

THESIS

SEDIMENTARY CHARACTER AND PROCESSES IN MUDSTONE INTER-LOBE
DEPOSITS OF THE SKULL CREEK FORMATION, FORT COLLINS, COLORADO

Submitted by
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ABSTRACT

SEDIMENTARY CHARACTER AND PROCESSES IN MUDSTONE INTER-LOBE DEPOSITS OF THE SKULL CREEK FORMATION, FORT COLLINS, COLORADO

Lobe-fringe deposits and interlobe strata are rarely described in sedimentary systems and often neglected in descriptions of delta successions, which mostly focus on delta top, delta front, and prodelta sediments. This may partly be the case because these deposits consist mostly of mudstones, which are generally neglected in all sedimentary systems except for black shales. Here, we describe nine siliciclastic facies of predominantly mudstones from the Cretaceous Skull Creek Formation of northern Colorado, USA. These nine facies are arranged in a 4.5 m thick predominantly fine-grained unit within the overall 25 m thick Skull Creek Formation. The nine facies are very fine to fine-grained dark massive mudstone lamina (F1), very fine-grained massive mudstone (F2), massive fine- to coarse-grained mudstone (F3), massive mudstone with fecal strings (F4), normally graded coarse to medium-grained mudstone (F5), medium- to coarse-grained lenticular siltstone (F6), siltstone lamina (F7), and massive calcitic coarse silt- to coarse-grained sandstone (F8A and F8B). From all these facies, massive fine- to coarse-grained mudstone (F3), normally graded coarse to medium-grained mudstone (F5) and siltstone lamina (F7) are the most common and comprise about 80-90 vol% of the succession. The succession consists of 16 coarsening- and fining-upward cycles, with the majority being coarsening-upwards (11), and only (5) fining-upwards. Stratigraphically, these cycles are between 5.5 and 120 mm thick, and are here subdivided into nine distinct stratigraphic zones. These zone

alternate between five fine-grained and four silt-rich zones. Each zone consists of a minimum of a portion of a cycle, and/or one or more coarsening- and fining-upwards units.

These facies were deposited in three depositional environments: lobe-fringe area, medial inter-lobe area, and distal inter-lobe area. The presence of both high-energy indicators, such as clay clasts, sharp erosional bases, scours, and fragmented fishbones, as well as the occurrence of sediments reflecting suspension deposition, indicates that the lobe-fringe environment was undergoing successive shifts from high to low energy conditions. Moving farther away from the lobe, sediments show overall moderate energy conditions reflected in normal grading and some erosional contact; nevertheless, moderate and low-energy conditions alternated. Furthest away from the lobe are the distal inter-lobe sediments that show tranquil sediment deposition with only minor moderate energy deposition reflected in sharp facies contacts, and some siltstone grains in facies 3. The presence of only one type of fecal string, in these sediments, and the little bioturbated nature of inter-lobe strata suggests that the environment had been likely dysoxic and stressed but was not entirely anoxic.

This study indicates that the Skull Creek Formation is primarily dominated by bed-load deposition, although the presence of suspension deposition—recorded only at times—in various facies suggests that quieter conditions occurred across all depositional areas. Even the interlobe deposits are significantly influenced by bed-load transport. Furthermore, the boundaries between the three depositional areas—lobe-fringe, medial inter-lobe, and distal inter-lobe areas—are not clearly defined and are regarded as transitional rather than firm. While unique facies mark each zone, the presence of overlapping facies across these zones makes it challenging to distinguish them clearly.

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Introduction

Mud-rich turbidite systems have not received much attention in the sedimentology literature (e.g., Talling et al. 2007), likely because they do not host the vast amount of economically viable resources as sand-rich turbidite systems (Bhattacharya and MacEachern, 2009). Nevertheless, as mudstones make up about two-thirds of the sedimentary record (Schieber, 1998) they are also present in all turbidite systems, and often in large quantities (e.g., Talling et al., 2007). Even though the depositional processes in many siliciclastic mudstone successions, which are often from shelf settings, are envisioned to be partly turbiditic in nature (Biddle et al., 2021), the dynamics of mudstone turbidite systems are not well understood (e.g., Birgenheier et al., 2017). Already showing partly turbiditic character but nevertheless still being located up on the shelf are distal muddy delta sediments, and these mudstones are equally badly understood as turbidites (e.g., Bhattacharya and MacEachern 2007; Birgenheier et al. 2017), because of their lack of hosting large hydrocarbon reserves.

Here, we investigate one specific mud-rich end member, the Lower Cretaceous pro-delta in the Cretaceous Interior Seaway of Northern Colorado – the Skull Creek Formation. In the Skull Creek Formation, as in all other delta successions, the distal and lateral mud-rich portion of the delta are the least studied (e.g., Bhattacharya and MacEachern, 2003). This study, therefore, focuses on sedimentation lateral to the delta depositional lobes, where it remains unclear which sediment gets delivered, by which processes, and how it looks in detail. These environments must be fairly common both in the distal and lateral to delta lobe settings, as they are preserved in the sedimentary record. However, their fine-grained nature makes them prone to intense

weathering that obscures or erases primary sedimentary structures, and features necessary for understanding their sedimentology and interpreting their depositional environment. This lack of detail makes it unclear which processes operate in these distal settings, and how they differ from lobe sedimentation.

This study focuses on this specific scientific knowledge gap using a very well-defined prodelta lobe succession (Masterson 2015; Sullivan et al. 2022), the Skull Creek Formation. The Skull Creek Formation is a fine-grained unit sandwiched by coarser-grained sediment packages that represent lobes and has been interpreted as interlobe sedimentation, likely lateral to individual lobes. These fine-grained deposits have only been characterized as “fine-grained” and possibly suspension-derived (Masterson 2015; Sullivan et al. 2022); however, they have not been investigated in sufficient detail to understand the depositional processes responsible for their formation. This study intends to shed light on this hitherto neglected depositional environment, which is an important aspect of understanding a delta system fully.

The study focuses on two outcrops of the Skull Creek Formation west of Fort Collins, Colorado (Fig. 2). In contrast to Masterson (2015) and Sullivan et al. (2022), who studied the entire Skull Creek Formation more synoptically, this study focuses on detailed characterization and analysis of two distinct fine-grained intervals, each 4.5 m in thickness, in the lower third of the succession (Fig. 2). These two outcrops are correlated over the 400 m gap between them alongside the margin of Horsetooth Reservoir.

Geological setting

During the Cretaceous Period, the North American Continent was located between 30° to 85°N, entirely north of the Equator (Irving, 1979). The climate at that time was warm and humid, comparable to the climate of the southern Atlantic coast of the United States today (McGookey et al., 1972). The Cretaceous period was a time of an increase in sea level until its peak in the Turonian (Upper Cretaceous; Obrdorivch and Cobban, 1975) and the widespread occurrence of marine sediments throughout the globe that record ample fluctuations in eustatic sea level (Haq et al., 1987).

During the Albian, the Cretaceous Interior Seaway (CIS) was established on the North American continent, running from the Gulf of Mexico to the Arctic (DeCelles, 2004) (Fig. 2). This seaway, characterized by a steep western and a gentle eastern slope (e.g., DeCelles, 2004), is seen as the foreland basin that formed in front of the Sevier Orogeny in the central US. The basin's unusual width of about 1000 km is explained as a consequence of mantle convection in addition to the down-warping of the continental crust (DeCelles and Giles, 1996), leading to additional subsidence even in places far west of the basin axis.

The first transgression of this seaway into the study area in northern Colorado is seen in the middle Albian when a delta system dominated sedimentation in the larger Fort Collins area. This delta was characterized by proximal sandy units as reflected in the Plainview Formation and Muddy (J)sandstones (Fort Collins and Horsetooth Members) of the Dakota Group, while distal

delta deposition is reflected in the fine-grained deposits of the Skull Creek Formation (Holbrook and Ethridge, 1996).

The Skull Creek Formation was deposited during the late Albian (Cobban, et al., 1994; Graham and Ethridge, 1995). The thickness of this unit reaches a maximum of 35m in outcrops in northern Colorado (Masterson, 2015). The Skull Creek Formation consists of organic-rich marine mudstone sediments deposited in a prodelta environment, and it is considered one of the important source rocks to the reservoirs in the Denver Basin (Graham and Ethridge, 1995).

The Denver Basin is an asymmetric foreland basin covering an area of 155,399 km², and it spans from southwestern Nebraska and parts of southeast Wyoming to northeast Colorado (Dechesne et al., 2011; Masterson, 2015). The basin formed during the Laramide orogeny from the Late Cretaceous to the Middle Eocene (Dechesne et al., 2011). The Denver Basin is bounded on the east and northeast by the Chadron and Cambridge arches, on the west by the Laramie and Front Range uplifts, and to the south and southeast by the Apishapa and Las Animas arches; the axis of the basin trends north- northeast (Belitz and Bredehoeft, 1988). The basin consists of sediments that range in age from the Paleozoic to the Early Cenozoic (Masterson, 2015). The maximum thickness of the sedimentary rocks in the Denver Basin reaches 4,100m near the city of Denver in Colorado (Belitz and Bredehoeft, 1988).

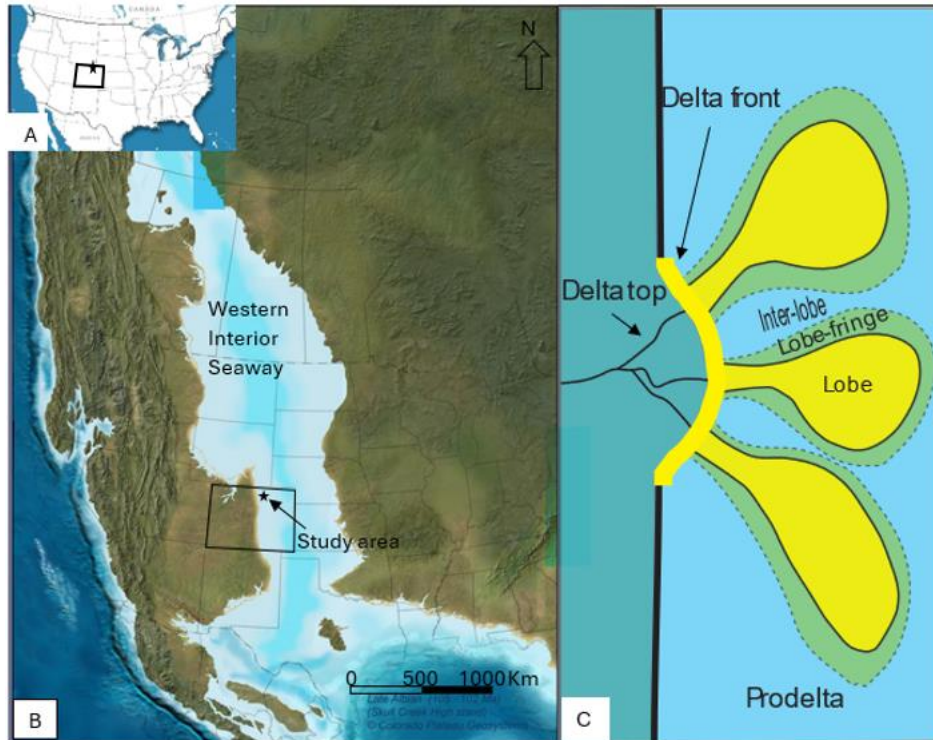


Figure 1. (A) Map of the United States of America map. The state of Colorado is outlined in black. The study area is indicated on the map as a black star. (B) Palaeogeographical map of western North America and the Western Interior Seaway at ca 105-102 Ma during the Late Albian Age of the Late Lower Cretaceous. The state of Colorado is outlined in black, and the study area is indicated on the map as a black star (modified from Blakey, 2013). (C) General delta depositional model and Inter-lobe area.

Methods

Sedimentology study of thin sections is widely considered one of the best methods to study organic-rich mudstones in order to understand all intricacies and details (Biddle et al., 2021). The sedimentological analyses presented in this thesis are based on the study of a fine-grained mudstone unit in the Cretaceous Skull Creek Formation (Dakota Group). This fine-grained mudstone was encountered in three measured sections at Horsetooth Reservoir west of Fort Collins, Colorado (Fig. 2). Two outcrops are located only a few meters lateral to each other; however, the third one is located on the south side of Dixon Dam (Graham and Ethridge 1995), and their locations are given as $40^{\circ}33'10''\text{N } 105^{\circ}08'50''\text{W}$, $40^{\circ}33'24''\text{N } 105^{\circ}08'57''\text{W}$, and $40^{\circ}33'23''\text{N } 105^{\circ}08'56''\text{W}$ (Fig. 2). To tie in the outcrop work with thin sections, 20 hand samples were collected from the three outcrops for thin section studies. All sections were documented in centimeter detail, building on previous work by Masterson (2015). However, the stratigraphic intervals where the samples were collected have been documented in millimeter-scale detail. All three sections documented in this study focused on grain size, composition, and sedimentary structures as visible macroscopically.

This study is based on measuring three outcrop sections in millimeter-scale detail within a part of the Skull Creek Formation previously documented by Masterson (2015). A total of 20 samples were recovered from massive mudstone units within the Skull Creek Formation, with 15 of them from different levels of section 1 (table 1), four from outcrop 2A (table 2), and one from outcrop 2B (table 3). All measured sections and sample locations are shown in Fig. 2.

The 20 hand samples were taken to the laboratory in the Geoscience Department at Colorado State University. Before the samples were cut perpendicular to bedding using a traditional rock saw, they were coated with epoxy resin to stop breakage and disintegration. Then, the samples were sent to TPS Enterprise in Texas to make thin sections. The thin sections were cut ultra-thin to a thickness of approximately 20 μ m and polished on one side to show the sedimentary fabric. The thin sections were prepared with blue epoxy impregnation to estimate the porosity or to better identify dissolved grains in thin sections.

For thin section stands, a Nikon Eclipse Ci-L microscope and a Nikon DS-Fi2 camera were used to identify the sedimentological features such as composition, grain size distribution, small-scale sedimentary structures such as bedding and lamination, and the contact between facies; also, fossils and trace fossils were documented. The charts from Baccelle & Bosellini, (1965) were used to estimate the percentage of sand, silt, clay, and organic matter.

Outcrop 1: 40°33'10"N 105°08'50"W.

Table. 1: All thin sections and their depth from outcrop 1.		
Number	Thin section	Depth (m)
1	Sp-20-7	7
2	Sp-20-7.7	7.7
3	Sp-20-7.8	7.8
4	Sp-20-8.15	8.15
5	Sp-20-8.56	8.56
6	Sp-20-8.87	8.87
7	Sp-20-8.9	8.9
8	Sp-20-9.6	9.6
9	Sp-20-9.6II	9.6
10	Sp-20-9.65	9.65
11	Sp-20-9.7	9.7
12	Sp-20-11.10	11.10
13	Sp-20-11.15	11.15
14	Sp-20-11.20	11.20
15	Sp-20-11.25	11.25

Outcrop 2A: 40°33'24"N 105°08'57"W.

Table. 2: All thin sections and their depth from the second location.		
Number	Thin section	Depth (m)
1	CSP-20-7.5	7.5
2	CSP-20-8.7	8.7
3	CSP-20-8.8	8.8
4	CSP-20-8.85	8.85

Outcrop 2B: 40°33'23"N 105°08'56"W.

Table. 3: All thin sections and their depth from the third location.		
Number	Thin section	Depth (m)
1	II CSP-20-9	9

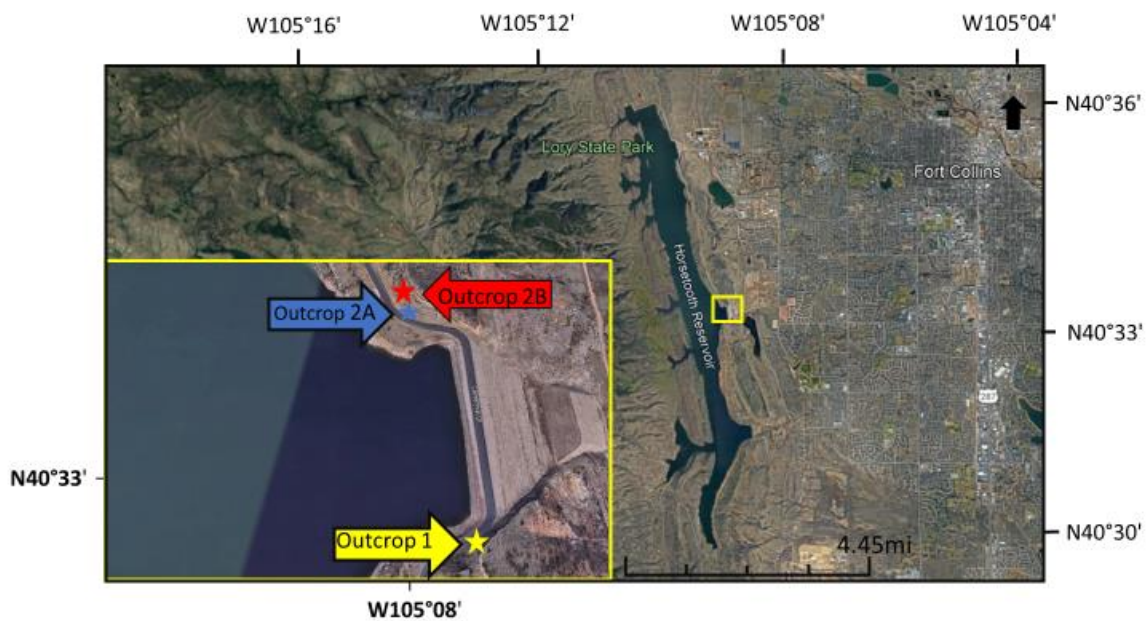


Figure 2. The figure shows the study area (yellow box) relative to western Fort Collins. The inset shows the location of the outcrop along the Horsetooth Reservoir. The images are modified from Google™ Maps. Abbreviated longitude and latitude are displayed along the top and right sides of the figure, as well as along the bottom and left sides of the inset.

Sedimentology

A total of nine distinct facies are identified within the Skull Creek Formation's massive fine-grained mudstone unit. These facies were identified through detailed analysis of thin sections and are distinguished based on grain size, composition, and the presence of sedimentary structures (Fig. 3). Each facies was deposited by a distinct process. Three facies display evidence of bioturbation, and six facies do not show that. These facies are ordered by grain size see (table 4).

Table. 4: Facies Classification, Description and Interpretation.

Facies Name	Composition	Description	Interpretation
<p>Very fine to Fine-grained dark massive mudstone lamina (Facies 1)</p>	<ul style="list-style-type: none"> • Quartz: 10vol% • Carbonate grains: 10vol% • Muscovite: 1-2vol% • Phosphate clasts: 5vol% • Organic matter: 15-20vol% • Fine-grained mud matrix: 50vol% 	<ul style="list-style-type: none"> • Grains are predominantly clay-size but between 5 and 10 vol% are very fine to fine silt-size grains. • Grains are angular to subrounded and well sorted; outsized grains are matrix-supported. • Facies forms black massive thin beds 0.05-0.1 mm thick that lack lateral thickness variations. • This lithology forms sharp contacts with over- and underlying facies. • Neither fossils nor trace fossils are present in this facies. 	<ul style="list-style-type: none"> • The dominance of small grains in this facies reflects low energy conditions; the evenness of thin beds of this facies together with the small grain sizes is interpreted to reflect suspension deposition. • However, the subrounded grains in this facies indicate some amount of abrasion of the grains and therefore potentially an influence of bed load transport on deposition. This could also have happened before these grains were integrated into this facies. • The overall well sorting of grains reflects generally similar energy conditions during deposition. • The sharp top contacts of this facies could stem from high energy deposition and potentially erosion from overlying facies, or, alternatively, from a sudden change of energy conditions. Bottom contacts, however, exclusively indicate a drastic change of energy conditions leading to the deposition of this facies. • The dark color is a reflection of high amounts of organic matter in this facies. This is an additional indicator of this facies being characterized by low sedimentation rates, and therefore an accumulation of large

			quantities of suspension settled organic material.
Very fine-grained massive mudstone (Facies 2)	<ul style="list-style-type: none"> • Quartz: 1-2 vol% • Carbonate grains: 3-5vol% • Organic matter: 10vol% • Fine-grained mud matrix: 85vol% 	<ul style="list-style-type: none"> • Fine-grained massive mudstone; grains floating in matrix are fine to very fine-grained silts, angular to sub-angular, moderately sorted. • Individual laminae are less than half a millimeter thick and change thickness laterally; no grading is observed. • Contacts between laminae of this facies and over- and underlying beds is always sharp; generally interbedded with facies 3. • Devoid of fossils and burrows. 	<ul style="list-style-type: none"> • Scarcity of grains and very fine-grained nature of sediment indicates tranquil depositional conditions. • The variation of laminae thickness across thin sections indicates either bed load transport of this facies, or erosion of overlying facies into these laminae. • The initial rounding of a portion of the scarce grains shows that those grains have been deposited with matrix; angular grains, however, are potentially diagenetic. • Moderate sorting is seen as reflecting a range of depositional energies; however, if mudstones have been deposited as clumps their grain size can't be determined. • Sharp contacts of this facies indicate distinct change of depositional energies. • Fine grain sizes show lack of coarse sediment input and therefore likely distal environment of deposition. • The absence of fossils and burrowing could indicate anoxic conditions (e.g., Egenhoff and Fishman 2013).
Massive Fine-to coarse-grained mudstone (Facies 3)	<ul style="list-style-type: none"> • Quartz: 15-20vol% • Plagioclase: 10vol% • K-feldspar: 1vol% • Muscovite: 1vol% • Calcite and dolomite: 1vol% • Phosphate clasts: 1vol% • Organic matter: 20vol% 	<ul style="list-style-type: none"> • Visible grains very fine to coarse silt (0.004 and 0.05 mm in diameter) dispersed in matrix of clay-size particles. • Grains are angular to subrounded and poorly sorted. • Grains are mud-supported. 	<ul style="list-style-type: none"> • Small grain size and clay-size matrix reflect overall tranquil energy conditions during deposition; however, grain size variations reflect different energy regimes because mid- and coarse-size silt grains do not originate from suspension settling (Yawar and Schieber 2017).

	<ul style="list-style-type: none"> • Fine-grained matrix: 45vol% 	<ul style="list-style-type: none"> • With very few exceptions, top and bottom contacts of facies 3 are gradational. • Laminae and thin beds are 1-38 mm thick, no thickness variations. • Organic matters occur in facies; elongate parallel to bedding, clearly defined. • Bioturbation is presented but fossils are not observed. However, fish bone remains are found in some areas of facies 3. 	<ul style="list-style-type: none"> • The lack of structures could indicate a predominance of suspension deposition; a suspension origin is also indicated by a lack of variation of facies 3 beds laterally. However, the larger silt grains likely reflect bed load transport. It is, therefore, probable that facies 3 reflects a mix of predominantly suspension deposition with some amount of bed load transport. • Deposition occurred in pulses: higher-energy events alternated with (most likely) long periods of suspension settling reflected in a predominance of small grains and the presence of some medium- to coarse-grained silt. • The rounding of some of the silt grains also supports the influence of bed load transport processes; angular grains are interpreted as either diagenetic or having been deposited by suspension settling. • The present fabric is likely the product of burrowing, which destroyed any of the original fabric. However, part of deposition was bed-load transport, which likely produced laminae or thin beds of coarser material that has been re-distributed throughout this facies by the organisms. • The gradational contacts of this facies indicate gradual changes in depositional energy.
<p>Massive mudstone</p>	<ul style="list-style-type: none"> • Quartz: 25vol% • Carbonate grains: 10vol% 	<ul style="list-style-type: none"> • Very fine siltstone to coarse-grained siltstone, sub-rounded and poorly sorted. 	<ul style="list-style-type: none"> • Size of grains suggests some amount of energy during deposition, likely bed load transport during sedimentation.

<p>with fecal strings (Facies 4)</p>	<ul style="list-style-type: none"> • Plagioclase and K-feldspar: 2-3vol% • Organic matter: 30vol% • Medium mudstone matrix: 30vol% 	<ul style="list-style-type: none"> • Contacts with other facies are gradational. • Devoid of sedimentary structures and fossils. • Phycosiphon-type fecal strings (Egenhoff and Fishman 2013) more than 2 mm in length; filled with dark mudstone equivalent to matrix and lined with quartz silt (Bednarz and McIlroy 2012). 	<ul style="list-style-type: none"> • Subrounded grains indicate transport prior to deposition; angular grains either diagenetic or not rounded due to short transport path and likely from a different source. • Gradational contacts reflect gradual changes in the depositional environment. • Massive fabric is likely produced by fecal strings. • Depositional environment is likely dysoxic because of abundant fecal strings; likely stressed environment because of only one type of fecal string.
<p>Normally graded coarse to medium-grained mudstone (Facies 5)</p>	<ul style="list-style-type: none"> • At the base • Quartz: 21vol% • Carbonate grains: 38vol% • Organic matter: 6vol% • Matrix: 35vol% • At the top • Quartz: 10vol% • Carbonate grains: 10vol% • Organic matter: 20vol% • Matrix: 60vol% 	<ul style="list-style-type: none"> • Normally graded very coarse to medium-grained mudstone; grains are angular to subrounded. • Poorly sorted at base, moderately sorted towards top. • Sharp contacts top under- and overlying facies. • Bioturbations absent at base, present at top. • Devoid of fossils and sedimentary structures. 	<ul style="list-style-type: none"> • Normal grading suggests deposition from waning flow depositing coarse grains first followed by smaller grain sizes. • Flows depositing this facies were high energy because of initial erosion followed by successively lower energy recording deposition. • Subrounded grains indicate some transport, angular grains show either very minor transport or are diagenetic. • Sharp bed contacts show significant change in depositional conditions. • The absence of fossils is interpreted to be diagenetic; bioturbation shows the presence of some oxygen during sedimentation.
<p>Medium-to coarse-grained</p>	<ul style="list-style-type: none"> • Quartz: 46vol% • Carbonate grains: 27vol% 	<ul style="list-style-type: none"> • Medium- to coarse-grained siltstone; siliciclastic and carbonate grains are angular to sub-rounded and poorly sorted. 	<ul style="list-style-type: none"> • Depositing flow waned from erosion (sharp erosional base) to deposition (lenticular bed).

<p>lenticular siltstone (Facies 6)</p>	<ul style="list-style-type: none"> • Plagioclase and K-feldspar: 11vol% • Organic matter: 1vol% • Matrix: 15vol% 	<ul style="list-style-type: none"> • Lenticular thin beds, 1mm thickness <1vol% of organic matter. • Sharp wavy boundaries with over- and underlying facies. • Devoid of burrows and benthic fossil remains; locally, prices fish bones sub-millimeter in length (0.09-0.35 mm) occur. • White in thin section, grey in outcrop. 	<ul style="list-style-type: none"> • Lenticular form of bed indicates deposition by bed load processes, likely during an event. • Sub-rounded grains reflect some transport; angular grains reflect either very little transport, transport in suspension if medium-grained silt (Yawar and Schieber 2017), or precipitation during diagenesis. • Poor sorting shows that some mixing of grains occurred after deposition. • Absence of benthic fossil remains and burrows indicate reduced oxygenation of the environment; however, as this facies was likely deposited during an event that may explain why neither burrows nor fossils are present.
<p>Siltstone lamina (Facies 7)</p>	<ul style="list-style-type: none"> • Quartz: 40vol% • Carbonate grains: 20vol% • Organic matter: 10vol% • Matrix: 10vol% • Cement: 20vol% 	<ul style="list-style-type: none"> • Coarse to very coarse siltstone, angular to subrounded grains, moderately sorted. • Continuous and discontinuous laminae and thin beds, (0.1-6) mm, partly pinching out. • Sharp contact with over- and underlying facies. • Devoid of sedimentary structures, fossils, and trace fossils. • White in thin section, gray in outcrop. 	<ul style="list-style-type: none"> • Abundance of coarse to very coarse silt and lack of matrix indicates relatively high depositional energy. • Changing thickness reflects bed load processes partly dominated sedimentation. • Some sediment transport indicated by sub-rounded grains; angular grains interpreted as either little transported and from a different source or diagenetic. • Moderate sorting reflects moderate energy fluctuations. • Sharp contacts show strong (and potentially quick) change of energy regime.
<p>Massive calcitic coarse silt- to coarse-</p>	<ul style="list-style-type: none"> • Grains: • Calcite: 75vol% • Cement: 25vol% 	<ul style="list-style-type: none"> • Grains are coarse silt to coarse sands, mostly composed of calcite; matrix is absent. 	<ul style="list-style-type: none"> • Relatively high-energy depositional environment based on coarse grain-size; calcite composition of most grains is interpreted as reworking of carbonate source

<p>grained sandstone (Facies 8A)</p>		<ul style="list-style-type: none"> • Grains are angular to sub-rounded, poorly sorted. • Devoid of internal structures (massive), contacts to over- and underlying facies are sharp. • Dark gray to black in outcrop, white to gray in thin section. • Devoid of fossils or burrows. • Distinct scour into underlying facies at base is common, generally 0.5-1 mm deep. 	<p>rock, potentially an updip carbonate environment? Sharp contacts confirm high energy of depositing flow, and scours indicate even higher energy erosion into underlying strata.</p> <ul style="list-style-type: none"> • Absence of matrix and coarse grain size indicates bed-load transport; absence of sedimentary structures are likely a result of rapid sedimentation. • Lack or minor rounding of grains indicates little sediment transport; poor sorting could mean fluctuating energy conditions, or partial liquefaction of sediment during dewatering. • Lack of burrows likely reflects partial (complete?) liquefaction; lack of fossils likely reflects lack of fossil material in the source area; however, the calcite grains probably originated from organisms (e.g., Flügel 2004).
<p>(Facies 8B)</p>	<ul style="list-style-type: none"> • Grains • Quartz: 18vol% • Rip-up clasts 5vol% • Calcite: 27vol% • Mud: 25vol% • Cement: 25vol% 	<ul style="list-style-type: none"> • Coarse sand at the base to coarse silt towards the top of individual beds; contacts are sharp to over- and underlying strata; in places 0.17 mm-deep scours at base. • Grains angular to sub-rounded; poorly sorted at base, moderately sorted at top. • Devoid of sedimentary structures, massive. 	<ul style="list-style-type: none"> • Grain size, sharp contacts to underlying strata as well as scours and rip-up clasts indicate relatively high energy deposition of facies. • The poor to moderate rounding reflects deposition not far from the source, and potentially some diagenetic impact, especially in the carbonates; the lack of sorting at the base shows that large and small grains were likely transported and then deposited together; the better sorting at the top indicates that with less energy the

		<ul style="list-style-type: none"> • Rip-up clasts are presented with about 1 mm in length. • Dark grey to black in outcrop, medium grey in thin section. • Underlying facies is generally massive fine to coarse-grained mudstone (facies 3). • Fragmented fish bones are present in places; no other fossils or burrows present. 	<p>large grains have been deposited out of the flow, and only the smaller grains remain.</p> <ul style="list-style-type: none"> • The massive nature of the beds is here interpreted to reflect rapid deposition likely from a waning flow as indicated by the decrease in grain size; alternatively, it could reflect liquefaction of water-rich sediment. • The fact that this facies is generally underlain by mudstones of facies 3 interpreted to reflect low-energy sedimentation indicates that facies 8B was deposited by a high-energy flow and is likely an event deposit. • The high-energy nature of the flow is also shown in the fragmentation of fish bones; the lack of fossils reflects a lack of them in the source area of the flow, and the absence of burrows shows then relatively quick nature of deposition and strengthens the interpretation of facies 8B being an event bed.
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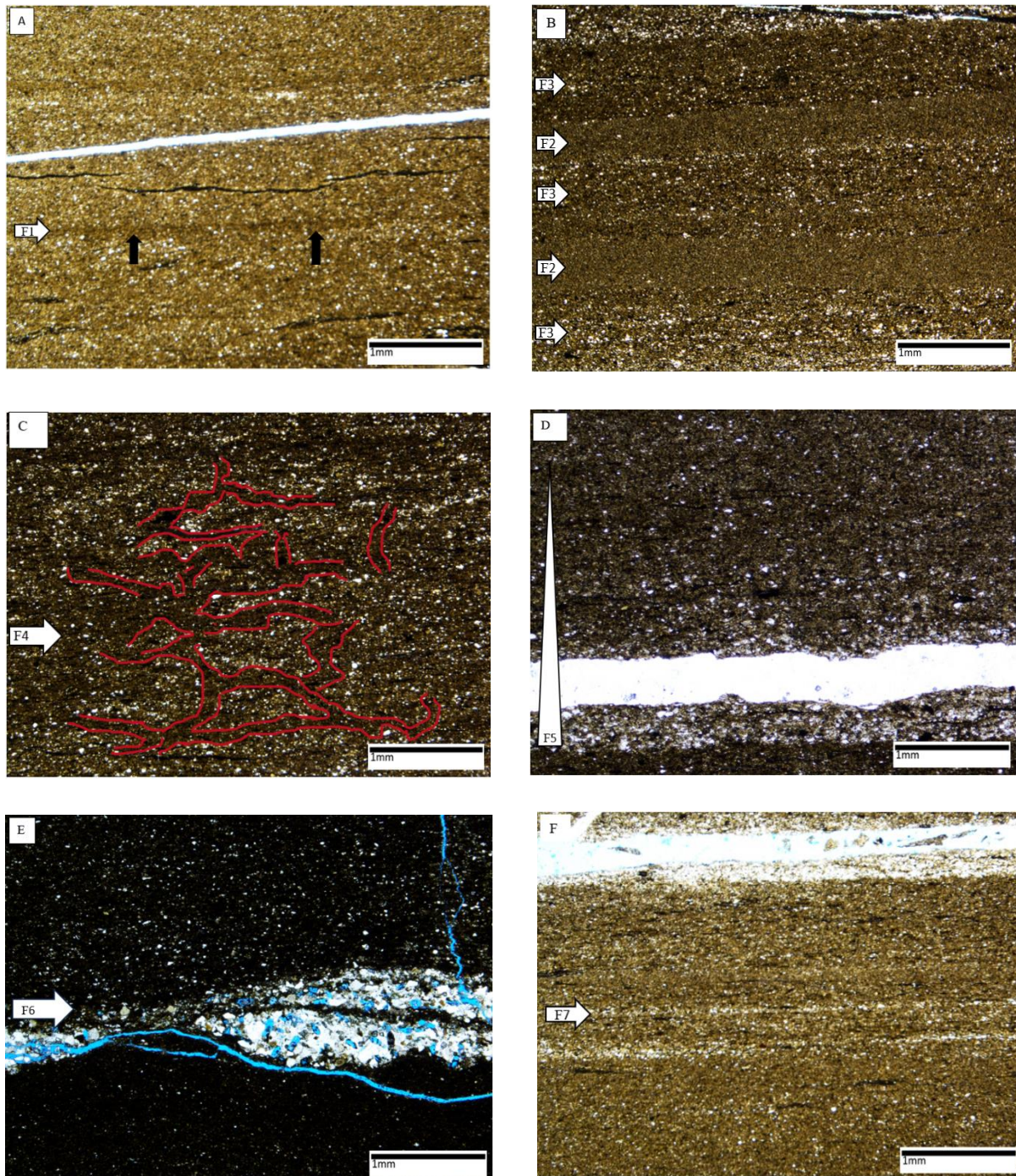


Figure 3. Facies of massive mudstone unite of Skull Creek Formation: (A) Very fine to Fine-grained dark massive mudstone lamina (F1) indicated by arrows. (B) Very fine-grained massive mudstone (F2) interbedded with Massive Fine- to coarse-grained mudstone (F3). (C) Sketch map showing fecal strings in the massive mudstone with fecal strings (F4). Normally graded coarse to medium-grained mudstone (F5). (E) Medium- to coarse-grained lenticular siltstone (F6) indicated by arrow. (F) siltstone lamina (F7).

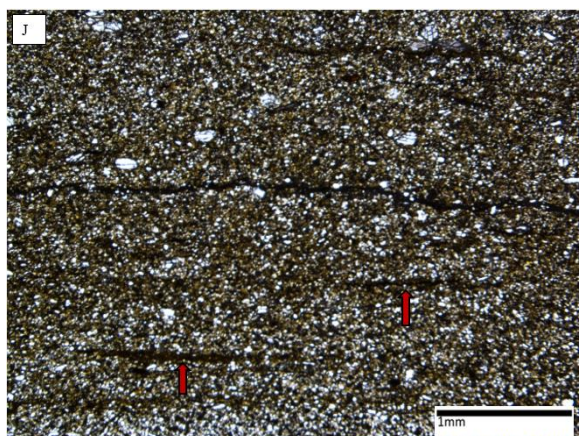
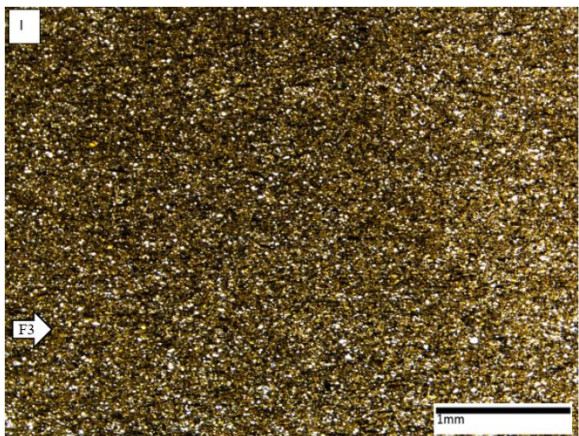
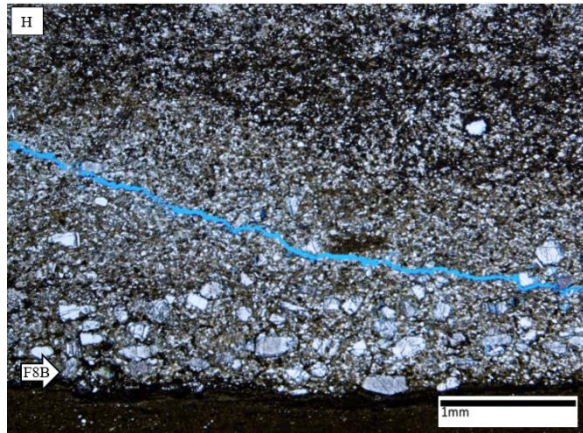
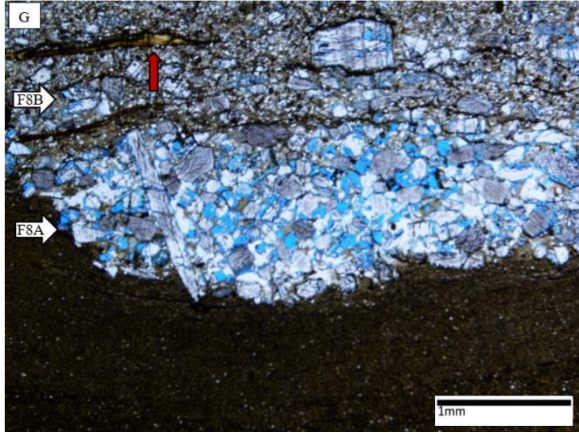


Figure 3 (continued): (G) Massive calcitic coarse silt- to coarse-grained sandstone (F8A) and (F8B) and fish bone remains indicated by the red arrow. (H) Massive calcitic coarse silt- to coarse-grained sandstone (F8B). (I) Massive fine- to coarse-grained mudstone (F3) that has been bioturbated. (J) Rip-up clasts indicated by red arrows in F8B.

Facies Architecture

The facies architecture is mostly based on one profile within the Skull Creek Formation because the overall fine-grained lithology of this section does not crop out well, is easily overgrown, or is covered by scree to the degree that it cannot be seen in the field. But even where it is possible to have these facies exposed, the sediment patterns in this outcrop are not easily visible or entirely invisible to the naked eye. However, the second section that is measured at a distance of about 400 m from the first one, shows the exact same facies patterns if correlated. Therefore, the assumption is made here that the facies patterns observed continue laterally for a significant distance without changing either the lithological character, or the thickness of the beds.

The succession consists of 16 coarsening- and fining-upwards cycles, which are generally asymmetric in nature (Fig. 4). The succession does not always show fining-upwards cycles on top of coarsening-upwards ones; on the contrary, most of the cycles are coarsening-upwards (11 out of 16) and are stacked on top of each other. Also, the coarsening-upwards cycles vary in thickness from 2 to 45 mm, while the fining-upwards cycles are between 18 and 758 mm thick. The succession in this study stratigraphically is subdivided into nine stratigraphic zones. Each zone consists of a portion or more than coarsening- and fining upwards units. There are five zones that are fine-grained units, and four zones are silt-rich or coarse-grained units. These zones exchange respectively from the fine zone to the coarse zone.

The entire succession is dominated by massive fine- to coarse-grained mudstone (F3) throughout, and only in some parts by normally graded coarse- to medium-grained mudstone (F5). The fining-upward units generally start with siltstone lamina (F7) and, in some places,

normally graded coarse to medium-grained mudstone (F5) at their base. The central part of the fining-upward units is composed of massive fine- to coarse-grained mudstone (F3) that is locally intercalated with massive mudstone with fecal strings (F4). The top of the fining-upward units is generally either entirely composed of facies 3 mudstones or shows an intercalation of very fine-grained massive mudstone (F2) and massive fine- to coarse-grained mudstone (F3), and in rare cases, very fine to fine-grained dark massive mudstone (F1).

The coarsening-upwards units, in most cases, start at the base with massive fine- to coarse-grained mudstone (F3), and only rarely commence with very fine-grained massive mudstone (F2) or very fine to fine-grained dark massive mudstone (F1). The central part of the coarsening-upward units is generally composed of massive fine- to coarse-grained mudstone (F3) interbedded with siltstone lamina (F7). Alternatively, it can be composed of medium-to-coarse-grained lenticular siltstone (F6) or, in places, normally graded coarse to medium-grained mudstone (F5). The top part of coarsening-upwards units is commonly made up of siltstone lamina (F7) and rarely shows medium-to-coarse-grained lenticular siltstone (F6), massive calcitic coarse silt-to-coarse-grained sandstone (F8A), or massive calcitic coarse silt-to-coarse-grained sandstone (F8B).

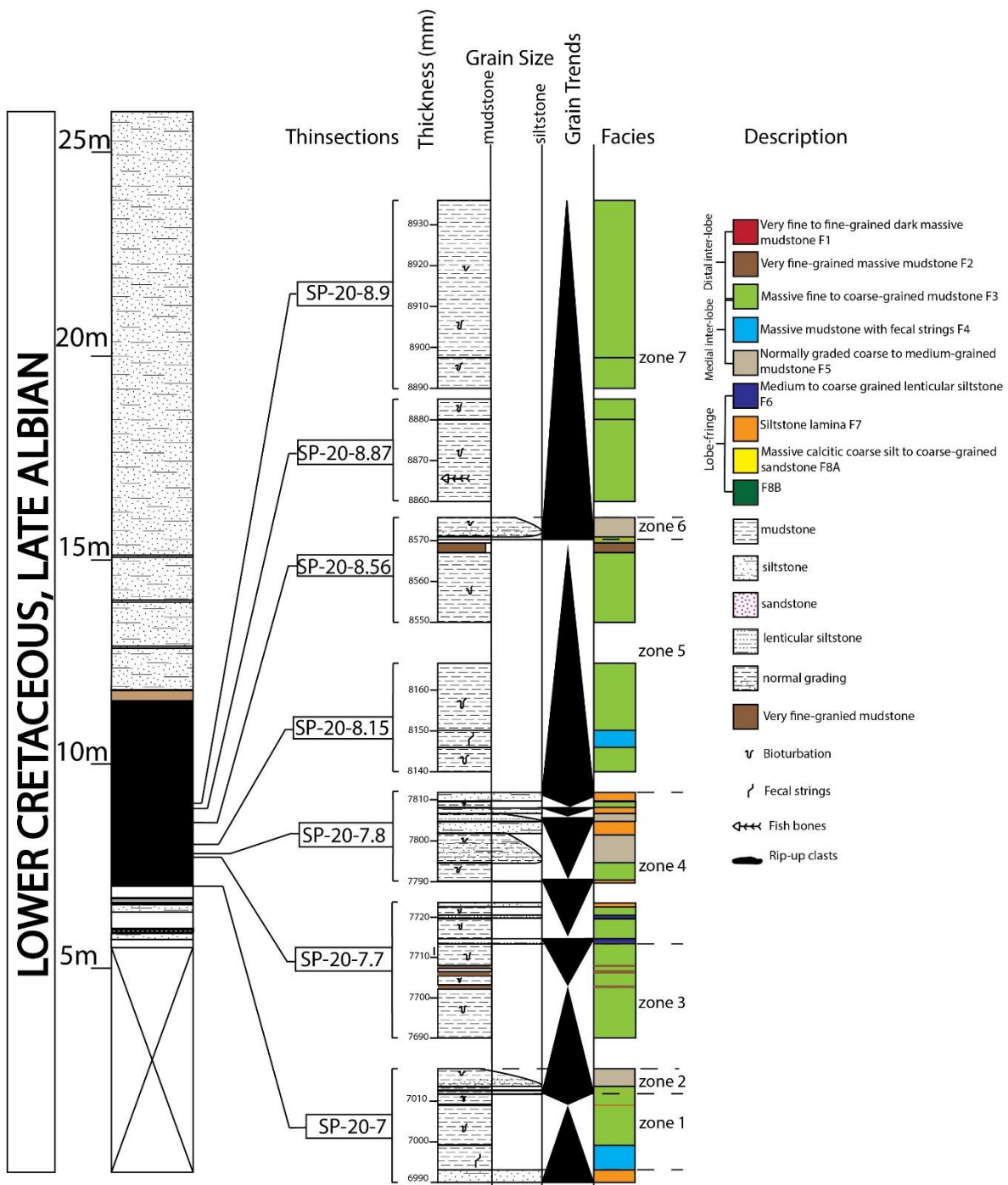


Figure 4. Stratigraphy column for the measured section of the Skull Creek Formation.

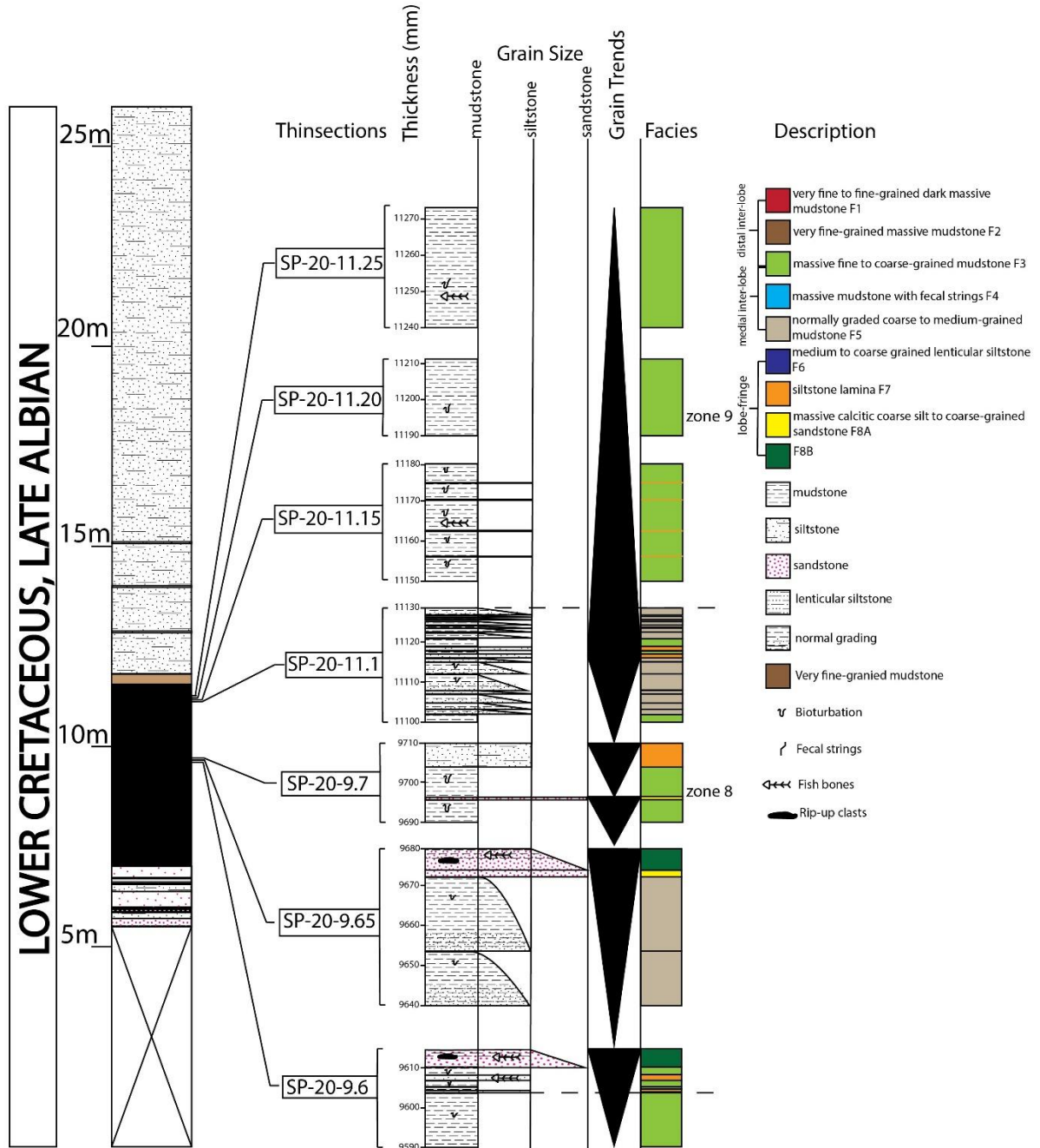


Figure 4 (continued). Stratigraphy column for the measured section of the Skull Creek Formation.

Depositional Model

Horizontal part

The studied interval in the Skull Creek Formation in Colorado shows three depositional areas, each of them characterized by a distinct array of facies. All of them represent sedimentation lateral to the main depositional site of the Skull Creek lobes in a prodelta system (Masterson, 2015), but they are clearly distinguishable based on facies occurrence within them. These three areas are referred to here as the distal inter-lobe, medial inter-lobe, and lobe-fringe (Fig. 5).

The distal inter-lobe area was mainly characterized by suspension deposition of fine mudstones (very fine to fine-grained dark massive mudstone lamina, F1, and very fine-grained massive mudstone, F2) and only at times records an influx of slightly higher energy deposits, likely dominated by bed-load processes (massive fine- to coarse-grained mudstone, F3). As both inter-lobe facies are sandwiched between lobe facies (Masterson, 2015) it is likely that when the lobe switched position, it deviated the sediment supply from the lobes to a different depositional site, which left the interlobe area sediment starved. It is here assumed that the distal inter-lobe areas were likely located between the lobes and not in a distal position of the lobes; this is especially valid when the prodelta lobes are assumed to be elongated in the direction of sediment transport (see Wilson and Schieber, 2014; Masterson, 2015) and not roundish as assumed in classical lobe models (Birgenheier et al., 2017). This also explains why the inter-lobe deposits are sandwiched between lobe deposits, which in distal lobe areas would not be the case. Suppose a hyperpycnal flow is envisioned to transport the sediment onto the lobe and beyond (Wilson and

Schieber, 2014) due to the directionality of the flow. In that case, the lobes become naturally elongate, and a lateral position to the main lobes is more likely for the inter-lobe sediments.

The fact that bioturbation is overall very low throughout all distal inter-lobe sediments suggests that this has not been a hospitable environment during deposition but a rather harsh one. Low presence of burrows is generally seen as indicating a stressed environment (Egenhoff and Fishman, 2013). The absence of burrows throughout distal inter-lobe deposits likely reflects that this was a highly dysoxic or maybe, in places, even anoxic environment. It is, therefore, suggested that the distal inter-lobe area, in contrast to the lobes themselves, does not provide suitable living conditions compared to their pro-delta lobe counterparts.

The medial inter-lobe deposits, in contrast, reflect a more intimate mix of suspension deposition and bed-load transport of sediment; however, bed-load processes dominate deposition. Most of the sediments in this area are massive mudstone with fecal strings (F4) and normally graded coarse to medium-grained mudstone (F5), which both suggest that these sediments were deposited in a relatively high-energy setting. Furthermore, the relatively high energy environment is reflected in scouring, leading to erosional basal contacts of facies 4 and 5, and the coarsest part of facies 5 sediments that show silt grains. Potential suspension sedimentation, however, is recorded in facies 3 sediments intercalated with facies 4 and facies 5 that are interpreted to be deposited by a mix of bed load transport and suspension settling.

The presence of bioturbation in the medial inter-lobe deposits indicates that some amount of oxygen was present during the sedimentation of these sediments. The depositional environment in this area is interpreted as having been dysoxic and likely stressed (Egenhoff and Fishman, 2013) because only one type of burrows is present in these sediments.

The lobe-fringe area was characterized by mostly bed-load deposition and only at times by suspension settling. The nature of the depositional flows was both erosive and depositional, as reflected in abundant scours, and overlying sediments. The erosive nature is reflected in the presence of clay rip-up clasts. The lobe-fringe deposits are strongly dominated by sediments recording bed-load transport. This area consists of four facies that are: medium-to coarse-grained lenticular siltstone (F6), siltstone lamina (F7), and massive calcitic coarse silt-to coarse-grained sandstone (F8A and F8B); nevertheless, massive fine- to coarse-grained mudstone (F3) is locally present in the lobe fringe deposits. The dominance of silt and even local sand grains of these facies reflect an increase in depositional energy with respect to distal and medial interlobe facies. The abundance of clay clasts, sharp erosional basis of individual beds or deep scours at the base of beds, the occurrence of fragmented fish bones, and the large size of some grains show the high-energy nature of these sediments. However, at times, this environment was characterized by quiet conditions as reflected in the presence of facies 3 massive mudstones. Facies 6 and facies 8A were most likely deposited during an event because fossils and burrows were not presented. Furthermore, the absence of burrows and sedimentary structure in this area could result in rapid deposition, most likely from a waning flow. In addition, the lack of fossils reflects a lack of them in the source area of the flow. The bioturbation in this area was observed in facies 3 only, so the depositional environment in the lobe-fringe is probably a dysoxic environment.

Vertical part

Inter-lobe areas like the one in the Skull Creek Formation seem to be dominated by distal inter-lobe deposits see (Fig. 5) (mostly facies 3, and subordinately facies 1 and 2). This indicates that in very fine-grained successions like the one investigated in this study, distal inter-lobe areas are more abundant than medial inter-lobe to lobe fringe facies- between individual lobes. Nevertheless, the Skull Creek succession records both, the lobe moving away from the study site in fining-upward successions, and the lobe moving closer to the depositional area indicated by coarsening-upward successions. A total of two coarsening- and fining-upward successions are present in the Skull Creek. However, no generalization is possible, showing that either coarsening or fining-upwards is more abundant based on the present data set where both grain size trends occur within this one fine-grained interval.

The entire succession is interpreted to reflect oxygen deficiency as indicated by the lack of a diverse trace fossil suite. It is assumed in this study that the oxygen levels decrease from the lobe fringe facies to the distal inter-lobe areas. This is partly reflected in the burrowing of the facies; however, only the fine-grained facies show burrowing, if present. All coarse-grained facies here interpreted to reflect event deposition (mostly storms) are interpreted to not show burrowing, likely because they were deposited and overlain by other beds too quickly to have significant burrows. Nevertheless, the distal parts of the inter-lobe areas are partly devoid of oxygen, as no burrowing is present in these rocks. Therefore, the succession reflects an oxygen-deficient depositional site grading laterally into a potentially anoxic environment based on trace fossil abundance or absence.

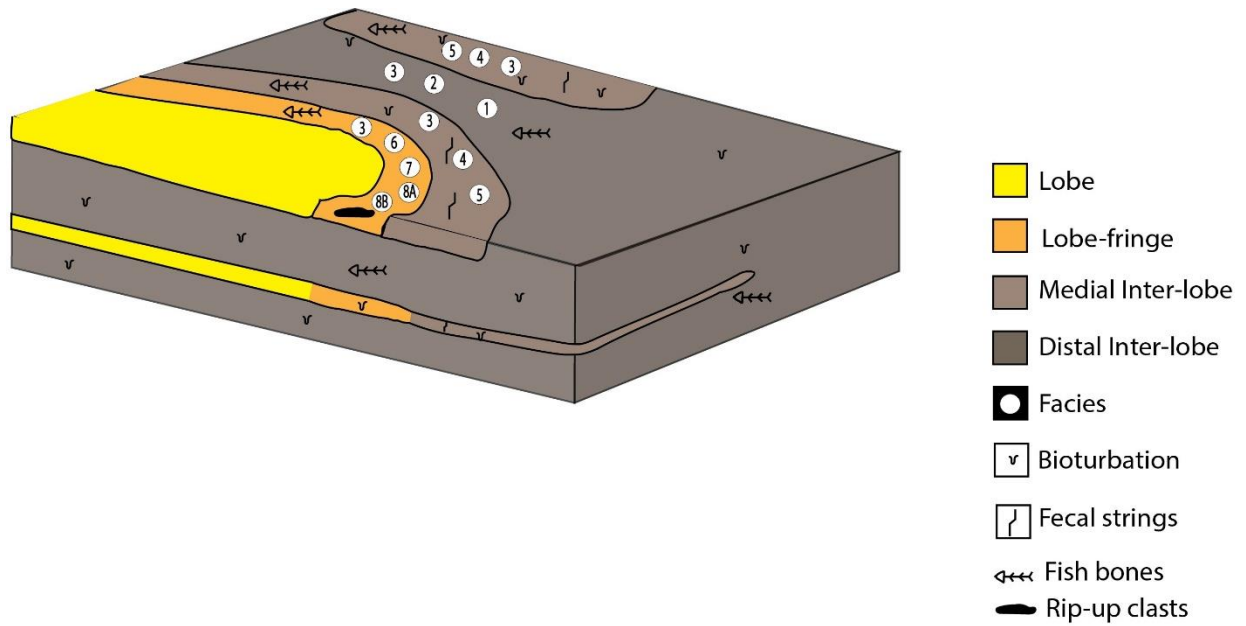


Figure 5. Schematic depositional block model block diagram for the Skull Creek Formation showing the interpreted locations of the 9 facies defined in this study.

Discussion

How can we be sure that the sediments described from the Skull Creek Formation are indeed lobe-fringe to distal inter-lobe deposits?

The succession in this study has been considered the most fine-grained portion of what was interpreted as representing lobes by Masterson (2015). It was considered sediment-starved because of its position in the most distal realm of a delta lobe. The same succession is interpreted here as representing an interlobe environment based on the same reasoning that Masterson (2015) originally applied: fine-grained, sediment-starved, and therefore likely distal to the main sediment delivery direction. The succession contains a range of grain sizes, from clay to coarse sandstone. The fine-grained mud-rich sediments, deposited by suspension, reflect distal inter-lobe deposits, while coarser siltstone and sandstone deposits, which result from bed load transport, represent lobe-fringe deposits. These sediments are typically found in the lateral area between lobes. Lateral lobe-fringe deposits experience a gradual decrease toward the distal inter-lobe. As suggested by Masterson (2015) and Wilson and Schieber (2014), hyperpycnal flows cause sediment-laden water to flow over the delta, leading to the formation of elongated lobes in the direction of flow. This lateral deposition process explains why sediments are found not only distally but also between lobes, forming inter-lobe environments. These inter-lobe areas, positioned between lobes, are characterized by sediment starvation. As the lobes shift, they divert sediment supply away from the inter-lobe areas, resulting in reduced sediment influx to these areas compared to the actively depositing lobes. This explains why the inter-lobe areas are fine-

grained, low-energy environments—conditions that arise when sediment supply is intermittent or absent due to lobe change. Therefore, these areas likely experience periods of sediment starvation, particularly when the lobe shifts, and sediment transport is diverted to a new location.

A fine-grained succession like the one described in this study is not commonly described in deltaic lobe environments, largely because it is often relatively thin because of sediment starvation and may have been eroded away in many successions. Alternatively, because of its fine grain sizes, it does not crop out or is not recognized if cropping out. For example, Kim and Cough (2000) describe lobe-fringe deposits without referencing inter-lobe strata. Similarly, Birgenheier et al. (2017) focus on mudstone deposition in the Cretaceous Western Interior Seaway, addressing environments like prodelta, mudbelt, and sediment-starved shelf, but omit inter-lobe strata from their discussion, despite showing a delta responsible for depositing mud on the shelf. Likewise, Bhattacharya and MacEachern (2009) describe prodelta and delta-front deposits but do not discuss inter-lobe or lobe-fringe environments. Studies like these suggest that inter-lobe areas may often be overlooked or underrepresented in traditional models of deltaic sedimentation.

A general model of delta deposition is currently focused only on the three main environments: delta top, delta front, and prodelta. However, a fourth setting – interlobe setting – may be advantageous to include in the general delta depositional model, as they form part of every delta depositional realm. They are currently not included, most likely because they do not form thick successions in deltas, nor are they considered economically important even though it is thought that they contain significant amounts of organic carbon (for the Skull Creek, see Sullivan et al., 2022). Acknowledging inter-lobe environments would therefore enhance our

understanding of deltaic sedimentation, particularly in terms of sediment transport, deposition, and organic carbon accumulation.

The importance of suspension deposition in inter-lobe areas?

In this contribution, the model of the Skull Creek formation is interpreted as depositing sediments in this mud-rich unit primarily by bed-load processes (Masterson, 2015; Sullivan et al., 2022). While this result may be surprising considering the small grain size of the Skull Creek strata, the sedimentary structures clearly point to a different story: all three depositional zones contain majorly facies that are characterized by bed load transport and depositional processes, such as medium- to coarse-grained lenticular siltstone (F6), siltstone lamina (F7), and massive calcitic coarse silt- to coarse-grained sandstone (F8A). Nevertheless, very fine to fine-grained dark massive mudstone lamina (F1) and very fine-grained massive mudstone (F2) are seen as representing suspension settling also in this study, but there is evidence indicative of bed-load transport. However, all facies that are either entirely or partly reflecting suspension deposition are present in small amounts throughout the Skull Creek Formation. This shows that suspension deposition in the Skull Creek Formation has been relatively rare and is not characterizing the formation throughout, not even in this distal setting away from the lobes, as assumed till now. The amount of suspension deposition increases from the lobe fringe to distal inter-lobe strata throughout the sediments of the Skull Creek Formation. While facies 3 is present in all three depositional zones, it still reflects some amount of suspension deposition, and its volume is small in lobe fringe deposits, while away from the lobe sediments, its amount consistently increases. This implies that considering even the relatively “high energy” lobe-fringe deposition put forth in this model, there existed a tranquil setting in

this same lobe-fringe area that played a role in the deposition of facies 3. This indicates that the Skull Creek Formation as a whole is dominated by bed load deposition, but there were times when the environment was quiet, as reflected in the presence of suspension deposition in all depositional areas.

How firm are lobe boundaries?

Any depositional model will show boundaries of facies as lines and relatively clearly defined in distinct places where depositional characteristics of sediments change (Birgenheier et al. 2017). In this model of the Skull Creek Formation, the same distinct boundaries characterize the three depositional areas, lobe-fringe, medial inter-lobe, and distal inter-lobe areas. However, the boundaries between the zones are not as easily defined because some of the same facies are present in each of the depositional zones, and they make a clear distinction of the three areas challenging at times. Nevertheless, the three depositional zones are defined based on distinct facies that only occur in this distinct zone and not in any of the others. For example, facies 1 and facies 2 are present exclusively in distal inter-lobe areas, and facies 4 is restricted to the medial inter-lobe zone. Facies 8A, and 8B are only observed in the lobe-fringe area. This distribution makes it possible to recognize these distinct environments as long as this critical facies is present. The overlap in the distribution of other facies (e.g. facies 3, or facies 5) shows, that some depositional processes and burrowing characteristics extend from one zone through the other and make a clear distinction between the three individual areas problematic. As long as the distinctive facies are present, which allows for recognizing one of the three areas, a depositional zone can be established, and, if the data set allows, a clear boundary can be drawn and represented by a line. However, when indicative facies for each of the three depositional

zones are missing as, for example, in the coarsening-upward cycle at meter 7.715 where the facies of the medial inter-lobe zone are missing. This approach cannot be applied, and in that case, facies boundaries will be approximate, and distinct lines to define them should be avoided.

What does burrowing/bioturbation reveal about oxygenation in lobe versus inter-lobe areas?

In this study, it is assumed that bioturbation reflects oxygen levels (Biddle et al., 2021; Egenhoff and Fishman, 2013), at least to a degree, and only in the fine-grained facies. Siliciclastic mudstones are typically not heavily affected by bioturbation, but some ichnospecies exist that do show adaptation to oxygen-deficient environments also occur in mudstones (Schieber, 2003). Fecal strings have been identified in this study, similar to several other siliciclastic mudstone units (e.g., Egenhoff and Fishman, 2013). However, the presence of only one type of fecal string suggests that any mudstone environment with a strongly reduced number of burrow types is probably a dysoxic and stressed environment (cf. Egenhoff and Fishman, 2013). Nevertheless, Masterson (2015) describes a large variety of ichnospecies grouped into up to 5 ichnofacies in the Skull Creek Formation directly overlying- and underlying the rocks studied in this investigation. Most of these ichnofacies occur in one particular kind of rock: the massive siltstone facies. These particular rocks show abundant burrowing, while similar facies in this study are burrow-free. This apparent contradiction can be explained in several ways: (1) the massive siltstone laminae in the coarse-grained parts of the Skull Creek Formation were not deposited as massive siltstones but as some other type of facies. Burrowing is the process that destroys any structures that were originally present in these rocks. The diverse ichnofacies described by Masterson (2015) are typical of a different type of environment deposited by unknown processes but look equivalent to the massive siltstone in the interval investigated in this

study; (2) the massive siltstone beds described by Mastersson (2015) are much thicker than the ones from this study. It is likely that even though depositional processes may have been equivalent to the oxygenation levels between lobe facies (Masterson, 2015), the inter-lobe areas (thin siltstone) may not be the same. While thick laminae require a lot of fluid in the depositing flow, very thin laminae like the ones in our study do not need much fluid to get deposited. With little fluid comes little oxygen; hence, it may not be enough to support a diverse trace of fossil fauna like the one on the lobes.

Summary and Conclusions

The fine-grained unit in the Skull Creek Formation consists of nine siliciclastic facies: very fine to fine-grained dark massive mudstone (F1), very fine-grained massive mudstone (F2), massive fine- to coarse-grained mudstone (F3), massive mudstone with fecal strings (F4), normally graded coarse to medium-grained mudstone (F5), medium- to coarse-grained lenticular siltstone (F6), siltstone lamina (F7), and massive calcitic coarse silt- to coarse-grained sandstone (F8A and F8B). These facies present 16 coarsening- and fining-upwards units in the succession, and these units subdivided the succession into nine stratigraphic zones, each zone containing a portion or more than fining- and coarsening unit. Of these zones, five are characterized by fine-grained units, while four are distinguished by silt-rich or coarse-grained units. The transition between zones alternates from fine-grained to coarse-grained characteristics.

This succession consists of 16 coarsening- and fining-upwards cycles. There are 11 coarsening-upwards cycles and five fining-upwards cycles. The thickness of these cycles is changed. The fining-upwards cycles mostly trend from the base siltstone lamina (F7) or normally graded coarse to medium-grained mudstone (F5) to the central massive fine- to coarse -grained mudstone (F3) or (F3) intercalation with massive mudstone with fecal strings (F4) to the top completely (F3) or facies 3 intercalation with very fine-grained massive mudstone (F2) and rarely very fine to fine-grained dark massive mudstone (F1). On the other hand, the coarsening-upwards cycles trend from massive fine- to coarse-grained mudstone (F3) or very fine-grained massive mudstone (F2) and rarely fine-grained dark massive mudstone (F1) to the central of the cycles where normally graded coarse to medium-grained mudstone (F5) or medium- to coarse-grained lenticular siltstone (F6) present to siltstone lamina (F7) or rarely medium- to coarse-

grained lenticular siltstone (F6), massive calcitic coarse silt- to coarse-grained sandstone (F8A), or massive calcitic coarse silt- to coarse-grained sandstone (F8B) on the top.

The facies in this study were deposited across three distinct depositional environments: the lobe-fringe area, the medial inter-lobe area, and the distal inter-lobe area. The lobe-fringe environment exhibited fluctuations between high and low energy conditions, as indicated by features such as clay clasts, sharp erosional bases, scours, and fragmented fishbones, along with the presence of sediments indicating suspension deposition, suggests that the lobe-fringe environment experienced successive shifts between high and low energy conditions. Moving away from the lobe, the medial inter-lobe area displayed moderate energy conditions, indicated by normal grading and erosional contacts, with alternating periods of moderate and low energy. The distal inter-lobe sediments, located furthest from the lobe, were primarily characterized by tranquil deposition, with minor, moderate energy deposition reflected in sharp facies contacts and some siltstone grains in facies 3. The boundaries between the lobe-fringe, medial inter-lobe, and distal inter-lobe areas are transitional, not distinct. Although each zone has unique facies, overlapping facies make it difficult to clearly differentiate them. The limited presence of fecal strings and low bioturbation in the inter-lobe sediments suggest a dysoxic and stressed environment, but it is not entirely anoxic.

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