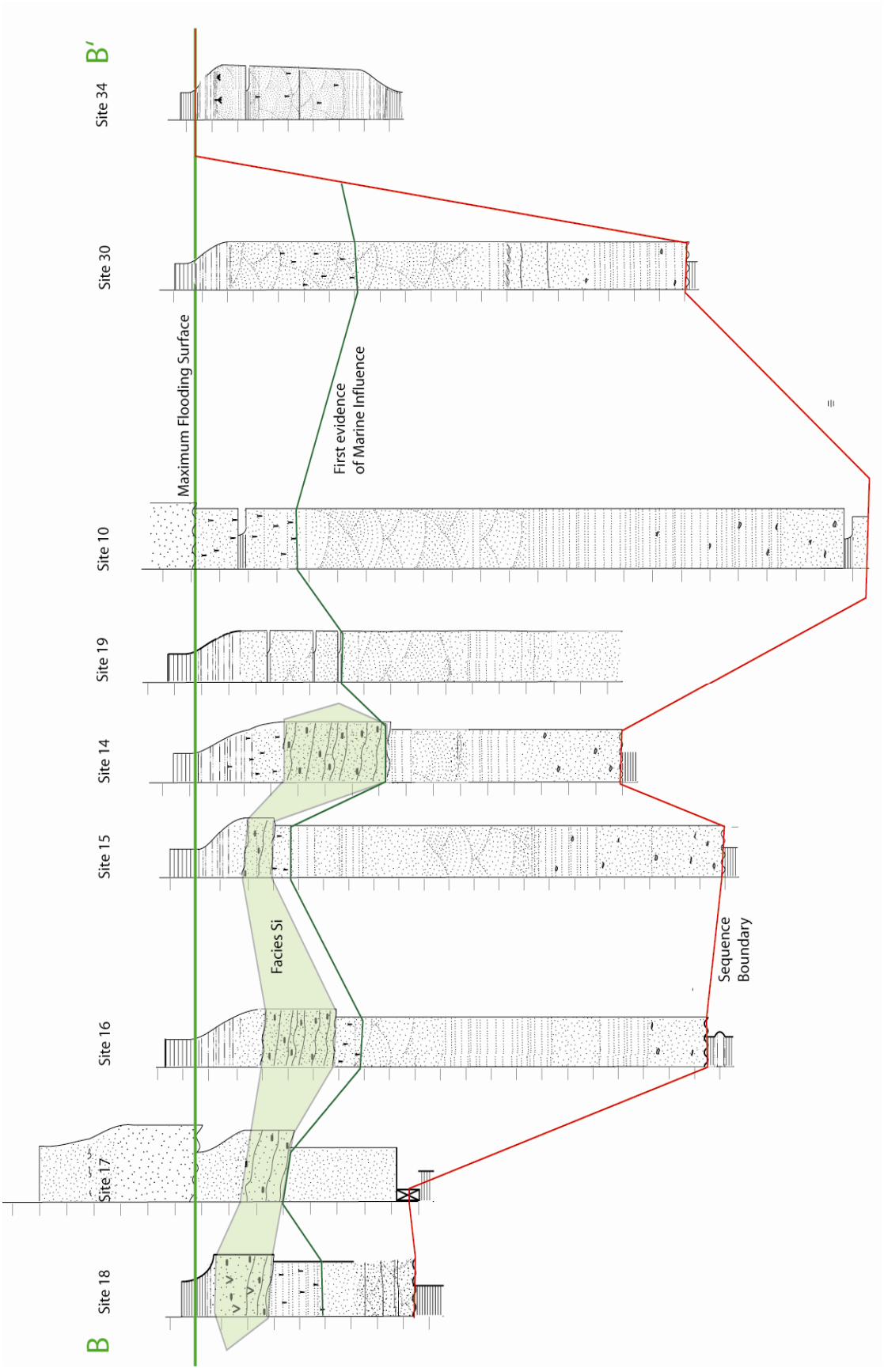
APPENDIX B

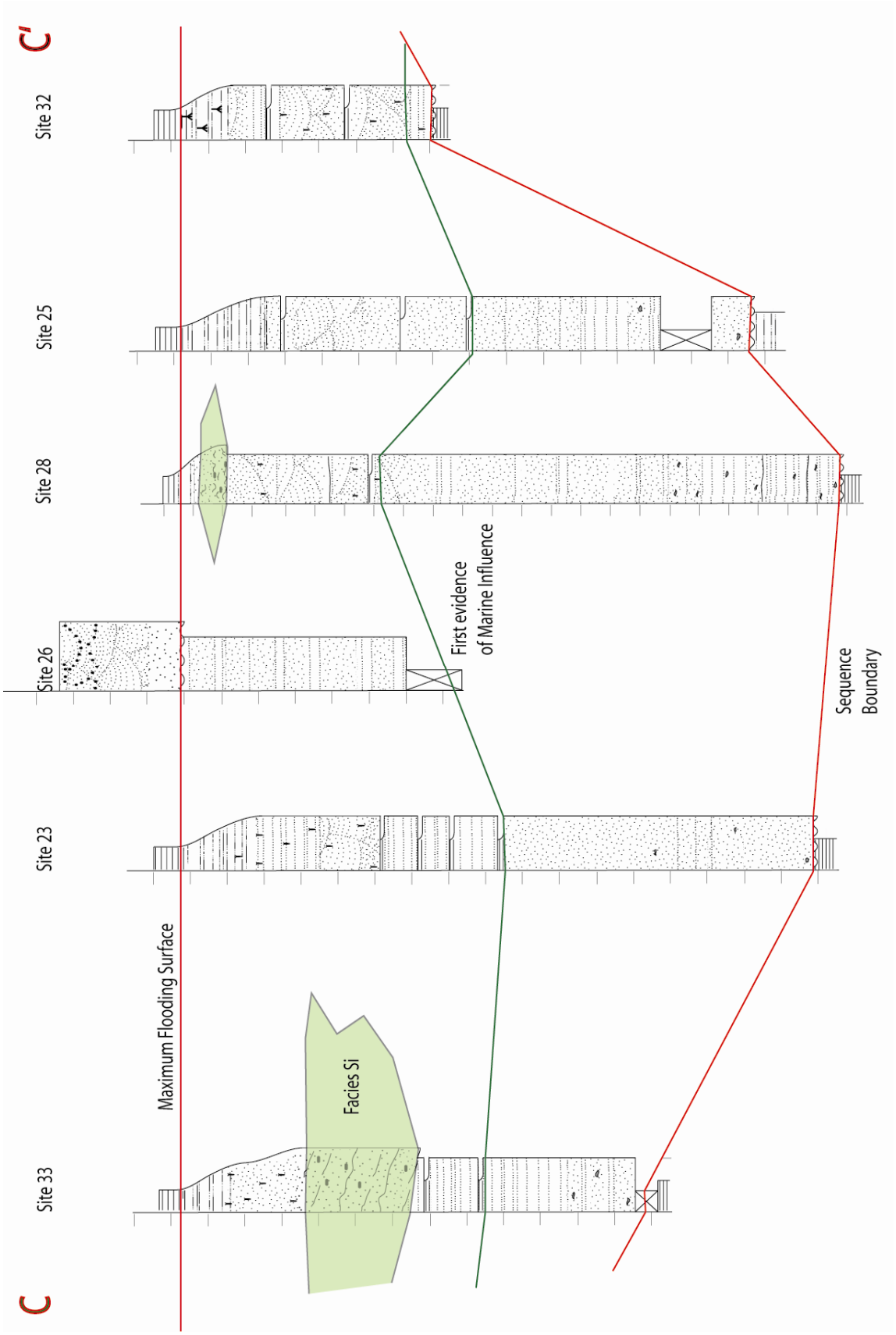
CROSS SECTION LINES


Edge of Colgate Depostion
SITE34
B'
JNF_6
SITE30
SITE35
C'
SITE12
SITE11
A
SITE9
SITE31
SITE32
SITE10
SITE13
SITE24
SITE36
21N 32E
SITE19
SITE25
SITE14
SITE20
SITE28
SITE15
SITE21
SITE18
SITE29
B
SITE17
SITE16
A'
SITE22
SITE26
SITE27
Edge of Colgate Depostion
SITE33
C
SITE23
Cross-Sections Lines
Devil's Creek Field Area
N
0
4,206
FEET

-


A'
Site 29
Site 28
Facies Si
Maximum Flooding Surface
First evidence
of Marine Influence
Site 21
Site 20
Site 19
Site 13
Site 9
Sequence
Boundary
Site 11
Site 12
A


B
B′
Site 18
Site 17
Site 16
Site 15
Site 14
Site 19
Site 10
Site 30
Site 34
Maximum Flooding Surface
First evidence
of Marine Influence
Facies Si
Sequence
Boundary


C
C'
Site 33
Site 23
Site 26
Site 28
Site 25
Site 32
Maximum Flooding Surface
Facies Si
First evidence
of Marine Influence
Sequence
Boundary

APPENDIX C

TABLE OF WELLBORES

TABLE OF WELLBORES

WELL NAME	WELL #	SEC.	TNSHP.	RNG.	API NUMBER	Bearpaw Top (ft)	J River Top (ft)	Clag. Top (ft)	Eagle Top (ft)
BN-MAVERICK DOME	1	17	13N	33E	25033210600000		2343	2093	1800
BROOKS RANCH	1-1	1	13N	38E	25033210730000		1949	1682	1484
HAKES	32-27	27	14N	34E	25033210590000	2950	1780	1480	1207
PETERSON	1	13	15N	30E	25033050980000		1454	1124	784
BURLINGTON NORTHERN	12-27	27	15N	34E	25033210200000	3051	1936	1581	1291
BURLINGTON NORTHERN	41-27	27	15N	34E	25033210170000	3057	1948	1625	1318
BURLINGTON NORTHERN	44-17	17	15N	35E	25033210210000	3051	1941	1611	1320
FEDERAL	12-22	22	16N	29E	25069210270000		1564	1250	867
FEDERAL	9-8	8	17N	31E	25033210300000	2506	1371	1071	731
FEDERAL 13-4	1	13	17N	33E	25033210270000	2371	1246	946	660
KENNELLY	21-24	24	17N	33E	25033211330000		1269	969	671
E J CHAPPEL	1	28	17N	39E	25033051100000		802	496	332
KASTEN	1	10	17N	44E	25055210920000		74	-86	-276
SIROKY	44-2	2	18N	23E	25027210920000		2370	1890	1452
WEINGART	1-27	27	18N	27E	25069210260000		1765	1345	928
MATOVICH	3-22	22	18N	30E	25033210350000		1473	1163	828
STREETS	11-15	15	18N	32E	25033210390000	2490	1410	1090	756
FRADY	44-2	2	18N	43E	25033051130000		302	142	-48
LARRY JORDAN	1	10	19N	23E	25027210350000		2268	1808	1368
WEAVER	1-26	26	19N	26E	25027210550000		1958	1545	1078
STATE	8-36	36	19N	32E	25033210320000	2462	1432	1108	798
SAYLOR	1	32	19N	34E	25033210090000		1425	1105	810
DAVID RIVENES	1	10	19N	37E	25033051170000		1147	820	629
LOVELADY-GOVT	1	12	19N	42E	25033051160000	1690	638	498	240
GOVT	1-B	24	19N	42E	25033051150000	1716	624	476	239
ERVIN L SMITH	1	24	20N	19E	25027210520000			2595	2116
COWELL	1	17	20N	25E	25027600290000		2159	1664	1244
PETERSON	1-14	14	20N	26E	2502721057000		2079	1650	1183
CROOKED CREEK CO-OP	1	21	20N	39E	25033600010000		1126	812	649
BINION RANCH	1	27	20N	43E	25055050010000	1778	712	565	308
HINNALAND	1	7	21N	22E	25027210170000		2633	2073	1638
MURRY-HOAG	10-32	32	21N	34E	25033210290000		1484	1144	844
FEDERAL	4-36	36	21N	36E	25033210370000		1288	960	738
STATE	1	1	21N	44E	25055050150000	1693	683	543	345
DOROTHY ROSSELAND	1	15	21N	44E	25055050090000	1743	696	543	286
OLIVER COLLINS	1-A	28	21N	44E	25055050050000	1675	663	503	245
GOVT	1	12	21N	45E	25055050140000			265	50
HAROLD WALLER	1	1	22N	19E	25027211450000			2593	2065

TABLE OF WELLBORES - CONTINUED

NAME	NUMBER	SEC	TNSHP	RNG	API NUMBER	Bearpaw Top (ft)	J. River top (ft)	Clag (ft)	Eagle Top (ft)
MEES	1-33	33	22N	20E	25027210880000		2825	2226	1699
LIMPUS	1	21	22N	22E	25027210180000		2580	2072	1560
FEDERAL-	1	8	22N	45E	25055210990000	1796	736	626	366
FEDERAL	1	17	23N	23E	25071210680000		2573	2085	1598
FEDERAL-B	21-16	21	23N	25E	25071211810000		2276	1784	1374
FEDERAL	1-2	2	23N	27E	25071210240000		2218	1783	1338
GOVT	1	12	23N	29E	25071217620000		1967	1607	1182
FEDERAL	1	2	23N	31E	25071050040000		1797	1422	1067
GOVERNMENT	1-A	10	24N	18E	25005218550000	3239	3075	2329	1939
RICHARD MAGDA	22-28	28	24N	20E	25005228950000	3081	2796	2053	1694
MACUM FEDERAL	22-23	23	24N	27E	25071215450000		2293	1873	1413
FEDERAL	1-27	27	24N	45E	25055051150000	1694	964	724	494
FEDERAL	10-3-25-18	10	25N	18E	25005235110000	3115	2917	2221	1887
WORTMAN	1	10	25N	20E	25005214590000	3179	2867	2259	1754
FEDERAL	F-8-25-21-	8	25N	21E	25005220260000	3138	2828	2208	1744
FEDERAL	1	35	25N	29E	25071215100000		2071	1716	1273
VESETH FEDERAL	27-1	27	25N	32E	25071210060000		1803	1521	1169
FEDERAL	1-21	21	25N	38E	25105212200000		1621	1406	1106
WILLOW CREEK	11-16	11	26N	18E	25005232760000	3307	3091	2360	1943
JACOBSON	7-27	27	26N	19E	25005212850000	3290	2998	2377	1849
US /M1572/	27-26-21-1	27	26N	21E	25005211540000			2402	1947
FEDERAL	11X-25	25	26N	28E	25071215440000	2630	2248	1825	1361
VESETH	13X-29	29	26N	28E	25071215420000	2734	2179	1754	1288
TREMBLAY-VESETH	33-1	33	26N	34E	25105210060000		1912	1595	1292
FEDERAL	13-3	13	27N	18E	25005219670000			2598	2233
MOORE	23-9	9	27N	25E	25005212340000	3314	2813	2458	1929
PRESTON BELL	31-27-31-2	31	27N	31E	25071215030000		2138	1798	1368
FRENCH	33-1	33	27N	32E	25071210070000		2172	1870	1483
FEDERAL	1-33	33	27N	35E	25105210910000			1741	1438
FEDERAL	41-31	31	28N	22E	25005218940000			2665	2235
SPENCER	28-28-28R	28	28N	28E	25071214770000		2276	1954	1492
KNUDSON	1	34	28N	31E	25071217730000			2096	1681
BRUCKNER ET AL	1-9	9	28N	36E	25105211950000		2235	1871	1619