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MARINE–CONTINENTAL TRANSITIONS IN A GREENHOUSE WORLD: RECONSTRUCTING LATE CRETACEOUS DELTAS OF PALEOPOLAR ARCTIC ALASKA AND UTAH

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MARINE–CONTINENTAL TRANSITIONS IN A GREENHOUSE WORLD: RECONSTRUCTING LATE CRETACEOUS DELTAS OF PALEOPOLAR ARCTIC ALASKA AND UTAH

by

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Dedication

I dedicate this dissertation to Dr. John Doyne Cooper. The late Dr. Cooper (June 12, 1939 – September 3, 2007) received his Master of Arts in Geology in January 1964 and Doctor of Philosophy Degree in Geology in December 1970 at the University of Texas at Austin. I met Dr. Cooper in 1998 as an undergraduate at California State University, Fullerton. Dr. Cooper, also known as "Coop," was a sedimentologist, stratigrapher, and paleontologist as well as my Earth History, Sedimentology, and Stratigraphy professor. Coop's passion for geology was infectious, his pursuit of scientific observations and hunt for the "smoking gun" unrelenting, and he always applied the principle of Occam's razor when drawing conclusions. Coop's standards and expectations were rigorous, not just for himself, but for those around him. Coop had a personal and classy way of leading and empowering many of his students to strive for excellence. I have never since met a professor who held such high personal standards for science or for people. John, you encouraged me and many others around you to become better people. Through your lectures, laboratory exercises, field trips, and scientific excursions I found my love and passion for sedimentology, stratigraphy, and ichnology. You were a dear friend, at times a father-figure whom I did not want to disappoint, and you remain a mentor. In this way, I continue to follow your footsteps on the trail, Coop!

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First and foremost, I thank Dr. Peter Flaig at the Bureau of Economic Geology in Austin, Texas. During the summer of 2006 and 2007, while we were graduate students at the University of Alaska Fairbanks, I worked as a field assistant during his PhD fieldwork. In order to reach Pete's study area, we would head north from Umiat, Alaska, on the Colville River boating past Shivugak Bluffs, some of the highest topographic rock exposures along that area of the Colville River. Both enamored by the vertical and lateral extent of these outcrops, Pete and I both knew that we would return to work this location. Peter, I would have never worked these outcrops if you had not selected me as your field assistant all those years ago. Thank you for your trust and respect. We always knew that Shivugak Bluffs was a special locality, and when you asked me to marry you there along the Cretaceous paleoshoreline August 20, 2010, you could not have made these Bluffs more breathtaking. Thank you for being my rock, and true partner.

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John Ames, Paula Beard, Patricia Bobeck, Cari Breton, Cathy Brown, and Robert Penman are thanked for their contributions to drafting, formatting, or grammatical suggestions to this dissertation. I also thank the following graduate students at UT Austin for their support and friendship through the years: Tricia Alvarez, Paul Betka, Darrin Burton, Jess Hudock, David Hull, Brian Kiel, Vishal Maharaj, Maria Prieto, Michael Prior, Migdalys Salazar, Ben Urick, and Kurtus Woolf. Special thanks to Edgardo Josue Pujols Vazquez for helping Pete and me GigaPan the Blackhawk Formation in Utah.

Last but not least, a heartfelt thanks to my dearest family and friends who have always believed in me and who have been supportive all these years.

Preface

Frank Charles Schrader began working as a geologist for the United States Geological Survey (USGS) in 1896 and led the first instrumental survey from the Yukon to the north coast of Alaska in 1901 (Schrader 1904; Sweet 2008). As a result of the Klondike gold rush by 1899, the USGS first learned of the probable existence of a passable route over the Brooks Range between the upper Koyukuk and Arctic slope (Schrader 1904; Fig. 1.1). Prior to 1901, only two journeys by westerners had yielded geographic information regarding Arctic Alaska: the first was undertaken in 1886 by the U.S. Navy and the second in 1890 by J.H. Turner (Schrader 1904). In 1901 the Schrader party set out from Skagway, Alaska, in early February and reached Point Barrow by September 8. The expedition traveled by railway, dog-sled team, river steamboat, and canoe, and portaged over Anaktuvuk Pass. Schrader Bluff, named after Frank C. Schrader, found at an elevation of 199 m (653 feet) and comprises an ~ 32 m high vertically dipping outcrop belt along the Anaktuvuk River in Arctic Alaska (Orth 1971). Schrader Bluff is significant, because it is the namesake for the Upper Cretaceous (Santonian−Paleocene) Schrader Bluff Formation, a primary focus of this dissertation (Fig. 1.2; Gyrc et al. 1951).

President Warren G. Harding, based on Schrader’s (1904) USGS report, set aside an area roughly the size of Indiana (~ 23 million acres) within the Alaska Territory as an emergency oil supply for the U.S. Navy (Gyrc 1988). This area, known as the National Petroleum Reserve–Alaska (NPRA), is located north of the Brooks Range on the Arctic coastal plain and is part of an area often referred to as the North Slope (Fig. 1.1). On

January 3, 1959, Alaska became the 49th state of the United States of America. In 1976, Congress transferred management of the NPRA from the U.S. Navy to the Bureau of Land Management (BLM) (Gyrc 1988). The NPRA contains some of the highest topography on the central North Slope including prominent cliffs exposed along the Colville River, which is the eastern boundary. Along the Colville River are the world-class rock exposures (90−120 m high) known as Shivugak Bluffs (Fig. 1.1). Shivugak, derived from the Eskimo word sivugak, refers to “the bluff as being first” (Orth 1971). This study is the first comprehensive, high-resolution sedimentologic investigation of the reference section and type locality for the Rogers Creek, Barrow Trail, and Sentinel Hill Members of the lower Schrader Bluff Formation at Shivugak Bluffs (Fig. 1.2; Gyrc et al. 1951; Mull et al. 2003; Decker 2007).

MARINE–CONTINENTAL TRANSITIONS IN A GREENHOUSE WORLD: RECONSTRUCTING LATE CRETACEOUS DELTAS OF PALEOPOLAR ARCTIC ALASKA AND UTAH

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The University of Texas at Austin, 2016

Supervisors: Charles Kerans and Stephen Hasiotis

Near horizontal (6° dipping) outcrop exposures of Upper Cretaceous (Santonian-Campanian) strata at Shivugak Bluffs in northern Alaska preserve an extensive record of a clinoform-topset system. These strata are generally subdivided lithostratigraphically into proximal shelf, deltaic, and shallow marine deposits of the Schrader Bluff Formation and lower delta plain, coastal plain, and fluvial deposits of the continental Prince Creek Formation. Shivugak Bluffs includes 400 m of continuous marine deposits overlain by 140 m of strata containing the marine–continental transition between the lower Schrader Bluff and Prince Creek formations. The marine-continental transition is one of the few outcrop expressions of an ancient, muddy, prograding river-dominated deltaic system that contains interdistributary bays that shoal upward into floodbasins with pedogenic modification. The lowermost 400 m of the lower Schrader Bluff Formation is divided into the Rogers Creek, Barrow Trail, and Sentinel Hill members interpreted as recurring deposits of river-dominated deltas comprising distributary mouth bars (DMBs), subaqueous terminal distributary channels (TDCs), interdistributary bays, medial delta front deposits, distal delta front deposits, and prodelta deposits interbedded with proximal shelf deposits. One interval within the Rogers Creek Member comprising the most hummocky cross-stratified (HCS) interval at Shivugak Bluffs is interpreted as wave-reworked DMB-TDC complexes or storm sheets. The Schrader Bluff (West Sak and Tabasco equivalent in the subsurface) and Prince Creek (Ugnu equivalent in the subsurface) formations are relevant to industry as outcrop analogs for numerous shallow, viscous- to heavy-oil reservoirs on the central North Slope, Alaska. From a reservoir perspective, a 36-m-thick subset of the Alaska succession within the Rogers Creek Member is compared to 36- and 34-m-thick wave-dominated successions of the Kenilworth and Grassy Members of the Blackhawk Formation in the Book Cliffs in eastern Utah. The Rogers Creek Member includes amalgamated DMB-TDC complexes (54%) with minor HCS wave-reworked deposits (46%). This succession is compared with the Kenilworth and Grassy members that exhibit predominantly swaley and HCS intervals (75–81%) with minor channel complexes (14–25%). The Blackhawk Formation, based on this analysis, is a poor reservoir analog for the lower Schrader Bluff Formation of Arctic Alaska.

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"May you walk in beauty.

May there be beauty before you.

May there be beauty behind you.

May there be beauty above and below you."

– Eskimo Blessing

CHAPTER 1 – INTRODUCTION

PROBLEM AND SIGNIFICANCE

High-latitude depositional systems—preserved in the rock record and those forming today—are some of the least explored and least studied areas to date (Fraticelli et al. 2014). Little has been documented about high-latitude deltaic or shallow marine environments, especially those deposited under greenhouse conditions (Davies et al. 2009; Fraticelli et al. 2014). Onshore deposits in Arctic Alaska (Fig. 1.1) are important because they contain paleopolar clastic successions deposited during the Cretaceous (66–145 Ma), when Earth was significantly warmer (Fig. 1.2; Walker et al. 2013), but stratigraphic studies are in their infancy. Alaska Cretaceous strata exposed on the North Slope in the Colville Basin preserve remnants of the paleo–Arctic Ocean and the coeval shoreline and coastal plain, representing one of the northernmost stratigraphic records known to the scientific community (Herman and Spicer 2010). There are no modern analogues for warm polar ecosystems. The Cretaceous record in Arctic Alaska, however, is useful for providing paleoenvironmental reconstructions of warm polar ecosystems.

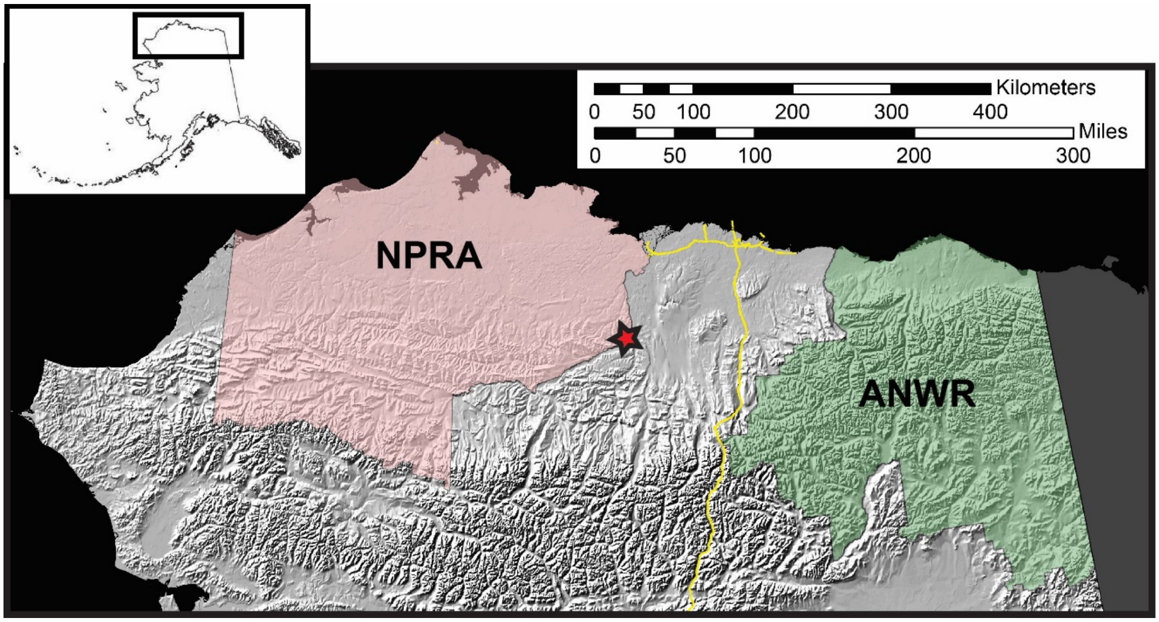

Figure 1.1. Regional shaded relief map of the Brooks Range and North Slope of Alaska with boundaries of the National Petroleum Reserve –Alaska (NPRA) and the Arctic National Wildlife Refuge (ANWR) (modified from Riehle et al., 1977). Red star indicates study area location, Shivugak Bluffs. Yellow lines represent portions of the Trans Alaska Pipeline System.

Strata in Northern Alaska are divided into four major tectonostratigraphic sequences (Fig. 1.3; Hubbard et al. 1987; Garrity et al. 2002): (1) the Franklinian, comprising Proterozoic to Devonian sedimentary, metamorphic, and igneous rocks that represent basement; (2) the Ellesmerian, composing heterogeneous Mississippian to Triassic marine and continental rocks deposited on a southward-dipping passive margin; (3) the Beaufortian, composed of Jurassic to Lower Cretaceous siliciclastic strata associated with rifting; and (4) the Brookian, comprising Cretaceous to Paleocene synorogenic siliciclastics eroded from the Chukchi Platform and the Brooks Range and deposited in the Colville Basin. The focus of this dissertation is one of several clastic

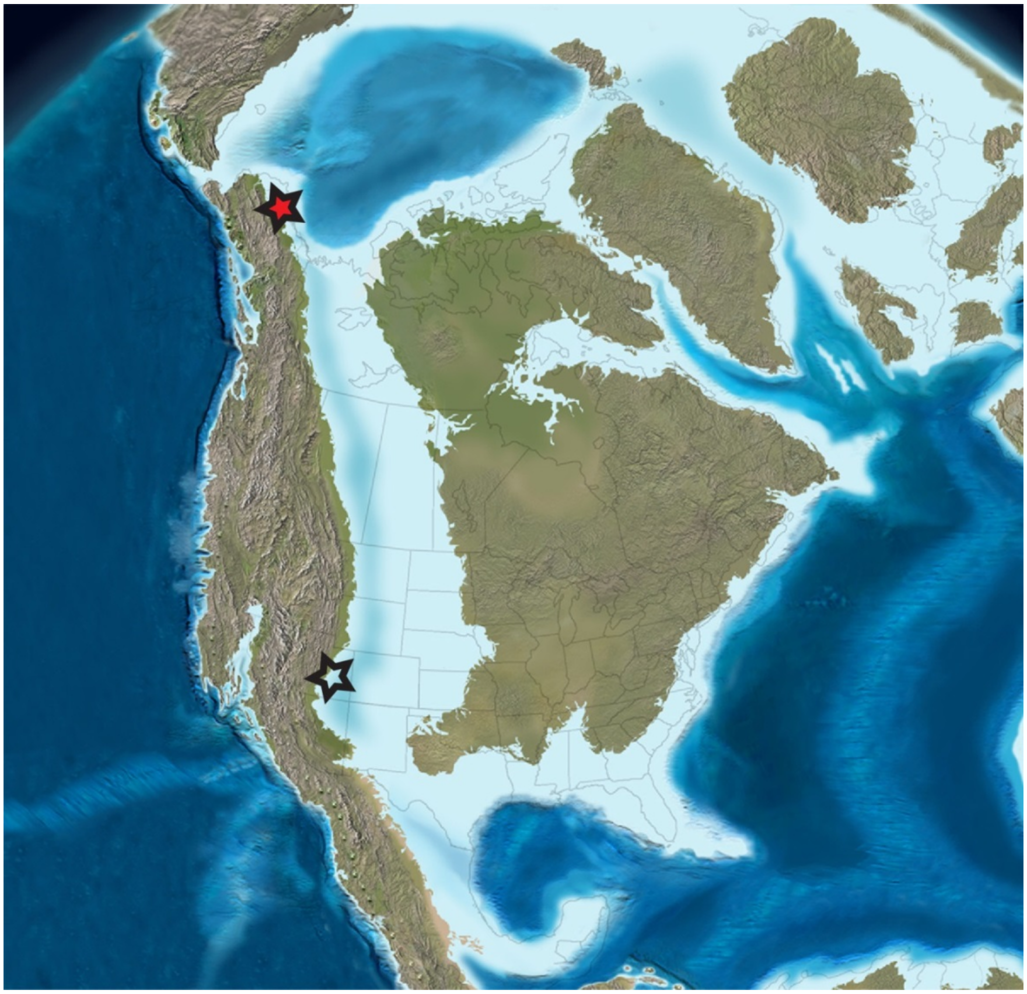

Figure 1.2. Paleogeographic map of North America during the Late Cretaceous (85 Ma) showing dissertation study areas: Arctic Alaska deposits within the Arctic Ocean (red star) and deposits in Utah in the Western Interior Seaway (translucent star; ©Ron Blakey, Colorado Plateau Geosystems, Inc.).

wedges within the Brookian tectonostratigraphic sequence (Fig. 1.3). Examination of a proximal to distal transect of this clastic wedge reveals fluvial (river), lower-delta-plain, and coastal-plain deposits of the Prince Creek Formation; deltaic, shallow marine, and proximal shelf deposits of the Schrader Bluff Formation; slope deposits of the Canning

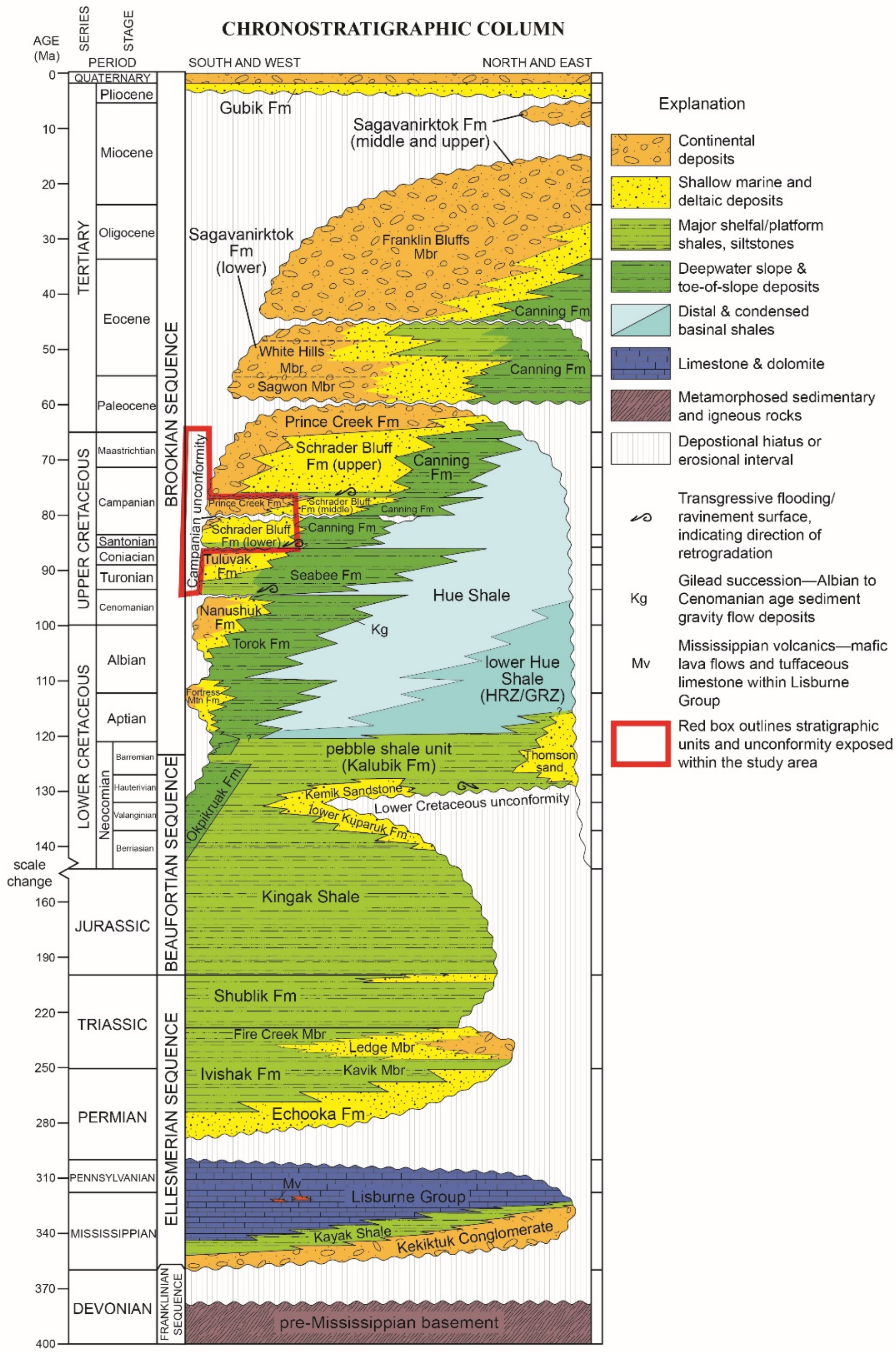

Figure 1.3. Chronostratigraphic column of northern Alaska; red box indicates study area and contact of the lower Schrader Bluff Formation with the Prince Creek Formation (modified from Herriott et al. 2011; Decker 2010; Garrity et al. 2005; Mull et al. 2003).

Formation, and deep-water deposits of the Hue Shale (Fig. 1.3; Mull et al. 2003; Garrity et al. 2005; Decker 2010; Herriott et al. 2011; Flaig et al. 2011, 2013).

The Santonian–Paleocene (86.3–56 Ma; Walker et al. 2013) Schrader Bluff and Prince Creek formations are commercially relevant because they contain up to 30 billion barrels of oil in place (Hartz et al. 2004; Attanasi and Freeman 2015) and constitute one of the largest hydrocarbon reservoirs in the United States (Croft et al. 1999). The Colville River, which forms the eastern boundary of the National Petroleum Reserve−Alaska (NPRA) exposes world-class outcrops of the Schrader Bluff and Prince Creek formations. Bluffs along the Colville River are outcrop analogues for several subsurface viscous- to heavy-oil reservoir systems, including: the West Sak, Tabasco, and Ugnu accumulations in the Kuparuk River field, the Orion and Polaris accumulations in the Prudhoe Bay field, and the Schrader Bluff accumulations in the Milne Point and Nikaitchuq fields (Croft et al. 1999; Alaska Oil and Gas Conservation Commission 2004, 2010).

The Prince Creek Formation is renowned for containing the largest concentration of high-latitude dinosaur fossils on Earth (Currie 1989; Clemens and Nelms 1993; Fiorillo and Gangloff 2000, 2001; Rich et al. 2002; Gangloff et al. 2005; Fiorillo et al. 2009, 2010a, 2010b; Gangloff and Fiorillo 2010; Flaig et al. 2013, 2014). Bluffs along the Colville River contain several high-density dinosaur bone-beds including the Kikak-Tegoseak, Sling Point, Liscomb, and Byers quarries. Analyses of the bonebeds and encasing strata have been integral to providing previous Arctic paleoenvironmental reconstructions (Fiorillo et al. 2010a; Flaig et al. 2014). Recently new taxa discovered in the Prince Creek Formation include a new species of centrosaurine ceratopsid

Pachyrhinosaurus perotorum (Fiorillo and Tykoski 2012); a new tyrannosaur *Nanuqsaurus hoglundi* (Fiorillo and Tykoski 2014); and a new species of saurolophine hadrosaurid similar to Edmontosaurus *Ugrunaaluk kuukpikensis* (Mori et al. 2016).

During the middle Santonian to Campanian (~ 72–85 Ma; Walker et al. 2013), the Arctic Ocean, Cretaceous Western Interior Seaway (CWIS), and Gulf of Mexico (GOM) were thought to be hydrologically connected seas (Fig. 1.2; Schröder and Adams 2013). This outcrop investigation focuses on fluvio-deltaic deposits, emplaced along the Arctic Ocean shoreline, and compares those deposits with deltaic deposits of the Blackhawk Formation, found along the CWIS. This work was conducted in order to generate a new understanding of the following questions:

1. Does outcrop data provide new insights regarding the primary controls on deposition and preservation of a Santonian–Maastrichtian clastic wedge in northern Alaska?
2. Do exposures of the lower Schrader Bluff Formation deposited at ~83º N paleolatitude preserve high-latitude signatures, and how might this Late Cretaceous high-latitude depositional system differ from mid-latitude Late Cretaceous depositional systems?
3. Do changes in environmental conditions in different latitudinal belts cause recognizable changes in shoreline and shelf depositional systems?

Remnants of the CWIS are currently preserved as world-class outcrops in the western United States and are often used as analogues by researchers working the subsurface in Alaska (Pattison et al. 2007). The lower to middle Campanian Blackhawk Formation contains up to 1 km of shallow-marine, deltaic, and fluvial sandstone,

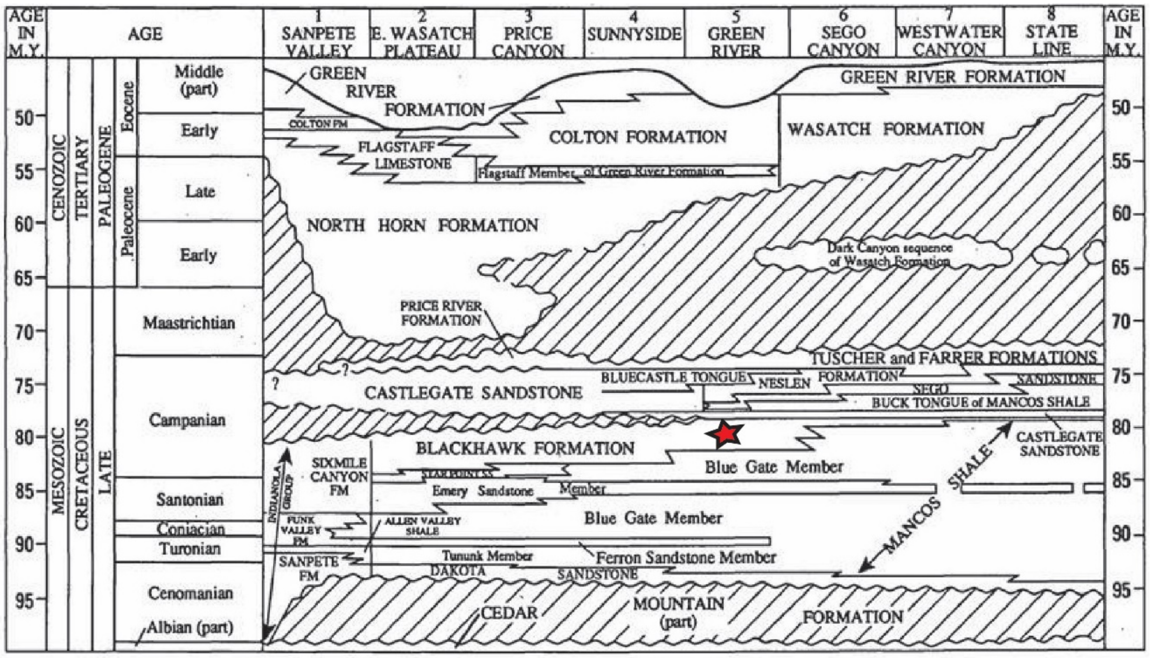

Figure 1.4. Chronostratigraphic diagram of the CWIS in a west-east trending transect of Albian to middle Eocene stratigraphy on the Wasatch Plateau in Utah to the Colorado state line. Red star indicates study area and location of the Blawkhawk Formation, which is compared to the lower Schrader Bluff Formation in Chapter 4 (Franczyk et al. 1990; modified from Fouch et al. 1983).

siltstone, and mudstone (Fouch et al. 1983; Franczyk et al. 1990; Horton et al. 2004; Fig. 1.4) deposited at mid- latitudes (~ 42° N paleolatitude) within the CWIS in the North American Cordilleran Foreland Basin (Figs. 1.2, 1.4; Kauffman and Caldwell, 1993; Hampson 2010). The North American Cordilleran Foreland Basin formed during the Jurassic–Eocene (155 to 55 Ma) contemporaneously with development of the Cordilleran orogenic wedge (DeCelles 2004). During its early and late history (155–110 Ma; 70–55 Ma) the basin was dominated by continental deposition, whereas marine waters inundated the basin between 110 and 70 Ma. Late Jurassic to early Late Cretaceous basin development was controlled by both flexural and dynamic subsidence (DeCelles 2004; Aschoff and Steel 2011). From Late Cretaceous to mid-Cenozoic time the basin was partitioned into sub-basins by basement-involved Laramide structures (DeCelles 2004).

Decades of fluvial-deltaic research in North America has been conducted on the evolution of the modern Mississippi River Delta (e.g., Fisk et al. 1954; Coleman 1988; Aslan et al. 2005) and the Paleogene and Neogene evolution of the Texas and Louisiana deltaic systems in the Gulf of Mexico between 25º and 30º N latitudes (Anderson et al. 1996; Galloway 2001). Other classic fluvial-deltaic investigations in North America focus solely on such ancient mid- to high-latitude systems of the CWIS as the Ferron Sandstone (Fig. 1.4) and Panther Tongue in Utah (42º to 55º N; Sageman and Arthur 1994; Barton 1997; Dean and Arthur 1998; Fielding 2010; Hampson et al. 2011) and the Dunvegan Formation in Alberta, Canada (65º to 75º N; Bhattacharya and Walker 1991; McCarthy and Plint 1999; Plint 2000). This dissertation extends investigations of ancient fluvial-deltaic systems farther north and also compares these systems to well-documented, mid-latitude successions. This dissertation describes the sedimentology and stratigraphy of the Schrader Bluff and Prince Creek formations from 11 measured sections totaling 532.45 m across 9.7 km at Shivugak Bluffs and compares these deposits with those of Blackhawk Formation in Utah (Fig. 1.5).

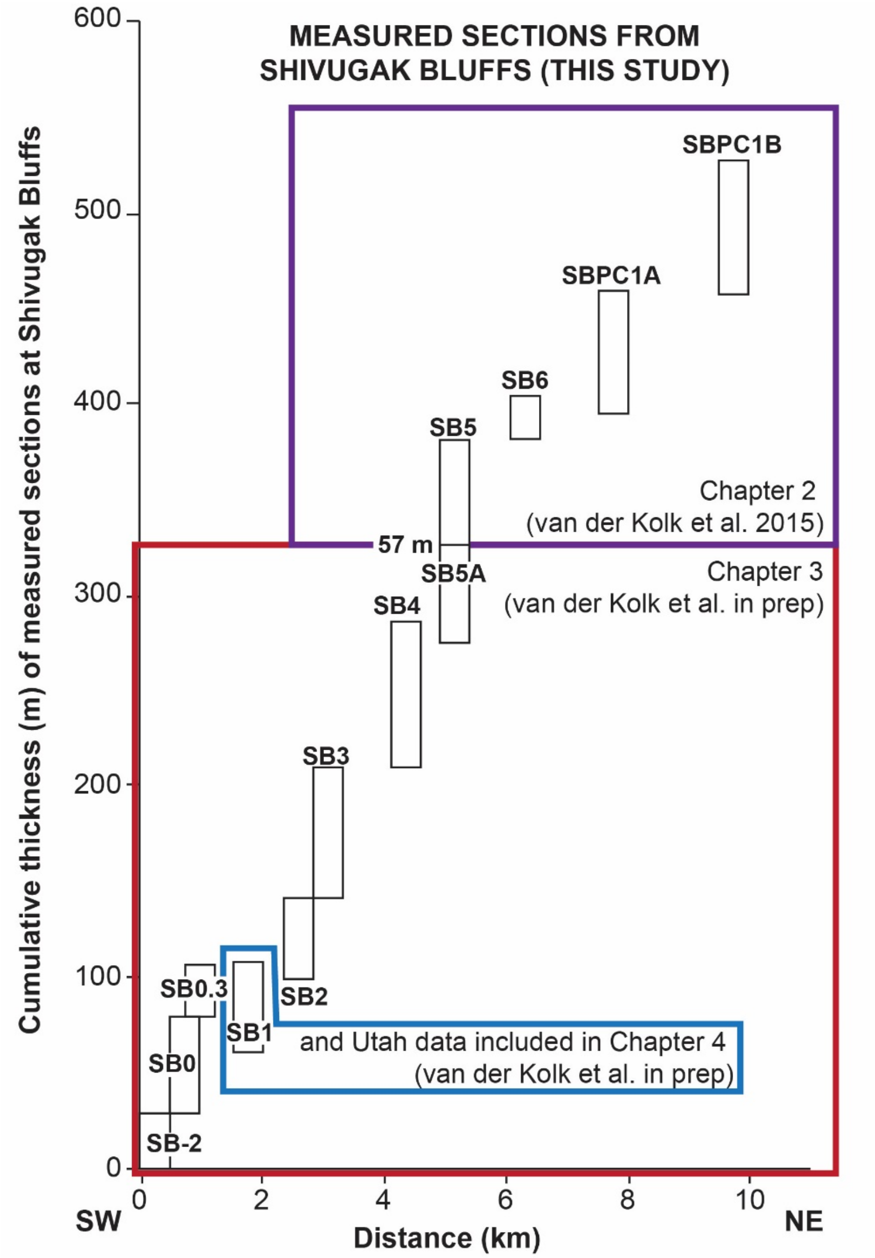

Figure 1.5. Plot showing cumulative thickness of 11 measured sections (SB-2, SB0, SB0.3, SB2, etc.) relative to the cumulative distance between measured sections SB-2 and SBPC1B at Shivugak Bluffs. Shivugak Bluffs is a southwest-northeast trending cliff face ~ 11 km long; strata dip between 3º to 6º to the north. A 532.45 m thick composite section was measured at Shivugak Bluffs. Purple, red, and blue boxes indicate chapters where this data is presented (Chapters 2–4).

DISSERTATION SCOPE

Continental-fluvial to shallow-marine transitional environments contain some of the most complex environments on Earth because of the large number of continental and marine processes active in coastal zones (e.g., Nittrouer and Wright 1994; Dalrymple and Choi 2006; Hasiotis and Platt 2012; Hasiotis et al. 2013). Although the overlying coastal plain to lower delta plain deposits of the Prince Creek Formation along the Colville River have been extensively studied (Flaig 2010; Flaig et al. 2011, 2012, 2014) the shallow-marine to transitional-continental deposits of the Schrader Bluff and basal Prince Creek formations at Shivugak Bluffs have never been thoroughly documented or interpreted. This dissertation contains three chapters (2–4) written as stand-alone manuscripts for submission to peer-reviewed journals for publication. Chapter 2 was submitted to the Journal of Sedimentary Research on October 6, 2014, accepted for publication on April 6, 2015, and published on August 12, 2015. Chapter 3 will be submitted to the Journal of Sedimentary Research. Chapter 4 will be submitted to Sedimentology.

Chapters 2 and 3 focus on sedimentologic and stratigraphic data collected at Shivugak Bluffs. Field work at Shivugak Bluffs was conducted from August 4th through August 26th, 2010; August 13th through August 31, 2011; and August 5th through September 2nd, 2012. Utah field work was conducted from May 29th through June 3, 2013 and June 14 through June16, 2013. Chapter 4 focuses on a sedimentologic comparison between Alaska and Utah localities. Chapter 5 is a general summary of the contents of this dissertation. The following paragraphs describe the relevance of chapters 2 through 4 in this dissertation.

Chapter 2 describes a muddy, river-dominated delta that prograded along a muddy coastline and transitioned from marine deposits into lower-delta-plain floodbasin lakes, pedogenically modified floodbasins (ancient soils often referred to as paleosols), and swamps to fluvial environments along the paleo–Arctic Ocean shoreline. The upper 196 m of strata at Shivugak Bluffs (Fig. 1.5) described in this manuscript comprise an overall coarsening upward succession interpreted as the transition from muddy prodelta, proximal delta front, and lower-delta-plain to fluvial environments. This investigation is one of the few studies to document ancient muddy progradating shorelines. Observations and interpretations in Chapter 2 will help improve future models of fluvial-dominated deltaic systems and help researchers interpret enigmatic sandbodies found in muddy delta front to prodeltaic environments.

Chapter 3 describes and interprets the lower 336 m of strata at Shivugak Bluffs as river-dominated deltas with minor wave- or storm-influence, interbedded with proximal marine shelf, lower delta plain and meandering river deposits. This succession is compared and contrasted to 196 m of strata in Chapter 2 to create a complete composite stratigraphic section and sequence stratigraphic framework for Shivugak Bluffs.

Chapter 4 is a comparison of a river-dominated deltaic succession of the Schrader Bluff Formation deposited in the paleo−Arctic Ocean with a wave- dominated deltaic successions of the Blackhawk Formation deposited in the CWIS. Chapter 4 compares 37 m of strata in the lower Schrader Bluff Formation at Shivugak Bluffs to 36 m of strata in the Kenilworth Mbr and 34 m of the Grassy Mbr of the Blackhawk Formation at the

Book Cliffs in central Utah (Fig. 1.2) with a goal of comparing river- versus wave-dominated deltas.

CHAPTER 2 – PALEOENVIRONMENTAL RECONSTRUCTION OF A LATE CRETACEOUS, MUDDY, RIVER-DOMINATED POLAR DELTAIC SYSTEM: SCHRADER BLUFF–PRINCE CREEK FORMATION TRANSITION, SHIVUGAK BLUFFS, NORTH SLOPE OF ALASKA, U.S.A.[1]

ABSTRACT

Upper Cretaceous (Santonian to late Campanian) strata from the upper 196 m at Shivugak Bluffs along the Colville River of northern Alaska preserve a paleopolar, fluvial–deltaic succession deposited along a prograding paleo–Arctic Ocean coastline. The uppermost lower Schrader Bluff Formation is best classified as a river-dominated delta based on muddy prodelta and delta-front deposits that contain abundant hyperpycnites, subaqueous terminal distributary channels, interdistributary bays, and mouth bars. This deltaic succession is overlain by distal distributaries and a braided fluvial system of the Prince Creek Formation. Channel measurements and paleo-discharge calculations from Prince Creek Formation distributaries indicate that rivers were the appropriate size and had the appropriate discharge to regularly produce hyperpycnites. Delta front and interdistributary bays transitioned into lakes and floodbasins on the lower delta plain, alongside distributary channels during delta lobe reorganization and abandonment. These floodbasins were subsequently transgressed and are overlain by proximal shelf and prodelta muds containing *Phycosiphon*. Overlying strata containing delta front, interdistributary bay, terminal distributary channel,

[1] This chapter was published in the Journal of Sedimentary Research on August 12, 2015.

distributary mouth bar, and distributary channel deposits signaled the reactivation of the delta lobe. Ultimately, these deltaic environments were incised into and became overlain by braided channel deposits during a marked drop in relative sea level and progradation of the fluvial system. Combining ichnologic and sedimentologic observations was critical to identify eleven distinct deltaic and continental paleoenvironments. This study documents the architecture and evolution of an ancient, high-latitude, muddy, river-dominated deltaic system and highlights the autogenic and allogenic processes preserved in the system.

INTRODUCTION

The Upper Cretaceous (Santonian–Maastrichtian) Schrader Bluff and Prince Creek formations that crop out along the Colville River in Arctic Alaska (Fig. 2.1) are some of the least studied in the United States, due to limited accessibility, the need for complex remote logistics, and recurring extreme weather conditions. The Schrader Bluff and Prince Creek formations are interpreted as being deposited at 80–85º N (Spicer and Parrish 1990a, 1990b; Spicer and Herman 2010; Flaig et al. 2011), making this a true paleopolar succession. These deposits are germane to the academic community because they record deposition along the paleo–Arctic Ocean shoreline and adjacent coastal plain during the Cretaceous greenhouse. When compared with temporally equivalent sedimentary successions in Canada, the Schrader Bluff Formation was deposited at higher paleolatitudes and likely represents the northernmost Santonian to Maastrichtian

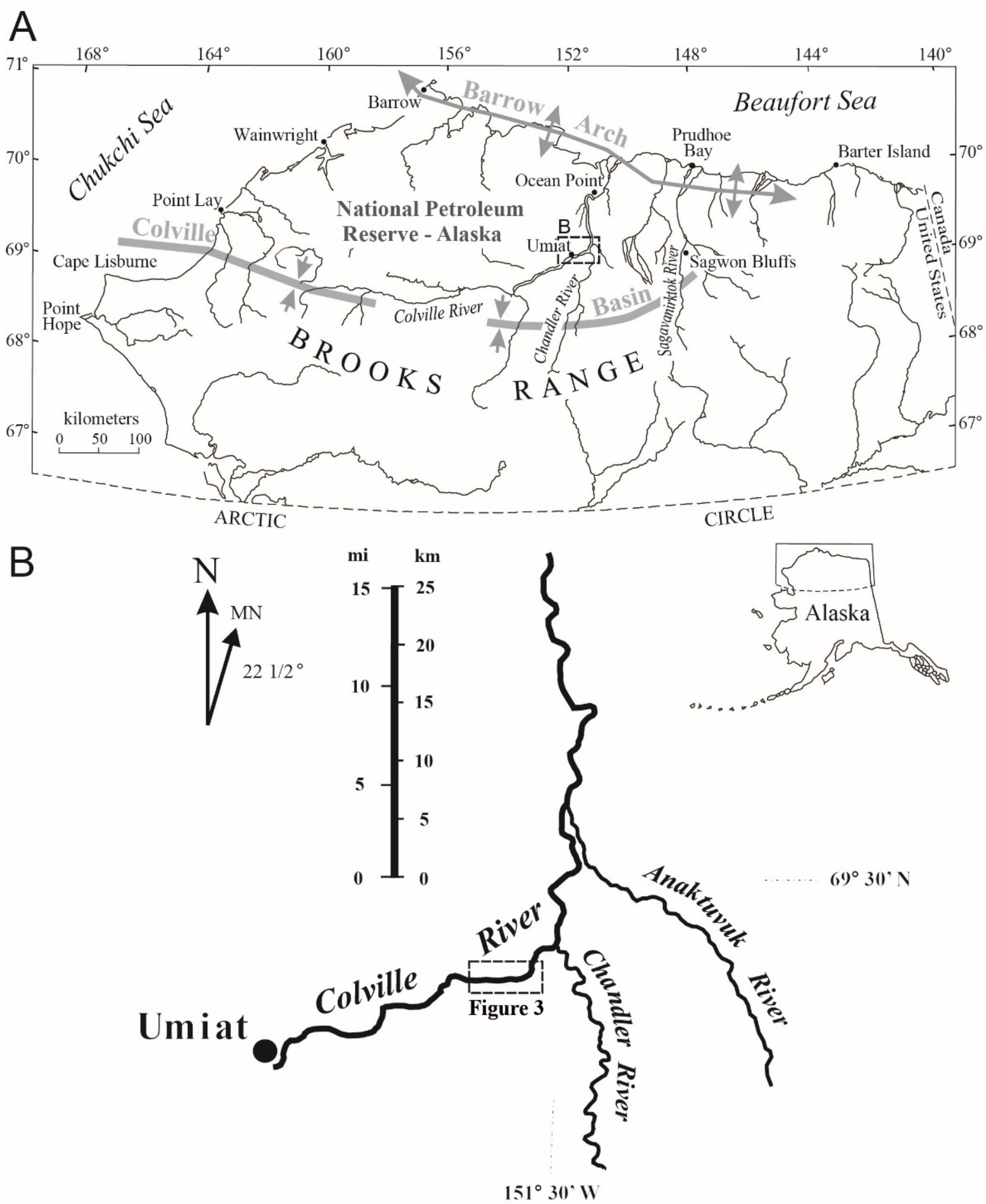

Figure 2.1. Maps showing locations in Arctic Alaska of the following: A) The Brooks Range, Colville Basin, Barrow Arch rift shoulder, National Petroleum Reserve–Alaska, Colville River, Umiat, Ocean Point, Prudhoe Bay, and the location of inset map in Part B; B) Inset map showing the location of the Shivugak Bluffs (Fig. 2.3) relative to Umiat as well as the Colville, Chandler, and Anaktuvuk Rivers in Alaska. Arrow depicts map relative to magnetic north (MN).

marine shoreline preserved in outcrop. Paleo-Arctic strata are historically underrepresented in literature summarizing Cretaceous seas, and when included in publications, the data are commonly cited as questionable or uncertain because investigations are often reconnaissance based (Frakes and Francis 1988; Schröder-Adams 2014).

The Schrader Bluff and Prince Creek formations are also relevant to industry as outcrop analogs for several shallow, viscous- to heavy-oil reservoirs in the central North Slope, Alaska (the West Sak, Tabasco, and Ugnu accumulations at the Kuparuk River field, the Orion and Polaris accumulations at the Prudhoe Bay field, and the Schrader Bluff accumulations at the Milne Point and Nikaitchuq fields; Fig. 1A, Croft et al. 1999; Alaska Oil and Gas Conservation Commission 2010). Although several recent studies have focused on the sedimentology of the Maastrichtian portion of the Prince Creek Formation (Flaig et al. 2011, 2013, 2014), few North Slope studies have described the Schrader Bluff Formation (e.g., Mull et al. 2003; Phillips 2003; Flores et al. 2007; LePain et al. 2008). None of these studies discuss the transitional stratigraphy between the Schrader Bluff and Prince Creek formations in detail.

Many researchers choose to investigate higher net-to-gross (Reading and Richards 1994) depositional systems for reservoir quality; however, investigations into complex, low net-to-gross depositional systems containing muddy, continental to shallow marine transitional environments that may include mud-rich successions with reservoir-quality elements preserved between larger sandbodies are less common. There are only few published reports of ancient muddy deltaic shorelines from progradational settings (Walker and Harms 1971; Hovikoski et al. 2008). This lack of detailed research has resulted in low-net-to-gross systems being more difficult to interpret and model in the subsurface, commonly forcing industry to generate several gross-depositional-environment maps that represent multiple working hypotheses for the same stratigraphic interval.

This paper documents the facies, sedimentary structures, ichnology, key surfaces, and sandbody and shale geometries found in a marine-to-continental transitional succession at Shivugak Bluffs on the North Slope of Alaska. Our objectives are to: 1) describe paleoenvironments found in paleopolar, muddy, river-dominated deltas along the Cretaceous paleo–Arctic Ocean coastline; 2) document events that include delta-lobe abandonment, progradation, flooding, reactivation, and fluvial incision in this fluvial–deltaic system; 3) identify key parameters for reconstructing low net-to-gross paleoenvironments and reservoirs; and 4) differentiate between autogenic and allogenic processes preserved along this ancient Arctic coastline. This study intends to bridge the gap between the rarely studied shallow marine sequences of the Schrader Bluff Formation (Phillips 2003; Flores et al. 2007) and the current depositional models of the continental Prince Creek Formation (Flaig et al. 2011, 2013, 2014).

BACKGROUND

Studies focusing on low net-to-gross fluvial–deltaic systems found along the Arctic Ocean shoreline during the Late Cretaceous are rare (Flaig et al. 2011, 2013, 2014). A high percentage of investigations are from lower-latitude ancient fluvial–deltaic systems and typically focus on the sandier deposits for reservoir analogs (Barton 1997; Olariu et al. 2010), whereas fewer studies focus on the muddier parts of the system. The stratigraphic succession at Shivugak Bluffs is an overall progradational succession (Decker 2010) that is interpreted to contain mud-rich prodelta, interdistributary-bay, floodbasin (i.e., lakes, paleosols, swamp margins), and coastal-plain deposits. The distal end of river-dominated deltas include subaerial terminal distributary channels and mouth bars that extend subaqueously beyond the air–water interface, and, even though this is often implied (Reynolds 1999; Olariu and Bhattacharya 2006; Bhattacharya 2010), the subaqueous extent of the system is not often fully represented in classic depositional models (Gani and Bhattacharya 2007). Studies of the distal portions of river-dominated deltas—such as prodelta, subaqueous terminal distributary channels, distal mouth bars, and distal delta front deposits—are also underrepresented in outcrop investigations (Allen 1965; Elliot 1974; Tye and Kosters 1986; Jorgensen and Fielding 1996; Lumsdon-West and Plint 2005; Ahmed et al. 2014). The same holds true for studies of the transition from marine to continental deltaic settings where interdistributary bays may infill and evolve into floodbasin environments.

GEOLOGIC AND CLIMATIC SETTING

During 1944 and 1951, the U.S. Geological Survey conducted field-based studies to define the general lithology and age range for outcrop belts on the central North Slope of Alaska that contain the Schrader Bluff and Prince Creek formations (Fig. 2.2A; Gyrc et al. 1951). This stratigraphic interval is exposed on the North Slope and in the foothills of the Brooks Range, but is commonly either scree covered, structurally deformed, or dips at ~ 90° and lacks lateral continuity (Brosge et al. 1966; LePain et al. 2008). The Schrader Bluff Formation, based on subsurface data, was subdivided into three members in ascending stratigraphic order: the Rogers Creek, Barrow Trail, and Sentinel Hill members (Fig. 2.2A; Whittington 1956). Due to the lack of distinctive lithologic characteristics, Mull et al. (2003) abandoned these formal member names after a regional synthesis of the area (Fig. 2.2B). Instead Mull et al. (2003) proposed the lower, middle, and upper Schrader Bluff Formation, but did not explicitly define or use this terminology in their chronostratigraphic diagram (Fig. 2.2B). Decker (2007, 2010) combined regional subsurface and surface data to compile the most up-to-date chronostratigraphic diagram for this stratigraphic interval using the lower, middle, and upper Schrader Bluff Formation nomenclature of Mull et al. (2003) (Fig. 2.2C). Research herein focuses on the abandoned Sentinel Hill Member of the Schrader Bluff Formation, which is now considered to be a mappable unit equivalent to the upper part of the lower Schrader Bluff Formation, as well as the contact of the Schrader Bluff with the overlying Prince Creek Formation.

The Schrader Bluff and Prince Creek formations were deposited in the Colville foreland basin at paleopolar latitudes of 80–85º N (Spicer and Parrish 1990a, 1990b; Spicer and Herman 2010; Flaig et al. 2011); the strata are currently exposed along the

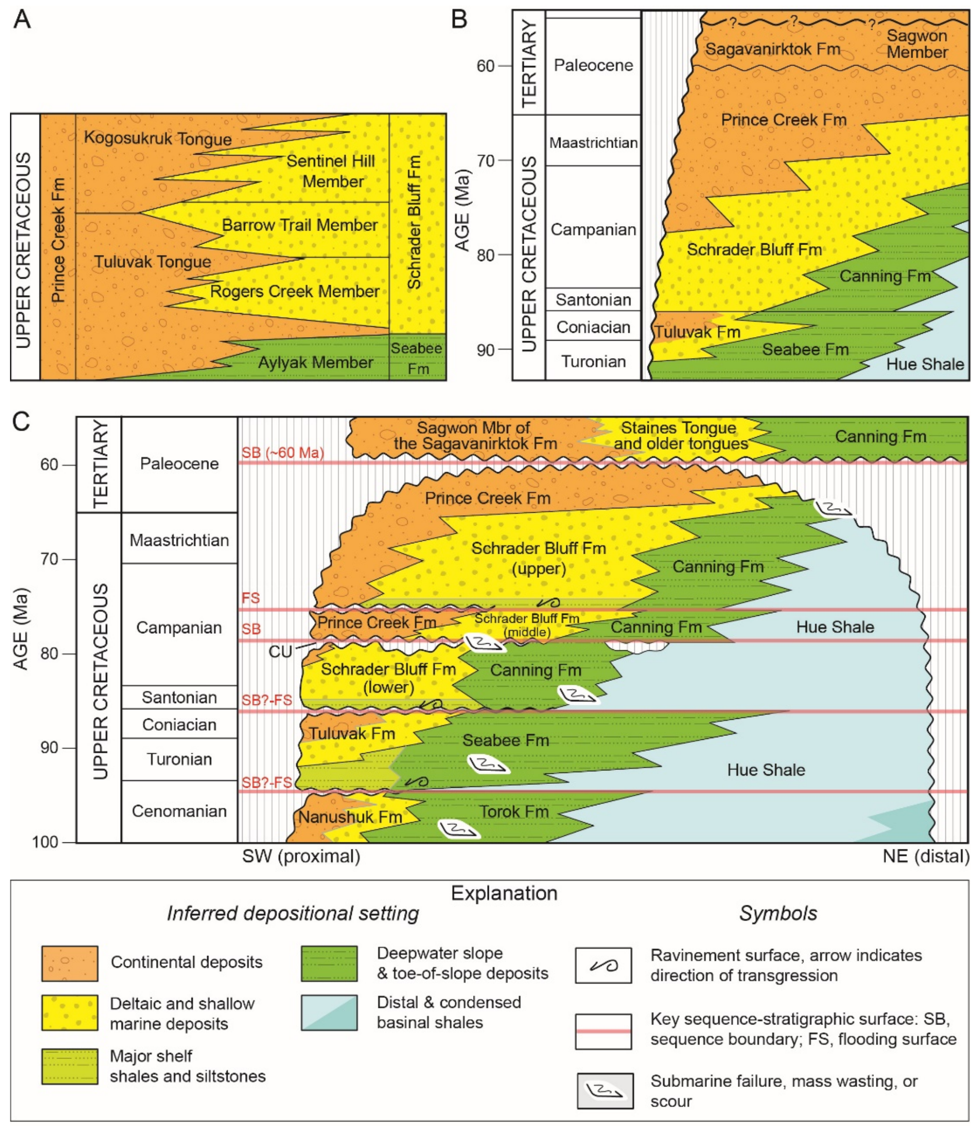

Figure 2.2. Stratigraphic nomenclature of the central North Slope of Alaska as described in the A) 1950s (Gyrc et al. 1951; Gyrc et al. 1956; Whittington, 1956), B) 2003 (Mull et al. 2003), and C) 2010 (modified from Decker 2010). Mull et al. (2003) abandoned the Roger's Creek, Barrow Trail, and Sentinel Hill Members documented in Part A, but based on Decker's (2010) surface-to-subsurface correlation these Members are only correlative to the lower Schrader Bluff Formation as shown in Part C. This study documents the Sentinel Hill Member of the lower Schrader Bluff Formation and the lower contact of the Prince Creek Formation along the Colville River. Abbreviations include: member (Mbr), formation (Fm), flooding surface (FS), sequence boundary (SB), and Campanian unconformity (CU).

Colville River between 67 and 71º N. The Colville Basin is bounded on the south by the Brooks Range and on the north by the Barrow Arch rift shoulder (see Fig. 2.1; Bird 2001). Infilling of the Colville Basin started during the Aptian to Albian due to lithospheric loading north of the evolving Brooks Range orogenic belt and subsequent unroofing (Moore et al. 1994; Cole et al. 1997). Upper Cretaceous sediments, principally sourced from the Chukchi Platform to the west, filled the basin axially, with a secondary component of transverse fill coming from the Brooks Range to the south (Hubbard et al. 1987; Mull et al. 2003; Houseknecht et al. 2009). This Cretaceous–Paleocene synorogenic clastic succession is commonly referred to as the Brookian tectonostratigraphic megasequence (Hubbard et al. 1987). A west-to-east (proximal to distal) transect of the central North Slope through strata of the Santonian−Maastrichtian Brookian clastic wedge reveals continental fluvial and coastal-plain deposits of the Prince Creek Formation; deltaic, shallow marine, and proximal shelf deposits of the Schrader Bluff Formation; slope deposits of the Canning Formation, and deep-water deposits of the Hue Shale (Fig. 2.2C; Decker 2010).

The most proximal and laterally extensive outcrops of the Schrader Bluff and Prince Creek formations are located at the eastern boundary of the National Petroleum Reserve−Alaska (NPRA) along the Colville River (see Fig. 2.1). At this boundary, northeast of Umiat, is an 11-km-long outcrop belt named Shivugak Bluffs. This outcrop belt contains one of the type localities for the lower Schrader Bluff Formation and was originally estimated to have 772.7 m (2,535 feet) of strata continuously exposed (Gyrc et al. 1956; Whittington 1956; Mull et al. 2003; Gillis et al. 2014). Flores et al. (2007)

described 115.8 m (379.8 ft) of strata at Shivugak Bluffs through the contact with the Prince Creek Formation. The age of the Schrader Bluff and Prince Creek formations at Shivugak Bluffs ranges from Santonian to late Campanian based on the occurrence of *Inoceramus (Sphenoceramus*) *patootensis* and the estimated age of microfauna (Jones and Gyrc 1960; Detterman et al. 1963; Flores et al. 2007), however, most of the stratigraphically higher Prince Creek Formation, farther north along the Colville River, is early Maastrichtian in age (Conrad et al. 1990; Flaig 2010; Fiorillo et al. 2010b, Flaig et al. 2011, 2013, 2014). Campanian to Maastrichtian shorelines of the Arctic Ocean trended northwest–southeast in the northeast part of the NPRA and north–south near the southeastern boundary of NPRA (see Fig. 2.1; Roehler 1987; Decker 2010). Outcrops at Shivugak Bluffs have a general west-to-east trend, making the outcrop belt a slightly oblique, dip-oriented section.

The predominantly continental-clastic Prince Creek Formation, exposed along the Colville River, comprises alluvial sandstone, siltstone, mudstone, carbonaceous mudstone, coal, bentonite, and tuff (Flaig et al. 2011, 2013). Three distinct channel forms: (1) large sinuous channels (suspended-load meandering trunk channels); (2) small sinuous channels (suspended-load meandering distributary channels); and (3) small low-sinuosity channels (fixed-ribbon sandbodies similar to anastomosed channels) along with several floodplain environments have been interpreted in the Prince Creek Formation (Flaig et al. 2011, 2013). All channels exhibit inclined heterolithic stratification (IHS), suggesting that a combination of tidal forces and seasonality affected sedimentation (Fiorillo et al. 2010b; Flaig et al. 2011, 2013, 2014). Paleocurrent orientations from trough cross-stratification in sinuous channels indicate that regional paleoflow in the early Maastrichtian varied from the northwest to southeast (Flaig et al. 2011). An overall vector mean of 60° for fluvial deposits (Flaig et al. 2011) is consistent with other published paleoflow data and clinoform dip direction indicating a regional east-northeast paleoflow down the axis of the Colville Basin during the Late Cretaceous (Mull et al. 2003; Phillips 2003; Houseknecht and Schenk 2005; Decker 2010).

Bentonite samples collected from the Maastrichtian Prince Creek Formation north of Shivugak Bluffs consist predominantly of smectite (montmorillinite) and plot within the rhyolitic to rhyodacitic compositional fields (Salazar-Jaramillo et al. 2015). The tuffs at Shivugak Bluffs were probably sourced from Okhotsk–Chukotka caldera eruptions in northeastern Russia (Miller et al. 2002; Flaig et al. 2014).

A regional unconformity—known informally as the mid-Campanian unconformity (Decker 2007), and referred to herein as the Campanian unconformity—is exposed at Shivugak Bluffs (Fig. 2.3). Shivugak Bluffs contains the only known outcrop expression of the Campanian unconformity (Fig. 2.2C). The lower Schrader Bluff Formation and the contact with the basal Prince Creek Formation were penetrated by an exploration well about 9 miles east of Shivugak Bluffs (Decker 2007). Seismic data indicate that the shelf margin coeval with the lower Schrader Bluff and basal Prince Creek Formations is truncated about 40 miles east of Shivugak Bluffs (Houseknecht and Schenk 2005; Decker 2010). Lithofacies described at Shivugak Bluffs likely extend to that shelf margin, where they are truncated by the Campanian unconformity, which has

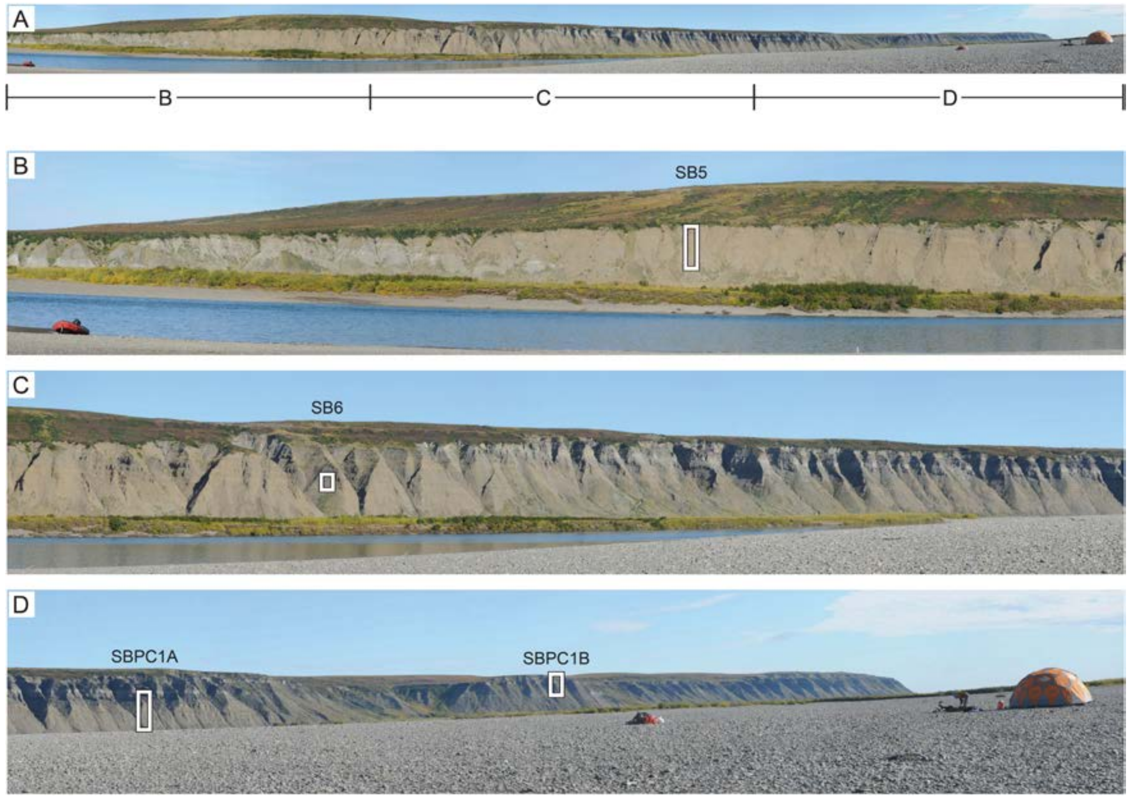

Figure 2.3. A) Photomosaic showing the westernmost 4 km of outcrop at Shivugak Bluffs along the Colville River including the transition between the Schrader Bluff and Prince Creek Formations. Photographs were recorded from state land looking northwest toward the National Petroleum Reserve (see Fig. 1). B–D) Three close-up images with positions depicted in Part A. Photo-panoramas include location of measured section SB5 (Fig. 2.4), SB6 (Fig. 2.5), SBPC1A (Fig. 2.6), and SBPC1B (Fig. 2.7). See Figure 2.1 for location of Shivugak Bluffs. Tent, geologist, and boat for scale.

removed to the east distal shelf sandstone, siltstone, and bentonitic shale of the lower Schrader Bluff Formation (Houseknecht and Schenk 2005; Decker 2007; Decker 2010).

The Late Cretaceous Arctic Ocean is thought to have been ice-free during the summer months, with only intermittent sea ice in the winter (Parrish et al. 1987; Zakharov et al. 1999; Miller et al. 2005; Davies et al. 2009). Empirical data commonly used for paleoclimate reconstructions includes: (1) physiognomic traits of vegetation for determining mean annual temperatures (MAT); (2) $\delta^{18}O$ and $\delta^{13}C$ variations in marine calcite used as proxy indicators of sea-level fluctuations and glaciations (Parrish and Spicer 1988a, 1988b; Spicer and Parrish 1990a, 1990b; Abreu et al. 1998; Ufnar et al. 2001; Miller et al. 2003, 2004); and (3) stable oxygen isotope analysis of dinosaur tooth enamel phosphate from early Maastrichtian Prince Creek Formation strata used as a proxy for surface-water isotopic compositions to augment data from pedogenic siderites (Ufnar et al. 2004; Suarez et al. 2013). Observations from vascular systems in fossil wood and vegetation physiognomy suggest that MAT decreased from the Aptian–Albian to the Maastrichtian in Arctic Alaska (Parrish and Spicer 1988a, 1988b; Spicer and Parrish 1990a, 1990b). Angiosperm leaf-margin analyses indicate a MAT of 11º C for the Arctic Alaska coastal plain during the Aptian–Albian, 6.3 ± 2.2º C for the Campanian–Maastrichtian, and 6–7º C for the Paleocene (Spicer and Parrish 1990b; Suarez et al. 2013). Estimates of MAT at elevation in the Brooks Range are lower and suggest small permanent ice fields and permafrost (Spicer 2003; Fiorillo et al. 2010a, 2010b). Winter freezing was likely in the Maastrichtian, even though periglacial conditions did not exist at sea level (Parrish and Spicer 1988a; Spicer 2003). Some authors suggest that seasonal marine ice-deposited lonestones in Chukotka high-latitude successions are time equivalent to the Schrader Bluff Formation (e.g., Ahlberg et al. 2002).

METHODS

Standard sedimentological techniques were used to record the stratigraphy at Shivugak Bluffs (Figs. 2.1 and 2.3). Due to the nearly vertical nature of the exposures, stratigraphic successions were recorded until bluffs became too steep to climb, at which point sections were moved along strike to the next available outcrop using marker beds. The 6º dip in strata allowed sections to be accessed laterally since they are offset horizontally along the outcrop belt (Fig. 2.3). Key marker beds were used to tie sections together and produce a composite section. GigaPan photo-panoramic hardware and software were employed to record photomosaics, verify correlations, and assess architectures. At Shivugak Bluffs, 650 m of stratigraphic section were measured and documented during three summer field seasons from 2010 to 2012. After applying corrections for measured sections that overlap, the overall stratigraphic thickness of the interfingering Schrader Bluff and Prince Creek formations at Shivugak Bluffs is 532 m. Data compiled for this paper were limited to the 196 m of strata in the uppermost part of the succession containing the transition between shallow marine deltaic and fluvial environments. This interval includes four measured sections: SB5, SB6 SBPC1A, and SBPC1B (Fig. 2.3). The location of each measured section along the outcrop belt is shown in Figure 2.3. Complete measured stratigraphic sections SB5, SB6 SBPC1A, and

SBPC1B are depicted in Figures 2.4–2.7. A fence diagram showing how the measured sections relate to one another is included in Figure 2.5A. Grain size, thickness and lateral continuity of facies, sedimentary structures, flora and fauna, and trace fossils were recorded in each succession. Trace fossils are generally listed in order of abundance, and were assigned to an ichnotaxon based on their architectural and surficial morphologies and infill pattern (e.g., Hasiotis and Mitchell 1993; Bromley 1996). Bioturbation indices are based on the ichnofabric index (Droser and Bottjer 1986).

FACIES ANALYSIS

Eight lithofacies (F-1 to F-8) are defined from measured sections on the basis of grain size and sediment texture, sedimentary structures, thickness, basal and upper contacts, diagenesis, ichnology, megafauna, and flora. A detailed description of all facies (F) is found in Table 2.1. The mudstone (F-1) and siltstone (F-2) facies are further subdivided into the subcategories A and B based on the presence or absence of lamination and such pedogenic features as rhizoliths, mottles, and ped structures (e.g., aggregated-to-blocky or platy characteristics). Sandstones were also subdivided based on the predominance of ripple cross-lamination (F-4A), trough cross-lamination (F-4B), or hummocky cross-stratification (F-4C).

The eight lithofacies combine to form eleven facies associations (FA-I to FA-XI) that record distinct architectural elements and paleoenvironments (Table 2.2). Facies associations were defined on the basis of inclusive facies, facies relationships, stacking pattern, trace-fossil assemblage, and outcrop geometries. Paleoenvironments include: proximal shelf (FA-I), prodelta (FA-II), distal delta front (FA-III), proximal delta front (FA-IV), terminal distributary channel (FA-V), distributary mouth bar (FA-VI), interdistributary bay (FA-VII), floodbasin (FA-VIII), small low-sinuosity channel (FA-IX), small sinuous channel (FA-X), and downstream-accretion-dominated channel (FA-XI).

FACIES ASSOCIATION I: PROXIMAL SHELF

Description: FA-I is the least abundant facies association at Shivugak Bluffs (Fig. 4). In measured section SB5, a 2-m-thick grayish brown relatively homogeneous mudstone (F-1A) is located between 57 and 59 m (Fig. 4). In SBPC1B, a 1.75-m-thick homogeneous carbonaceous mudstone (F-6) with plant and wood debris is located between 69 and 70.75 m (Fig. 6).

Interpretation: FA-I mudrocks are interpreted as proximal marine shelf deposits produced from suspension by hypopycnal plumes (Nittrouer et al. 1984; Parsons et al. 2001; Bann et al. 2004). Proximal shelf deposits comprise homogeneous mudrock successions and do not always appear to be bioturbated on a macroscopic scale, but when examined microscopically shelfal mudrocks are often bioturbated (Berger 1979; Pedersen and Calvert 1990; Macquaker and Keller 2005; van der Kolk 2010). In SBPC1A (Fig. 6), FA-I overlies lacustrine deposits (FA-VIIIA). In SBPC1A, FA-I contains the marine trace fossil *Phycosiphon* (*Ph*). The upper contact of FA-I is typically with prodelta deposits (FA-II).

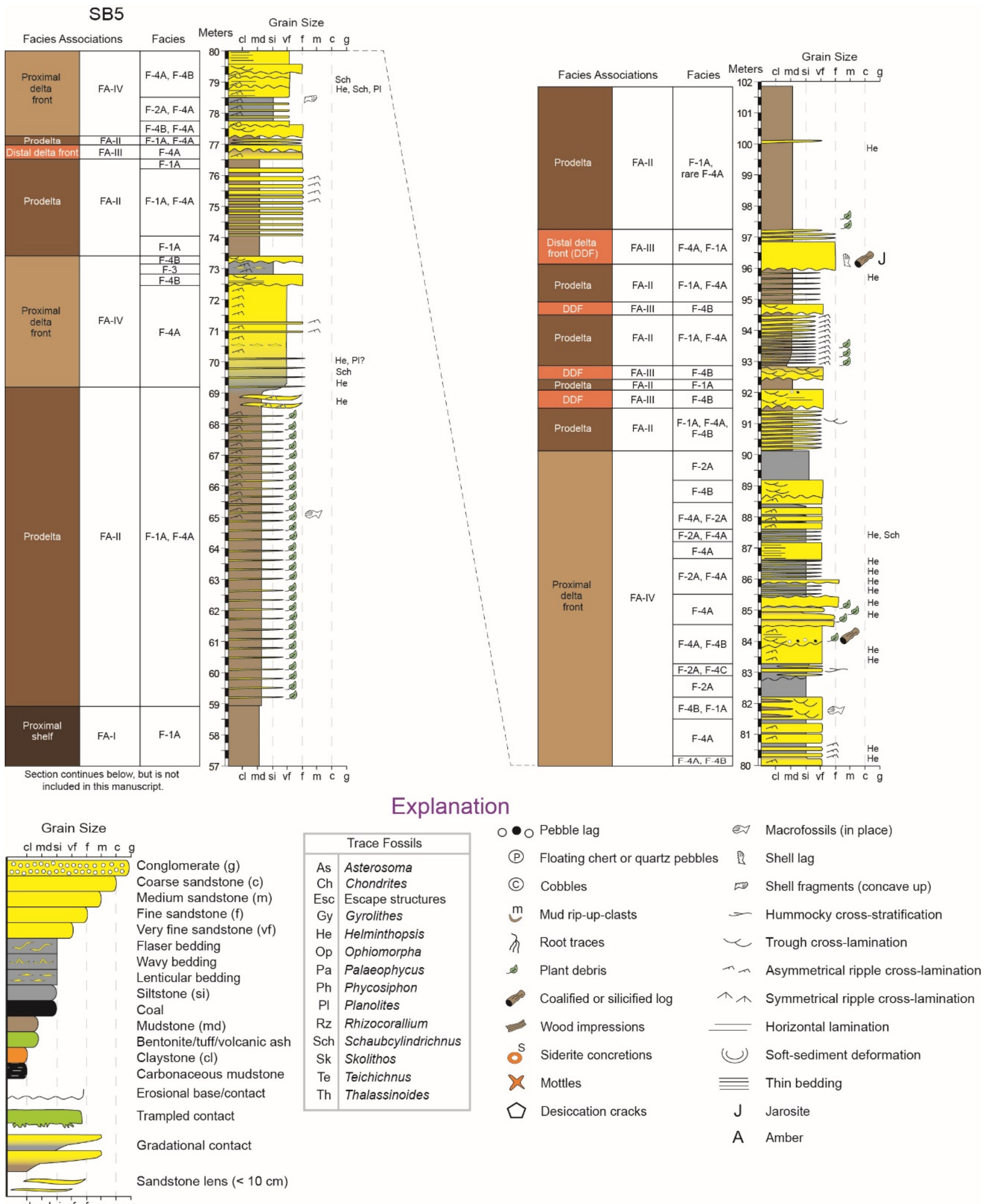

Figure 2.4. Measured section SB5 including proximal shelf (FA-I), prodelta (FA-II), distal delta front (FA-III), and proximal delta front (FA-IV) deposits found at Shivugak Bluffs (Fig. 2.3B). Explanation describes symbols for all measured sections (Figs. 2.4–2.7).

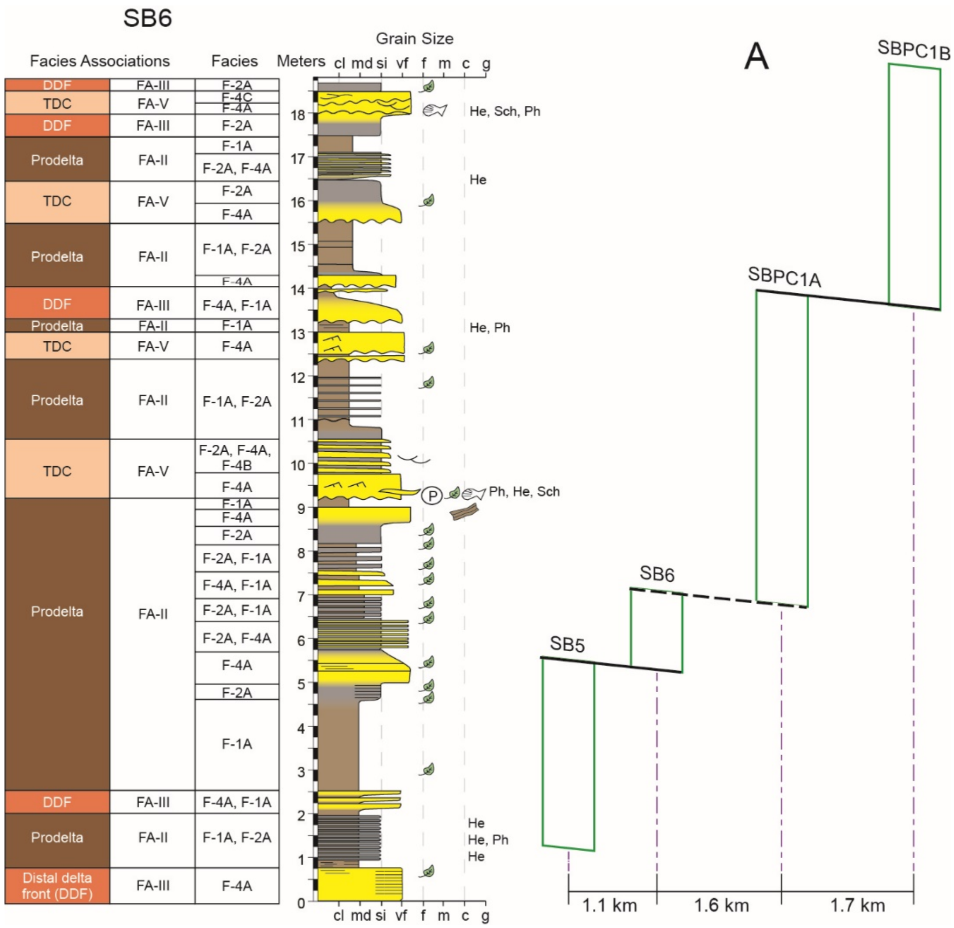

Figure 2.5. Measured section SB6 including prodelta (FA-II), distal delta front (FA-III), and terminal distributary channel (FA-V) deposits found at Shivugak Bluffs (Fig. 2.3C). See Figure 4 for explanation of stratigraphic column. A) Stratigraphic relationships between measured sections SB5, SB6, SBPC1A, and SBPC1 (Figs. 2.4–2.7). Dashed line between SB6 and SBPC1A represents inferred contact.

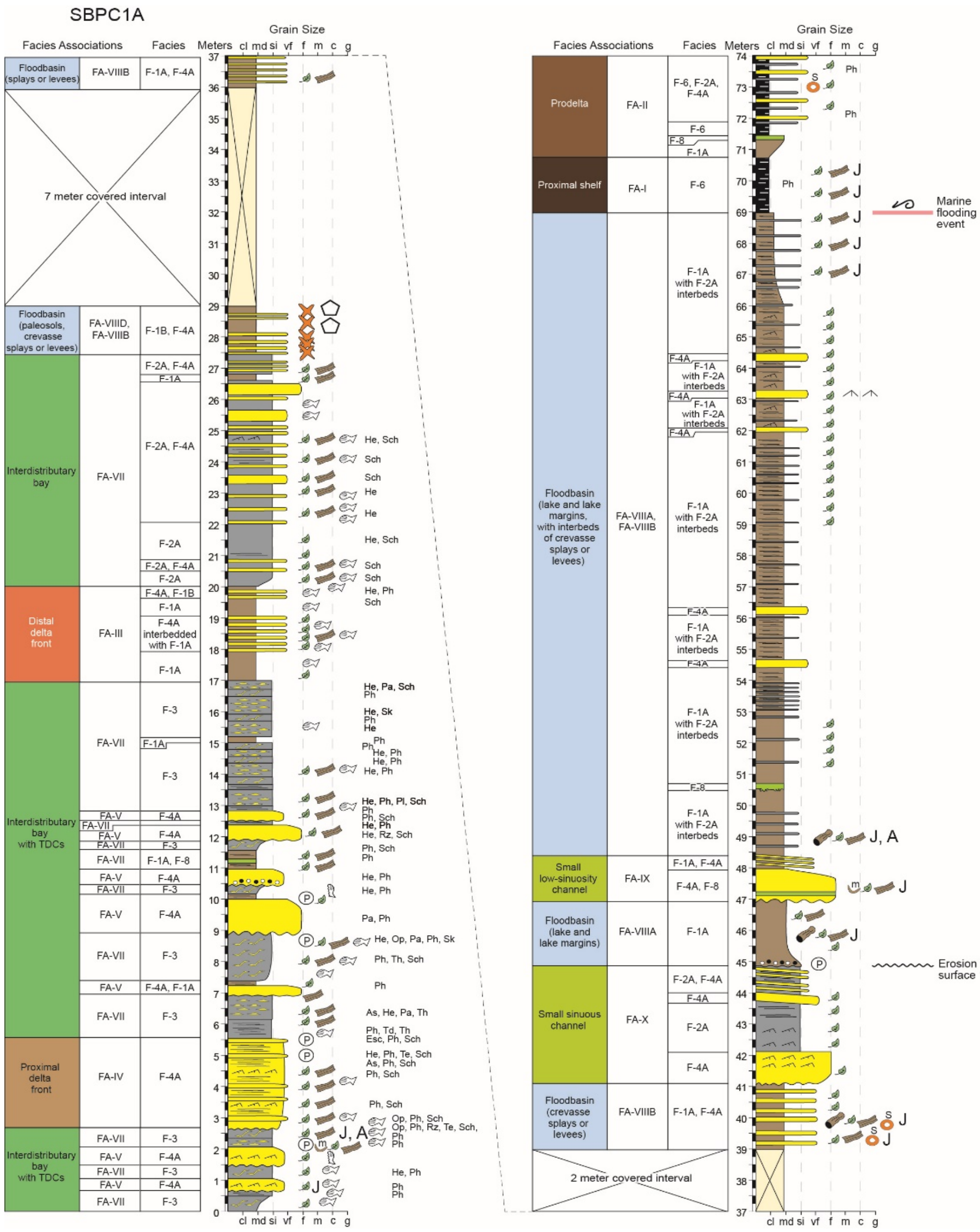

Figure 2.6. Measured section SBPC1A including proximal shelf (FA-I), prodelta (FA-II), distal delta front (FA-III), proximal delta front (FA-IV), interdistributary bay (FA-VII), terminal distributary channels (TDCs; FA-V), floodbasin (FA-VIII), small sinuous channel (FA-X), and small low-sinuosity channel (FA-IX) deposits found at Shivugak Bluffs (Fig. 2.3D). Figure includes erosion surface 1 at 45 m and a marine flooding event at 69 m. See Figure 2.4 for explanation of stratigraphic column.

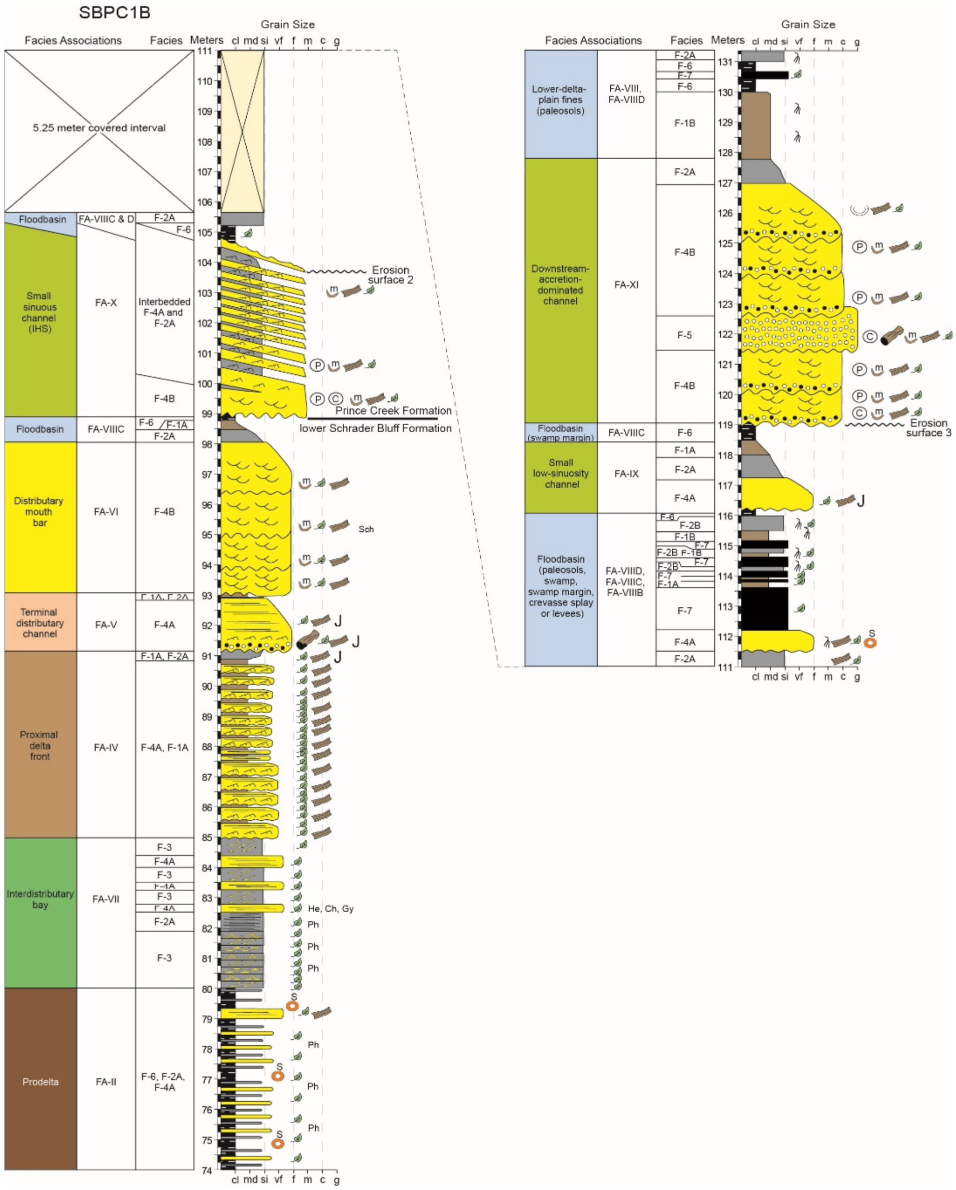

Figure 2.7. Measured section SBPC1B including prodelta (FA-II), interdistributary bay (FA-VII), proximal delta front (FA-IV), terminal distributary channel (FA-V), distributary mouth bar (FA-VI), floodbasin (FA-VIII), small low-sinuosity channel (FA-IX), downstream-accretion-dominated channel (FA-XI) and lower-delta-plain fines (FA-VIII) found at Shivugak Bluffs (Fig. 3D). Figure includes inferred contact of between the Schrader Bluff and Prince Creek Formations at 99 m, erosional surface 2 at 104.75 m, and erosional surface 3 at 119 m. See Figure 2.4 for explanation of stratigraphic column.

Table 2.1. Description of the 8 facies identified in the Schrader Bluff and Prince Creek Formation, North Slope, Alaska.

Facies ID		Lithology	Thickness	Contacts	Grain Size & Sediment Texture	Diagenesis, Flora, and Megafauna
Facies 1A	**Mudstone**	Massive to planar-laminated mudstone	0.1 -1.0 m	Basal Sharp to gradational Upper Sharp to gradational	Massive to laminated mudstone with interspersed organics; rare silt layers. Rare Ripples, quartz and chert pebbles.	Common Carbonized plant debris and invertebrates. Rare Gastropods, pelecypods, and inoceramids.
Facies 1B		Rooted, aggregated-to-blocky or platy, common root traces	0.1-2.0 m	Basal Sharp to gradational or disturbed Upper Sharp to gradational or disturbed	Massive to aggregated rooted mudstone with blocky to platy structures and interspersed organics. Reddish-orange to yellow mottles.	Common Siderite nodules, carbonaceous root traces, carbonized wood and plant fragments, and jarosite.
Facies 2A	**Siltstone**	Massive, ripple cross-laminted, planar laminated, siltstone	0.1- 1.0 m	Basal Sharp to gradational Upper Sharp to gradational	Massive or rippled siltstone interspersed with clay-size particles or organics.	Common Carbonized plant debris, jarosite, gastropods, and pelecypods.
Facies 2B		Siltstone with common root-traces	0.1-0.5 m	Basal Sharp to gradational Upper Sharp to gradational	Aggregated, rooted siltstone with a blocky to platy structure and interspersed organics. Ripples common.	Common Carbonaceous root traces, jarosite, carbonized plant debris.
Facies 3	**Flaser-, wavy-, and lenticular-bedded siltstone and mudstone**		0.2 -0.75 m	Basal Sharp to gradational Upper Sharp to gradational	Interbedded silt and mud. Lenticular siltstone and ripples are typically incomplete. Variable amounts of silt and mud. Organics on ripples.	Common Carbonized plant debris, invertebrates. Rare Quartz and chert pebbles, mud rip-up clasts.
Facies 4A	**Very-fine to fine-grained ripple cross-laminated to planar-laminated or massive sandstone**		0.05-1.8 m	Basal Sharp, gradational to erosional Upper Sharp to gradational	Very fine- to medium-grained moderately sorted, subrounded to subangular quartz & chert-rich sand. Mud drapes on ripples. Common quartz and chert pebbles, and mud rip-up clasts. Primary current and parting lineation.	Common Siderite nodules, carbonized roots and plant fragments, jarosite, clams. Rare Silicified or coalified logs, inoceramids.
Facies 4B	**Fine-, medium-, or coarse-grained trough cross-laminated or trough-cross bedded sandstone**		< 7.5 m; 0.25 to 1.0 m	Basal Sharp, erosional to truncated Upper Gradational	Fine-grained sandstone: well-sorted, well-rounded quartz and chert–rich sandstone. Medium-grained sandstones: moderately sorted, subrounded to subangular quartz and chert-rich sand. Coarse-grained sandstone: moderately well-sorted subrounded to subangular quartz and chert-rich sand.	Common Quartz and chert-pebble-capped trough cross-laminations, mud rip-up clasts, carbonate concretions, silicified or carbonized plant debris.

Table 2.1 (continued)

Facies 4C	**Very fine-grained hummocky cross-stratified sandstone**	< 0.3 m	Basal Sharp to gradational Upper Sharp to gradational	Very fine-grained, moderately sorted subrounded to subangular quartz and chert-rich sand	-
Facies 5	**Pebbly and/or boulder conglomerate**	< 0.5 m	Basal Erosional Upper Gradational	Quartz and chert pebbles, cobbles, and boulders (up to 30 cm long); mud/peat rip-up clasts. Clast- to matrix-supported. Poorly sorted, well-rounded pebble-to boulder-sized clasts of quartz, chert and minor quartzite rock fragments. Matrix: medium- to coarse-grained, poorly sorted, subrounded to subangular quartz- and chert-rich sand	Common Silicified or carbonized plant debris, wood impressions, coalified logs and peat.
Facies 6	**Carbonaceous mudstone**	0.1 to 0.4 m	Basal Sharp to gradational Upper Sharp to gradational	Black to dark brown, abundant organics, clay with shale partings, parting lineation.	Common Carbonized plant debris, carbonate concretions.
Facies 7	**Coal**	0.1-1.5 m	Basal Sharp to gradational Upper Sharp to gradational	Composed entirely of carbonized plant fragments, brittle with common vitreous luster. Common mud interbeds.	Common Carbonized plant debris, coalified logs, jarosite. Rare Amber.
Facies 8	**Bentonite**	0.1-0.2 m	Basal Sharp, gradational or distrubed Upper Sharp, gradational, disturbed	Massive, chiefly composed of clay from altered volcanic ash. Weathers white or yellow.	

Table 2.2. Summary of facies, ichnology, ichnofacies, diagnostic features, and occurrence for each facies association in the Schrader Bluff and Prince Creek Formations.

Facies Association (FA)		Interpretation	Facies (F)	Ichnology	Ichnofacies	Diagnostic Features	Occurrence
Shallow marine and deltaic	FA-I	Proximal shelf	F-1A or F-6	rare *Ph*	Cruziana	Mudrock dominated.	Typically below prodelta (FA-II) deposits.
	FA-II	Prodelta	F-1A, F-4A, F-2A, F-6 and rare F-4B, F-8	*He, Ph, Sch* or monospecific *Ph* or *He*	Cruziana	Clams rare to common.	Above proximal shelf (FA-I) deposits. Generally below proximal delta front (FA-IV) and encasing distal delta front (FA-III) and terminal distributary channels (FA-V).
	FA-III	Distal delta front	F-4A, F-2A, F-4B, F-1A	Rare *He, Ph, Sch*	Cruziana	Isolated unconfined sheet sandstones.	Commonly isolated in prodelta (FA-II) deposits. Typically associated with terminal distributary channels (FA-V) and interdistributary (FA-VII) deposits.
	FA-IV	Proximal delta front	F-4A, F-2A, F-4B with rare F-4C, F-1A, and F-3	He, Sch, Pl, Ph, Op, Rz, Te, As, Esc	Cruziana	Unconfined sandbodies.	Encased in prodelta (FA-II) or interdistributary deposits, except in SBPC1B there is an upper contact with a terminal distributary channel (FA-V).
	FA-V	(Subaqueous) Terminal distributary channels	F-4B, F-4A,F-2A, and rare F-4C	*Ph, He,Sch, Pa* and *Rz*	Cruziana	Clean, confined sandbodies.	Overlie proximal-delta-front (FA-IV) deposits and are overlain by distributary mouth bars (FA-VI).
	FA-VI	Distributary-mouth bar	F-4B	Absent	--	Well-sorted sandstone.	Overlie terminal distributary channels (FA-V) and are overlain by floodbasin swamp margin (FA-VIIID) deposits.

Table 2.2 (continued)

	FA-VII	Interdistributary bay	Common F-3 and F-2A, occassional F-4A, and rare F-8	*He, Ph, Sch, Pa, Sk, Pl, Op, Th, As,Td,*Ch, Gy	Cruziana	Flaser bedding and invertebrates common.	Associated with proximal-delta-front (FA-IV), distal-delta-front, and prodelta (FA-VII) deposits. Terminal distributary channels (FA-V) are commonly associated in FA-VII.
Flood-basin and lower delta plain fines (FA-VIII)	FA-VIIIA	Lake and lake margins	F-1A, F-2A, and rare F-8	*Pl,* dinoturbation	--	Rhythimically laminated mudrocks.	Located above and below a small low-sinuosity channel (FA-IX). Also, overlies a small sinuous channel and is overlain by proximal shelf (FA-I) deposits.
	FA-VIIIB	Crevesse splays or levees	F-4A, F-2A, and F-1A	Absent	--		Overlies interdistributary-bay (FA-VII) deposits and overlain by small sinuous channels (FA-X). Intercalated with lake and lake-margin (FA-VIIIA), swamp and swamp- margin (FA-VIIIC), and paleosol (FA-VIIID) deposits.
	FA-VIIIC	Swamp and swamp margin	F-7, F-6, and F-1A	Absent	--	Coal and carbonaceous shale are common.	Intercalated with crevasse splays or levees (FA-VIIIB) and paleosols (FA-VIIID).
	FA-VIIID	Paleosols	F-1B and F-2B	Absent	--	Rhizoliths common.	Overlies interdistributary bay (FA-VII) and overlain by low-sinuosity distributary channels (FA-IX). Intercalated with swamp and swamp margins (FA-VIIIC) and crevasse splays or levees (FA-VIIIB).
Fluvial	FA-IX	Small low-sinuosity channels (fixed-anastomosed)	F-4A, F-2A, F-1A, and rare F-8	Absent	--		Encased in lake and lake-margin (FA-VIIIA) deposits as well as swamp-margin deposits (FA-VIIIC) in a floodbasin (FA-VIII).

Table 2.2 (continued)

FA-X	Small sinuous channels (meandering)	F-4B, F-4A, and F-2A	Absent	--	Inclined heterolithic strata common.	Encased floodbasin deposits including swamp margin (FA-VIIIC) and crevasse splays or levees (FA-VIIIB).
FA-XI	Downstream-accretion-dominated channels (braided)	F-4B, F-5, and F-2A	Absent	--		Encased in swamp-margin (FA-VIIIC) and paleosol (FA-VIIID) deposits in a floodbasin (FA-VIII).

FACIES ASSOCIATION II: PRODELTA DEPOSITS

Description: Representative successions of FA-II are found in all four measured sections (Figs. 2.4‒2.7). FA-II in SB5 and SB6 comprise interbedded mudstone and very thin sandstone (cf. Collinson and Thompson 1989); some sandstone interbeds thicken upward (Fig. 2.8 and 2.8E). Mudstone intervals 0.25–10.0 m thick are laminated with siltstone, or are very thin-bedded to thick bedded (Figs. 2.8, 2.9). In SB5, the thickest succession of FA-II (59.0–69.0 m) contains 10 m of brown, planar-laminated to very thin-bedded mudstone (F-1A) with numerous 2–8 mm thick tan brown, very fine-grained sandstone interbeds (F-4A). In SB5 and SB6, FA-II mudstone-dominated intervals (1–4 m thick) have ripple laminations, whereas 6-cm-thick trough cross-stratified sandstone (F-4B) interbeds are rare (Figs. 2.4, 2.5). Inverse gradational contacts between mudstone and centimeters-scale siltstone or siltstone and very fine-grained massive sandstone beds are common. Abundant plant fragments are commonly found above very fine- to fine-grained massive or ripple-laminated sandstone interbeds. Mudstones often contain dark brown to black, organic-rich laminations. Thin, 2–3-cm-thick mudstone beds rarely contain the trace fossil *Helminthopsis* (*He*), but where present they are abundant with an ichnofabric index of 4 to 5. The only megafauna in these deposits are inoceramid fragments (up to 20 cm long).

A more organic-rich FA-II interval between 72 m and 80 m in SBPC1A (Fig. 2.6) is composed of thin- to thick-bedded (10–40 cm thick) carbonaceous mudstone (F-6) with thin interbeds of siltstone (F-2A; 5.0-cm-thick), and thin interbeds (5–10 cm thick) of very fine-grained sandstone (F-4A). Very fine-grained sandstone beds contain abundant *Ph.* Plant fragments are also abundant and rare carbonate concretions (5−10 cm thick) of an unknown origin are found at several discrete intervals. A 10-cm-thick bentonite is found at 71.25 m in SBPC1A. FA-II typically overlies proximal shelf (FA-I) deposits, is encased in distal delta-front (FA-III) deposits, or is associated with intervals that contain terminal distributary channels (FA-V; Figs. 2.4–2.7).

Interpretation: FA-II is interpreted as prodelta deposits. Homogeneous, massive mudrock deposits and finer-grained intervals are interpreted as being deposited from suspension by hypopycnal plumes (Parsons et al. 2001), whereas centimeters-scale siltstone and very fine-grained massive sandstone beds with inverse grading are attributed to deposits of hyperpycnal flows (Bhattacharya and MacEachern 2009; Fielding 2010). Many rivers alternate between hypopycnal and hyperpycnal conditions (Mulder and Syvitski 1995; Nemec 1995; Kineke et al. 2000; Parsons et al. 2001). The lack of bioturbation in prodelta environments is interpreted to be the result of repeated rapid sedimentation events (MacEachern et al. 2005, MacEachern and Gingras 2007; Bhattacharya and MacEachern 2009). Monospecific trace-fossil assemblages with high bioturbation indices in discrete layers of strata, such as those dominated by *He* and *Ph*, suggest relative quiescence and lower sedimentation rates (Neill and Allison 2005) immediately following deposition of each package that allow colonization predominantly by such vermiform animals as polychaetes or priapulid worms (e.g., Wetzel and Bromley 1994; Uchman 1995).

The slight lithologic differences between prodelta deposits in SB5 and SB6, versus those in SBPC1 may be explainable by a more protected depositional environment with increased proximity to the coastline (Meybeck 1982). The more organic-rich prodelta deposits between 72 and 80 m in SBPC1 are interpreted as a more proximal succession, such as an interdistributary-bay fill, than the prodelta successions interpreted in SB5 and SB6. This interpretation is based on: 1) the higher concentration of organics in SBPC1; and 2) the vertical stacking pattern in SBPC1, indicating an overall drop in relative sea level, and close proximity to subaerially exposed sediments (Figs. 2.6–2.7).

Bentonite found interbedded within FA-II is air-fall glassy volcanic ash deposited along the prodelta that is diagenetically altered to smectite (Smith 1967). Bentonite layers are common at Shivugak Bluffs and, in this study, have been found in prodelta (FA-II), interdistributary bay (FA-VII), and floodbasin (FA-VIII) deposits.

FACIES ASSOCIATION III: DISTAL DELTA FRONT

Description: FA-III is found in SB5, SB6, and SBPC1 (Figs. 2.4–2.6). Multiple tiers of FA-III are located between 91.50 and 97.25 m in SB5 (Fig. 2.4). FA-III comprises ripple cross-laminated, planar-laminated, massive, or trough cross-stratified very fine- to fine-grained, sheet-like sandstone (F-4A and F-4B). FA-III sandstones are occasionally interbedded with mudstone (F-1A) or siltstone (F-2A) but are dominantly encased in mudstone (F-1A). The thickest sandstone beds in FA-III range from 0.20 to 0.90 m in SB5 and SB6 (Figs. 2.4, 2.5). FA-III can have both inversely and normally graded beds (Fig. 2.5). In SBPC1A, FA-III consists of a 3-m-thick succession of mudstone (F-1A)

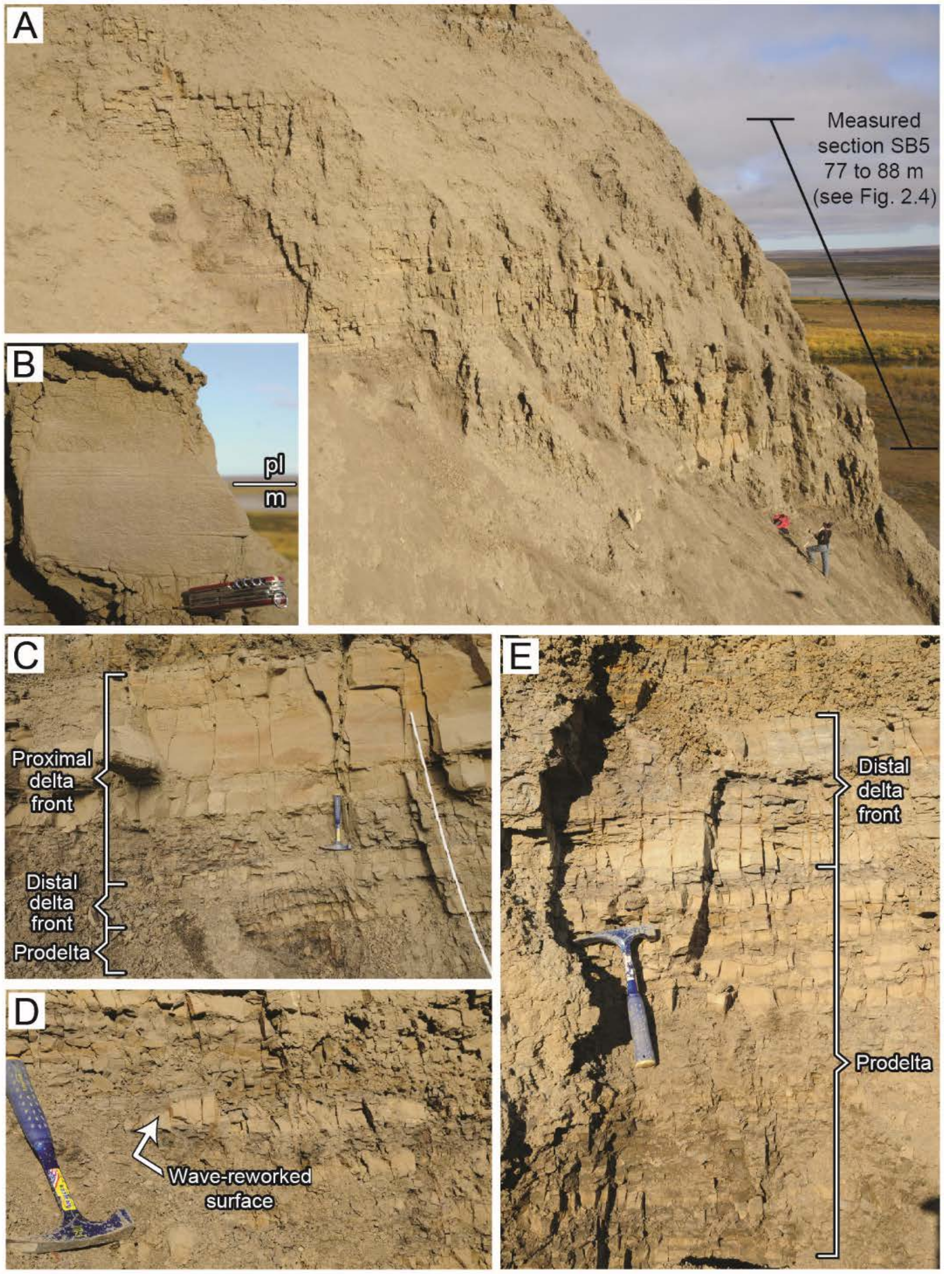

Figure 2.8. A) The outcrop expression of measured section SB5 between 77 and 88 m. B) Massive and planar-laminated sandstone interpreted as hyperpycnite sheet sandstone at 72.7 m in SB5. C) Prodelta (FA-II), distal delta front (FA-III), and proximal delta front (FA-IV) deposits near 79.7 m in SB5. D) Wave-reworked surface at 82.7 m from SB5. E) Prodelta (FA-II) and distal delta front (FA-III) deposits near 91.9 m in SB5. Knife = 9 cm long. Rock hammer = 30 cm long.

Figure 2.9. A) The outcrop expression of measured section SB6 between 0 and 19.75 m. B) Brackets show locations of "clean" lensoidal sandstones along the same stratigraphic horizon interpreted as terminal distributary channels (TDCs; FA-V) encased in prodelta (FA-II) and distal-delta-front (FA-III) deposits. C) A close-up of two terminal distributary channels that are 40 cm thick. D) Terminal distributary channel (FA-V) with a levee (Lv) margin. E) The upper sandstone in a multistory terminal distributary channel has an erosional base, trough-cross stratification (tr), and massive (m) bedding.

with 10- to 15-cm-thick, massive, very-fine grained sandstone (F-4A) with abundant plant material and rare gastropods. FA-III typically overlies prodelta (FA-II) deposits and is typically associated with terminal-distributary-channel (FA-V) and interdistributary-bay deposits (FA-VII).

Interpretation: FA-III is interpreted as distal-delta-front deposits. Distal-delta-front deposits have thicker sandstone beds (> 0.10 m thick) than prodelta deposits (FA-II), but those sandstones are generally thinner (< 1.0 m) than proximal-delta-front sandstones (FA-IV; Fielding 2010; Hurd et al. 2014). Higher mud-to-sand ratios are found in distal-delta-front deposits than in the proximal-delta-front deposits (Fielding 2010; Hurd et al. 2014). Both inversely and normally graded beds are commonly associated with hyperpycnites and indicate waxing- and waning-energy conditions (Mulder et al. 2003). Distal-delta-front deposits generally lack trace fossils, implying such stresses as elevated water turbidity, turbulence, and salinity fluctuation and soupground conditions that limited niche space for endobenthos (e.g., MacEachern et al. 2007; Hurd et al. 2014).

FACIES ASSOCIATION IV: PROXIMAL DELTA FRONT

Description: A typical succession of FA-IV is found from 77.25 to 90.10 m in SB5 (Fig. 2.4). FA-IV successions are 2.80, 4.0, and 12.85 m thick in measured section SB5 and SBPC1 and comprise very fine- to fine-grained amalgamated sandstone with rare to common siltstone interbeds (F-2A). Sandbodies can be amalgamated and are commonly trough cross-stratified (20.0 cm thick), massive (30.0 cm thick), and ripple or planar laminated (12.0 to 30.0 cm thick; F-4A and F-4B). Siltstone interbeds range from laminated to 1.0-m-thick structureless intervals. Trace-fossil assemblages in SB5 commonly include *He*, *Schaubcylindrichnus* (*Sch*), and *Planolites* (*Pl*) in discrete intervals, but in SBPC1A FA-IV contains *Ph*, *He*, *Sch*, *Asterosoma* (*As*), *Rhizocorallium* (*Rz*), *Teichichnus* (*Te*), and rare *Ophiomorpha* (*Op*). FA-IV is typically encased in either prodelta (FA-II) or interdistributary-bay deposits. Both FA-IV successions in SB5 are bounded above and below by prodelta deposits (FA-II; Fig. 4). FA-IV between 2.75 and 5.5 m in SBPC1A is bounded above and below by interdistributary-bay deposits with terminal-distributary-channel deposits (FA-V; Fig. 2.6). FA-IV between 85 and 91 m in SBPC1B overlies interdistributary-bay deposits and is overlain by terminal-distributary-channel deposits (Fig. 2.7).

Interpretation: Amalgamated sandstone with rare to common interbeds of siltstone (Figs. 2.4, 2.6) are interpreted as proximal-delta-front deposits (e.g., Fielding 2010; Hurd et al. 2014). Proximal-delta-front deposits differ from the distal-delta-front deposits (FA-III) by having thicker amalgamated sandstone bodies (> 1 m thick) and dominantly high sand-to-mud ratios (Fielding 2010; Hurd et al. 2014). Deltaic deposits with decimeter-thick beds that make up thick sandbodies (> 1 m) are often interpreted as medial-proximal delta-front deposits (Fielding 2010; Hurd et al. 2014). Several intervals in SB5 contain interbedded rippled and parallel-laminated or interbedded parallel-laminated and structureless sandstone beds that indicate waxing and waning deposition, common to hyperpycnal beds (Mulder et al. 2003; Olariu et al. 2010). In SB5, *He* is more abundant in proximal-delta-front deposits when compared to the distal-delta-front deposits. In SBPC1A, trace-fossil assemblages become even more diverse in proximal-delta-front deposits that are encased in what are interpreted as interdistributary-bay deposits (FA-VII; Fig. 2.6). Ichnological signatures in deltaic settings often reflect a diverse range of productivity depending on environmental conditions (Bann and Fielding 2004; Hurd et al. 2014).

FACIES ASSOCIATION V: TERMINAL DISTRIBUTARY CHANNELS

Description: FA-V is found in SB6 and SBPC1B (Figs. 2.5, 2.7, 2.9). Multiple tiers of FA-V are found between 9 and 19.75 m in SB6 (Figs. 2.5, 2.9A). FA-V comprises clean, very fine- to fine-grained, lensoidal sandbodies 0.1–1.5 m thick encased in FA-II and FA-III (Fig. 2.9B–C). Sedimentary structures range from trough cross-stratification (F-4B), massive (F-4A), or rare hummocky cross-stratification (F-4C) with common parallel laminations or ripple laminations (F-4A) at the top. FA-V sandstones tend to have a concave-up basal erosional surface and often have elevated margins (Fig. 9D). FA-V may be single or multistory (Fig. 2.9C–E), and can exhibit a basal lag of plant fragments, inoceramid hash, and pebbles. Near SB6, up to seven lensoidal sandbodies are observed to occupy the same stratigraphic horizon laterally along ~ 150 m of outcrop (Fig. 9B). Stratigraphically above lensoidal sandstones, massive or ripple-laminated siltstone (F-2A) interbedded with very fine sandstone (F-4A) is rare to common. *Ph* and *He* are common, whereas *Sch* and *Rz* are rare and are typically found closer to the upper bounding surface.

Interpretation: Sandbodies of FA-V are interpreted as marine deposits because they typically contain inoceramid debris and trace fossils *Ph* and *He* with rare *Sch* and *Rz*. These sandbodies probably formed in a physicochemically stressed environment driven by the frequent influx of sediment laden freshwater from up-dip delta distributaries, based on the trace-fossil assemblage and stratigraphic position (Bhattacharya and MacEachern, 2009), similar to the proximal-delta-front deposits in SB5. Although somewhat similar to other laterally discontinuous, isolated sandbodies encased in mudstone commonly interpreted as gutter casts (Myrow 1992), these sandbodies are uniquely uniform in shape, width, and thickness along the same stratigraphic horizon. Gutter casts, when observed along the strike of an outcrop belt, commonly exhibit a series of different morphologies with a variety of sizes and shapes due to variable currents and degree of erosion found perpendicular to the shelf margin (Myrow 1992). Also, no significant erosional surfaces or relief is found in the mudstone and siltstone deposited between the lensoidal sandstones, which would be expected if these sands formed from wave-induced events. These single to multistory sandbodies of FA-V are arcuate features typically found in tiers, similar to each other in size and thickness, which exhibit scoured bases, complex fill including basal lags and trough cross-stratification, and elevated margins that pinch out laterally into mudstone. Although this evidence does not rule out the possibility that these sandbodies could be considered examples of the multitude of features described as gutter casts, the relative lack of evidence for wave- or tide-controlled sedimentation in this part of the Schrader Bluff Formation suggests that the process driving formation of these features is predominantly fluvial. These observations suggest that sandbodies of FA-V are best interpreted as the subaqueous, distal-most expression of distributary channels and their associated levees similar to those described in the Wax Lake Delta that have formed from a jet plume, where an inertia-driven flow passes through a flow constricting area (Wellner et al. 2005).

Isolated FA-V sandbodies found encased in prodelta (FA-II) and distal-delta-front (FA-III) deposits are interpreted as channelized subaqueous terminal distributary channels, which is supported by the basal erosion surface, channel-form architecture, primary sedimentary structures, trace fossils, and the close stratigraphic relationship of these channels to the delta front (Olariu et al. 2005). Subaqueous terminal distributary channels at Shivugak Bluffs contain sedimentary structures and trace fossils similar to the terminal distributary channels found in the Campanian Panther Tongue of the Star Point Formation (Olariu et al. 2005; Olariu and Bhattacharya 2006); however, the terminal distributary channels in the Schrader Bluff Formation are observed to incise into and be encased in prodelta (FA-II) and distal-delta-front (FA-III) deposits, unlike those in the Panther Tongue (Olariu et al. 2005). These lensoidal sandbodies are therefore interpreted to be the seaward extensions of subaerial channels.

FACIES ASSOCIATION VI: DISTRIBUTARY MOUTH BARS

Description: The only incidence of FA-VI is found between 93.0 and 98.5 m in SBPC1B (Figs. 2.7, 2.10, and 2.11A−D). FA-VI comprises well-sorted, fine-grained, medium-bedded large-scale and small-scale trough cross-stratified sandstone (F-4B) with cross sets up to 15 cm thick that are organized into four, 1.0–1.2-m-thick stories (Figs.

2.7 and 2.11B−D). These sandbodies may contain entrained mud-rip ups (up to 5 cm in diameter), plant fragments, wood debris (Fig. 2.11D), and rare *Sch*. The uppermost sandstone fines upward from a fine-grained sandstone (F-4A) into a siltstone (F-2A). FA-VI directly overlies subaqueous terminal distributary channels and delta-front deposits in many areas along the outcrop belt (Fig. 2.11E) and may also overlie and be overlain by floodbasin (FA-VIII) deposits, including mudstone (F-1A) and carbonaceous mudstone (F-6).

Interpretation: The 5-m-thick multistory sandbody of FA-VI is interpreted as distributary-mouth-bar deposits. Sandbodies with similar characteristics in this stratigraphic position, above proximal-delta-front deposits (FA-IV), terminal distributary channels (FA-V), or interdistributary-bay deposits (FA-VII), and below floodbasin and distributary channels similar to small sinuous channels (FA-X) are commonly interpreted as mouth bars (Fielding et al. 2005; Fielding 2010).

Although these sands appear somewhat similar to braided-channel deposits dominated by downstream accretion (FA-XI), they are much finer grained then braided channels of the Prince Creek Formation (very fine to fine grained versus coarse grained), are extremely well sorted, lack a basal lag, and do not contain the pebbles and cobbles common to downstream-accretion-dominated channels of the Prince Creek Formation (FA-XI). They may also rarely contain *Sch*, consistent with their classification as marine deposits.

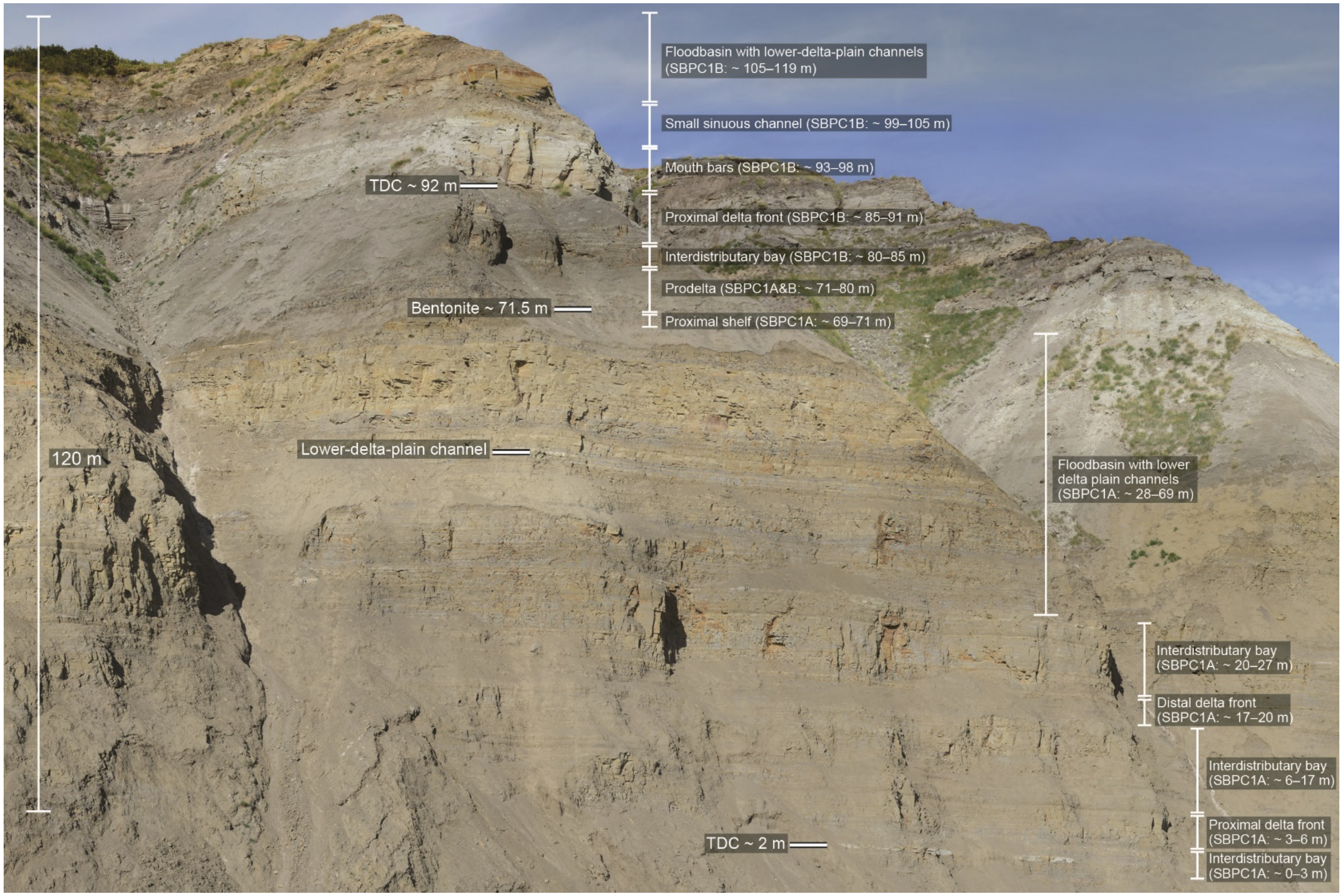

Figure 2.10. A) Representative outcrop expression of 120 m of measured section of SBPC1A and B (Figs. 2.6, 2.7) including meter equivalents, paleoenvironmental interpretations, and overall stacking pattern.

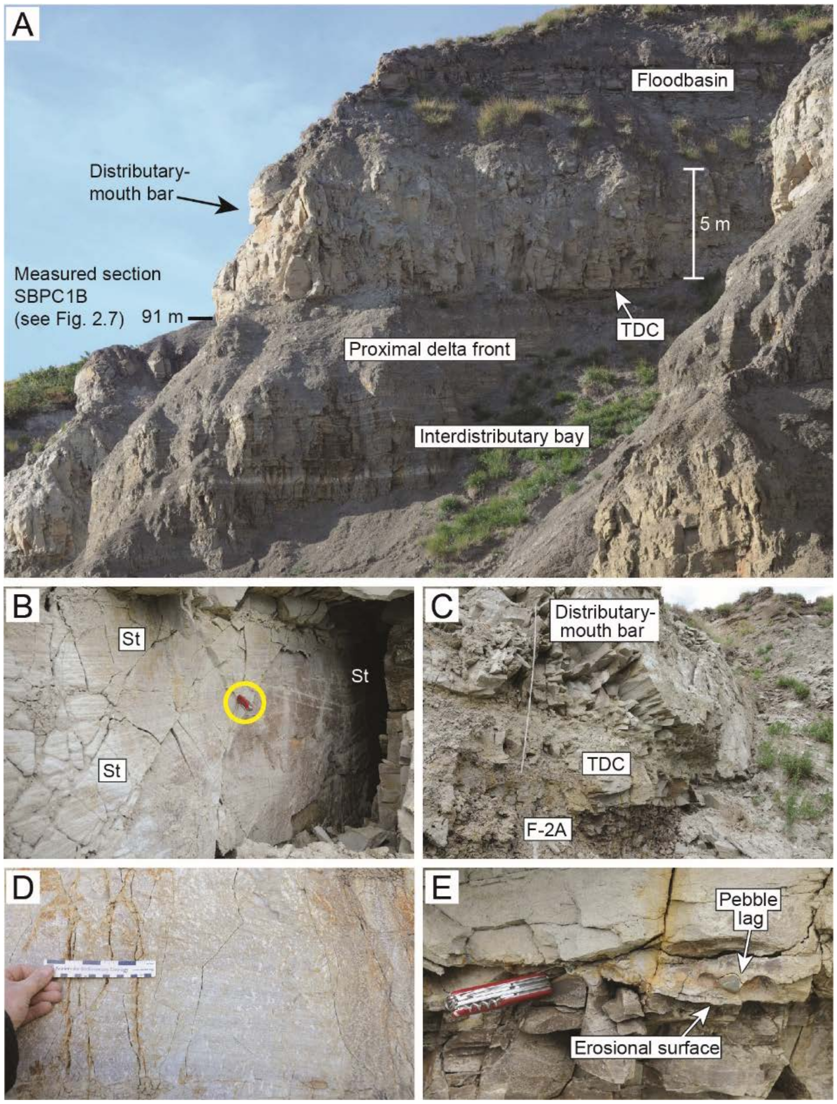

Figure 2.11. A) Approximately 20 m of outcrop exposure from measured section SBPC1B showing interdistributary bay (FA-VII), proximal delta front (FA-IV), terminal distributary channel (TDC; FA-V), a 5-m-thick sandbody interpreted as a distributary mouth bar (FA-VI), and floodbasin (FA-VIII) deposits. B) Large-scale trough cross-stratification (St) in sandbody interpreted as a distributary mouth bar. Knife in yellow circle = 9 cm long. C) Siltstone (F-2A) in proximal delta front (FA-IV) deposits, terminal distributary channel (FA-V), and distributary mouth bar (FA-VI) deposits. D) Close up of well-sorted, trough cross-stratified fine-grained sandstone in Part B. Measuring stick = 2 m long. E) Pebble lag at base of terminal distributary channel at 91.25 m in SBPC1B. Knife = 9 cm long.

FACIES ASSOCIATION VII: INTERDISTRIBUTARY BAY

Description: A typical succession through FA-VII is found between 5.5 and 17 m in SBPC1A (Fig. 2.6, 2.10). FA-VII ranges from 2.0 to 11.5 m thick (Figs. 2.10, 2.11A). In SBPC1A, massive, laminated, ripple-laminated (F-2A), flaser (F-3) and lenticular-bedded (F-3) siltstone are found interbedded with massive or planar-laminated mudstone (F-1A) and planar-laminated sandstone (F-4A; Fig. 2.12). Several mudstone and siltstone intervals coarsen upward and are capped by erosionally based very fine- to fine-grained massive sandstones (35 to 50 cm thick; FA-V). FA-VII contains abundant pelecypod bivalves and gastropods as well as a highly diverse trace-fossil assemblage including *He, Ph, Sch*, *Palaeophycus* (*Pa*), *Skolithos* (*Sk*), *Pl, Op, Thalassinoides* (*Th*), *As*, *Chondrites* (*Ch*), *Gyrolithes* (*Gy*), and *Teredolites* (*Td*; Figs. 2.6, 2.7). From 5.5 to 27.5 m in SBPC1A, the trace-fossil assemblage of FA-VII decreases up section until there is no occurrence of trace fossils or invertebrates.

Between 20.0 to 27.5 m in SBPC1A, massive, laminated, and rare ripple-laminated siltstone (F-2A) contains conformable interbeds of very fine-grained massive sandstone (0.1 to 0.4 m thick; F-4A). FA-VII overlies prodelta (FA-II), distal-delta-front (FA-III), and proximal- delta-front (FA-IV) deposits and underlies floodbasin (FA-VIII) deposits. Compared with the occurrence of FA-VII below 20 m, FA-VII above 20 m (Fig. 2.13A) contains no sands with erosional bases and has significantly less ichnologic diversity, containing only abundant *He* with relatively few *Ph* and *Sch.* A 5-cm-thick bentonite layer is found in FA-VII at 11.25 m in SBPC1A (Fig. 2.6).

Interpretation: Flaser- and lenticular-bedded siltstone has been described from embayed, semiprotected areas that develop between distributary channels in delta lobes, such as interdistributary bays (Elliott 1974; Phillips 2003; Bhattacharya 2010). Interdistributary bays are typically shallow, open-water settings that exhibit varying salinities from normal-marine to brackish or freshwater since they can be open to the sea or connected to the sea by tidal channels (Elliott 1974; Phillips 2003). Interdistributary-bay deposits at Shivugak Bluffs with pelecypods, gastropods, and a broad range of trace fossils are suggestive of open bays (Elliott 1974; Phillips 2003). Intervals with a less diverse trace-fossil assemblage are often associated with interbedded, planar-laminated sandstones (F-4A) interpreted as sandy hyperpycnal flows associated with the distal-delta-front deposits or the most distal portions of mouth bars (17.0 to 20.0 m in SBPC1A; Mulder et al. 2003; Fielding 2010). The intervals with less diversity, associated with hyperpycnal deposits, suggest that salinities may have fluctuated between fresh, brackish or normal marine conditions with or without higher sedimentation rates (Bhattacharya and MacEachern, 2009). Similar interdistributary-bay deposits without hyperpycnites but containing a higher frequency of storm deposits have been described along the Colville River in the Upper Schrader Bluff Formation (Maastrichtian) near Ocean Point (Fig. 2.1; Phillips 2003). Interdistributary-bay deposits at Ocean Point range from 4 to 11.4 m thick (Phillips 2003) and are consistent with thicknesses of 2.0 to 11.5 m reported here for interdistributary-bay deposits at Shivugak Bluffs.

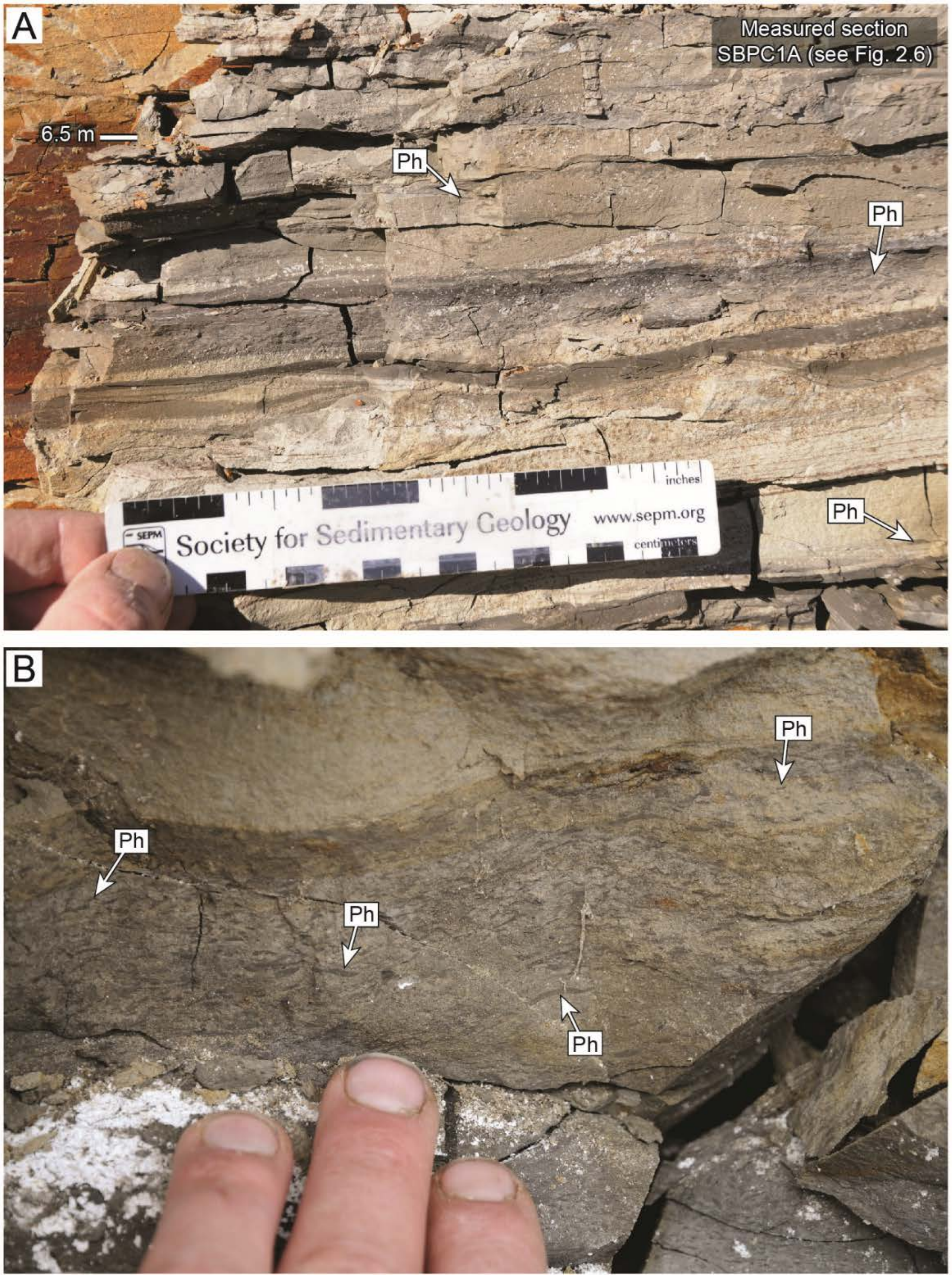

Figure 2.12. A) Wavy and lenticular bedding (F-3) with *Phycosiphon* (Ph) interpreted as interdistributary-bay deposits in measured section SBPC1A. B) *Phycosiphon* (Ph) in a siltstone (F-2A) between 0 and 3 m in SBPC1A.

Figure 2.13. A) Outcrop expression of A) distal delta front (FA-III) and interdistributary bay (FA-VII) deposits at approximately 20 m in SBPC1A, and B) floodbasin (FA-VIII) with erosion surface 1 (indicated by dashed line marked E.S. 1) at 45 m and small low-sinuosity channel (FA-IX). Circle shows chert pebbles removed from erosion surface 1. C) Inset showing close-up of pebbles in place.

FACIES ASSOCIATION VIII: FLOODBASIN AND LOWER-DELTA-PLAIN FINES

Description: FA-VIII ranges from 0.5 to 20.5 m thick in SBPC1A and B (Figs. 2.6, 2.7). The thickest successions are 20.5 m, 5 m, and 4.5 m found between 48.5 to 69 m in measured section SBPC1A, 111 m to 116 m in SBPC1B, and 127 to 131.5 m in SBPC1B (Figs. 2.6, 2.7). FA-VIII comprises interbedded mudstone (F-1A and B), siltstone (F-2A and B), thin beds of massive or ripple-laminated sandstone (F-4A), carbonaceous mudstone (F-6), coal (F-7), and bentonite (F-8; Fig. 14). Organic-rich beds are often mottled or rooted with carbonaceous roots up to 0.5 cm wide and 7 to 30 cm long.

Interpretation: FA-VIII is interpreted as floodbasin and lower-delta-plain deposits based on the abundance of interbedded fine-grained facies lacking marine trace fossils, numerous organic and rooted horizons, and the association with interbedded facies interpreted as fluvial in origin (Allen 1965; Reineck and Singh 1980). Floodbasins are relatively flat, poorly drained, and are the lowest lying portions of the overbank associated with distributive fluvial systems and the lower delta plain (Kruit 1955; Allen 1965). Floodbasin deposits typically represent long-term accumulation of fines in floodwaters that settle out of suspension after reaching low-lying basins flanking alluvial ridges (Allen 1965). Floodbasin deposits in the Mississippi River and the Brazos River overbanks range from 8 to 80.5 km long, 3.2 to 24.1 km wide, and 6.7 to 42.7 m in maximum thickness (Fisk 1944, 1947; Bernard et al. 1962). The proportion of fine-grained sediments tends to be higher in floodbasins than in associated and interfingering levee successions, even though the grain-size range of floodbasins is not significantly different from those associated with distal levees (Allen 1965). The bentonite layer at 50.5 m in SBPC1A has irregular undulations along the upper contact (Fig. 2.14C). Bentonites with irregular undulations found in floodplain deposits of the Prince Creek Formation have been interpreted as deposited in small ponds or lakes with the deformed bedding resulting from trampling by dinosaurs (Fiorillo et al. 2010b; Flaig et al. 2011, 2013, 2014). The bentonite layer at 50.5 m in SBPC1A is assigned the same interpretation. FA-VIII overlies distributary-mouth bars (FA-VI) and interdistributary bays (FA-VII), and is typically intercalated with small low-sinuosity channels (FA-IX), small sinuous channels (FA-X), or downstream-accretion-dominated channels (FA-XI). The sediments in floodbasins (FA-VIII) are further subdivided into FA-VIII A-D representing lake and lake margins (FA-VIIIA), distal crevasse splays or levees (FA-VIIIB), swamp and swamp margins (FA-VIIIC), and those deposits modified into paleosols (FA-VIIID).

FACIES ASSOCIATION VIIIA: LAKE AND LAKE MARGINS

Description: FA-VIIIA comprises rhythmically laminated or massive mudstone (F-1A) with thin interlaminations of organics or siltstone (F-2A). Strata between 48.5 and 69.0 m in SBPC1A are organized into packages 0.10, 0.50, and 0.75 m thick (Fig. 2.6). Commonly these fine-grained packages are interspersed with massive, symmetric- and asymmetric-ripple-laminated sheet-like sandstone (F-4A). No softground trace fossils are observed here except for one bentonite layer at 50 m in SBPC1A containing *Pl* (Fig. 2.6). Muddy intervals contain abundant carbonaceous plant material and wood impressions,

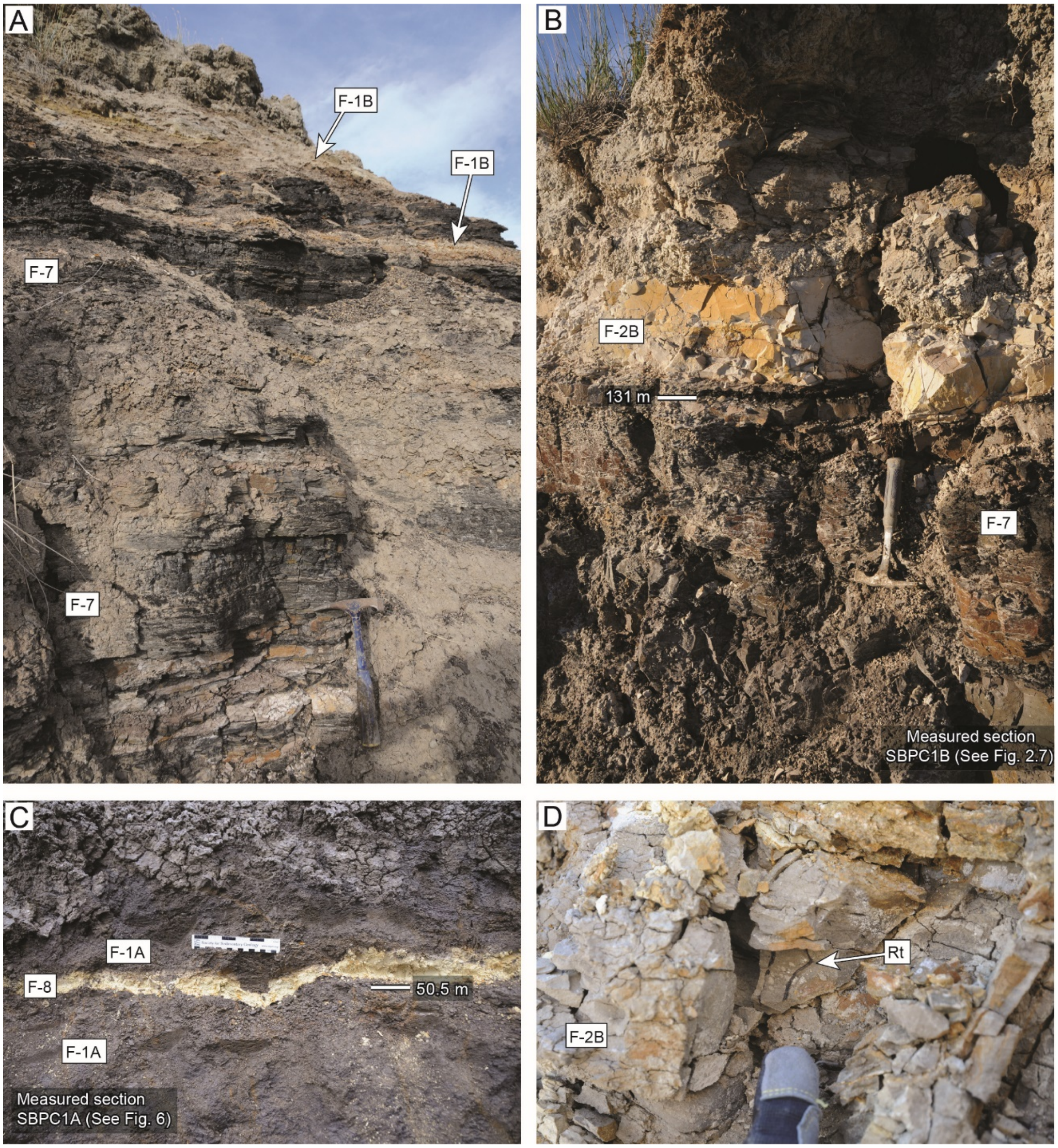

Figure 2.14. A) Coal (F-7), and rooted mudstone (F-1B) between 112 and 116 m in SBPC1B interpreted as floodbasin (FA-VIII) deposits. B) Coal (F-7) and tuffaceous massive siltstone (F-2B) at 131 m in SBPC1B interpreted as lower delta plain fines (FA-VIII). C) A bentonite (F-8) layer encased in a floodbasin mudstone (F-1A) at 50.5 m in SBPC1A. Mudstone injected down into bentonite layer is interpreted as a dinosaur footprint. D) Rooted (Rt) siltstone (F-2B) interpreted as floodbasin paleosol (FA-VIIID).

whereas siderite concretions and jarosite are present at discrete intervals. Logs and pieces of amber are rare.

Interpretation: Nonrooted mudstones containing siderite, jarosite, and logs are interpreted as lake and lake-margin deposits on the lower delta plain, and are similar to those in the Prince Creek Formation found along the Colville River, north of Shivugak Bluffs (Flaig et al. 2011, 2013). Rhythmic thin- to medium-laminated (1 to 10 mm) mudstones are interpreted as lake deposits (Astin 1990; Besly and Collinson 1991; Tanner 2004), which may be relatively thick (e.g. 20 m, Besly and Collinson 1991). In SBPC1A, 20.5 m of predominantly laminated mudstone overlies small sinuous and low-sinuosity channels (FA-IX) and is overlain by proximal shelf deposits (Fig. 2.6).

FACIES ASSOCIATION VIIIB: CREVASSE SPLAY OR LEVEES

Description: FA-VIIIB comprises thin- to thick-bedded massive or ripple-laminated sheet-like sandstone (F-4A) and very thin- to thick-bedded massive siltstone (F-2A). Carbonaceous plant debris, wood impressions, siderite concretions, and jarosite are common. Rooted, thick-bedded massive sandstone (80 cm thick) at 111.5 m in SBPC1B has an erosional base, although most of these deposits in the study area have conformable lower contacts (Fig. 2.7).

Interpretation: FA-VIIIB is interpreted as distal crevasse splays and levees deposited in a floodbasin (FA-VIII). Crevasse splays are formed when excess water leaves a channel and either breaks through a levee or overcomes a lower position along the river (Happ et al. 1940; Allen 1965). Natural levees border stream channels and are thicker closer to the edge of the channel and thin into floodbasins (Allen 1965). Suspended detritus commonly settles from overbank flows in floodbasins (Allen 1965). Crevasse splays and splay complexes have been shown to make up the bulk of the Prince Creek Formation along the Colville River (Flaig et al. 2011, 2013, 2014).

Facies Association VIIIC: Swamp and Swamp Margins

Description: Coal (F-7), carbonaceous mudstone (F-6), and mudstone (F-1A) form FA-VIIIC and are found only in SBPC1B (Fig. 2.7). Coal beds in these intervals range from 0.10 to 1.85 m thick (Fig. 2.14A), and carbonaceous mudstone layers range from 0.25 to 0.6 m thick.

Interpretation: Coal, carbonaceous mudstone, and less-organic mudstones (FA-VIIIC) are interpreted as swamps, marsh, and mire deposits in floodbasins (Fisk 1947; Allen 1965; Tatsch 1980; Flores and Hanley 1984; Flaig et al. 2011). Coals are also considered histosols (Retallack 2001), whereas rooted carbonaceous mudstones are considered histic protosols that are not at the grade of coal (cf. Mack et al. 1993). Swamps and associated swamp-margin paleosols are common in the Prince Creek Formation (Flaig et al. 2013).

Facies Association VIIID: Paleosols

Description: FA-VIIID comprises interbedded mudstone (F-1B) and siltstone (F-2B) containing rhizoliths, mottles, desiccation cracks, plant fragments, or wood debris (Fig. 2.14D). Carbonaceous rhizoliths are up to 0.5 cm in diameter and 20 to 30 cm long. Between 27.5 and 29 m in SBPC1A, FA-VIIID comprises aggregated blocky or platy mudstones (0.1 to 0.5 m) with desiccation cracks and reddish-orange to yellow mottling (Figs. 2.6, 2.14) found directly above interdistributary-bay deposits (FA-VII). Rooted mudstone (0.1 to 2 m thick; F-1B) and siltstone (0.1 to 0.5 m thick; F-2B) also occur above 114 m in SBPC1B (Fig. 2.7) and are associated with carbonaceous mudstone (F-6) and coal (F-7; Fig. 2.14) interpreted as pedogenically modified swamp and swamp-margin deposits (FA-VIIIC).

Interpretation: Mottled and rooted mudstone and siltstone (F-1B and F-2B) are interpreted as carbonaceous paleosols (Mack et al. 1993; Flaig et al. 2011, 2013). Floodbasin deposits are often subject to desiccation and local oxidation as the water tables fluctuate (Anderson 1961; Allen 1965). Organic debris in floodbasin deposits commonly form mottled and homogenized soil zones with rootlets, peat, drifted leaves, tree roots, stumps, and other plant material (Fisk 1944, 1947; Anderson 1961; Lattman 1960; Bernard et al. 1962; Allen 1965). Flaig et al. (2013) documented weakly developed paleosols similar to modern aquic subgroups of Entisols, Inceptisols, and potential acid sulfate soils that formed on low-lying, low-gradient coastal-plain deposits in the early Maastrichtian Prince Creek Formation. At Shivugak Bluffs, paleosol horizons with macrofeatures similar to modern aquic subgroups of Entisols and Inceptisols are found stratigraphically above interdistributary-bay deposits (FA-VI), swamps (F-6, F-7), and overbank deposits (F-1A, F-2A) that cap channels dominated by downstream accretion (FA-XI; Flaig et al. 2011).

FACIES ASSOCIATION IX: SMALL LOW-SINUOSITY CHANNELS

Description: Typical successions through FA-IX can be found from 116 to 119 m in SBPC1A, and 47 to 48.5 m in SBPC1B (Figs. 2.6, 2.7). FA-IX is dominated by a single-story, fine- to medium-grained, massive to current-rippled sandbody (F-4A) up to 1.0 m thick that overlies an arcuate, concave-up erosional base. Mud rip-up clasts are common near the base; wood and plant fragments are also abundant. A fining-upward succession into silt and mud typically overlies the sandbody, sometimes containing a thin layer of sand–mud couplets of inclined heterolithic stratification (IHS). FA-IX also contains rooted siltstone (F-2B) and massive to planar-laminated (F-1A) mudstone. A bentonite (F-8) was also found in one small low-sinuosity channel (Fig. 2.13B). Sandbodies of FA-IX are laterally restricted (tens of meters wide) and pinch out laterally into floodbasin deposits (F-1A and B, F-2A and B, F-4A, F-6, and F-7; Fig. 2.15A).

Interpretation: Small low-sinuosity channels of FA-IX are interpreted as fixed-ribbon sandbodies (Flaig et al. 2011) similar to anastomosed channels (e.g., Nadon 1994; Flaig et al. 2011). Fixed-ribbon sandbodies, typically found as multiple sandbodies arranged in tiers at the same stratigraphic level have been previously identified in the Prince Creek Formation (Flaig et al. 2011). Anastomosed channels tend to remain fixed in position due to low stream power, low gradients, and stable banks produced by abundant silt, mud, and vegetation (Smith 1976; Nadon 1994), all of which are common on the lower delta plain. Anastomosed channels are common in systems with high-suspended-load concentrations (Smith 1983; Smith et al. 1989), which has been suggested for distributaries of the Prince Creek Formation (Flaig et al. 2011, 2013, 2014).

Figure 2.15. A) Small low-sinuosity (fixed) channel (FA-IX) encased in floodbasin (FA-VIII) deposits. B) Small sinuous channel (FA-X) interpreted as a meandering distributary channel. Image includes lateral-accretion surfaces and an erosion surface at the base of the channel.

FACIES ASSOCIATION X: SMALL SINUOUS CHANNELS

Description: A typical succession through FA-X can be found from 41 to 45 m in SBPC1A and 99 to 104.5 m in SBPC1B (Figs. 2.6, 2.7, nd 2.15). Small sinuous channels consist of a single-story, 4–5.75-m-thick erosionally based sandbody dominated by fine- to medium-grained ripple- to trough cross-lamination (F-4A, F-4B) that fines upward into IHS containing siltstone (F-2A) and sandstone interbeds (Figs. 2.6, 2.7). Pebbles, rare cobbles, mud rip-up clasts, jarosite, wood, and plant fragments are found at the base and on the toes of trough and ripple cross-lamination. Sandbodies of FA-X are laterally extensive (up to hundreds of meters) and are intercalated with floodbasin deposits (FA-VIII). Sandbodies of FA-X overlie and are underlain by floodbasin deposits (FA-VIII).

Interpretation: Small sinuous channels of FA-X are interpreted as suspended-load meandering distributary channels (Flaig et al. 2011). High-sinuosity (meandering) is indicated by IHS with paleoflow indicators from trough or ripple cross-stratification crossbeds at a high angle relative to the dip of the IHS, indicating lateral accretion (Allen 1963, Collinson 1978, Thomas et al. 1987, Flaig et al. 2011). Fine-grained deposits near the top of FA-X record vertical accretion of fines at the tops of pointbars during low flow (Allen 1963, Thomas et al. 1987). The basal erosional surface of the meandering channel at 99 m represents a major, mappable contact between the lower Schrader Bluff Formation and the Prince Creek Formation along the Colville River (Fig. 2.7).

FACIES ASSOCIATION XI: DOWNSTREAM-ACCRETION-DOMINATED CHANNELS

Description: A typical succession through FA-XI can be found from 119 to 128 m in SBPC1B (Fig. 2.7). FA-XI is an ~ 8-m-thick, multistory, coarser-grained sandbody containing conglomerate (F-5) and medium- to coarse-grained trough- and ripple-cross-laminated sandstone (F-4A, F-4B; Fig. 2.16A). The main sandbody comprises multiple stories, each 1–2 m thick, with basal scour surfaces typically containing pebbles, cobbles, mud rip-up clasts, wood debris, and plant fragments, all of which can also be found on the toes of trough- or ripple-cross lamination (Fig. 2.16B, C). FA-XI is capped by a massive to ripple-cross-laminated siltstone (F-2A). Sandbodies of FA-XI are laterally extensive (100s to 1000s m) and overlie and are underlain by swamp-margin deposits (FA-VIIIC).

Interpretation: FA-XI is interpreted as the deposits of coarse-grained, sandy to pebbly braided rivers. Little evidence of lateral accretion is evident in FA-XI, whereas downstream accretion, indicated by paleoflow subparallel to the dip direction of bounding surfaces, dominates (Figs. 2.15, 2.16). Concave-up scoop-shaped erosion surfaces coupled with trough crossbeds and paleocurrent orientations indicate downstream migration of high-flow-velocity bedforms in the channel during flooding events (Allen 1983; Bridge 1985). The lack of lateral-accretion surfaces and the predominance of downstream accretion suggest that these are deposits of braided rivers (Miall 1977; Bridge 1985). The contact at 119 m in SBPC1B places medium- to coarse-grained pebbly fluvial deposits over finer-grained floodplain deposits, suggesting a significant drop in base level (Fig. 2.7) resulting in the progradation of braided streams over the lower delta plain. Siltstone (F-2A) found above FA-XI records abandonment or migration of the channel and deposition of associated floodplain fines.

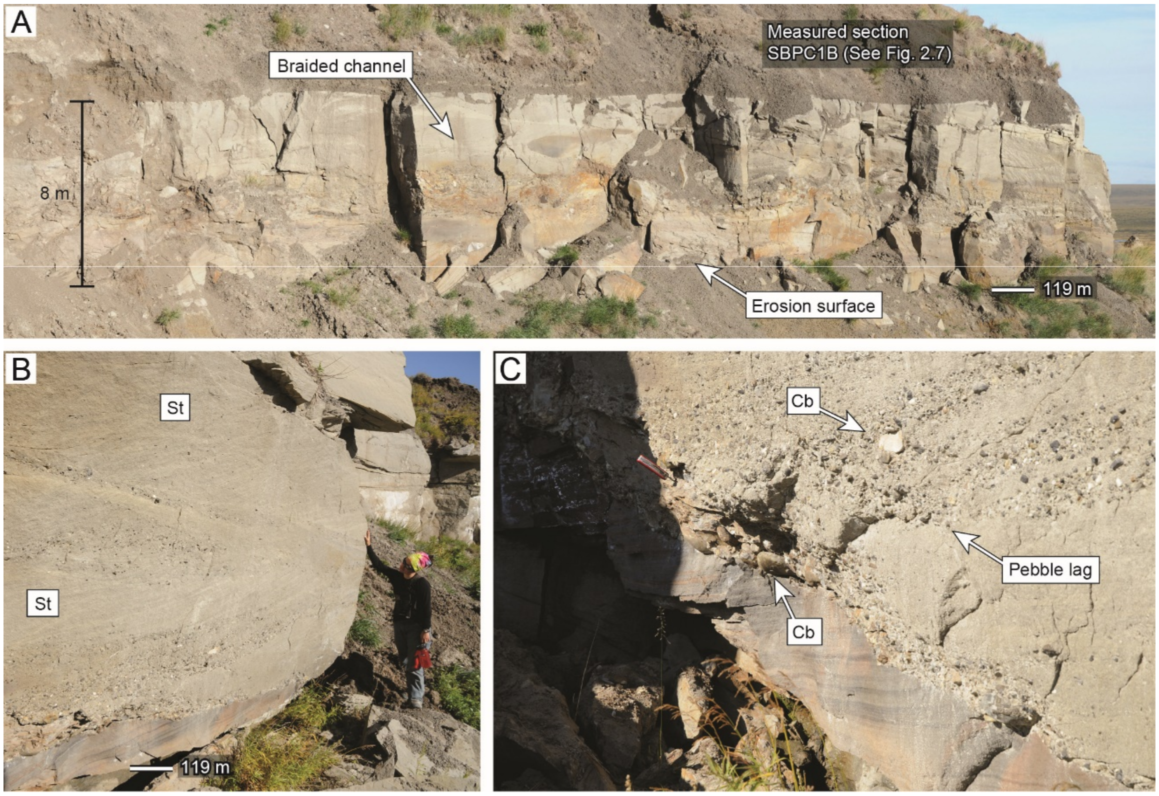

Figure 2.16. A) Downstream-accretion-dominated sandbody (FA-X) interpreted as a braided channel along with erosion surface 3. B) Trough cross-stratification (St) in FA-X. C) Close-up of pebbles and cobbles at the base of, and within, FA-X.

SIZE AND PALEO-DISCHARGE ESTIMATES FOR RIVERS

Estimating the size and paleo-discharge of river systems that fed the delta fronts of Schrader Bluff Formation deltas helps to determine the likelihood that rivers of the Prince Creek Formation might have produced hyperpycnites. In order to provide a significant estimate from a diverse dataset we chose to use channel width, depth, and paleo-discharge calculations from fluvial channels in the Schrader Bluff−Prince Creek system (Table 2.3) from: 1) the largest, second-order meandering distributaries found in

Table 2.3. Measured and calculated fluvial channel dimensions and discharge for the Prince Creek Formation.

Prince Creek Formation Channel	**Measured Depth (D)**	**Width* (W)**	**Area (A)**	**Dominant Bedform**	**Dominant Grain Size**	**Velocity (U)**	**Discharge (Q)**
	m	m	m^2			m/s	m^3/s
Largest Second-Order Meandering Distributary Channel (Flaig et al. 2011)	6	66	256	Ripples to 3D dunes	Fine-grained sand	1.5	384
Meandering Distributary at 99-105 m in SBPC1 (this study)	7	87	395	Ripples to 3D dunes	Fine-to medium-grained sand	1.5	593
Average First-Order Trunk Channel (Flaig et al. 2011)	13	268	2,264	Ripples to 3D dunes	Medium-grained sand	1.75	3,962

*W = $8.88d_m^{1.82}$, where d_m = mean bankfull depth (Bridge and Mackey 1993). d_m = one-half of the maximum bankful depth (D).

A = 0.65(DW); Q = AU.

U based on bedform phase diagrams of Rubin and McCulloch (1980), Bhattacharya and Tye (2004), and Bhattacharya and MacEachern (2009).

the bulk of the overlying Prince Creek Formation along the Colville River from Flaig et al. (2011); 2) the average first-order trunk channels from the same part of the system from Flaig et al. (2011); and 3) the meandering- distributary-channel deposit at 99−105 m in SBPC1B that is found directly above the mouth-bar deposits of the Schrader Bluff Formation at Shivugak Bluffs.

Flaig et al. (2011) indicate that the second-order distributary channels in the Prince Creek Formation are 2−6 m deep, while the largest channels, assumed to be first-order trunk channels, are 9−17 m deep. They used a combination of channel-depth measurements taken directly from outcrops (Ethridge and Schumm 1978, Gardner 1983) and the Leclair and Bridge (2001) method, which assumes that crossbed set thickness is equal to one-third dune height, and that flow depth is six to ten times dune height. Using the empirical regression equation of Bridge and Mackey (1993) derived from modern depth–width relationships to estimate the width of channels, Flaig et al. (2011) suggest that the largest mid-size channels (6 m depth) are ~ 66 m wide and the average trunk channel (13 m depth) is ~ 268 m wide. The apparent depth of the meandering-distributary- channel deposit found at 99−105 m is ~ 7 m, assuming that the finest-grained strata at the top of the channel are likely missing. This measurement is comparable to the depth of the largest second-order distributaries of Flaig et al. (2011). Using the Bridge and Mackey (1993) equation we obtain a channel width of ~ 87 m for that distributary channel.

Considering the aforementioned width and depth calculations and applying the method of Bhattacharya and MacEachern (2009) that assumes that the true cross-sectional area of a curved channel is 0.65 times the rectangular area, we obtain a cross-sectional area of 256 m^2 for the largest mid-size channels of the Prince Creek Formation described in Flaig et al. (2011), 395 m^2 for the distributary-channel deposit found at 99−105 m, and 2264 m^2 for the average trunk channel from Flaig et al. (2011).

Channels of the Prince Creek Formation contain very-fine to medium-grained sand. Paleo-velocities for channels were estimated using the bedform phase diagrams of Rubin and McCulloch (1980); see Bhattacharya and MacEachern (2009) for discussion. Velocity estimates for the largest mid-size channels of Flaig et al. (2011) and the distributary channel found at 99−105 m are thought to have been, at a maximum, 1.5 m/s. Velocity estimates for the average trunk channel (Flaig et al. 2011) were, at a maximum, 1.75 m/s. When area and maximum velocity are known, discharge can be calculated for these channels. Discharge estimates for the largest mid-size channels of Flaig et al. (2011) are 384 m^3/s, the distributary channel found at 99−105 m is 593 m^3/s, and the average trunk channel of Flaig et al. (2011) is 3962 m^3/s.

Comparing paleodischarge estimates for rivers of the Prince Creek Formation with criteria presented by Mulder and Syvitski (1995) for modern rivers, which suggest that rivers with relatively high sediment concentrations and average discharge of ~ 10−4000 m^3/s routinely produce hyperpycnal flows, suggests that Prince Creek Formation rivers may have regularly produced hyperpycnal plumes. This assumption is strengthened by the fact that Prince Creek Formation channels have been interpreted as suspended-load channels based on numerous outcrop characteristics (Flaig et al. 2011, 2013, 2014). Additionally, Flaig et al. (2014) also describe recurring, viscous hyperconcentrated flows on the distal coastal plain, which would require high suspended-sediment concentrations in order to form.

DISCUSSION

PALEOENVIRONMENTAL RECONSTRUCTION AND SYSTEM EVOLUTION

Herein we describe and interpret a mud-dominated, ~ 200-m thick overall coarsening- upward succession at Shivugak Bluffs that overlies shelf deposits of the Schrader Bluff Formation. We detail the shallow marine to continental transition and interpret the major boundary between the marine deposits of the Schrader Bluff Formation and the lower-delta-plain and coastal-plain deposits of the Prince Creek Formation at 99 m (Fig. 2.7). Our intention is to provide a case study of a marine–continental transition in a paleopolar setting (Figs. 2.4–2.16) with the ultimate goal of providing a model of paleoenvironmental evolution that expands upon current fluvial–deltaic depositional models (Fig. 2.17).

The succession at Shivugak Bluffs is interpreted to have evolved through time and space from muddy, distal delta deposits to a sandy braidplain (Fig. 2.17A−G). The most distal expression of the delta consists of interbedded prodelta (FA-II), distal-delta-front (FA-III) and proximal- delta-front deposits (FA-IV) with interbedded subaqueous terminal distributary channels (FA-V; Fig. 2.17A). As the delta prograded basinward, delta-front deposits and distal mouth bar deposits were overlain by interdistributary-bay deposits (FA-VII) interbedded with terminal distributary channels (FA-V; Fig. 2.17B).

This vertical succession can be found in association with prograding deltas, which may juxtapose these environments (Elliott 1974; Einsele 1992; Bhattacharya 2010). During what we interpret as a continued advancement of the delta, with the bulk of sedimentation occurring on other parts of the delta, interdistributary bays (FA-VII) shoal upward and their deposits are modified to paleosols (FA-VIIID) interbedded with crevasse splays (FA-VIIIB), distal distributary channels (FA-IX and FA-X), and lakes (FA- VIIIA; Fig. 2.17C). During delta-lobe abandonment phases, the lowest-relief areas of the delta, such as distributary channels or interdistributary bays, can be flooded and transformed into transgressive estuaries or barrier-shoreface deposits (Elliot 1974; Coleman 1988; Bhattacharya 2010). In this case, however, progradation continued in the area and the interdistributary bays instead evolved into floodbasins containing thick lacustrine deposits (Fig. 2.17D). Similar deltaic-to-lake progradational successions have been described in the Cenomanian Dunvegan Formation of the Alberta foreland basin in NE British Columbia, Canada (Plint et al. 2001; Lumsdon-West and Plint 2005). Floodbasin and fluvial channel deposits at Shivugak Bluffs do not contain trace fossils indicative of fully marine or physicochemically stressed marine conditions (e.g., Bromley 1996; Hasiotis and Platt 2012); therefore, these deposits that overlie interdistributary bay deposits likely reflect physicochemical conditions characteristic of continental processes associated with river and lake systems (e.g., Hasiotis and Platt 2012; Hasiotis et al. 2012).

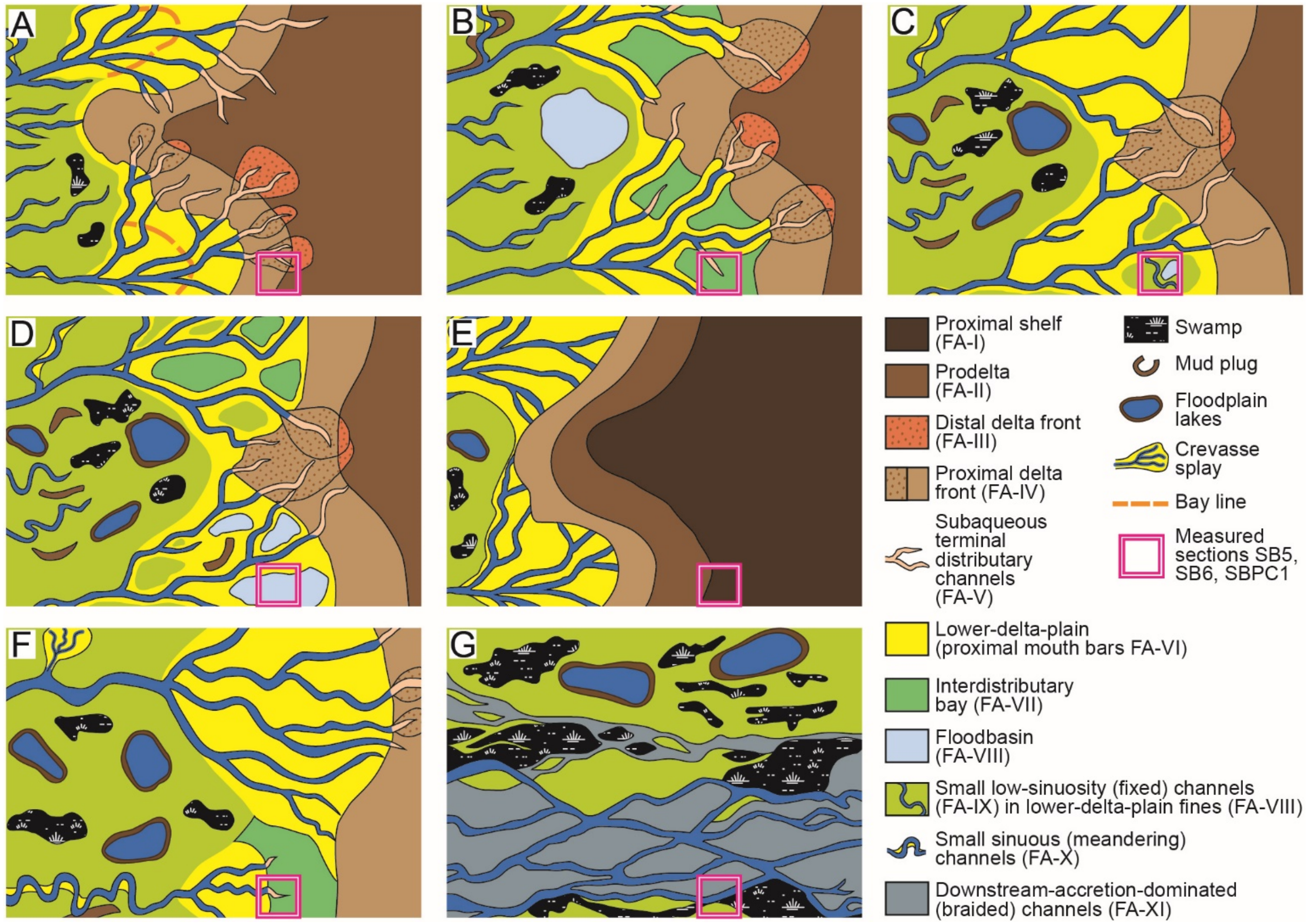

Figure 2.17. Depositional models showing the evolution of paleoenvironments at Shivugak Bluffs based on measured stratigraphy in SB5, SB6, SBPC1A and B. The area where these measured sections are located is denoted by a pink box.

At 45 m in SBPC1A an extensive pebble lag with an erosional base containing anomalous extraformational black chert pebbles as large as 12 cm is found encased in floodbasin deposits, and is described herein as erosional surface 1 (Figs. 2.6, 2.13B, C). There is no shell debris or marine deposits associated with these outsized clasts that would suggest a marine affinity, nor is there evidence to suggest seasonal ice-rafted debris. These outsized, well-rounded chert clasts were instead likely sourced from an up-dip fluvial system and perhaps were deposited due to a river flood. This is the first observation of outsized, anomalous clasts in this part of the succession at Shivugak Bluffs, and we interpret this to indicate a moderate drop in base level. For simplicity, this is not depicted in the depositional models (Fig. 2.17). We choose to make this interpretation, even though the lag is overlain by finer-grained floodbasin deposits, because of the abundance of outsized clasts that are typically found along erosional surfaces (Plint 1991) and the fact that both small low-sinuosity (FA-IX) and small sinuous (FA-X) channels are also found in this interval (41–48.5 m in SBPC1A) and not below (27.5–41.0 m in SBPC1A) or above (48.5–69.0 m in SBPC1A). A thick lake deposit containing interbedded splay deposits overlies the channel-rich interval.

At 69 m in SBPC1A, a flooding event places proximal shelf deposits (FA-I) over floodbasin deposits (FA-VIII; Fig. 2.17 E). Following this apparent transgression a normal deltaic progradational succession returns to the study area. Prodelta, delta-front, interdistributary-bay, and terminal-distributary-channel deposits are overlain by a laterally extensive mouth-bar deposit (Fig. 2.17F). Mouth bars are subsequently overlain by floodbasin deposits and a small sinuous distributary channel. In SBPC1B, an erosional surface is found at 105 m and is labeled erosional surface 2. Although we did not find outsized clasts at this location, erosional surface 2 appears to remove the normal fining-upward succession found at the top of most small low-sinuosity channels of the Prince Creek Formation (Flaig et al. 2011). Erosion surface 2 incises into and removes up to 1 m of distributary-channel sediments in outcrop at SBPC1B (Fig. 2.7). We suggest that this surface marks a second moderate drop in base level, although again for simplicity no representation of this is depicted in depositional models (Fig. 2.17). Erosional surface 2 is overlain by additional floodbasin deposits and a small low-sinuosity channel. At 119 m in SBPC1B (Fig. 2.7) coarse-grained pebbly braided fluvial channels occupy the entire outcrop belt (Fig. 2.17 G). This surface at 119 m records the largest drop in base level in the study area and has been interpreted previously to correlate, based on biostratigraphy and well correlations, with a regional submarine surface of mass wasting seen in seismic (Houseknecht and Schenk 2005; Decker 2007). This surface was initially described as the mid-Campanian unconformity, but because palynology results suggest that strata at Shivugak Bluffs may be late Campanian in age (Decker 2007; Flores et al. 2007) we choose to use the term Campanian unconformity until there is better age control for those strata. Erosion surface 1, 2, and 3 are each interpreted as an unconformity and are located within a 74-m thick interval in SBPC1A and B (Figs. 2.6 and 2.7). These multiple unconformities are interpreted as forming a candidate composite unconformity, based on the proximal depositional setting. The braided streams at Shivugak Bluffs are ultimately overlain by lower-delta-plain fines, including swamp deposits and paleosols.

EVIDENCE FOR RIVER DOMINANCE IN DELTAS OF THE SCHRADER BLUFF FORMATION

Strata in this study area at Shivugak Bluffs record a river-dominated deltaic succession. The deltaic nature of the system is indicated by an overall coarsening-upward succession (CUS) containing facies and paleoenvironments typical of a prograding delta including prodelta, delta front, subaqueous terminal distributary channels, lower delta plain, and upper delta plain (e.g., Reynolds 1999; Bhattacharya 2010; Olariu et al. 2010). Distributary channels are found in this succession near the top of the CUS in what is interpreted as the lower delta plain. The presence of distributary channels at the top of the overall CUS, overlying delta-front and mouth-bar deposits, reinforces the interpretation that this succession is best classified as a delta (Olariu et al. 2010).

A major piece of evidence supporting the interpretation that river processes dominantly controlled deltaic sedimentation is the abundance of hyperpycnites on the prodelta. Hyperpycnites are typically found on the fronts of river-dominated deltas because sediment-laden discharges from suspended-load rivers deposit sediment as a combination of underflows (hyperpycnites) and hypopycnal plumes along the prodelta and delta front (Bhattacharya and MacEachern 2009; Olariu et al. 2010). In river-dominated deltas these deposits are preserved because they are not extensively modified by wave or tidal action (Bhattacharya et al. 2007; Bhattacharya 2010). Early

Maastrichtian rivers of the Prince Creek Formation are interpreted to have been flashy, suspended-load rivers that may also intermittently have carried hyperconcentrated flows to the lower delta plain (Flaig et al. 2011, 2013, 2014). Suspended-load rivers, such as those with recurring hyperconcentrated flows, were probably responsible for supplying sediment to the prodelta and delta front at Shivugak Bluffs (Fig. 8).

Abundant terminal distributary channels are also most commonly preserved along river-dominated delta fronts (Olariu and Bhattacharya 2006). The fact that there are several stratigraphic intervals at Shivugak Bluffs that preserve distal subaqueous terminal distributaries, with some of those intervals containing what we interpret to be multiple channels at the same stratigraphic level, indicates that river processes mainly controlled sedimentation on the delta front and prodelta. Although subaqueous terminal distributaries have been described from delta- front deposits elsewhere (e.g., Panther Tongue of the Star Point Formation; Olariu et al. 2010), they are rarely described in association with prodelta deposits (Notom Delta of the Ferron Sandstone; Ahmed et al. 2014). Stratigraphic relationships at Shivugak Bluffs combined with channel size and paleo-discharge estimates indicate that conditions along the Cretaceous Arctic Ocean shoreline must have been ideal to produce hyperpycnal flows and permit terminal distributaries to reach prodelta environments. Rivers of the Prince Creek Formation have been shown to be of the correct size, with the appropriate discharge (Table 3) and suspended-sediment concentration, to produce hyperpycnites (Flaig et al. 2011, 2013, 2014). When elevated river discharge is independent, and overwhelms the ocean coastline, ocean flooding events and sedimentation are prevalent (Wheatcroft 2000). Increased seasonal river discharge due to flooding in the upland watershed from either prolonged periods of snow melt, monsoonal conditions, or intense rainout effects due to sustained polar warmth (Wheatcroft 2000; Suarez et al. 2013) are a few of the meteorological conditions proposed herein that would cause ocean flooding events and the production of hyperpycnites, hypopycnites, and well-sorted subaqueous terminal-distributary-channel deposits in prodelta environments (Fig. 9 and 17A).

Mouth bars in this portion of the stratigraphy at Shivugak Bluffs are chiefly composed of small- to large-scale, trough cross-stratified sandstone with minor ripple cross-lamination. They appear well sorted and contain relatively little mud, and rare *Sch*. These barforms are unlike hummocky cross-stratified and symmetrical-ripple cross-laminated sandbodies more typical of wave- or storm-dominated delta fronts (Hampson and Howell 2005, Bhattacharya 2010) and unlike mud-rich tidal bars found on the fronts of tide-dominated deltas (Willis and Gabel 2001; Legler et al. 2014; Dalrymple et al. 2012) that typically contain abundant mud drapes, mud rip-up clasts, and evidence of tidal influence (e.g., double mud drapes, herringbone cross-stratification). The fine-grained sandstones in these mouth bars are notably similar in composition and sorting to the very fine-grained sandstones interpreted as terminal distributary channels.

Flaser and lenticular bedding, found in interdistributary-bay deposits and rare IHS in distributary channels, does indicate some tidal influence on parts of the delta at Shivugak Bluffs (Figs. 6, 7). This type of bedding is typical of tidally influenced embayments and tidally influenced river systems (Elliott 1974; Thomas et al. 1987; Phillips 2003; Bhattacharya 2010; Flaig et al. 2011). Wave influence on sedimentation is suggested by rare hummocky cross-stratification found at the top of a terminal distributary channel associated with distal-delta-front deposits, and a rare occurrence in proximal-delta-front sandstone. Hummocky cross-stratification is extremely rare in this portion of the stratigraphy, however. Although sedimentary structures indicative of tide and wave influence are found in this interval at Shivugak Bluffs, they constitute a minute percentage of the overall stratigraphy and, in consequence, had little effect on delta formation and sedimentation patterns. This muddy, fluvially dominated delta, therefore, may have formed between other deltas along this progradational shoreline (Hovikoski et al. 2008) and/or in an embayed portion of the coastline, protected from waves, similar to the present-day Yukon River Delta or Lena Delta.

IMPORTANCE OF ICHNOLOGY FOR DIFFERENTIATING ARCTIC PALEOENVIRONMENTS

The identification of trace fossils and trace-fossil assemblages in facies and facies associations (i.e., ichnofacies) of the Schrader Bluff and Prince Creek formations is essential to differentiate between continental, brackish water-transitional, and fully marine environments at Shivugak Bluffs (cf. Savrda 1995; Bromley and Ekdale 1986; Taylor and Goldring 1993; Goldring 1995; Wetzel and Uchman 1998; Hasiotis 2002, 2007; Hasiotis and Platt 2012; Hasiotis et al. 2012, 2013). Without recognizing ichnological diversity and the unique ichnological suites present in different stratigraphic intervals, differentiation between most paleoenvironments in the study area would be difficult, if not impossible, because many of these environments contain similar grain sizes, sedimentary structures, and sandbody and shale geometries. Even where differences in sedimentologic characteristics were evident, trace-fossil identification was still useful in differentiating between paleoenvironments. For example, prodelta deposits and lacustrine deposits are composed of nearly identical lithofacies. Only the prodelta deposits contained a monospecific trace-fossil assemblage of *Ph,* which distinguishes them from floodbasin deposits. The occurrence of *Ph* also helped to identify the marine flooding surface at 69 m in SBPC1A (Fig. 6). Distal- and proximal-delta-front deposits are identified not only by a change in sand content but also by an increase in trace-fossil diversity found in proximal-delta-front deposits. Although terminal-distributary-channel deposits may rarely contain wave-reworked upper surfaces, and are commonly encased in prodelta and delta-front deposits in the Schrader Bluff Formation, the presence of a physicochemically stressed trace-fossil assemblage also differentiates them from lower-delta-plain channels. Distributary- mouth bars at Shivugak Bluffs might be mistaken for braided-stream deposits, if not for their well-sorted nature, distinctive position in the stratigraphic succession, and the rare occurrence of *Sch* (see Fig. 7). Interdistributary bays contain a high-diversity assemblage including *He, Ph, Sch, Pa, Sk, Pl, Op, Th, As,* and *Td* (see Figs. 6, 7). This assemblage helped to distinguish interdistributary-bay mudstones from strikingly similar muds found in floodbasins, which contain no trace fossils. Rhizoliths and dinosaur footprints also helped identify continental deposits and helped discriminate between marine deposits with similar sedimentological characteristics. The lack of any trace fossils in all lower-delta-plain channels of the Prince Creek Formation helped to identify them as active freshwater distributary channels in a continental setting.

At Shivugak Bluffs, interdistributary bays contain a high-diversity of fully marine trace-fossil assemblages *(He, Ph, Sch, As, Sc, Rz, Te, Pa, Op,* escape traces*)* when compared to terminal distributary channels, and prodelta deposits, which have a reduced biodiversity *(He-Ph and Sch).* This reflects the high physicochemical stress related to frequent hypopycnal and hyperpycnal flows (Bhattacharya and MacEachern 2009; Hurd et al. 2014).

Overall, trace-fossil and lithofacies associations in the marine deposits at Shivugak Bluffs are assigned to the Cruziana Ichnofacies. The more proximal deposits contain minor components of the Skolithos Ichnofacies (*Op, Sch*), whereas the muddier, more distal components have a reduced ichnodiversity *(He, Ph, Sch;* MacEachern et al. 2005). In contrast, continental deposits contain dinosaur footprints, rhizoliths, and simple burrows (e.g., *Pl, Pa*) and are assigned to the Scoyenia Ichnofacies (Hasiotis 2002, 2004, 2008).

INTERPLAY OF AUTOGENIC AND ALLOGENIC PROCESSES AT SHIVUGAK BLUFFS

Strata at Shivugak Bluffs are interpreted to record the effect of both autogenic and allogenic processes on this Cretaceous polar delta. Autogenic processes that are known to affect sedimentation on deltas include, but are not limited to, river avulsion (Smith et al.

1989; Kraus 1996; Mohrig et al. 2000; Stouthamer et al. 2011), delta-lobe abandonment (Bhattacharya 2010), and compaction and dewatering of sediments (Meckel et al. 2007; Tornqvist et al. 2008). Strata at Shivugak Bluffs preserve multiple progradational deltaic successions that are at least, in part, affected by all of these autogenic processes.

Periodic river avulsion on deltas at Shivugak Bluffs are recorded by prodelta and distal- delta-front deposits that contain predominantly muddy intervals that alternate with proximal- delta-front deposits that contain sandstone interbedded with siltstone (see 59–73.5 m and 73.5–90 m in SB5; Fig. 4). When river systems occupied portions of the delta near Shivugak Bluffs, thick sandy hyperpycnite beds (> 1 m thick) were deposited along the delta front (Bhattacharya and MacEachern, 2009; Figs. 4, 5). Abundant subaqueous terminal distributary channels isolated in prodelta, distal-delta-front, and interdistributary-bay deposits suggest that there were additional distributaries up-dip adjacent and subordinate to the main feeder system on the lower delta plain (see 9–18.5 m in SB5 and 0–13 m in SBPC1; Figs. 5, 6).

Delta-lobe abandonment and progradation at Shivugak Bluffs is documented in the facies transition between 0 and 29 m in SBPC1A (Fig. 6). In this interval, interdistributary-bay deposits shoal up-section into paleosols, crevasse splays, and levees in a floodbasin (Figs. 6, 17B, C). This is followed by small sinuous and low-sinuosity channels and a 20-m-thick, lacustrine-rich floodbasin deposit. Abrupt facies transitions commonly occur between interdistributary and distributary areas (Bhattacharya and Walker, 1991). The transition from marine deposits (e.g., interdistributary bays) to 20.0-

m-thick lacustrine-rich floodbasin deposits on deltas has historically been attributed to both delta-lobe abandonment and growth faulting (Plint et al. 2001; Lumsdon-West and Plint 2005; Kim and Paola 2007; Kim et al. 2010). For example, deltaic-to-lake successions have been identified in the Dunvegan Formation, which were deposited during normal, autocyclic delta progradation (Plint et al. 2001; Lumsdon-West and Plint 2005). Thick lake to floodbasin deposits can also result from growth faulting on a delta (Kim and Paola, 2007; Kim et al. 2010). Growth faulting was, however, unlikely at Shivugak Bluffs. A seismic cross section of east-dipping Late Cretaceous clinoforms in the Colville Basin reveals listric growth faults penetrating the lower Schrader Bluff Formation northeast of Shivugak Bluffs (Houseknecht and Schenk 2005). This fault zone is outboard of the underlying Nanushuk shelf edge, ~ 45 km due east of Shivugak Bluffs (Houseknecht and Schenk 2005; Decker 2010), and would likely only affect accommodation and associated sedimentation in the lower Schrader Bluff and Prince Creek formations basinward of the study area. This suggests that delta-lobe abandonment and aggradation are the most likely processes for the transition from interdistributary-bay deposits to floodbasin deposits at Shivugak Bluffs.

Sediment compaction on deltas typically helps to create accommodation necessary to preserve thick sediment packages (Meckel et al. 2007; Törnqvist et al. 2008). The thick and relatively mud-rich deltaic succession at Shivugak Bluffs was also affected by sediment dewatering and compaction due to sediment loading. This process may also be responsible for some facies changes within the succession. One of the most notable flooding surfaces at 69 m in SBPC1A, however, places proximal shelf deposits and a new deltaic sequence over floodbasin deposits (Fig. 6). This juxtaposition of proximal shelf deposits over floodbasin deposits is typical for sedimentation at the end of an abandoned delta lobe cycle (Figs. 6, 7). Abandoned delta lobes often subside through time and are transgressed, generating local flooding surfaces (Emery and Myers, 1996). When the river switches back into the area, a new delta lobe is formed through progradation of a deltaic shoreline (Emery and Myers 1996). This switch back and reactivation of a new river-dominated delta lobe between 69 and 99 m is the last evidence of the marine lower Schrader Bluff Formation along the Colville River at Shivugak Bluffs (Figs. 2C, 6, and 7).

Allogenic processes such as eustasy and tectonism are also known to affect deltaic successions in foreland basins (Kamola and Huntoon 1995; Hampson 2010). These processes can create erosional and flooding surfaces and drive facies changes identifiable in the rock record. Eustatic sea-level rise can flood all or parts of a delta, whereas sea-level fall can drive incision and bypass on deltas (Schumm 1993; Emery and Myers, 1996). There are few radiometric dates from volcanic ash layers that are time equivalent to the middle and upper Schrader Bluff Formation to help constrain the age of the lower Schrader Bluff Formation and correlate to eustatic sea-level curves (Flaig 2010; personal communication M. Wartes, Alaska Division of Geology & Geophysical Surveys 2014). There does not, however, appear to be a record of drastic sea-level fluctuations during the time that the lower Schrader Bluff Formation was thought to have been deposited

(Snedden and Liu 2011). Orogenic loading can create crustal flexure and accommodation, whereas unroofing typically reduces accommodation and allows coarser-grained clastics to prograde across a basin (e.g., Flemings and Jordan 1990; Catuneanu 2004). Three key erosion surfaces (erosion surface 1, 2 and 3; Figs. 6, 7) were identified at Shivugak Bluffs. In SBPC1A at 45 m, an erosional base and anomalous pebble lag indicate a moderate drop in base level which is interpreted as the first incidence of sediment bypass in the study interval. In SBPC1B the surface at 104.5 m records a major incision, whereas the surface at 119 m in SBPC1B records a major progradation of coarse-grained fluvial systems over lower- delta-plain deposits. These observations suggest that all three erosional surfaces are subaerial unconformities in the Prince Creek Formation and are interpreted to reflect a change in base level that involves either sediment bypass or incision, probably driven by allogenic processes. Collectively, these features are interpreted as a composite unconformity. This composite unconformity correlates with a major, regional submarine surface of mass wasting, seen in seismic sections, that erodes down into the coeval clinoform that would have been present in the subsurface east of Shivugak Bluffs (Houseknecht and Schenk 2005; Decker 2007, 2010). Previous work correlated this Campanian unconformity at Shivugak Bluffs into the subsurface through a compiled regional cross section that includes seismic, well-log data, and biostratigraphy of cored intervals (Flores et al. 2007; Decker 2007, 2010). This surface is most likely the result of a major tectonic event that cannot be expanded upon with our dataset. The largest sedimentary clasts (pebbles and cobbles) in the 196 m described in this investigation occur at 45 m in SBPC1A and in the braided system at 119 m in SBPC1B, suggesting that this tectonic event could have been related to an unroofing event, either in the Chukchi Platform or the Brooks Range orogenic belt (Houseknecht et al. 2009).

Implications for Reservoir Modelers

Exploiting reservoirs formed by deltas requires predictive models (Bhattacharya 2010). Although paleoenvironments and architectures of lower-delta-plain strata of the Maastrichtian Prince Creek Formation are well documented in outcrops along the Colville River to the north of Shivugak Bluffs and studies have produced paleoenvironmental reconstructions for the continental portion of the stratigraphy (Flaig et al. 2011, 2012, 2014), this study expands on that interpretation by examining slightly older strata containing paleoenvironments down depositional dip on the distal lower delta plain and delta front to prodelta (Fig. 17). Shivugak Bluffs is an ideal outcrop analog for heavy- to viscous-oil reservoirs found nearby on the North Slope such as the Orion and Polaris Oil Pools, Milne Point, and Nikaitchuq (Croft et al. 1999; Alaska Oil and Gas Conservation Commission 2010) because they contain complex vertical and lateral facies relationships and sandbody geometries in a marine-to-continental transitional system, similar to those documented in younger shallow reservoirs nearby (Houseknecht and Bird 2005). The depositional model presented here can also serve as a predictive model for other, low-net-to-gross reservoirs in the world that formed on muddy deltaic shorelines.

Sandbody and shale attributes of the river-dominated-delta succession at Shivugak Bluffs should be important to the petroleum industry. Subaqueous terminal distributary channels are found to be associated with both muddy prodelta (FA-II) and distal-delta-front (FA-III) deposits. Even though subaqueous terminal distributary channels should be commonly documented in the rock record, this is one of the few reports where terminal distributaries are incised into and encased in prodelta deposits in outcrop. This finding is significant because recognition of these channels in outcrop, core, or wireline well logs could help researchers identify the paleogeographic position within the muddier portions of a fluvial−deltaic system. The presence of abundant terminal distributary channels also indicates that the feeder systems of a river-dominated delta, a higher-net-to-gross interval, may be found stratigraphically up depositional dip (Olariu and Bhattacharya 2006). Other successions containing prodelta and distal-delta-front deposits of river-dominated deltas should be reinvestigated for terminal distributaries encased in prodelta and delta-front deposits, because these terminal distributaries contain relatively clean sandstones encased in mudstone. These sandbodies are channel-form, elongate along dip, and laterally restricted along strike. Although the terminal distributaries are only a few meters wide and less than 1 m thick, they are filled with predominantly well-sorted, quartz-rich sandstone and contain almost no mud. This fact suggests that both the terminal distributary channels and the sandier portions of river-dominated deltas, especially those in the more up-dip locations, could act as potential reservoirs.

The distributary-mouth bars at Shivugak Bluffs comprise 5.0 m of mud-poor, well-sorted, predominantly large-scale trough-cross-stratified sandstone. The sandbodies are multistory and laterally extensive, continuously exposed for ~ 4 km along the outcrop belt. The cleanliness of the sands, consistent thickness of the sandbody, and uniform composition over this relatively large lateral extent suggests that these could be excellent reservoirs.

Erosional surfaces 1–3 at Shivugak Bluffs are indicated by either a pebble lag or incision (Figs. 6, 7). We interpret these erosional surfaces as zones of sediment bypass, where large accumulations of coarser-grained material would have been deposited down paleogeographic dip from Shivugak Bluffs. In this case, however, portions of the coeval clinoform down depositional dip has been removed during formation of the Campanian unconformity (Houseknecht and Schenk 2005; Decker 2010). With respect to the surface at 119 m, a braid plain on what is interpreted as upper delta plain overlies lower-delta-plain deposits, indicating a major drop in base level and the most significant bypass zone in the composite unconformity. This is the first documented evidence of braided channels in the Prince Creek Formation (Flaig et al. 2011). Although the braided channels contain poorly sorted sand and pebbles, they would also form a good reservoir.

A HIGH-LATITUDE SIGNATURE?

A diagnostic high-latitude signal may be difficult to identify in this deltaic succession, even though strata at Shivugak Bluffs were deposited at paleopolar latitudes of 80–85º N (Spicer and Parrish 1990a, 1990b; Spicer and Herman 2010; Flaig et al. 2011). Flaig et al. (2011, 2013, 2014) also found that identifying a high-latitude signal was difficult in the early Maastrichtian Prince Creek Formation. These investigations (Flaig et al. 2011, 2013, 2014), however, put forth several lines of evidence to suggest that a flashy system on the lower delta plain may record seasonally fluctuating flow related to a paleopolar light and temperature regime. Evidence for this includes roots in most channels coupled with IHS, suggesting highly variable flow (Flaig et al. 2011); paleosol micro- and macromorphology suggesting repeated wetting and drying of soils (Flaig et al. 2013); and recurring hyperconcentrated flows potentially related to seasonal snowmelt in the nearby Brooks Range (Flaig et al. 2014). This study identifies abundant hyperpycnites in prodelta, distal-delta-front, and proximal-delta-front environments, as well as distal subaqueous terminal distributary channels. These deposits suggest frequent ocean flooding events and a flashy river system.

Compared to low-latitude successions in the Western Interior Seaway, the lower Schrader Bluff Formation contains distinct faunal and trace-fossil assemblages. Inoceramids are more common and historically have been used for biostratigraphy in this Late Cretaceous interval in the Arctic, whereas ammonites are more commonly used in the Western Interior Seaway for biostratigraphic control (Jones and Gyrc 1960; Detterman et al. 1963; Kauffman 1977). No ammonites were documented in this study. Inoceramid shell debris, however, is common in the lower Schrader Bluff Formation. The trace fossil *Ophiomorpha* is also extremely rare compared to low-latitude depositional systems in the Western Interior Seaway (e.g., Hoyt and Weimer 1965; Frey and Howard 1982, 1985; MacEachern and Pemberton 1992; Anderson and Droser 1998).

Lonestones, interpreted as ice-deposited pebbles emplaced seasonally in marine sediments in high-latitude environments, have been documented in successions time-equivalent to the Schrader Bluff Formation (Parrish and Spicer 1988a; Ahlberg, et al. 2002; Spicer 2003). Only a few outsized pebbles, however, were found floating in siltstone and sandstone layers in interdistributary-bay deposits at Shivugak Bluffs (2 m and 8.75 m in SBPC1A; Fig. 6). Multiple pebbles scattered throughout muddy marine shelf intervals have classically been identified as ice-rafted debris (van der Kolk 2010). Most pebbly intervals at Shivugak Bluffs are interpreted as lag deposits associated with the Campanian composite unconformity and are not interpreted as ice-rafted debris.

CONCLUSIONS

Strata in the uppermost 196 m at Shivugak Bluffs on the North Slope of Alaska record deposition in a muddy, river-dominated deltaic environment. Paleoenvironments include proximal shelf, prodelta, distal and proximal delta front, as well as interdistributary bays, terminal distributary channels, mouth bars, floodbasins, low-sinuosity, high-sinuosity, and downstream-accreting channels. Floodbasin environments include lakes, swamps, crevasse splays, and overbank, most of which contain varying degrees of pedogenic modification (i.e., paleosols). Facies, facies relationships, sandbody geometries, stacking pattern, and key surfaces, which include erosion surfaces and a flooding surface, helped to establish the sequence of events that allow for development of an evolutionary paleoenvironmental model that includes delta progradation, delta-lobe abandonment, and reactivation. The preservation of hyperpycnites and terminal distributary channels, as well as mouth-bar properties and the presence of distributary channels at the top of an overall coarsening-upward succession, indicate that this is a delta best interpreted as river-dominated. Prince Creek Formation distributaries are shown to be the appropriate size with the appropriate discharge to regularly produce hyperpycnites. Terminal distributary channels are documented in prodelta deposits, which are rarely described in the literature. Identification of trace fossils and ichnological assemblages were critical to differentiating paleoenvironments on the prodelta, delta front, and lower delta plain. Autogenic processes controlling sedimentation on the delta included avulsion, delta-lobe abandonment and reactivation, and sediment loading. Allogenic processes may have included relative sea-level rise and fall and orogenic loading and unroofing in the nearby Brooks Range orogenic belt.

Modelers of shallow, viscous to heavy-oil reservoirs on the North Slope should consider Shivugak Bluffs as the best analogue for muddier transitions between the Schrader Bluff–Prince Creek formations. Although terminal distributary channels may be difficult to identify, once they are recognized they become a valuable tool to infer the probable position of strata along a dip slope and the paleogeographic location in the fluvial–deltaic system. For modelers, the presence of abundant terminal distributary channels also infers that a river-dominated delta and a higher-net-to-gross interval will be found up stratigraphic dip. Mouth bars in this river-dominated succession also appear to be an excellent reservoir. Also, braided-river deposits identified for the first time in the Prince Creek Formation would serve as excellent hydrocarbon reservoirs in the subsurface.

A convincing high-latitude signal is difficult to identify in strata at Shivugak Bluffs. Regardless, abundant hyperpycnites and terminal distributary channels, along with the lack of ammonites and the rare occurrence of the trace fossil *Ophiomorpha*, may record a unique faunal assemblage and a flashy fluvial feeder system. This may represent a cryptic high-latitude signal in this Cretaceous paleopolar deltaic succession.

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CHAPTER 3 – EVOLUTION OF A HIGH-LATITUDE, RIVER-DOMINATED DELTA: THE UPPER CRETACEOUS SCHRADER BLUFF FORMATION, SHIVUGAK BLUFFS, ARCTIC ALASKA[2]

ABSTRACT

Upper Cretaceous (Santonian–Campanian) strata at Shivugak Bluffs along the Colville River of northern Alaska preserve a 542 m-thick continuous record of a paleopolar deltaic system within an overall fining-upward Arctic clinoform-topset. Facies, ichnology, stratal geometries, and stacking patterns suggest that the entire deltaic system is best classified as river-flood dominated, with minor wave or storm reworking. This interpretation is based on: 1) recurring < 15-m-thick amalgamated packages of distributary mouth bar (DMB) and subaqueous terminal distributary channel (TDC) complexes along the proximal delta front; 2) abundant hyperpycnites along the medial and distal delta front; 3) well-sorted TDCs encased in delta-front and prodelta deposits; and 4) 15–19% hummocky and swaley cross-stratified DMB and TDC complexes. Paleocurrents from DMBs and TDCs indicate deposition of north-facing delta lobes. This study details key elements in an ancient proximal delta front including: variable medial and distal DMB facies and architecture; rare deltaic storm sheets; and muddy interdistributary bays. We recommend new terminology for subaqueous TDC networks that include high width-to-depth, low width-to-depth, and prodelta TDCs. Seasonal alpine snowmelt and/or storms are proposed as the mechanism(s) behind recurring floods that

[2]A version of this chapter will be submitted to the Journal of Sedimentary Research.

built the delta. Cyclical trends in sand- to mud-prone, river-dominated deltaic deposits at Shivugak Bluffs reveals two progradational–aggradational (PA), two aggradational–progradational–degradational (APD), and two retrogradational (R) accommodation succession sets. The oldest APD and R succession sets comprises sand-rich, river-dominated deltas, whereas the younger APD succession set comprises mud-rich, river-dominated deltas. Autogenic processes (e.g. avulsion, lobe switching) likely drove grain-size fluctuations and stacking patterns.

INTRODUCTION

Outcrops on the North Slope of Alaska include the highest latitude (paleolatitude ~ 80–83° N; Ziegler et al. 1983; Parrish and Spicer 1988) Upper Cretaceous stratigraphic successions accessible today (Herman and Spicer 2010). These paleopolar strata preserve a record of sedimentation under a greenhouse climate during which flashy depositional environments with distinct flora and fauna developed (Spicer and Parrish 1990a, 1990b; Fiorillo et al. 2009; Spicer and Herman 2010; Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015). This study provides a paleoenvironmental reconstruction and sequence stratigraphic framework for polar deltaic, shallow marine, and coastal-plain deposits of the Upper Cretaceous (Santonian–Campanian) lower Schrader Bluff and Prince Creek formations (fms) (*sensu* Decker 2007, 2010) found along the Colville River at Shivugak Bluffs on the North Slope of Alaska (Figs. 3.1, 3.2). This manuscript is the second in a series (see van der Kolk et al. 2015) to document strata at Shivugak Bluffs, an ~ 11-km-

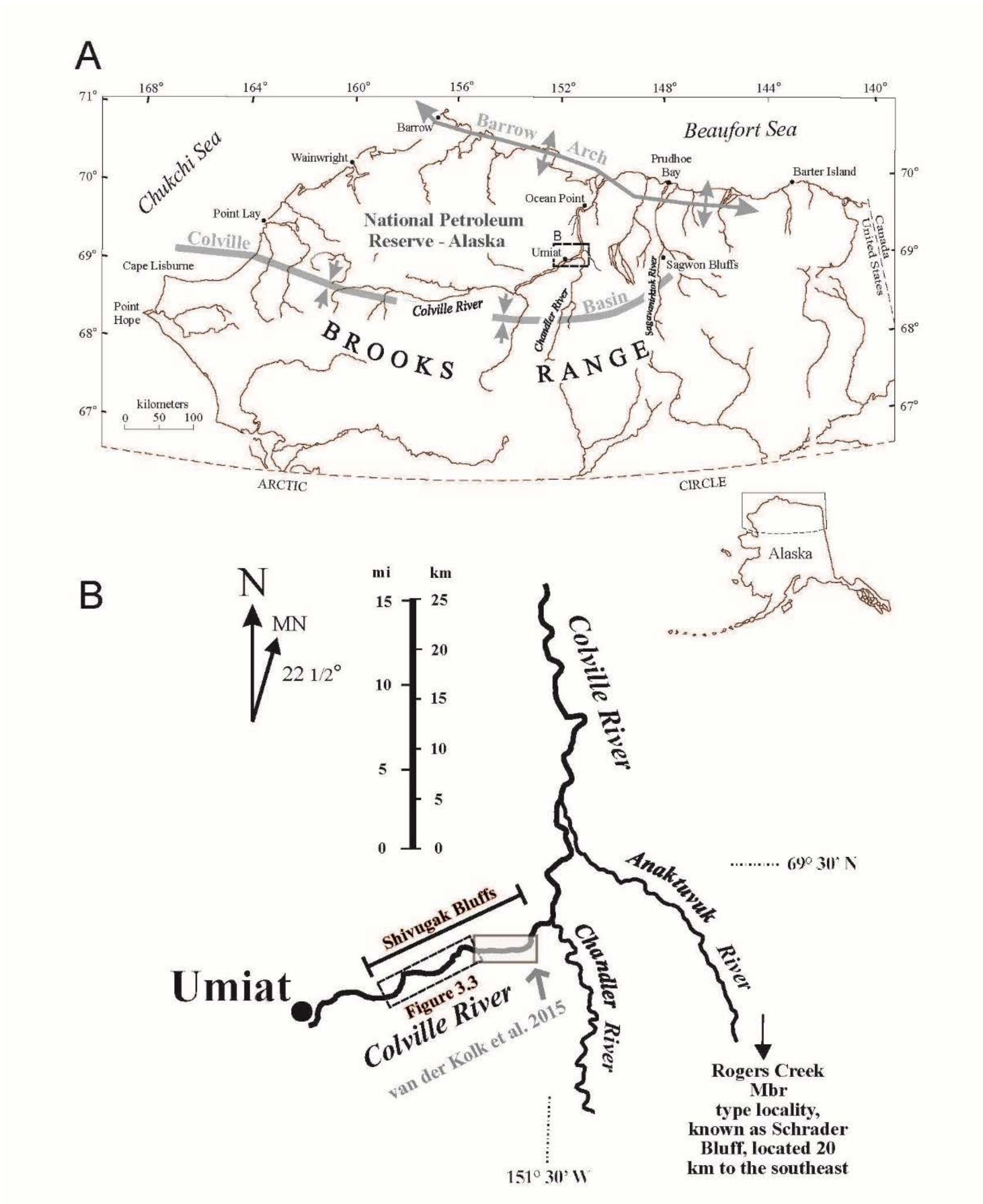


Figure 3.1. Maps of Arctic Alaska. A) The Brooks Range, Colville Basin, National Petroleum Reserve–Alaska, Colville River, Umiat, Prudhoe Bay, Ocean Point, and the location of inset map B. B) Inset map of study area along the Colville River at Shivugak Bluffs (box of location in Fig. 3.3) relative to a previous study at Shivugak Bluffs (van der Kolk et al. 2015). MN = magnetic north.

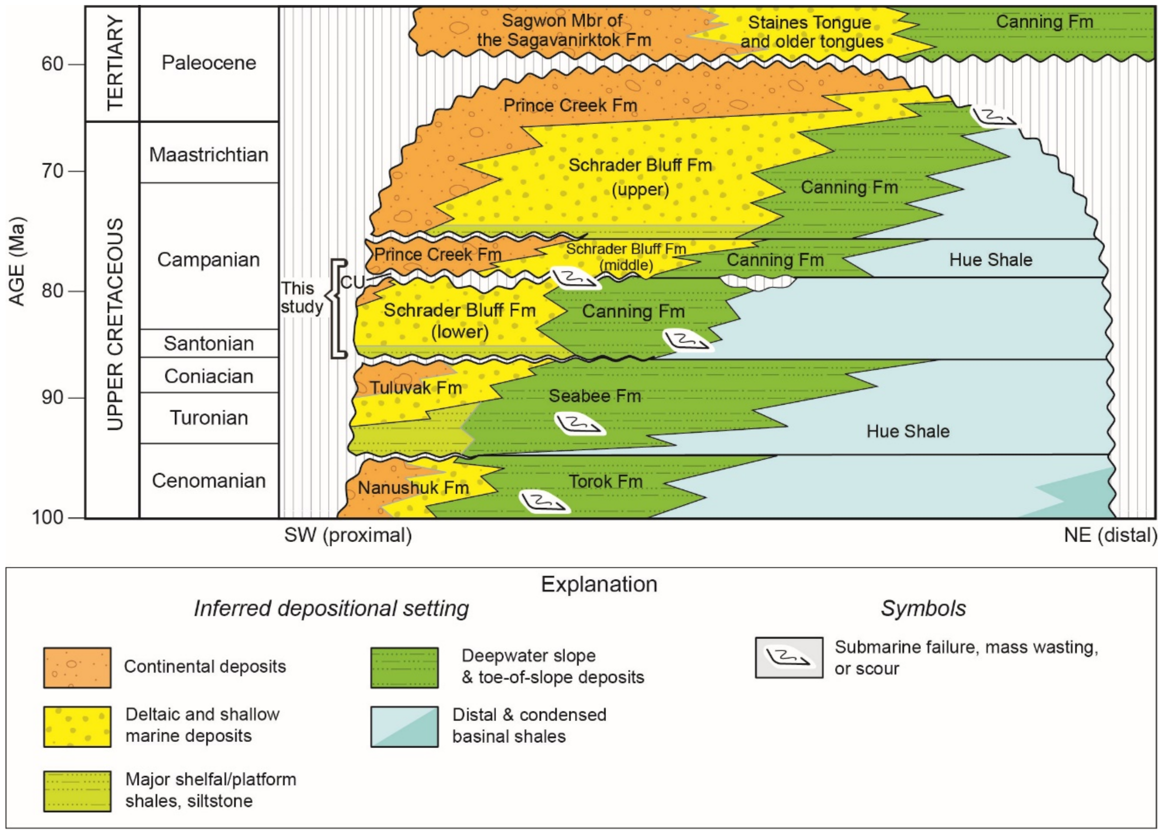


Figure 3.2. Lithostratigraphic diagram showing a southwest–northeast transect of Cenomanian–Paleocene deposits in the Colville Basin (modified from Decker 2010). Bracket indicates location of the detailed stratigraphy for Shivugak Bluffs in Figure 3.3. Abbreviations: Campanian Unconformity (CU), formation (Fm), and member (Mbr).

long outcrop belt comprising over 500 m of vertically continuous strata with ~ 2–4 km of lateral exposure (Figs. 3.1, 3.3). Extensive work has been conducted along several Arctic river-cut cliffs to the north of this study area on younger Cretaceous (Maastrichtian) strata that contain distributary channels and associated floodplain deposits of the continental Prince Creek Fm (Flaig et al. 2011, 2013, 2014). A recent study at Shivugak Bluffs, documented 196 m of younger strata containing the deltaic transition between the

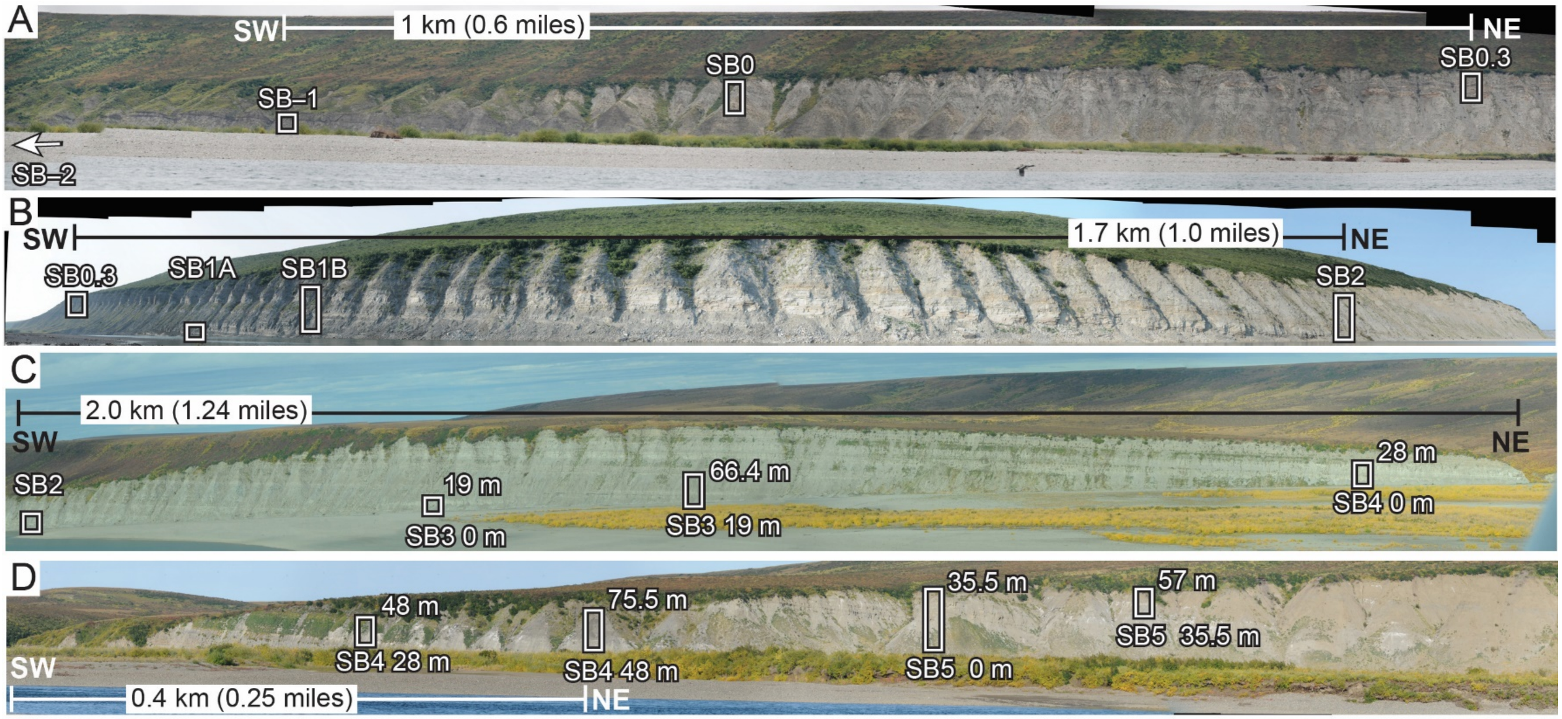


Figure 3.3. Photomosaics of the easternmost 7 km of outcrop at Shivugak Bluffs along the Colville River, including deposits of the Schrader Bluff and Prince Creek formations. Photographs were recorded from state land facing northwest toward the National Petroleum Reserve (see Fig. 3.1). Diagram includes A) Photomosaic of measured section SB-2, SB-1, and SB0; B) Photopanorama of measured sections SB0.3, SB1A, SB1B, and SB2; C) Aerial photomosaic of measured sections SB2, SB3, and SB4 (0 to 28 m); and E) Photomosaic of measured sections SB4 (28 to 75.5 m), and SB5A. See Figure 3.1B for location of photomosaics at Shivugak Bluffs. Approximate locations of all measured sections indicated by white boxes. Stratigraphic thicknesses listed in meters (m).

lower Schrader Bluff Fm and the basal Prince Creek Fm (Fig. 3.1; van der Kolk et al. 2015).Until now a ~ 336-m-thick succession of the lower Schrader Bluff Fm stratigraphically below this shallow marine–continental transition (Fig. 3.3) had remained unstudied (Whittington 1956; Brosge and and Whittington 1966). This succession is described and interpreted here for the first time, and is necessary to understand such an important transition in a paleopolar, greenhouse climate.

This study examines a three-dimensional (3D)-outcrop dataset to determine how paleoenvironments evolved at Shivugak Bluffs. Since the upper 196 m of strata at Shivugak Bluffs were interpreted to record muddy, river-dominated deltaic deposits (van der Kolk et al. 2015), the lower two-thirds of strata at Shivugak Bluffs are examined to test the hypothesis that these strata are also deltaic in nature. This investigation describes relatively thick successions of what we interpret as distributary mouth bar (DMB), terminal distributary channel (TDC), and medial delta front (MDF) complexes, and discusses whether the system is best classified as a river-dominated deltaic system or other paralic setting. In addition, we explore the role that recurring river floods may have had in the construction of this high-latitude deltaic system, and discuss potential driving forces behind those flood events. The distributary feeder network in the Prince Creek Fm has previously been classified as a suspended load, seasonally(?) flashy system that produced recurring hyperpycnal flows (Flaig et al 2011; van der Kolk et al 2015), and seasonal alpine snowmelt has been proposed as one potential driver for this fluctuating discharge (Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015). River-flood events are seasonal increases in mean river discharge that can be driven by prolonged monsoonal conditions, seasonal snowmelt, or short-lived (e.g., days to weeks) extreme rainfall events possibly from sustained polar warmth (e.g., Wheatcroft 2000; Davis and FitzGerald 2004; Fielding et al. 2005a, 2005b; Suarez et al. 2013, 2016). Van der Kolk et al. (2015) identified hyperpycnites (Mulder et al. 2001, 2003) and subaqueous TDCs in the upper 196 m at Shivugak Bluffs, and river-flood events were proposed as the depositional mechanism for those deposits.

The purpose of this paper is to: 1) describe the sedimentary structures and facies, ichnology, architectural elements, and stacking pattern of sediments exposed in the lower 336 m at Shivugak Bluffs (Figs. 3.1–3.3) that were deposited along the Late Cretaceous paleo-Arctic Ocean shoreline; 2) interpret the paleoenvironments and discuss the depositional mechanisms; 3) develop a composite section and sequence stratigraphic framework for the lower Schrader Bluff and Prince Creek fms by combining data and analyses from the 336-m thick succession described herein with strata in the uppermost 196-m at Shivugak Bluffs that contain a younger, muddy, river-dominated deltaic system (van der Kolk et al. 2015); and 4) discuss the major components of this clinoform-topset-dominated deltaic system for researchers working in fine-grained, river-dominated deltaic systems and for modelers of shallow, viscous- to heavy-oil reservoirs on the central North Slope of Alaska.

Developing a composite stratigraphic section for Shivugak Bluffs is critical to improve our understanding of the evolution of the Upper Cretaceous clinoform topsets (*sensu* Johannessen and Steel 2005) that filled the Colville Basin predominantly from west to east (Figs. 3.1, 3.2), recording deposition on the paleopolar coastal plain, delta plain, delta front, and offshore shelf (Fig. 3.2). Few studies of siliciclastic depositional systems are able to examine the complete evolution of clinoform-topset successions, including the key transitional zone between the delta front and lower delta plain, due to limitations in the rock record (Hovikoski et al. 2008; Gugliotta et al. 2015). For example, topset facies near the air-water interface are prone to reworking by waves and tides and, if preserved, may become top-truncated by transgressions (Bhattacharya 2010; Gugliotta et al. 2015). As a result, pedogenically modified deltaic tops (Plint et al. 2001; Lumsdon-West and Plint 2005; van der Kolk et al. 2015) and foreshore deposits are relatively rare in the rock record (Schwartz 2005). Shivugak Bluffs contain pedogenically modified deltaic strata, and are arguably the best locality to study large-scale cyclical trends in an evolving deltaic-clinoform-topset system that developed along the paleo-Arctic Ocean coastline (van der Kolk et al. 2015).

GEOLOGIC BACKGROUND

The Colville Basin, a west–east-elongate foreland basin in Arctic Alaska (Fig. 3.1), formed during the Jurassic to Early Cretaceous from loading of the lithosphere by thrust sheets associated with the ancestral Chukotka and Brooks Range orogenic belts (Fig. 3.1A; Bird and Molenaar 1992; Moore et al. 1994, 2002; Cole et al. 1997; Bird 2001; Houseknecht et al. 2009; Houseknecht and Bird 2011). The Barrow Arch is an active structural high developed during the Early Jurassic as a result of uplift and rifting that created the Canada Basin (Grantz and May, 1983; Bird and Molenaar 1992; Homza et al. 2011). The Barrow Arch forms the northern limit of the Colville Basin (Bird 2001), whereas the Brooks Range orogenic belt forms the southern boundary (Fig. 3.1A). From the Cretaceous through early Paleocene, the Colville Basin was connected to the paleo-Arctic Ocean (Embry and Dixon 1990; Moore et al. 1994; Mull et al. 2003; Decker 2010; Houseknecht and Bird 2011), which comprised many subbasins and seas including the Chukchi and Beaufort Seas (Grantz et al. 1994). During the Early Cretaceous, sediments sourced from paleotopographic highs of the Chukotka borderland magmatic belt, the ancestral Wrangel–Herald thrust belt, and the Brooks Range orogenic belt began to fill the Colville Basin generally from west to east, primarily along the basin axis, developing 2-km-thick clinoforms comprising the Nanushuk-Torok fms (Fig. 3.2; McMillen 1991; Houseknecht et al. 2009; Houseknecht and Bird 2011). Recent detrital zircon analyses indicate that the Brooks Range to the south of the elongate basin (Fig. 3.1A) became a more significant source of sediment during the Late Cretaceous (Lease 2015; personal communication D. Houseknecht, United Stated Geological Survey 2015). By the Late Cretaceous (Cenomanian) sedimentation rates decreased; however, sediment dispersal patterns remained similar during deposition of the next sequence of clinoforms that included the Tuluvak-Seabee and Prince Creek-Schrader Bluff fms (Fig. 3.2; Bird and Molenaar 1992; Bird 2001; Houseknecht and Schenk 2005; Decker 2010; Houseknecht and Bird 2011; Lease 2015).

By the Campanian, rivers of the Prince Creek Fm flowed east-northeast along the axis of the basin toward the developing coastal plains (Prince Creek Fm) and deltaic shorelines of the Schrader Bluff Fm (Flaig et al. 2011; van der Kolk et al. 2015). Strata to the west of the study area in the National Petroleum Reserve–Alaska (Fig. 3.1A) that once contained the Schrader Bluff and Prince Creek fms have mostly been uplifted and eroded. Remnants of contemporaneous strata located even further to the west in the Chukchi Sea (Fig. 3.1A) suggest that Prince Creek Fm rivers had the potential to drain an estimated area of ~ 330,000 km^2 (Smiley 1966; Sherwood et al. 1998; Houseknecht et al. 2015).

Shivugak Bluffs provides an outcrop analogue for North Slope hydrocarbon reservoirs, as younger intervals of the Schrader Bluff and Prince Creek fms form regionally extensive viscous- to heavy-oil accumulations known as the West Sak (Schrader Bluff Fm equivalent) and Ugnu (Prince Creek Fm equivalent) reservoirs on the North Slope (Werner 1987; Hallam et al. 1992). Recent estimates of oil in place (OIP) in the West Sak and Ugnu sands of the Prudhoe Bay, Kuparuk River, and Milne Point reservoirs range from 23–36 billion barrels (Hartz et al. 2004; Attanasi and Freeman 2015). These estimates are larger than the original OIP in the Sadlerochit Group (Permian to lower Triassic) reservoirs of Prudhoe Bay, suggesting that the Schrader Bluff–Prince Creek fms as a whole are one of the largest oil reservoirs in the U.S.A. (Klein et al. 1974; Houseknecht and Bird 2006; Houseknecht et al. 2016).

PREVIOUS WORK

The Santonian–Paleocene Schrader Bluff Fm comprises several widespread, mappable units on the central North Slope of Alaska, and is informally divided into the lower, middle, and upper Schrader Bluff Fm (Fig. 3.2; Decker 2007, 2010; Gillis et al. 2014; Herriott et al. 2015; van der Kolk et al. 2015). The lower Schrader Bluff Fm is interpreted to be Santonian to late Campanian in age (Fig. 3.2) based on the occurrence of *Inoceramus (Sphenoceramus) patootensis* and microfaunal assemblages (Jones and Gryc 1960; Detterman et al. 1963; Flores et al. 2007a, 2007b; LePain et al. 2008; Decker 2010; van der Kolk et al. 2015). The lower Schrader Bluff Fm was further subdivided into lower, middle, and upper units (Decker 2007, 2010; Gillis et al. 2014) that are equivalent to the Rogers Creek, Barrow Trail, and Sentinel Hill members (mbrs) as defined by Whittington (1956). The three mbrs were abandoned by Mull et al. (2003), but we herein propose the reinstatement of these mbrs at Shivugak Bluffs based on the results from our investigation, and this terminology is used throughout the manuscript.

Few localities on the North Slope are suitable for large-scale sedimentologic investigations due to extensive faulting, folding, and a lack of continuous exposures (Phillips 2003; LePain et al. 2008; van der Kolk et al. 2015). Fortunately, Shivugak Bluffs—the type locality for the Sentinel Hill Member (Figs. 3.1, 3.3)—contains nearly horizontal strata (~6° dip) and both vertically and laterally extensive exposures comprising all three members of the lower Schrader Bluff Fm (e.g., Whittington 1956; Brosge and Whittington 1966; van der Kolk et al. 2015). The basal flooding surface of the lower Schrader Bluff Fm and associated tuffaceous mudstone is not exposed at Shivugak Bluffs; however, this interval outcrops 30 km to the southeast at a locality known as Schrader Bluff along the Anaktuvuk River (see Fig. 3.1B; Gryc et al. 1951; Whittington 1956; Mull et al. 2003). These strata are significant because they represent additional fine-grained deposits, the basal strata of the Rogers Creek Mbr, which are not exposed in the study area and, therefore, are not documented in this study.

A recent study interpreted the mid-to-upper succession of the Sentinel Hill Mbr at Shivugak Bluffs as deposits of a muddy, river-dominated deltaic system that shoaled up into pedogenically modified coastal-plain and floodbasin deposits (van der Kolk et al. 2015). This interval is one of the few complete sequences of muddy, progradational shorelines with subaerial exposure that have been documented from the rock record (Walker and Harms 1971; Hovikoski et al. 2008; van der Kolk et al. 2015). This succession of the Sentinel Hill Mbr is interpreted as a muddy, river-dominated deltaic end member (van der Kolk et al. 2015) on the basis of abundant hyperpycnite sheet sandstones and TDCs with rare DMBs that lack wave and tide modification (cf. Coleman and Wright 1975; Galloway 1975; Bhattacharya and Walker 1992).

The Prince Creek Fm that overlies the Sentinel Hill Mbr at Shivugak Bluffs and outcrops extensively along the Colville River to the north between Shivugak Bluffs and Ocean Point (Fig. 3.1A) comprises distributary channel systems that also fed the deltaic and shallow marine systems of the Rogers Creek and Barrow Trail mbrs at Shivugak Bluffs. The Prince Creek Fm comprises three types of distributary channels and associated floodplain deposits (Flaig et al. 2011). Prince Creek Fm channels include first-order meandering trunk channels 9–17 m deep with estimated widths of 140–435 m (average sinuosity 1.6), second-order meandering distributary channels 2–7 m deep with estimated widths of 10–87 m (average sinuosity 2.19), and third-order fixed channels 1.5–3.0 m deep with estimated widths of 5–19 m (average sinuosity not applicable; Flaig et al. 2011; van der Kolk et al. 2015). Braided channels, estimated to be up to 10 m deep, are rare, and their deposits are only found at the top of Shivugak Bluffs (van der Kolk et al. 2015). Average paleodischarge estimates of 384–593 m^3/s were calculated for the largest second-order distributary channels and 3,962 m^3/s was calculated for the average first-order trunk channel. Rivers in the Prince Creek Fm were the appropriate size and had the proper discharge to recurrently produce hyperpycnites (Flaig et al. 2011; van der Kolk et al. 2015).

Shivugak Bluffs contain the only known outcrop expression of a regional unconformity, initially named the mid-Campanian unconformity (mCU; Decker 2007, 2010). Van der Kolk et al. (2015) reinterpreted the mCU as a composite unconformity based on the identification of three notable erosion surfaces at Shivugak Bluffs, and used the term Campanian unconformity (CU) in their study (Fig. 3.2). Field, seismic, and well data indicate that the unconformity continues into the subsurface to the east and northeast, and notably separates the lower Schrader Bluff Fm from the middle Schrader Bluff Fm regionally (Decker 2007; Gillis et al. 2014; Herriott et al. 2015).

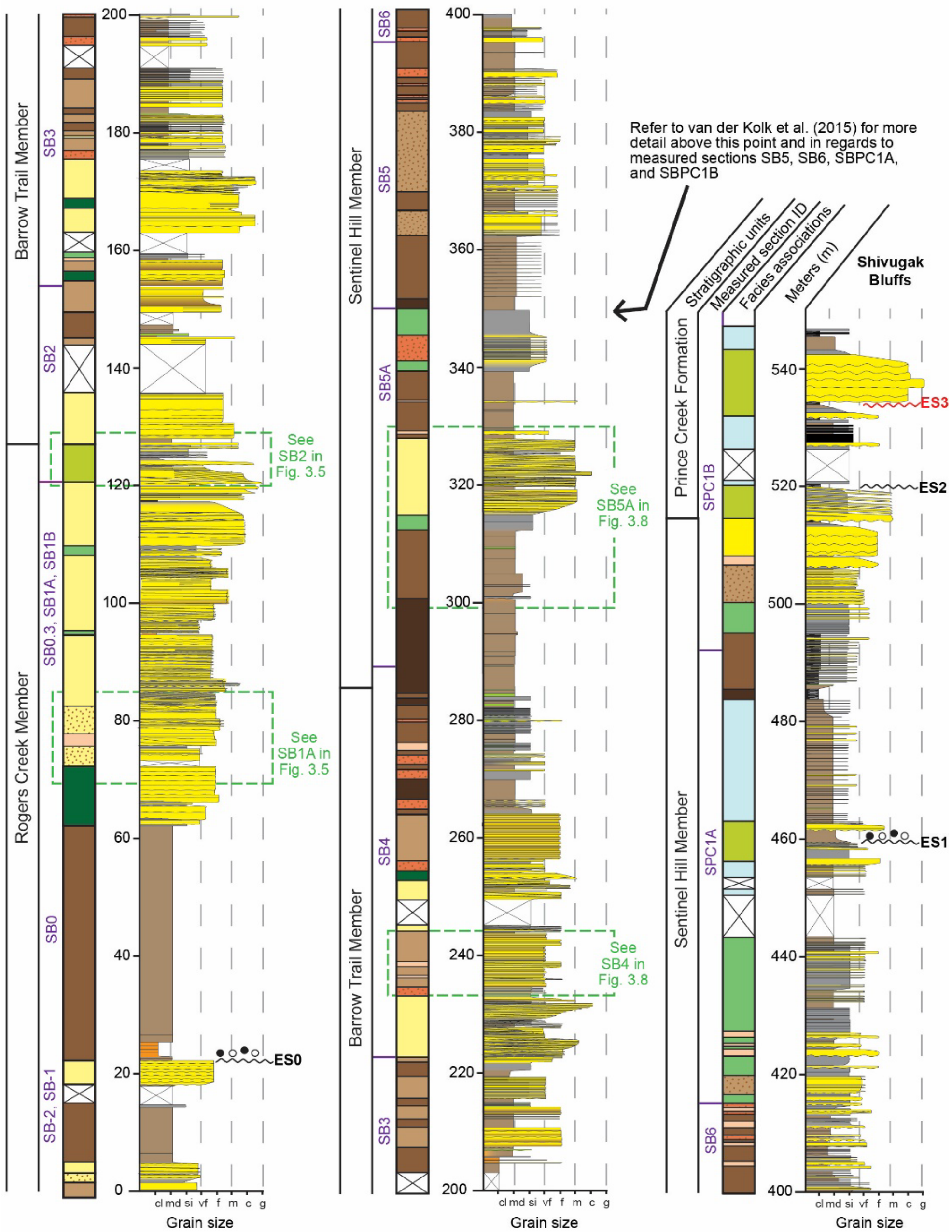


Figure 3.4. Composite section of the Rogers Creek, Barrow Trail and Sentinel Hill Mbrs of the lower Schrader Bluff Fm at Shivugak Bluffs relative to measured sections listed in Figure 3.3 and van der Kolk et al. (2015). Refer to Figure 3.4 for stratigraphic position and Appendix A for more detail. Key for measured sections and interpretations are in Figures 3.5 and 3.8.

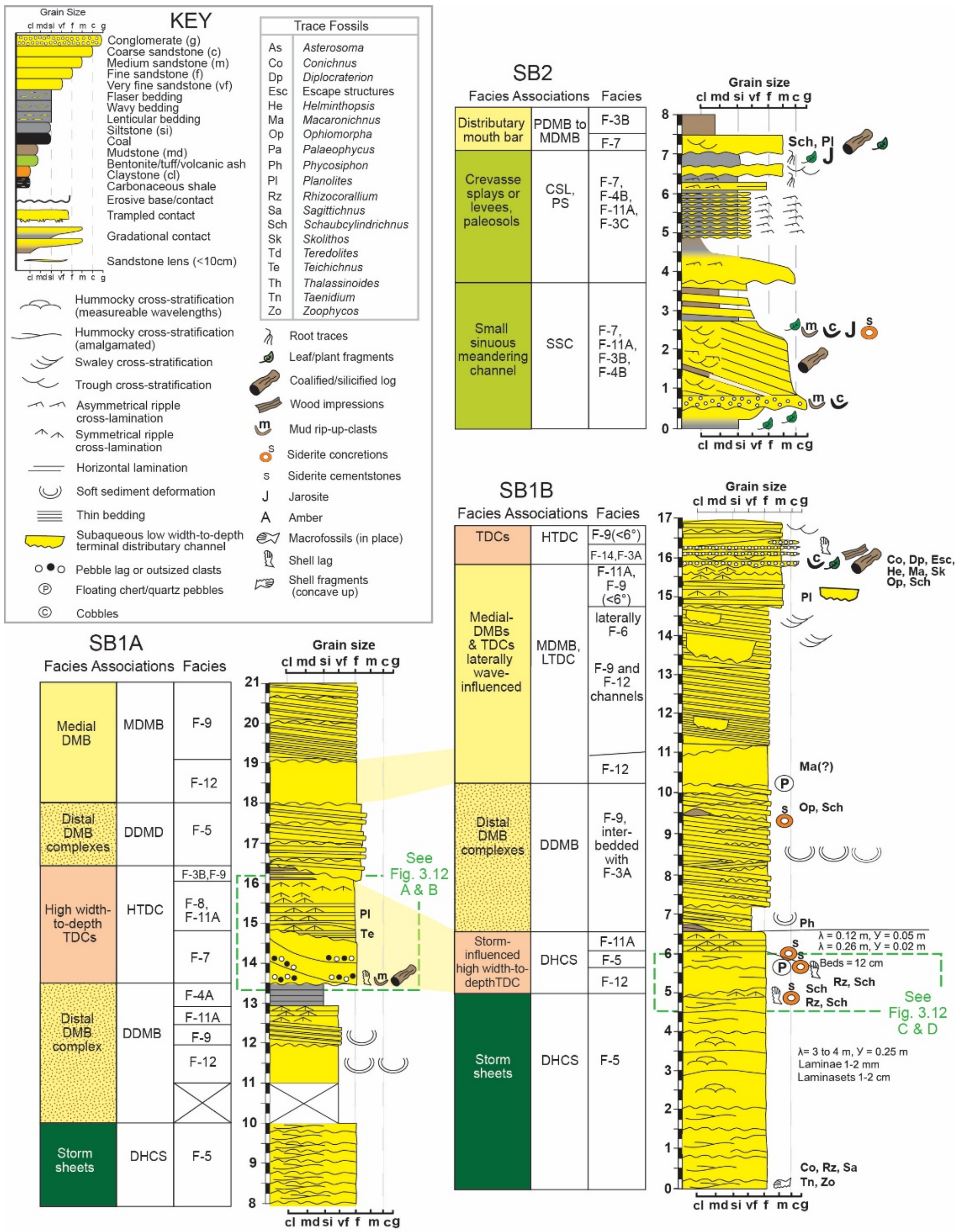


Figure 3.5. Excerpts from measured sections SB1A, SB1B, and SB2 from Appendix A showing storm sheets (DHCS), distal distributary mouth bars, high width-to-depth terminal distributary channels (HTDC), medial distributary mouth bars (MDMBs), small sinuous meandering channel (SSC), crevasse splays or levees (CSL), and paleosols (PS). Stratigraphic position listed in Figure 3.4 and explanation for facies associations are listed in Figure 3.8.

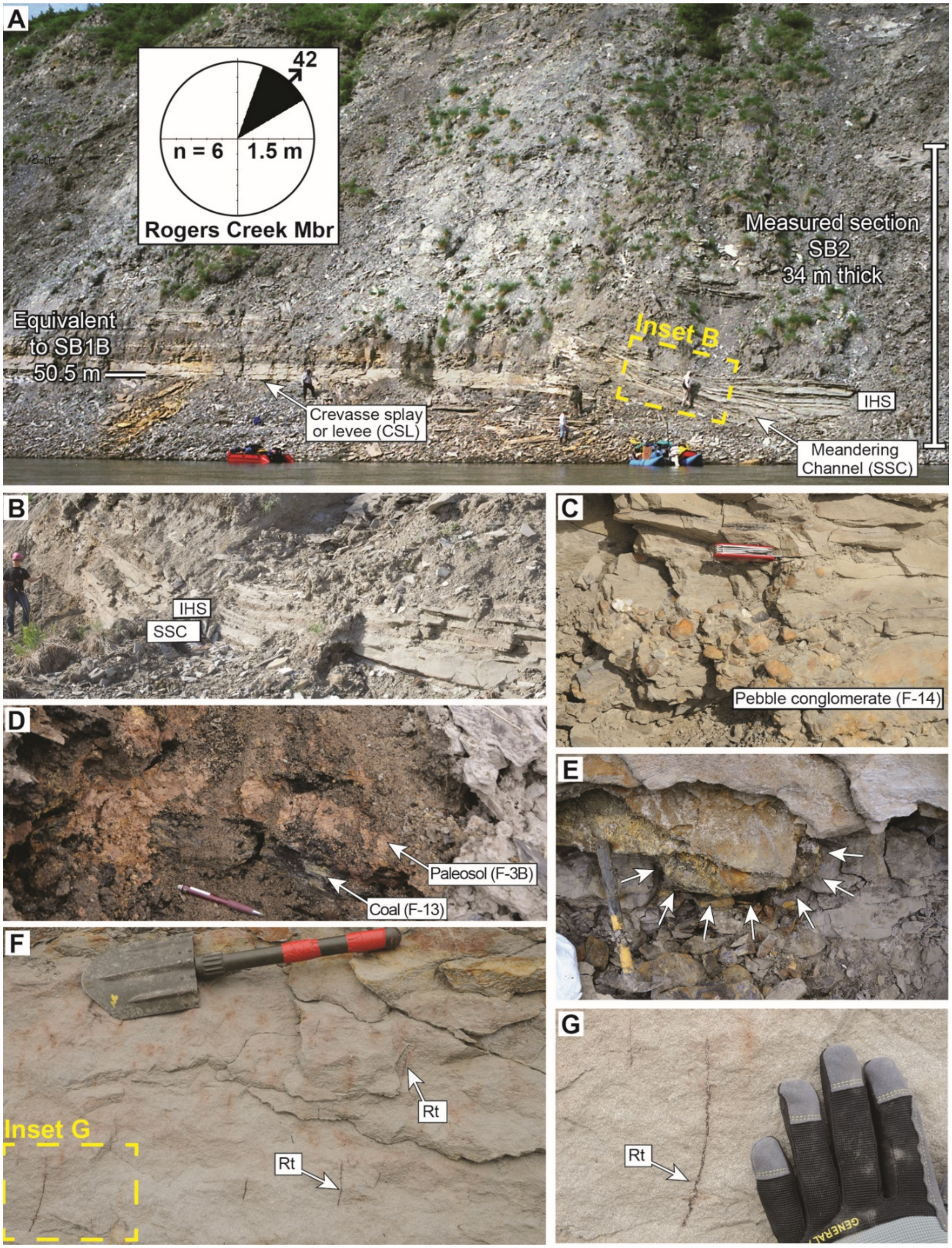

A
42
n = 6
1.5 m
Rogers Creek Mbr
Measured section
SB2
34 m thick
Equivalent
to SB1B
50.5 m
Inset B
Crevasse splay
or levee (CSL)
IHS
Meandering
Channel (SSC)
B
IHS
SSC
C
Pebble conglomerate (F-14)
D
Paleosol (F-3B)
Coal (F-13)
E
F
Rt
Inset G
Rt
G
Rt

Figure 3.6. Distributary channels and floodplain (FA-I) deposits, mapped as the Rogers Creek Mr of the lower Schrader Bluff Fm, but defined lithostratigraphically as the Prince Creek Fm at Shivugak Bluffs. A) Outcrop of inclined heterolithic strata (IHS) in a small sinuous (meandering) channel (FA-I: SSC), location of measured stratigraphic section SB2 (34 m thick), and paleocurrent orientation (refer to Fig. 3.8 for key) with an overall vector mean of 042° recorded from IHS in the SSC. B) Inset shows close-up of lateral accretion surfaces (IHS) in small sinuous channel in A; geologist 1.5 m tall for scale. C) Pebble conglomerate at base of meandering channel in SB2; knife 9 cm long. D) Coal (F-12) and salmon-colored mudstone (F-3C) interpreted as swamp deposits (FA-I: SW) and paleosols (FA-I: PS), pencil 16 cm long. E) Cross-sectional view of deformed bedding interpreted as dinosaur footprints indicated by arrows; yellow maddox 40.5 cm long. F) Vertical, siderite-stained root traces and siderite-lined rhizoliths or roots (Rt) in medium-grained sandstone (F-12) interpreted as a crevasse splay or levee (FA-I: CSL) marked as 50.5 m in photo A; and G) Inset shows sideritized root in F.

METHODS

A 336-m-thick composite section (Figs. 3.3, 3.4, Appendix A) was measured from continuous exposures in the lower two-thirds of the outcrop belt at Shivugak Bluffs using standard sedimentological techniques. An additional 196 m of section described by van der Kolk et al. (2015) (Fig. 3.4, Appendix A) stratigraphically above the study section is also discussed, making the total thickness of strata investigated at Shivugak Bluffs 542 m. This includes a 10-m-thick coarse- to medium-grained sandstone with minor pebbles and cobbles exposed at the top of Shivugak Bluffs but not included in van der Kolk et al. (2015) (Fig. 3.4). Nine stratigraphic sections were measured, interpreted, and summarized for this study (Fig. 3.4, Appendix A). The location of each measured section is shown in Figure 3.3. Data recorded includes grain size, sedimentary structures, surfaces, flora, fauna, trace fossils, and paleocurrent orientations (Appendix A). Terminology previously defined by Ingram (1954), Campbell (1967), and Reineck and Singh (1973) for bedding and laminae thickness were used. Cross strata as defined by McKee and Weir (1953) and Blatt et al. (1980) was also adopted here. Trace fossils were assigned to an ichnotaxon based on their surficial morphologies and fill pattern (e.g., Hasiotis and Mitchell 1993; Bromley 1996) and are recorded in order of abundance. Ichnofabric indices (ii) were recorded after Droser and Bottjer (1986). Photomosaics from high-resolution digital imagery aided in the facies and architectural analyses, and were used to correlate outcrop stratigraphy.

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Thirteen lithofacies (F-1 to F-13) are defined based on grain size and sediment texture, sedimentary structures, bedform or bed thickness, total interval thickness, basal and upper contacts, ichnology, megafauna, and flora (Table 3.1). For consistency with previous facies descriptions at Shivugak Bluffs (van der Kolk et al. 2015), mudstone (F-3) and siltstone (F-4) are further subdivided into facies subcategories (F-3A, F-3B, F-4A, F-4B) based on the presence or absence of laminations and such pedogenic features as rhizoliths, mottles, and ped structures (e.g., platy or aggregated-to-blocky characteristics). Asymmetric and symmetric rippled-laminated sandstones are also separated into subcategories F-11A and F-11B (Table 3.1).

The 13 lithofacies combine to form a range of depositional environments categorized into four major facies associations (FA-I to FA-IV) defined by distinctive inclusive facies, facies relationships, trace-fossil assemblage, surfaces, geometries, and stacking patterns (Table 3.2). FA-I includes continental distributary channel and floodplain environments with small sinuous distributary channels (SSC), crevasse splays and levees (CSL), swamps and swamp margins (SW), and pedogenically modified lithofacies (PS). FA-II comprises river-dominated deltaic environments along the proximal delta front and includes three types of DMBs and two types of subaqueous TDCs. Other environments of FA-II include medial delta front (MDF), distal delta front (DDF), interdistributary bay (IDB), prodelta (PD), and prodelta subaqueous TDCs and levees (PDTDC). FA-III includes wave- and storm-influenced deltaic deposits dominated by swaley cross-stratification (DSCS) and hummocky cross stratification (DHCS). FA-IV includes proximal shelf environments (SHF).

Table 3.1. Description of the 13 facies identified in the Schrader Bluff and Prince Creek Formation, at Shivugak Bluffs, North Slope, Alaska

Lithology	Facies ID	Laminae, Laminaset, or Bed thickness (m)	Total Interval Thickness (m)	Contacts	Grain Size & Sediment Texture	Flora and Megafauna
Bentonite	**F-1**	0.01 to 0.40	--	Basal undulating, rippled to sharp. Upper gradational, sharp, to interbedded.	Bentonite layers are dominantly soft, clay-rich layers.	There is a 1-cm thick, well-indurated, calcite-cememted layer at the base of a 20 cm thick bentonite bed at SB3-58.8. The upper contact is interbedded with mudstone.
Claystone	**F-2**	0.005 to 0.01	0.20 to 2.40	Basal sharp, erosional or gradational. Upper sharp.	Very thin to medium laminae (0.5 to 10 mm).	Rare: Iron-stained fractures and plant-debris.

Table 3.1 (continued)

Mudstone	Structureless,planar - laminated, and/or ripple-laminated mudstone	**F-3A**	0.001 to 0.20	0.05 to 36.9	Basal sharp, erosional, rippled, or gradational. Upper sharp, erosional,, undulating, rippled, or gradational.	Structureless, planar-laminated, ripple-laminated, thin to medium beds. Bentonite stringers (< 0.01 m thick) common between SB4 47.5 and 48.2 m and SB5 18 to 19.75 m.	Common: Bivalves and inoceramids.
	Carbonaceous, mottled to rooted mudstone	**F-3B**	> 0.01	0.20 to 0.30	Basal sharp. Upper sharp or disturbed.	Structureless, salmon-color mottling in SB1B.	Common: Sideritized or carbonized root traces.
Siltstone	Structureless, planar laminated, and/or ripple-laminated thin-bedded siltstone	**F-4A**	0.05 to 4.50	0.001 to 0.25	Basal sharp, rippled, to gradational. Upper sharp, undulatory, erosional, gradational.	Structureless, planar-laminated, thin bedded. Interbedded with thin bedded mudstone (2 to 3 cm), very fine to fine bedded sandstone.	
	Structureless to ripple-laminated siltstone with rhizoliths	**F-4B**	> 0.01	0.15 to 0.65	Basal sharp, undulatory to rippled. Upper erosional, undulatory to gradational.	Structureless to ripple laminated, siltstone. Aggregated-to-blocky, and friable.	Rare: Sideritized or carbonaceous rhizoliths.

Table 3.1 (continued)

	Flaser-, wavy-, to lenticular- bedded siltstone	**F-4C**	0.001 to 0.06	0.5 to 2.5	Basal sharp or gradational. Upper gradational	Alternating organic-rich and cleaner siltstone or sandstone intervals (laminated to 6 cm thick).	Common: Carbonized plant debris.
Sandstone	Hummocky cross-stratified sandstone	**F-5**	0.10 to 0.50	0.40 to 4.50	Basal erosional to gradational. Upper gradational to erosional.	Very fine to fine-grained, thin to thick bedded sandstone.	Rare: Plant material, locally high volumes of logs and wood debris. Rare: black chert and shell lags.
	Swaley cross-stratified sandstone	**F-6**	0.15 to 0.75	0.6 to 3	Basal undulatory to erosional. Upper erosional.	Medium-grained thick bedded sandstone, rare shell detritus and mud rip-ups.	
	Trough cross-stratified sandstone	**F-7**	0.05 to 0.75	0.05 to 3.25	Basal erosional. Upper erosional, undulatory to sharp.	Very fine to coarse-grained sandstone, very thin to thick bedded sandstone. Rare: pebble lags on foresets or pebble, mud-, coal rip-ups, shell debris lags at base.	Common: Logs and plant material. Shell debris contains bivalve and nested inoceramid fragments (up to 22.5 cm).
	Planar tabular cross-bedding to sigmoidal crossbeds	**F-8**	0.3 to 0.5	0.3 to 1	Basal sharp to erosive. Upper sharp to erosive.	Medium-grained sandstone; possible siltstone or muddy sandstone cross-stratum in cross-strata sets.	

Table 3.1 (continued)

	Inclined, very thin to thin bedded sandstone beds	**F-9**	0.003 to 0.01	0.50 to 1.50; up to 2.5 m laterally	Basal erosional to sharp. Upper sharp.	Topset, foreset and bottomset architectural elements.	Rare: sideritized root traces.
	Plane-parallel lamination	**F-10**	< 1 cm	0.20 to 0.50	Basal sharp. Upper sharp.	Medium to very thick laminae (3 mm to <1 cm)	Common: plant debris.
	Symmetric ripple-lamination	**F-11A**	0.06 to 0.12	0.06 to 0.5	Basal erosional to sharp. Upper sharp to erosional.	Very fine to coarse-grained sandstone.	Common: siderite cement.
	Asymmetric ripple cross-laminated sandstone	**F-11B**	0.04 to 0.10	0.2 to 2.4	Basal sharp, rippled to gradational. Upper erosional to sharp.	Very fine- to medium-grained, laminated to thin bedded sandstone.	Common: plant fragments and logs, inoceramid fragments, whole bivalves.
	Structureless or bioturbated sandstone	**F-12**	**--**	0.2 to 1.6	Basal sharp. Upper sharp.	Structureless, silty, very fine sandstone. Bioturbated intervals have ii = 5 to 6.	Common: plant fragments.
Coal		**F-13**	0.05 to 0.40	--	Basal undulating. Upper sharp.		Common: plant fragments and logs.
Pebble conglomerate		**F-14**	0.25	--	Basal erosional. Upper erosional.	Chert and quartzite pebbles up to 9 cm in diameter.	Abundant wood debris.

Table 3.2. Summary of facies associations, architectural elements and ichnology of the Schrader Bluff and Prince Creek formations at Shivugak Bluffs.

Facies Association (FA)	**Environment**	**FA Code**	**Inclusive Facies, Surfaces, and Geometries**	**Ichnology**	**Ichnofacies**
FA-I Distributary Channels and Floodplains	Small sinuous channel (meandering)	SSC	Inclined heterolithic strata with trough cross-stratified sandstone (F-7), mudstone (F-3B), asymmetric ripple laminated sandstone (F-11B), and siltstone (F-4B).	Wood debris	–
	Crevasse splays or levees	CSL	Structureless sandstone (F-12), asymmetric ripple-laminated sandstone and siltstone (F-11B and F-4B).	Rhizoliths, rhizocretions, and rhizohalos common. Rare dinosaur trampled surfaces.	Scoyenia
	Swamp and swamp margin	SW	Coal (F-13) and mudstone (F-3B).	Common: Rhizoliths, rhizocretions, or rhizohalos.	Scoyenia
	Pedogenically modified lithofacies	PS	Carbonaceous, massive or ripple-laminated mudstone with rhizoliths (F-3B), rooted to massive siltstones (F-4B).	Common: Rhizoliths, rhizocretions, and rhizohalos.	Scoyenia

Table 3.2 (continued)

FA-II Storm-Flood Dominated Delta Deposits	Proximal delta front distributary mouth bars (DMBs)	MDMB	**Medial DMB:** Very fine to medium-grained sandstones that form bar-scale inclined topsets, foresets, and bottomsets (F-9). Rare symmetric and asymmetric ripple cross-stratified sandstone (F-11A and F-11B). Can fine upward (SB1B 44.5 to 47.5 m). Amalgamated foresets, trough cross-stratification and massive sandstone are beheaded. Rare swaley cross-stratificatied sandstone (F-6).	*He*, *Ph*, *Sch*, *Ma*, *Sk*, and *Op*	Cruziana–Skolithos
		DDMB	**Distal DMB:** Amagalmated subparallel laminated sandstones (F-9). Associated with HCS (F-5), mudstone (F-3A) and symmetric ripple laminations (F-11A), and soft-sediment deformation.	He, Ph, Ph-He, Sch, rare Op, Pl, Tn	Cruziana
	Proximal delta front Terminal distributary channels (TDCs)	HTDC	**High width-to-depth channels**. Commonly form multi-story sheet sandbodies (up to 2 m-thick) with lateral accretion, trough-cross stratification (F-7), pebble conglomerate (F-14), logs, intraformational sandstone clasts (up to 7 cm wide), siderite, siltstone, and mudstone clasts, and pelecypod shell debris. Laterally a 2-m thick sandbody becomes massive (F-12) and hummocky cross-stratified (F-5).	*He, Ph, Sch, Co, Dp, Esc. Pl* and *Te* (upper channel fill), rare rhizoliths (SB1B & SB0.3 in trough cross-stratified beds)	Skolithos, Scoyenia

Table 3.2 (continued)

	LTDC	**Low width-to-depth channels**. Chutes with concave-up erosional surfaces filled with structureless to trough cross-stratified sandstone (F-6). Chutes form isolated channel-form sandbodies that cross-cut older, medial DMBs.	Absent	–
Medial delta front	MDF	Medium to coarse trough cross-stratified sandstone (F-7), asymmetric ripple lamination (F-11B).	*He, Ph, Sch, Pl, Te, Pa, As, Gy, Rz, Co?*	Cruziana
Distal delta front	DDF	Thin beds of asymmetric ripple-laminated sandstone (F-11B), planar or ripple-laminated siltstone (F-4B), rare bentonite (F-1).	*He, Ph, Sch*	Cruziana
Interdistributary bay	IDB	Flaser, wavy, and lenticular bedded siltstone with lenses of very fine-grained sandstone (F-4C), planar laminated to thin bedded siltstone (F-4A).	*He, Ph, Ma,* rare *As* and *Co*	Cruziana–Skolithos
Prodelta	PD	Structureless, planar- or ripple-laminated mudstone (F-3B), siltstone (F-4A) and rare bentonite (F-1).	*Ph, He, He-Ph, Sk*	Cruziana
	PDTDC	**Prodelta channels.** Trough cross-stratified sandstone (F-7), asymmetric wave ripple-laminated sandstone (F-11B), and/or structureless sandstone (F-12). "Bouma-like" turbidity deposits similar to those described in van der Kolk et al. (2015). Laterally siltstone (F-4A).	Absent	–

Table 3.2 (continued)

FA-III Wave-Influenced Delta Deposits	Storm sheets	DSCS	Swaley cross-stratification (F-6), symmetric wave ripples (F-11A), trough cross-stratification (F-7).	Absent	–
		DHCS	Very fine to fine-grained hummocky cross-stratified sandstone (F-5), symmetric wave ripples (F-11A), rare asymmetric ripples (F-11B), laminated to thin bedded siltstone (F-4A).	*He*, *Sch*, *Tn*, *Sa*, *Ph*, *Rz*, *Zo*	Cruziana
FA-IV Shelf	Proximal shelf	SHF	Black, organic-rich mudstone (F-3A), minor claystone (F-2) and bentonite (F-1).	Potential cryptobioturbation	Cruziana

FACIES ASSOCIATION I: DISTRIBUTARY CHANNELS AND FLOODPLAINS

Description.—The least common and typically thinnest facies association comprises: coal; carbonaceous or rooted mudstone; rooted siltstone; and massive, ripple cross- laminated, or trough cross-stratified, very fine- to coarse-grained sandstone with rare basal pebble conglomerate (Fig. 3.6; Table 3.1, 3.2). The thickest succession of FA-I is laterally continuous across measured sections SB0.3, SB1B and SB2, and is up to 7-m thick in SB2 (Figs. 3.4, 3.5; Appendix A). At the base of SB2 (0–7 m; Fig. 3.6A), a fine- to medium-grained, trough cross-stratified sandstone with an erosional base and basal pebble conglomerate (Fig. 3.6A–C) grades upward into inclined heterolithic stratification (IHS) with rare climbing current ripples and siltstone-mudstone interbeds. Paleocurrent orientations recorded from a trough cross-stratification in SB2 at 1.5 m (n=6) have an overall vector mean of 042°. Coal (5–40 cm thick) is interbedded with variegated mudstone, and rarely underlain or overlain by root-bearing mudstone (Fig. 3.6D). In SB1B (24.5 m), 14-cm long sideritized rhizoliths vertically penetrate low-angle trough-cross bedding, and subparallel-laminated sandstone. This horizon is overlain by a relatively thin, rooted facies of FA-I interbedded with laminated to thin-bedded, very fine-grained sandstone (F-10) containing *Asterosoma* (As) and *Helminthopsis* (He; 24.5–27 m in SB1B).

Interpretation.—Coal interbedded with carbonaceous mudstone, rooted mudstone, and siltstone is interpreted as mires or swamps (SW) with weakly developed paleosols (PS; Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015). Sideritized rhizoliths are also common in parallel-laminated and rippled sandstones interpreted as pedogenically modified crevasse splays or levees (CSL; Fig. 3.6A, F, G) on the lower delta plain (see Flaig et al. 2011, 2013, 2014). The basal surface of an extensive and pedogenically modified CSL at 50.5 m in SB1B that extends to SB2 (> 1 km long; Fig. 3.6A) exhibits disrupted bedding (Fig. 3.6E) interpreted as dinosaur trampled beds (Fiorillo et al. 2010b; Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015). Previous studies have documented rooted horizons on the tops of sand-rich, coarsening upward successions that are interpreted as pedogenically modified CSL and DMBs (Baganz et al. 1975; Lumsdon-West and Plint 2005; Flaig et al. 2013). Rooted surfaces of TDCs and mouth bars (SB0.3, 18.5–20.5 m; SB1B, 50.25–52.75 m) indicate that the top of a local progradational deltaic succession was subaerially exposed, pedogenically modified, and vegetated (e.g., Hasiotis 2002, 2007). IHS (Fig. 3.6A, B) at the base of SB2 (0–3.75 m in Fig. 3.5) are interpreted as forming from a combination of seasonal or shorter time-scale fluctuations in river discharge (Flaig et al. 2011; Gugliotta et al. 2016) and tidal influence on the river system (Thomas et al. 1987; Flaig et al. 2011). Trough-cross bedded and subparallel-laminated sandstone at 24.5 m in SB1B is interpreted as a TDC that overlies a DMB (FA-II: DMB-TDC complexes), which was subaerially exposed and vegetated (PS; SB1at 24 m in Appendix A). The horizon is overlain by interbedded and pedogenically modified mudstone and very fine-grained sandstone with As and He, interpreted as interdistributary bay deposits (FA-II, IDB; 24.5–27 m in SB1B; see also van der Kolk et al. 2015). FA-I contains distal, small sinuous distributary channels and associated floodplain deposits on the lower delta plain, similar to those preserved in strata of the Prince Creek Fm along the Colville, Kogosukruk, and Kikiakrorak rivers (Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015).

FACIES ASSOCIATION II: RIVER-DOMINATED DELTAS

PROXIMAL DELTA FRONT DISTRIBUTARY MOUTH BAR-TERMINAL DISTRIBUTARY CHANNEL (DMB-TDC) COMPLEXES

Description.—Several 2.5–15.0-m-thick intervals are separated into four distinct subcategories of architectural elements (Figs. 3.5, 3.7–3.12). Two of these are tabular in form and two are channel form. Planar-laminated, high-angle (20−25°) foresets (0.25–0.5 m thick) comprise very fine- to coarse-grained sandstone and form 0.5–2.5 m thick tabular bedsets (Fig. 3.9). Planar laminated, low-angle (< 10°) foresets (0.10–0.5 m thick) comprise very fine-grained sandstone that form up to 3.75-m-thick tabular bedsets. The latter occurs in less resistant intervals due to interbeds of mudstone, siltstone, and sandstone that may exhibit hummocky cross stratification (HCS) or soft-sediment deformation (Figs. 3.10, 3.11).

The most abundant tabular architectural element is bedsets made up of high-angle (20−25°) foresets that commonly have sharp or conformable basal contacts and erosional upper contacts. Occasionally, both the topsets and bottomsets of these foresets are preserved (Fig. 3.9). Foresets stack vertically and laterally in outcrop to form simple to complex amalgamated sandstone packages (< 15-m thick; Figs. 3.9, 3.11). High-angle (20−25°) foresets with more abundant erosional surfaces are also interbedded with wedge-shaped tabular (planar) crossbeds and planar wedge-shaped cross-stratification with sigmoidal internal cross strata (Fig. 3.9E). Swaley cross-stratification (F-6) is associated with these bedforms in SB0 (37.75–39.75 m), SB1 (13.5–14.75 m), and SB4 (4.5 m and 29.5–30.4 m). Planar-laminated, high-angle foreset dominated tabular bedforms commonly coarsen upward, but may fine upward (SB1A and SB1B, Appendix A). Planar-laminated high-angle and low-angle foreset dominated tabular bedforms have diverse trace-fossil assemblages including *Phycosiphon* (Ph), *Helminthopsis* (He), Sch, *Planolites* (Pl), and *Ophiomorpha* (Op). Planar-laminated high-angle foreset dominated tabular bedforms also include rare *Macaronichnus* (Ma) and *Skolithos* (Sk) and planar-laminated low-angle foreset dominated tabular bedforms have rare *Taenidium* (Tn).

High and low width-to-depth channel forms are associated with tabular bedforms (Table 3.2; Figs. 3.11, 3.12) described above and are common architectural elements in SB1A, SB1B, and SB4 (Appendix A). High width-to-depth channel-form sandbodies are thicker (1.5-m thick) and commonly fill, drape, or conformably overly scour surfaces (Fig. 3.11). Low width-to-depth channel-form sandbodies are thinner (0.25–0.5-m thick) and erode into, truncate, or penetrate older bedforms (Fig. 3.11). High width-to-depth channel-form bedsets form multistorey, trough cross-stratified sandstone successions that are ledge forming, whereas low width-to-depth channel-form beds form narrow, massive or trough-cross-stratified sandbodies with concave basal erosional surfaces. Bioturbation was not found in low width-to-depth channel-form beds, whereas high width-to-depth channel-form sandstone have a range of trace fossils including He, Ph, Sch, *Conichnus* (Co), *Diplocraterion* (Dp), escape structures (Esc), Pl, and *Teichichnus* (Te). Trough cross-stratification have paleocurrent orientations that range from 210° to 160° (Fig. 3.7, Appendix A).

Interpretation.—Tabular bedsets of FA-II are interpreted as DMBs, whereas channel-form beds and bedsets are interpreted as subaqueous TDCs. Planar-laminated high-angle foreset dominated tabular bedforms are interpreted as medial DMB (MDMB), and planar-laminated low-angle foreset dominated bedforms are interpreted as the most distal DMB deposits (DDMB). High width-to-depth channel-form sandbodies are interpreted as high width-to-depth subaqueous TDC (HTDC), and low width-to depth channel-form sandbodies are interpreted as low width-to-depth subaqueous TDC (LTDC). Associated DMBs and TDCs commonly form complexes of compensationally stacked, sand-rich architectural elements (Fig. 3.11) along the proximal delta front (Olariu and Bhattacharya 2006; Flaig et al. 2016). DMBs form, and are well developed, near river outlets at the coastline, and are confined to the active portion of the delta during flooding events (Kroonenberg et al. 1997; Fielding et al. 2005a, 2005b; Ahmed et al. 2014). River-mouth discharge has been described as forming tear-drop-shaped DMBs from fully turbulent jet flow via friction-, inertia-, or buoyant-dominated processes where there is no significant tide or wave influence (Bates 1953; Wright 1977; Wellner et al. 2005; Ahmed et al. 2014). Inertia-dominated discharge from fully turbulent flow with low-lateral spreading angles and progressive lateral and longitudinal deceleration produces inclined planar laminations typically capped with ripple lamination (Bates 1953; Wright 1977; Wellner et al. 2005), similar to sedimentary structures and architectures within MDMBs and DDMBs at Shivugak Bluffs, although they generally lack ripple laminations. Previous investigations have documented friction- and inertia-dominated DMBs in the Ferron Sandstone with similar sedimentary structures and architectures to those at Shivugak Bluffs (Zhu 2010; Ahmed et al. 2014).

MDMBs contain 2D, small-scale foresets (up to 2.5-m thick) exposed as tabular architectural elements in outcrop both in along-strike and along-dip exposures (Fig. 3.9). The facies and 2D geometries are similar to those described from fan-shaped, lobate sandbodies consistent with low angle, lateral spreading deposits (Bates 1953; Wright 1977; Wellner et al. 2005). MDMBs had sustained hyperpycnal flows (e.g., parallel-laminated foresets) along with minor traction deposits formed from frictional fluid flows (e.g., planar cross-beds and internal sigmoidal cross-bedded sandstones; Fig. 3.9E; Bhattacharya 2010; Ahmed et al. 2014). DDMBs have similar sedimentary structures as MDMBs (Figs. 3.9, 3.10B) but contain laminated beds that dip at lower angles, are commonly interbedded with mudstone (F-3A) and siltstone (F-4A), and are associated with intervals of HCS (F-5) and/or localized areas of soft-sediment deformation (Figs. 3.10, 3.12C–D). These facies (F-3A, F-4A, and F-5) form DDMBs that are interpreted as the distal most extension of mouth bars (i.e., jet deposits) along the delta front (Figs. 3.5, 3.10; Wellner et al. 2005).

Subaerial to subaqueous TDCs typically cap river-dominated deltaic successions and are critical sediment dispersal pathways that help to develop the lobate shape of river deltas (Olariu and Bhattacharya 2006). Roots and marine trace fossils preserved in HTDCs indicate that the lower Schrader Bluff Fm had both subaerial and subaqueous TDCs associated with DMBs in proximal delta front environments. No bioturbation was observed in LTDCs, suggesting high-energy, high turbidity, or low salinity conditions that excluded marine biota (Hasiotis and Platt 2012; Hurd et al. 2014). Tn and Ma in DMBs, however, indicate burrows of such deposit feeders as echinoids, arthropods, annelids, and polycheate (*Ophelia*) worms (Clifton and Thompson 1978; Goldring et al. 2004). Dp and Co indicate dwelling burrows of such suspension feeders as crustaceans (shrimp), anemone, or bivalves (Frey and Howard 1981; Goldring et al. 2004; Jackson et al. 2016).

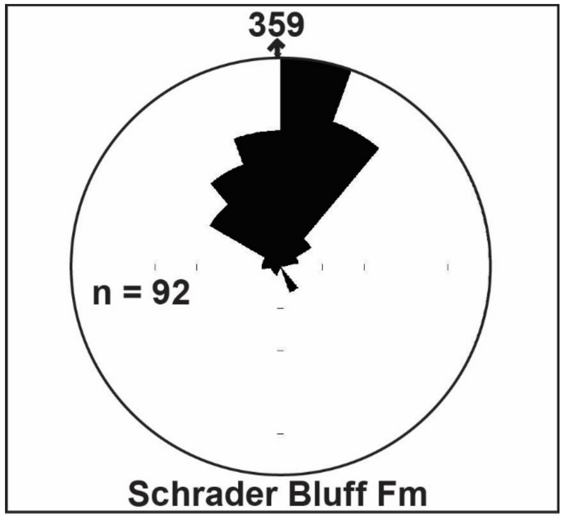


Figure 3.7. Paleocurrent orientation (refer to Fig. 3.8 for key) with an overall vector mean of 359° recorded from TDCs in deltaic deposits.

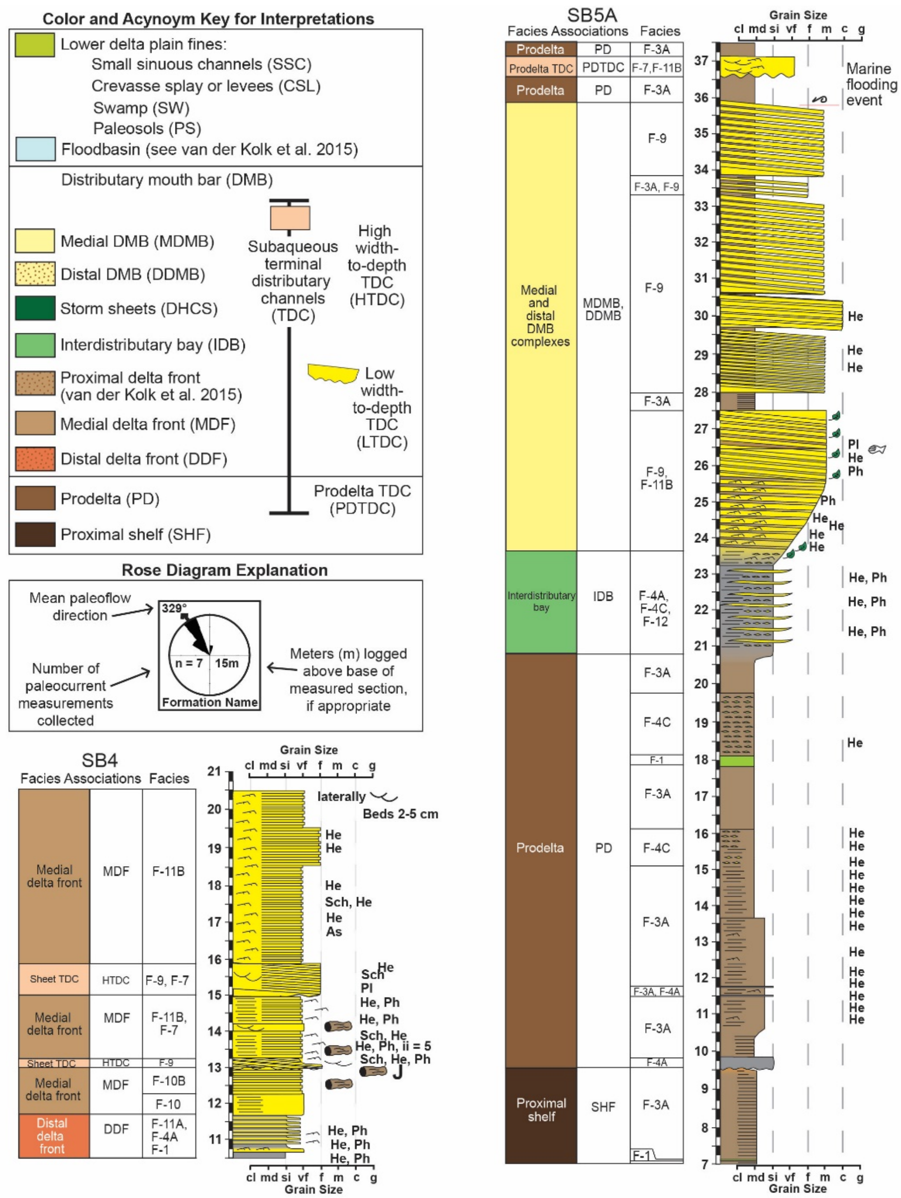


Figure 3.8. Excerpts from measured sections SB4 and SB5A from Appendix A showing proximal shelf (SHF), prodelta (PD), prodelta terminal distributary channels (PDTDC), distal delta front (DDF), medial delta front (MDF), high width-to-depth terminal distributary channels (HTDCs), interdistributary bays (IDBs), medial and distal distributary mouth bars (MDMB and DDMB). Stratigraphic positions relative to the lower Schrader Bluff Formation is listed in Figure 3.4. See Figure 3.5 for key.

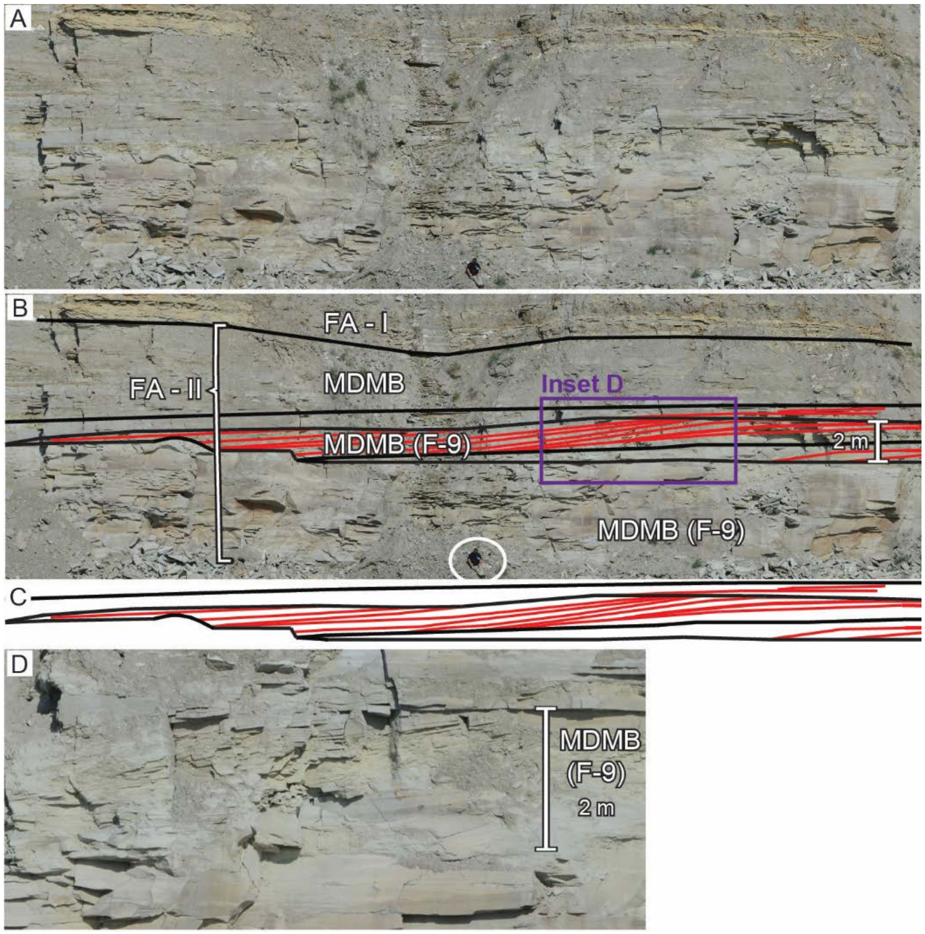


Figure 3.9. Medial distributary mouth bars (MDMB), a common architectural element in proximal delta front deposits (see FA-II) at Shivugak Bluffs. A) Photomosaic of MDMB lateral to strata documented in SB1 (Appendix A). B) Line drawing of A. C) Line drawing of B. D) Close-up of small-scale, low-angle clinoform foresets (FA-II: MDMB) from inset D shown in B.

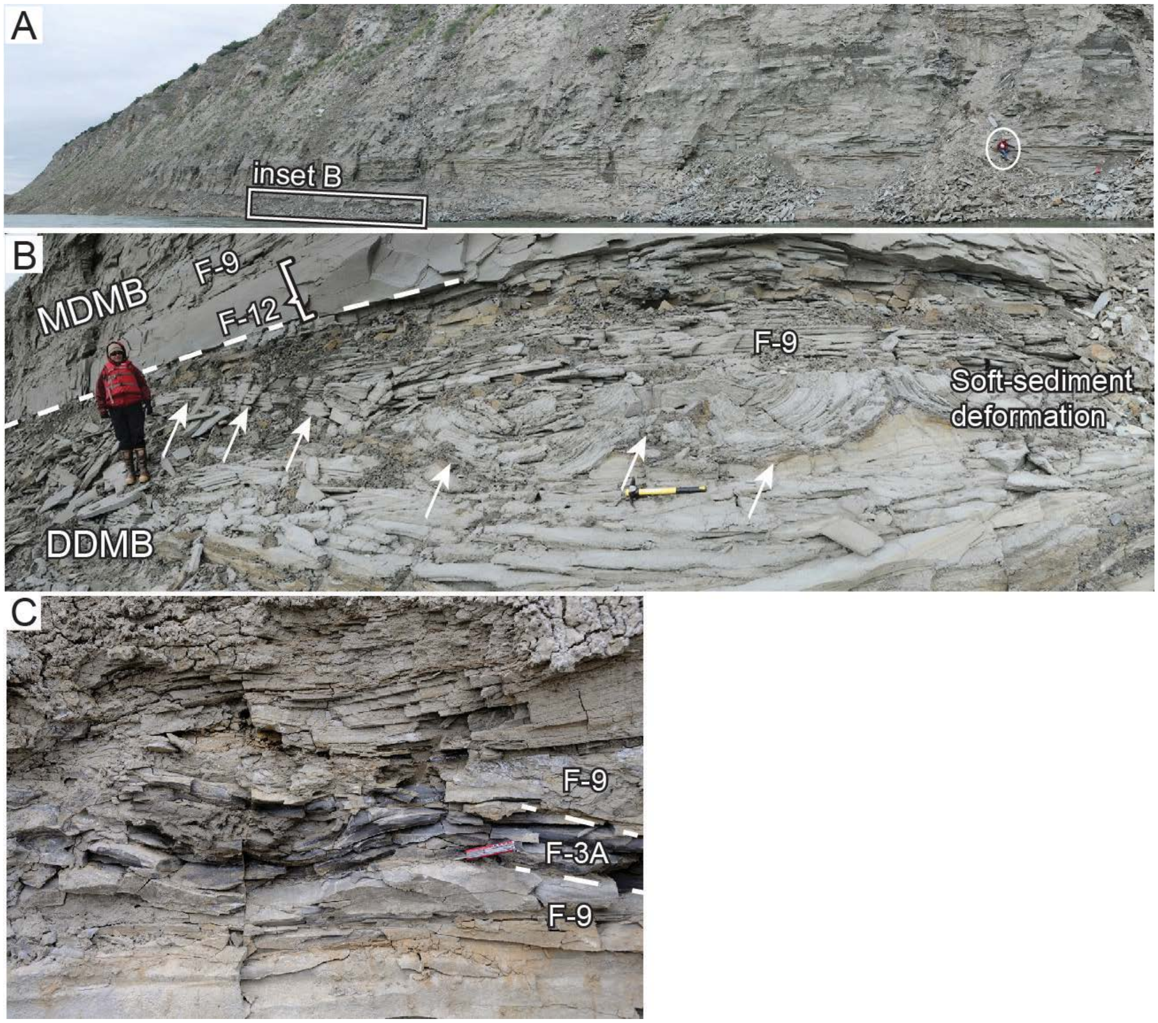


Figure 3.10. Distal distributary mouth bars (DDMB), a common architectural element in proximal delta front deposits within SB1 (see FA-II) at Shivugak Bluffs. A) Photograph of the Rogers Creek Mbr showing a less resistant interval of a DDMB. B) Photomosaic of DDMB from inset A described between 10 and 18 m in SB1A (Figs. 3.4, 3.5). Arrows point to package of low-angle planar laminations of a DDMB that laterally alters to soft-sediment deformation. Yellow maddox = 40.5 cm long. C) Bottomset toes deposited on top of mudstone that are deformed from sediment loading of a saturated substrate.

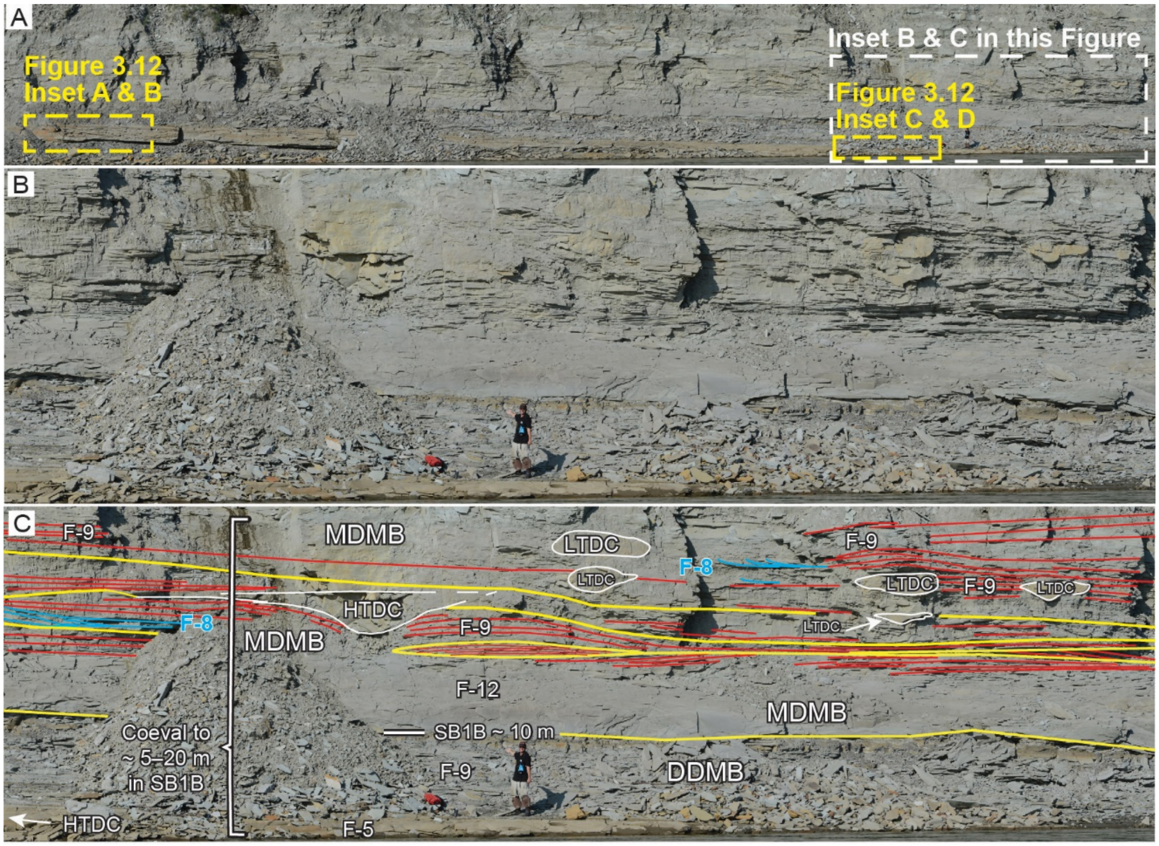


Figure 3.11. Distal and medial distributary mouth bars and associated terminal distributary channels in the Rogers Creek Mbr. A) Photomosaic of outcrop exposure near SB1B. B) Line drawing of A showing facies and architectural elements in distal distributary mouth bar (DDMB) and medial distributary mouth bar (MDMB) including a high low width-to-depth terminal distributary channel (HTDC) and low width to depth terminal distributary channels (LTDCs). Facies include hummocky cross stratified sandstone (F-5), inclined, very thin to thin bedded sandstone (F-9), and rare planar sigmoidal cross beds (F-8).

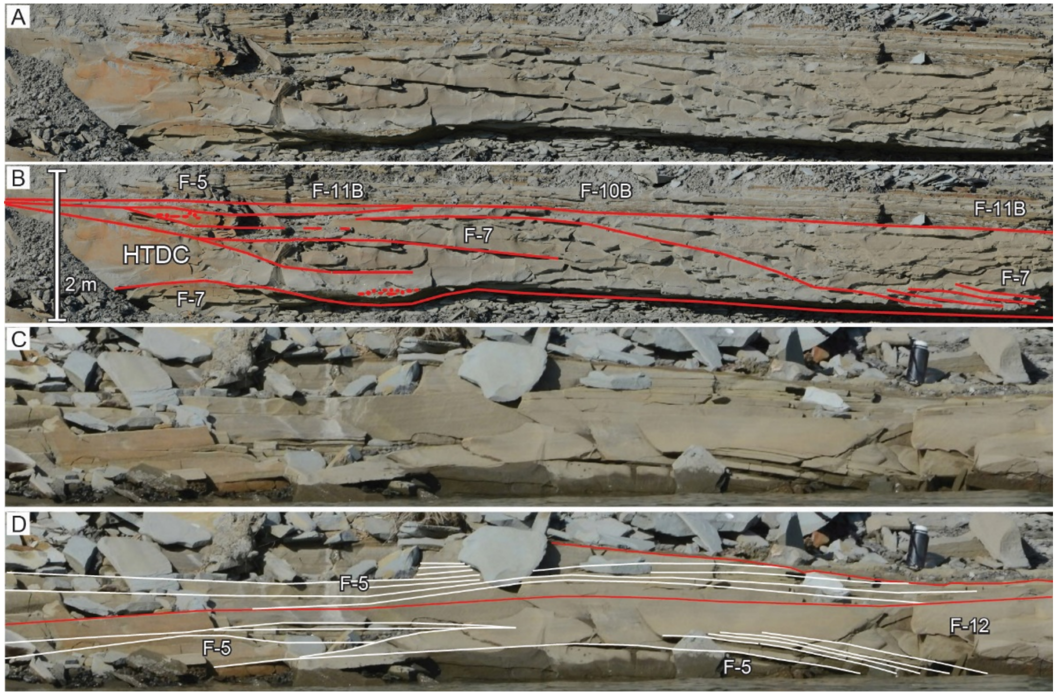


Figure 3.12. Terminal distributary channels become hummocky cross-stratified laterally (see Figure 3.11A. A) Photomosaic of a HTDC with trough cross-stratified sandstone between SB1A and SB1B (Figs.3.4, 3.5, Appendix A). B) Line drawing of A showing a series of small- and large-scale trough cross-stratification (F-7) filling scoured surfaces. Basal lags comprise black chert pebbles, bivalves, and intraformational clasts. There is an apparent migration of the channel system to the right of the image. C) Approximately 80 m away from the HTDC, photographed in A and B in SB1A, the same sandbody laterally becomes hummocky cross-stratified (F-5) due to wave reworking interpreted as storm-influence (DHCS) as shown in SB1B (Fig. 3.5). D) Line drawing of C showing F-5 and massive (F-12) sandstone. Bottle = 21 cm tall.

MEDIAL DELTA FRONT (MDF)

Description.—Strata in intervals 0.75–7.5-m-thick (e.g., 11.75–20.5 in SB4) comprise laterally continuous stacked sheet-sandstone successions that do not vary greatly in thickness (Fig. 3.13A). Continuous intervals contain very thin to thick beds of bioturbated (F-12), massive (F-12), asymmetric ripple-laminated (F-11B), parallel-laminated (F-10) and/or rare trough cross-stratified (F-7) tabular sandstone (Fig. 3.8). Tabular bedsets commonly clean upward (more sand, less mud) and are typically capped by DDMB or MDMB complexes or subaqueous TDCs (Fig. 3.8). At 28.5 m in SB3 the top of a coarsening upward succession becomes rooted. Tabular sandstones have wispy, subordinate mudstone beds with curvilinear lower and upper contacts (Fig. 3.13B. Ichnofabric indices range from 1 to 6, but many intervals have consistently high ii (5, 6; Fig. 3.13C). Deposits are commonly bioturbated with Ph, He, Sch, and As, and rare *Rhizocorallium* (Rz), *Gyrolithes* (Gy), and Co (Appendix A; Table 2).

Interpretation.—Laterally continuous 0.75–7.5-m-thick intervals record sand and mud deposition along the medial delta-front (MDF) downdip of DMBs and updip of distal-delta-front (DDF) deposits (Fig. 3.14E). This interpretation is based on recurring, laterally and vertically continuous, bioturbated sandstone beds (Fig. 3.13) with remnants of rare trough-cross stratification and hyperpycnal flows recorded by massive, planar-laminated, and asymmetric rippled (Tabc) intervals. This succession is similar to MDF deposits in the Ferron Sandstone in Utah (Olariu and Bhattacharya 2006; Fielding 2010). SB4 (13–16 m) contains 0.25–1-m-thick packages of subaqueous sheet HTDCs interbedded with MDF deposits (Fig. 3.13B). MDF deposits at Shivugak Bluffs dip into the subsurface (Fig. 3.13A) and likely extend beyond the 2 km of outcrop on the basis of observed lateral continuity. No single MDF bed was observed to pinch out at the scale of the 2-km bluff exposure. Thick packages of interbedded siltstone, sandstone, and bioturbated fine-grained sandstone have previously been interpreted as medial to proximal delta-front deposits (Hurd et al. 2014), and the MDF deposits in the lower Schrader Bluff Fm are consistent with these interpretations.

DISTAL DELTA FRONT (DDF)

Description.—Deposits 0.25–5-m thick in SB3 (21.5–23.0 m; 40.5–46.0 m), SB4 (10.25–11.75 m; 30.4–32.75 m; 41.25–50.0 m), and SB5A (48.0–53.0) (Appendix A) contain relatively thick siltstone successions (F-4A) up to 1.5-m thick and very fine- to medium-grained, plane-parallel laminated to massive sandstone (F-10; F-12) that overlie proximal-shelf (SHF) deposits encased in prodelta (PD) deposits (see SB4 45.7–50.0, Fig. 3.14, Appendix A), or underlie MDF deposits (see SB4 11.75 m and 32.75 m; Fig. 3.8; Appendix A). When similar deposits are not encased in PD deposits, they are found stratigraphically below MDF deposits (see SB3 23 m, SB4 32.75 m, Appendix A), and are thinly interbedded with bentonite (F-1), mudstone (F-3A), siltstone (F-4A), and asymmetrically ripple-laminated, very fine-grained sandstone (F-11B). Deposits such as this found below MDF deposits typically have low ichnodiversity (*He*, *Ph*, *Sch*), whereas deposits encased in PD (Fig. 3.14E) or SHF deposits do not have any trace fossils. An interval with this composition in SB5A, between 48 and 53 m, predominantly comprises very fine-grained sandstone (F-11B; > 1-cm and < 10-cm thick) encased in interdistributary bay deposits (see FA-II IDB section) and >1 cm thick sandstones with mud drapes that resemble starved ripples (Appendix A).

Interpretation.**—**Strata with this set of facies, ichnology, and architecture are interpreted as distal delta front (DDF) deposits based on stratigraphic relationships and such inclusive facies as asymmetric ripple-laminated sandstone (F-11B) and planar or ripple-laminated siltstone (F-4B) (e.g., Fielding 2010). DDF deposits at Shivugak Bluffs in the Sentinel Hill Mbr have previously been defined as isolated sheet sandstone beds > 0.10-m and < 1.0-m thick (van der Kolk et al. 2015). The Rogers Creek and Barrow Trail mbrs at Shivugak Bluffs include a succession with much higher sand-to-mud ratios and much thicker DDF intervals (up to 5-m thick), but with very thin to thin, laminated beds of interbedded siltstone and sandstone.

DDF deposits differ from PD deposits because DDFs are relatively sand-rich intervals (Fig. 3.14A) that have > 1-cm- and < 10-cm-thick discrete sheet siltstone and sandstone (Fielding 2010; Hurd et al. 2014; van der Kolk et al. 2015). DDF deposits have an ichnologic assemblage (He, Ph, Sch) consistent with a physicochemically stressed environment driven by frequent influx of sediment-laden freshwater, likely from updip distributaries (e.g., Bhattacharya and MacEachern 2009; Jackson et al. 2016). DDF intervals associated with PD and SHF without macroscopic bioturbation formed in more physicochemically stressed environments with potentially lower oxygen and higher turbidity (e.g., Jackson et al. 2016).

INTERDISTRIBUTARY BAY (IDB)

Description.—Strata between 24.5 and 27 m in SB1 contain claystone (F-2; 10–11-cm thick; Appendix A) with abundant plant debris interbedded with mudstone (F-3B) and very fine-grained sandstone (F-10; > 30-cm thick) with inoceramid shell hash lining basal erosion surfaces. In SB1 between 38–40 m siltstone (F-4B) with ripple-laminated (F-11B) and trough cross-stratified (F-7) sandstone are prevalent. Fine-grained siltstone (F-4A) between 38 and 40 m in SB1B thicken to the east (up to 4 m). In SB5A (47–57 m) lenticular-, flaser- (F-4C), and asymmetric ripple-bedded siltstone (F-4) dominate. SB5A (21–23.5 m; 47–57 m) contains 1–4-m-thick intervals of flaser, wavy, and lenticular bedded siltstone (F-4C) with lenses of very fine-grained sandstone (F-12), as well as planar-laminated to thin-bedded siltstone (F-4A). Organic-rich, lenticular and rippled siltstones (F-4A) between 21 and 23.5 m in SB5A are interbedded with very fine-grained sandstone lenses (F-12) 2-cm thick and up to 1-m wide. Ichnogenera in include He, Ph, and rare As. These deposits are interbedded with rooted intervals interpreted as paleosols (FA-I: PS).

Interpretation.—Mudstone and siltstone intervals at Shivugak Bluffs in SB1B at 24.5–27 m and 38–40 m are interpreted as interdistributary bays (IDBs) associated with proximal depositional environments (PS, MDMB–DDMB). Facies in SB5 between 21–23.5 and 47–57 m are interpreted as IDBs associated with distal depositional environments (MDMB, DDF and PD; Fig. 3.8; Appendix A). IDB deposits form between deltaic distributaries or as spits built by longshore drift after lobe switching (Elliot 1974). The opening and closing of bays is influenced by the advancement of levees, marsh

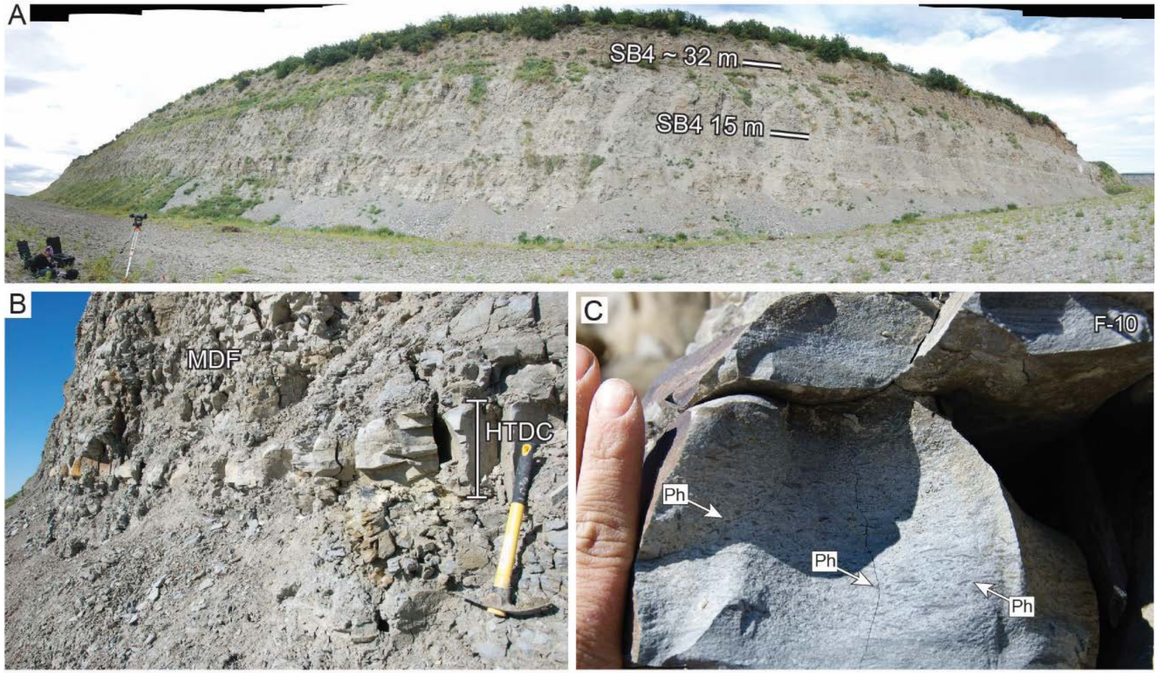


Figure 3.13. Medial delta front deposits in the Barrow Trail Mbr. A) Photomosaic of representative proximal-medial delta front (MDF) deposits from SB4 (0–32 m). See Representative section of SB4 (10.5–20.5 m) is included in Figure 3.8. B) Photograph of high width-to-depth subaqueous terminal distributary channel (HTDC) encased within MDF deposits (FA-II), yellow maddox = 40.5 cm long. C) MDF sandstone dominated by the trace fossil *Phycosiphon* with an ichnofabric index of 6.

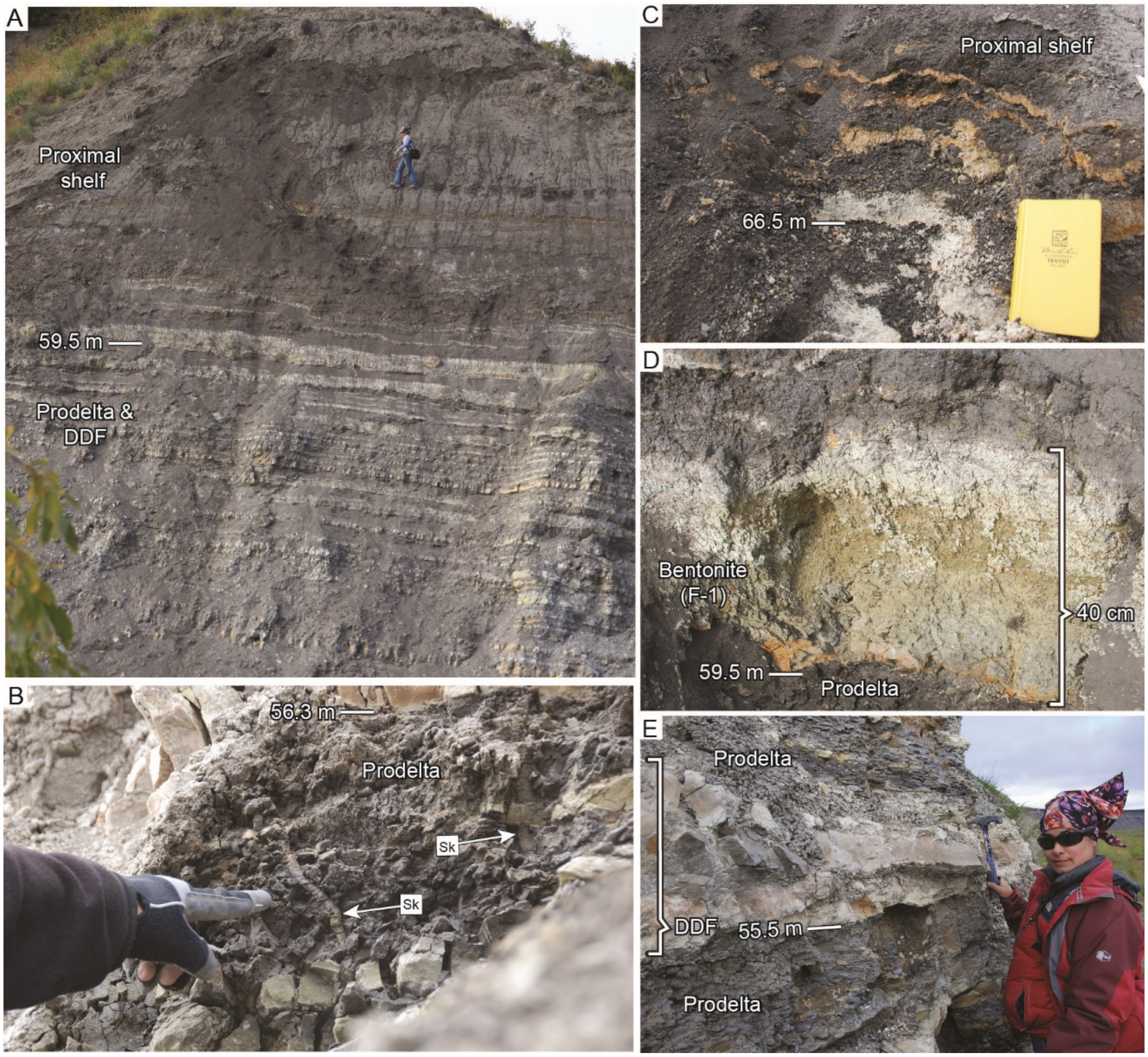


Figure 3.14. Transition of the Barrow Trail and Sentinel Hill mbrs in SB4 (see Fig. 3.17). A) Outcrop expression of measured section SB4 between ~ 41 and 73 m containing interbedded distal delta front (DDF), prodelta (PD) and proximal shelf (SHF) facies; B) The widest burrows (10 to 15 mm wide) within the lower Schrader Bluff Formation at Shivugak including the rare occurrence of *Skolithos* in prodelta mudstone; C) Organic-rich mudstone (F-3A) and thin bentonite layers (2 to 10 cm thick; F-1) interpreted as proximal shelf deposits; D) An example of one of the thickest bentonite layers (up to 40 cm thick) in the lower Schrader Bluff Formation; and E) Erosional basal surfaces of sandstone interpreted as distal delta front deposits encase within prodelta deposits at 55.5 m.

ridges, and minor channels on the lower delta plain or by wave reworking the coastline (Elliot 1974; Pulham 1989). Relatively thin IDB deposits in this study are not as thick or as well developed as those documented up section in the Sentinel Hill Mbr at Shivugak Bluffs (van der Kolk et al. 2015). We interpret MDMBs, DDMB, and DDF as forming 0.5–5 m thick irregular, 3D-lobate features that produce variable bathymetry. This allowed protected embayments to develop and form IDBs between smaller compensationally stacked DMB and DDF lobes (Wellner et al. 2005).

Lenticular-, flaser-, and asymmetric rippled intervals are similar to facies previously interpreted as IDB deposits in the Schrader Bluff Fm (van der Kolk et al. 2015) and in a younger interval 70 km north along the Colville River at Ocean Point (Phillips 2003). Unlike previously described IDBs (cf. van der Kolk et al. 2015), intervals documented in this study have lower ichnodiversity. IDBs generally have a trace-fossil assemblage that includes He and Ph; however, sandy intervals have Ma and rare As and Co. Parallel- to ripple-laminated and trough cross-stratified very fine-grained sandstone interpreted as DDMBs prograded into and interfinger with IDB deposits. IDBs in measured section SB1 (24.5–27 m) (Appendix A) are underlain by rooted HTDCs and are overlain by paleosols and distal DMBs, similar to back-barrier lagoons in the modern Brazos delta (Rodriguez et al. 2000). IDBs within fluvial-dominated deltaic systems are characterized by extensive vegetation and rooted facies, which indicate subaerial exposure and pedogenic modification (Fisk 1961; Allen 1965; Elliot 1974; Pulham 1989). IDB deposits with low-diversity marine trace-fossil assemblages indicate physiochemically stressed conditions (e.g., Bhattacharya and MacEachern 2009; van der Kolk et al. 2015).

PRODELTA (PD)

Description.—Mudstone, siltstone, and very fine- to fine-grained sandstone intervals in SB–2, SB–1, SB2, SB3, SB4 and SB5A range from 0.3–40 m thick (Fig. 3.4). The best representative successions for this association are in SB-2 between 4.5–14.5 and 22–26.5 m (Appendix A). These intervals (Figs. 3.14, 3.15) comprise laminated to medium-bedded (up to 15 cm), homogeneous mudstone (F-3A) with very thin-bedded (1 cm) siltstone (F-4A) up to 0.5-m thick, and laminated to thin-bedded (1–6 cm) claystone (F-2). Bentonite (F-1) is present but rare (Fig. 3.14). Lithologic boundaries range from gradational coarsening upward to fining upward contacts, or are sharp or erosional. Ichnogenera include He and Ph (ii 2 to 4) and rare Sk (up to 10 mm wide; Fig. 3.14B).

Interpretation.—Thick successions (Figs. 3.8, 3.14) of laminated to medium-bedded mudstone, siltstone, sandstone, and claystone with gradational contacts are interpreted as interbedded hyperpycnites and hypopycnites deposited in a prodelta (PD) environment (e.g., Bhattacharya and MacEachern 2009). PD intervals are typically found above SHF deposits and below MDF and IDB deposits. In some intervals, bentonite and siltstone layers in PD intervals are asymmetrically rippled or contain entrained sand detritus and bentonite rip-up clasts (up to 3-cm wide), suggesting higher energy conditions that include river-borne currents or wave-enhanced sediment gravity flows (e.g., Gani and Bhattacharya 2007; Plint 2014). Ichnogenera are consistent with highly variable physicochemical conditions commonly observed in deltaic environments (e.g., Hurd et al. 2014; Jackson et al. 2016).

PRODELTA SUBAQUEOUS TERMINAL DISTRIBUTARY CHANNELS AND LEVEES (PDTDC)

Description.—Structureless (F-12), trough-cross stratified (F-7) and ripple-laminated very fine- to medium-grained sandstones (F-11B) fill erosional surfaces forming lensoidal to arcuate sandbodies that incise into PD deposits in SB4 (equivalent to 50.5–51.75 m) and SB5A (36.5 m and 41.75 m; Fig 3.8). In SB4, laminated siltstones between 50.5 and 51.75 m are laterally associated with a lensoidal sandbody (Appendix A). These isolated sandstones encased in mudstone range from 0.25–0.6 m thick.

Interpretation.—Mud-poor (clean), confined lensoidal to arcuate sandbodies are interpreted as prodelta subaqueous TDCs and levees (PDTDCs). Laminated and massive siltstone between 50.5 to 51.75 m in SB4 is interpreted as subaqueous levees due to the lateral association with PDTDCs (cf. van der Kolk et al. 2015). PDTDCs are similar to TDCs (0.1–1.5-m thick) previously described in PD deposits in the Sentinel Hill Mbr of the lower Schrader Bluff Formation (van der Kolk et al. 2015). Stratigraphically older PDTDCs documented herein are slightly thinner, but are interpreted to represent a similar architectural element based on similar sandbody geometries, sedimentary structures, and association with PD facies. Compared to other TDCs documented in this investigation from updip locations, PDTDCs have sedimentary structures more akin to LTDC, but are geometrically more similar to HTDCs due to the high width-to-depth ratios of PDTDCs.

Figure 3.15. Basal succession (SB-2) of the Rogers Creek Mbr exposed at Shivugak Bluffs. A) Weathered outcrop expression of low-inclined, very thin to thin bedded sandstone (F-9), mudstone (F-3A), and claystone (F-2) to show pebbles and cobbles (denoted by white circles) encased in mudstone above an erosional surface as indicated by white arrows. An erosional surface (ES0) with 0.6 m of relief, located in SB-2 at 22 m (Appendix A) erodes into the top of MDMB complexes and is consistently overlain with clasts encased in mudstone where exposed (between both SB-2 and SB-1 and beyond). Rock hammer = 30 cm long. C) Claystone (F-2) layer in SB2 bioturbated with Phycosiphon (Ph; ichnofabric index of 5).

FACIES ASSOCIATION III: WAVE- AND STORM-INFLUENCED DELTA DEPOSITS

STORM SHEETS

Description.—FA-III contains hummocky cross-stratified sandstone (F-5) 0.25- to 5.25-m thick, and SCS sandstone (F-8) 0.5–2.75 m thick commonly associated with DDMBs, MDMBs, and subaqueous HTDCs (Fig. 3.12, Appendix A). HCS and SCS in measured sections total 12.25 m in SB1, 4.5 m in SB3, and 2.4 m in SB4 (Appendix A), decreasing up stratigraphic section in abundance compared to other sedimentary structures (Appendix A). HCS are up to 4 m in wavelength and 0.25-m thick, and are associated with symmetric wave ripples (F-11A, 2–12 cm thick; Fig. 3.5). The thickest HCS intervals occur as sheet bedsets at the base of SB1A (0–10 m) (Fig. 3.5; Appendix A), and the thicknesses of HCS intervals range between 8.45 to 12.25 m over a 0.2 km transect. The few gutter casts observed in the lower Schrader Bluff Fm occur at the base of SB1A (between 0–10 m). Gutter casts are laterally connected through their association with thick HCS sandstone beds, are shallow and rounded, and infilled with matrix-supported basal lags. Basal lags consist of logs, black chert pebbles, shell debris, and mud-rip up clasts. Ichnogenera include He, Ph, Sch, Rz, Tn, *Sagittichnus* (Sa), and *Zoophycus* (Zo).

Interpretation.—SCS deltaic intervals (DSCS)—associated with medial to proximal delta front deposits—and HCS deltaic intervals (DHCS)—associated with MDMBs, DDMB and HTDCs—were deposited under storm-wave influence (Prave et al. 1996). The ledge-forming HCS sandbody associated with the 12.25-m-thick HCS interval

(SB1; 5–6.5 m), laterally becomes structureless and transitions into migrating multistory channel (HTDC) composed of trough crossbedding (F-7) (up to 2-m thick; Fig. 3.12). This sandbody is overlain and underlain by DDMBs. Trough-cross bedded intervals are interpreted as subaqueous HTDCs. This vertical and lateral succession indicates that DMBs and TDCs can transition laterally into DHCS and DSCS. This suggests that portions of the delta front at Shivugak Bluffs were likely reworked by waves (Rodriguez et al. 2000).

Gutter casts with pebble lags at the base of HCS bedsets indicate strong basal scouring and storm-wave deposition that are typical of wave-reworked storm sheets in deltaic successions (Clifton 1981; Dott and Bourgeois 1982; Myrow and Southard 1991; Cheel and Leckie 1993; Gani and Bhattacharya 2007). HCS overlain by symmetric ripple laminations (Fig. 3.8) indicates combined oscillatory flow and unidirectional currents during storm waves followed by waning storm conditions (Cheel and Leckie 1993; Gani and Bhattacharya 2007). SCS can form in shallower environments than does HCS (Leckie and Walker 1982; Duke 1985). HCS and SCS intervals can be sheetlike, indicating shoreface deposition (Leckie and Walker 1982; Duke 1985). Both HCS and SCS, however, are also found in delta-front deposits, indicating storm-wave influence and/or wave reworking of the delta front and prodelta (Prave et al.1996; Rodriguez et al. 2000). The lack of trace fossils in DSCS suggests deposition under high-energy conditions not suitable for colonization by local fauna.

FACIES ASSOCIATION IV: PROXIMAL SHELF (SHF)

Description.—Thick intervals (1–16 m) of very thin- to thin-bedded (1–10-cm thick) organic-rich mudstone are very thin to medium laminated (0.5 to 10 mm) in SB4 (42.5–45.8 m; 57.5–75.5 m) and SB5A (0–9.5 m; Fig. 3.8; Appendix A). FA-IV is more organic-rich then other muddy intervals (Fig. 3.14) and ranges from dark gray to black mudstone with rare orange and white clay-rich bentonite (F-1) layers (2–40 cm thick; Fig. 3.14).

Interpretation.—Thick mudstone successions represent proximal shelf deposits (SHF) that formed from flocs of fine particles that disseminated across the shelf and settled out of suspension (Kuehl et al. 1986; Hardy and Wren 2009). Organic-rich laminae reflect periodic marine plankton blooms preserved penecontemperaneously with river-flooding events (e.g., hypopycnite plumes; Nittrouer et al. 1984; Parsons et al. 2001; Bann et al. 2004). Bentonite layers represent airfall volcanic ash that settled out of suspension in low-energy environments, which diagenetically altered to smectite (Smith 1967; Salazar-Jaramillo et al. 2015).

PALEOFLOW

Ninety-eight paleoflow measurements were recorded from trough cross-stratification at Shivugak Bluffs, and are displayed as 11 rose diagrams adjacent to the corresponding stratigraphic intervals in Appendix A. All paleocurrent measurements were plotted as polar lines on rose diagrams in 20 degree categories. Two additional rose diagrams are included in figures 3.6 and 3.7 to show paleoflow differences between the deposits identified as river channels (SSCs) and those interpreted as TDCs. The vector mean was calculated and paleoflow was compared to previous paleocurrents recorded from distributary channels within the younger (Maastrichtian) Prince Creek Fm north of the study area (Figs. 3.6, 3.7, Appendix A).

River Channels.—Paleocurrent orientations recorded from a subaerial, small sinuous distributary channel (SSC) in SB2 at 1.5 m (n=6) indicate that local paleoflow was to the northeast, with an overall vector mean of 042° (Fig. 3.6A, Appendix A). This interval technically would be mapped as the Rogers Creek Mbr of the lower Schrader Bluff Fm, but by lithostratigraphic definition would be described as Prince Creek Fm. Paleocurrents recorded from the bulk of the younger Prince Creek Fm (n=68, Flaig et al. 2011) along the Colville River exhibit an overall mean vector of 060° (Flaig et al. 2011), which is 018° to the east of the overall mean vector from the channel in SB2.

TDCs.—Paleocurrent orientations recorded from TDCs in the lower Schrader Bluff Fm (n=92) range from 210° to 160° (Fig. 3.7, Appendix A) with the bulk of paleoflow being toward the north, expressed as an overall mean vector of 359° (Fig. 3.7, Appendix A).

Interpretation.—Paleoflow from the SSC in SB2 is consistent with previous studies of in-channel paleocurrent, indicating regional paleoflow in channel systems toward the northeast (Phillips 2003; Mull et al. 2003; Flaig et al. 2011). The mean resultant vector from TDCs in the lower Schrader Bluff Fm is 359°, which is 67° to the north of the overall vector mean of 060° for paleocurrents in Prince Creek Fm channels (Flaig et al. 2011) and 43° to the north of the paleocurrents in the SSC at Shivugak Bluffs. This suggests that the paleoflow of deltaic deposits are generally to the north. Paleoflow orientations for trough-cross stratified TDCs within deltaic successions at Shivugak Bluffs are consistent with and are interpreted as a north-facing delta lobe.

STACKING PATTERN OF FACIES ASSOCIATIONS AT SHIVUGAK BLUFFS

A proposed depositional model illustrating facies association relationships and generalized paleoenvironmental reconstruction of Shivugak Bluffs is depicted in Figure 3.16. Figure 3.17 illustrates how the facies associations stack vertically. Figure 3.18 depicts a wheeler diagram of the conceptual model in Figure 3.17. The base of the lower Schrader Bluff Fm is defined regionally as a mud-dominated, marine-flooding surface immediately overlying the Tuluvak Fm (Decker 2010; Fig. 3.2). This contact between the Schrader Bluff and Tuluvak fms is not exposed in outcrops along the Colville River (Mull et al. 2003, 2004). Sandbodies at the base of SB-2 (and laterally equivalent SB-1) section are at an unknown stratigraphic height above the top of the Tuluvak Fm and are interpreted as relatively thin DMB complexes (4–4.5 m thick) separated by 13.5 m of prodelta deposits (SB-2, 0–22 m, Appendix A). Sandbodies in SB-2 and SB-1 represent the initial pulse of sedimentation from a delta that prograded into the Shivugak Bluffs region (Figs. 3.16, 3.17), based on an overall coarsening and shoaling upward succession

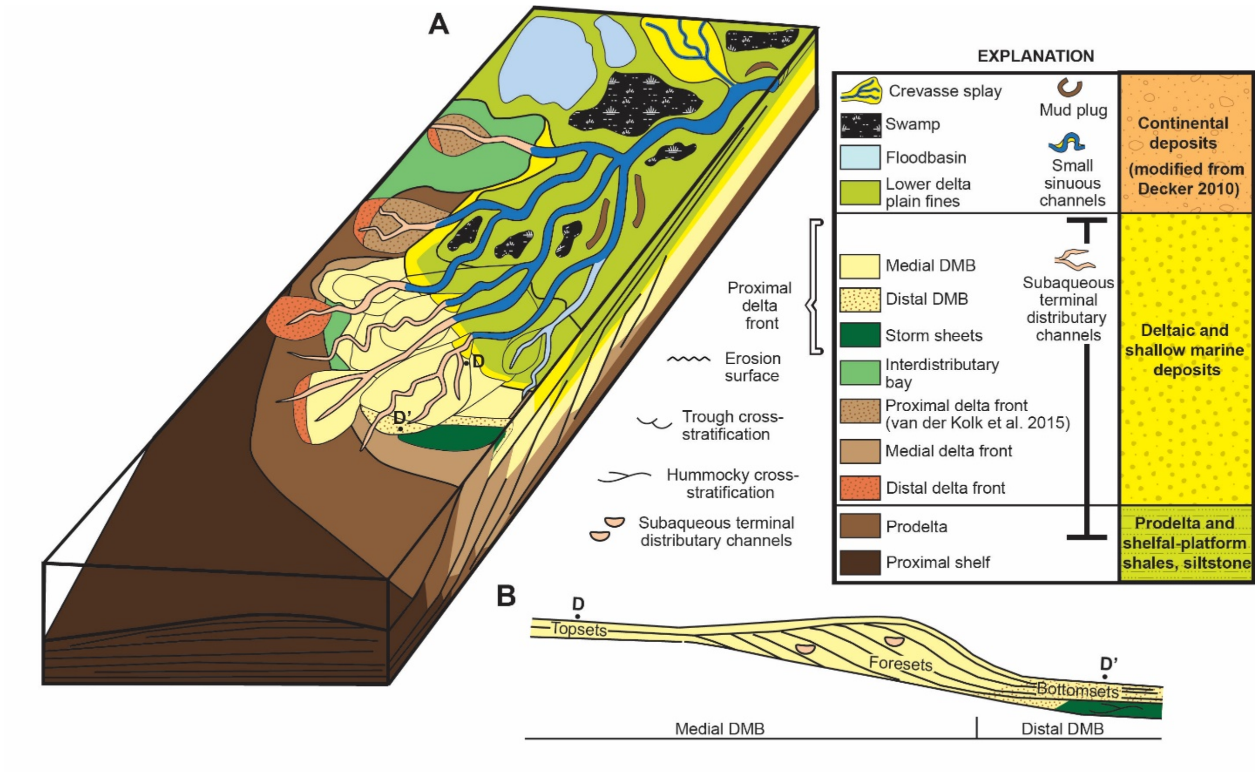
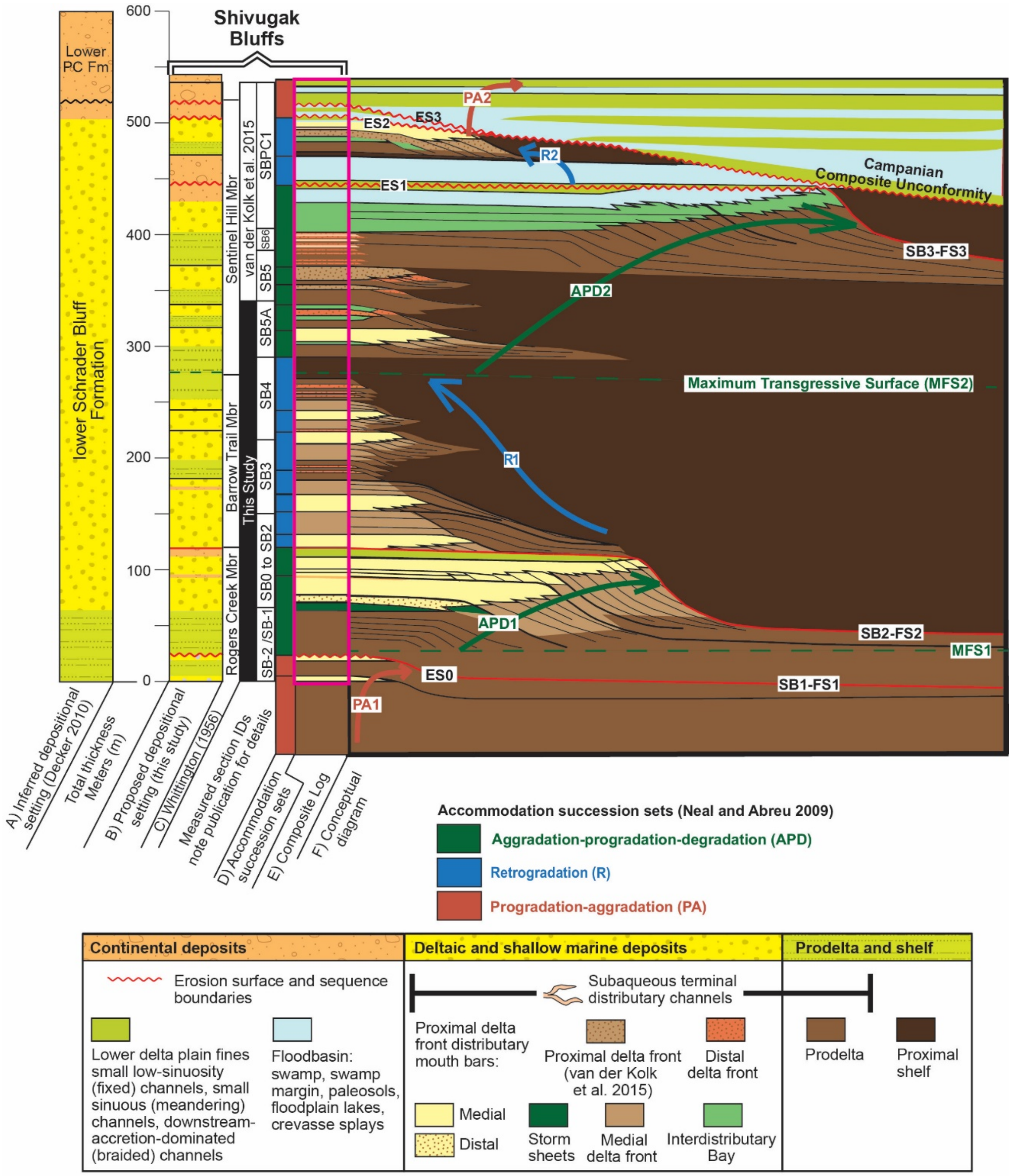


Figure 3.16. Proposed depositional model of the lower Schrader Bluff and Prince Creek formations at Shivugak Bluffs in A. Explanation includes color codes depicting depositional environments relative to lithostratigraphic diagram (modified from Decker 2010) in Figure 3.2 (Decker 2010). Cross section schematic of proximal to distal transects D-D' of distributary mouth bars in proximal delta front environments in B (modified from Wright 1977) as depicted in A.



Shivugak Bluffs
Lower PC Fm
lower Schrader Bluff Formation
Sentinel Hill Mbr
Barrow Trail Mbr
Rogers Creek Mbr
van der Kolk et al. 2015
This Study
SBPC1
SB6
SB5
SB5A
SB4
SB3
SB0 to SB2
SB-2 /SB-1
PA2
ES3
ES2
R2
ES1
Campanian Composite Unconformity
SB3-FS3
APD2
Maximum Transgressive Surface (MFS2)
R1
APD1
SB2-FS2
MFS1
ES0
SB1-FS1
PA1
A) Inferred depositional setting (Decker 2010)
Total thickness Meters (m)
B) Proposed depositional setting (this study)
C) Whittington (1956)
Measured section IDs note publication for details
D) Accommodation succession sets
E) Composite Log
F) Conceptual diagram
Accommodation succession sets (Neal and Abreu 2009)
Aggradation-progradation-degradation (APD)
Retrogradation (R)
Progradation-aggradation (PA)
Continental deposits
Erosion surface and sequence boundaries
Lower delta plain fines small low-sinuosity (fixed) channels, small sinuous (meandering) channels, downstream-accretion-dominated (braided) channels
Floodbasin: swamp, swamp margin, paleosols, floodplain lakes, crevasse splays
Deltaic and shallow marine deposits
Subaqueous terminal distributary channels
Proximal delta front distributary mouth bars:
Medial
Distal
Proximal delta front (van der Kolk et al. 2015)
Distal delta front
Storm sheets
Medial delta front
Interdistributary Bay
Prodelta and shelf
Prodelta
Proximal shelf

Figure 3.17. A schematic showing a SW-NE transect of the lower Schrader Bluff Fm. A) Schematic of inferred depositional setting of the lower Schrader Bluff Formation (Fm) from lithostratigraphic diagram (Fig. 3.2; Decker 2010). See figure 3.16 for key. B) Newly proposed depositional setting using Decker's (2010) color scheme of the lower Schrader Bluff Fm, based on measured sections described in this study and those from van der Kolk et al. (2015) at Shivugak Bluffs. C) Three members (mbrs) of the lower Schrader Bluff Fm originally proposed by Whittington (1956). D) Accommodation succession sets (Neal and Abreu 2009) assigned to depositional sequences listed in E. E) Composite log of Shivugak Bluffs, represented as pink box, showing vertical stacking patterns of facies associations. The explanation also corresponds with the proposed depositional model in Fig. 3.16. F) Conceptual diagram of an approximately southwest -northeast transect of the lower Schrader Bluff Fm measured sections SB-2 to SB5A from this investigation, and the stratigraphically younger succession that previously documented the uppermost 196 m at Shivugak Bluffs (SB5 to SBPC1 in van der Kolk et al. 2015). ES1, ES2, and ES3 are sequence boundaries and are interpreted as the Campanian Composite Unconformity (van der Kolk et al. 2015). ES3 is likely equivalent to the mid-Campanian Unconformity of Decker (2007, 2010) and E1, E2 and E3 become a composite sequence boundary down depositional dip as the lower Schrader Bluff Formation dips into the subsurface to the east.

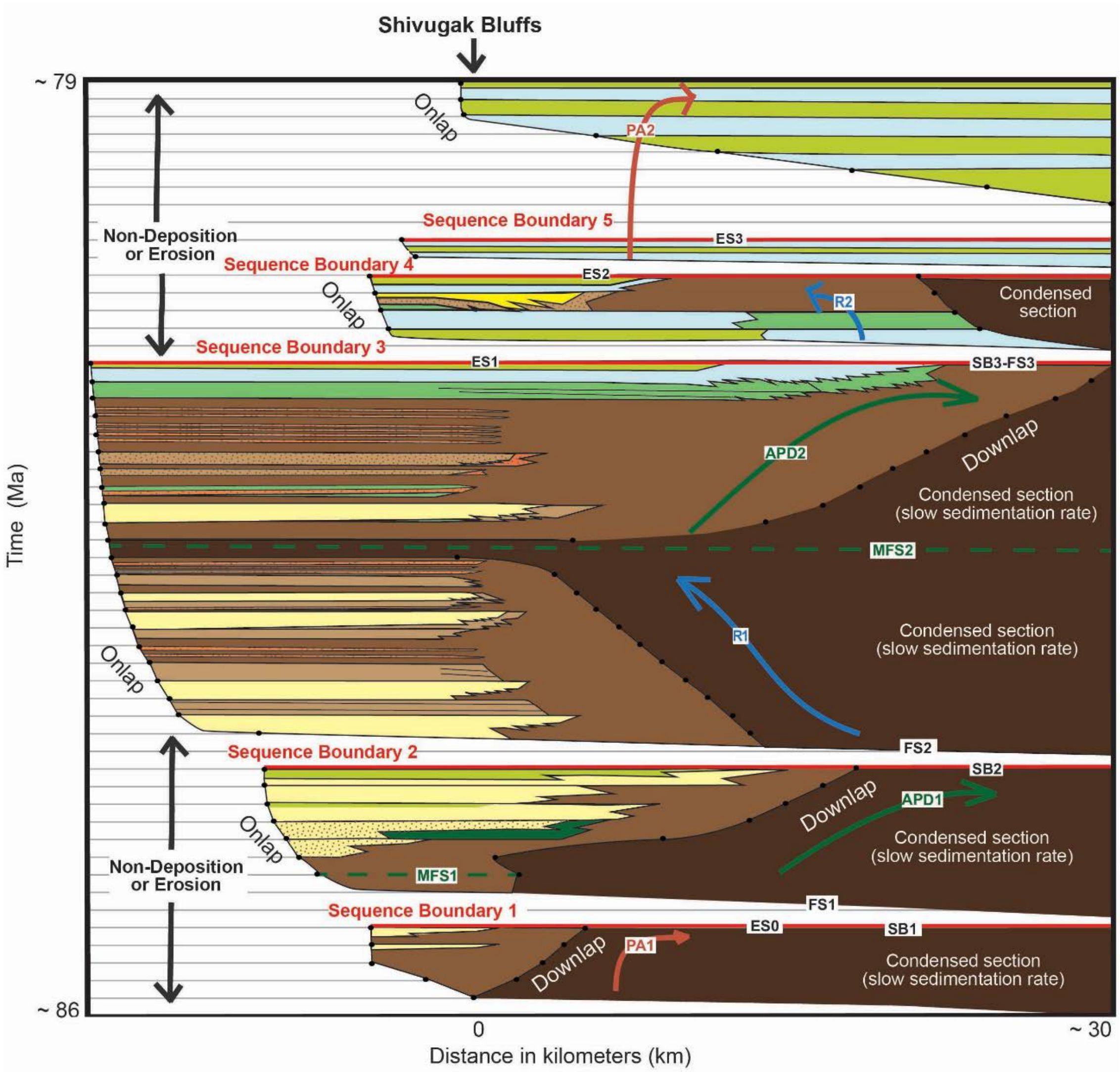


Figure 3.18. Wheeler diagram of the stratigraphic interval at Shivugak Bluffs from the conceptual model and key proposed in Figure 3.17.

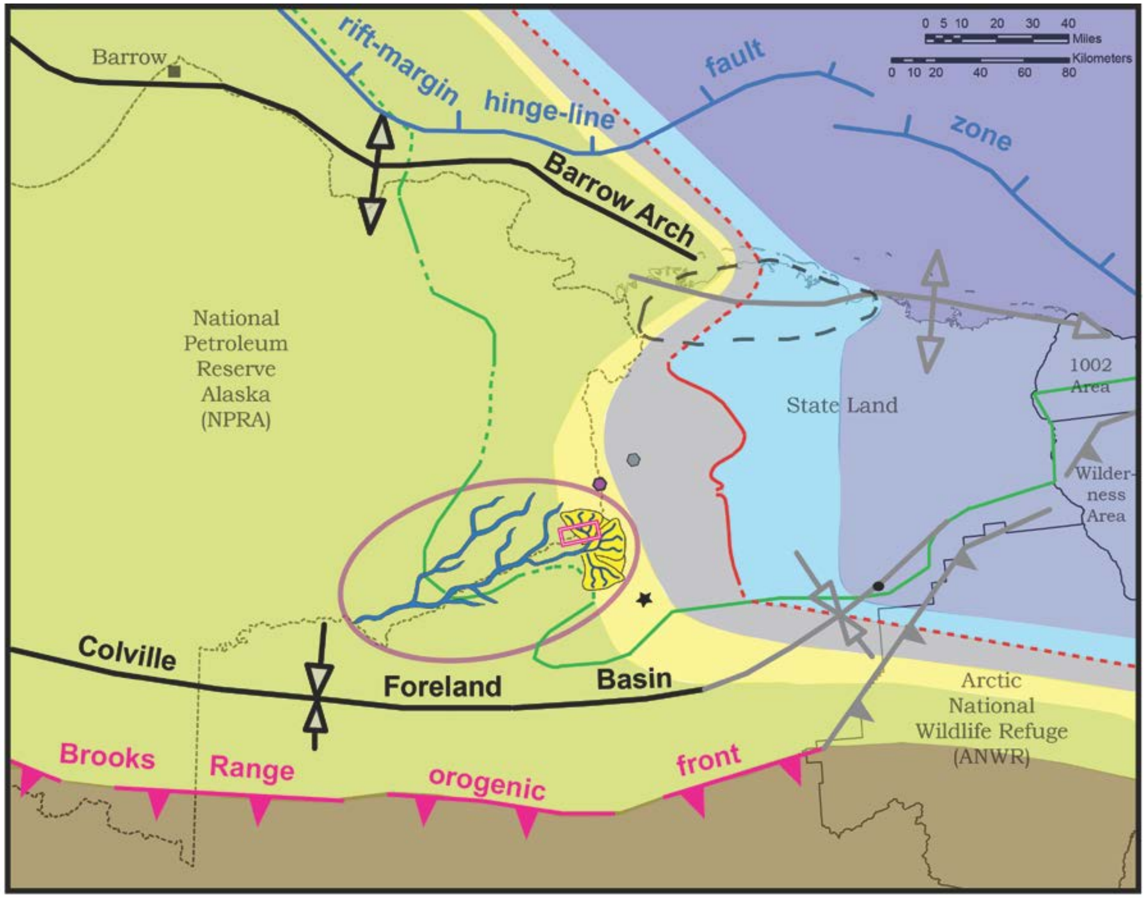


Figure 3.19. Proposed paleogeogrpahic model of the Prince Creek Fm, lower Schrader Bluff Fm, Canning Fm, and Hue Shale in Arctic Alaska. Explanation is included in Figure 3.20.

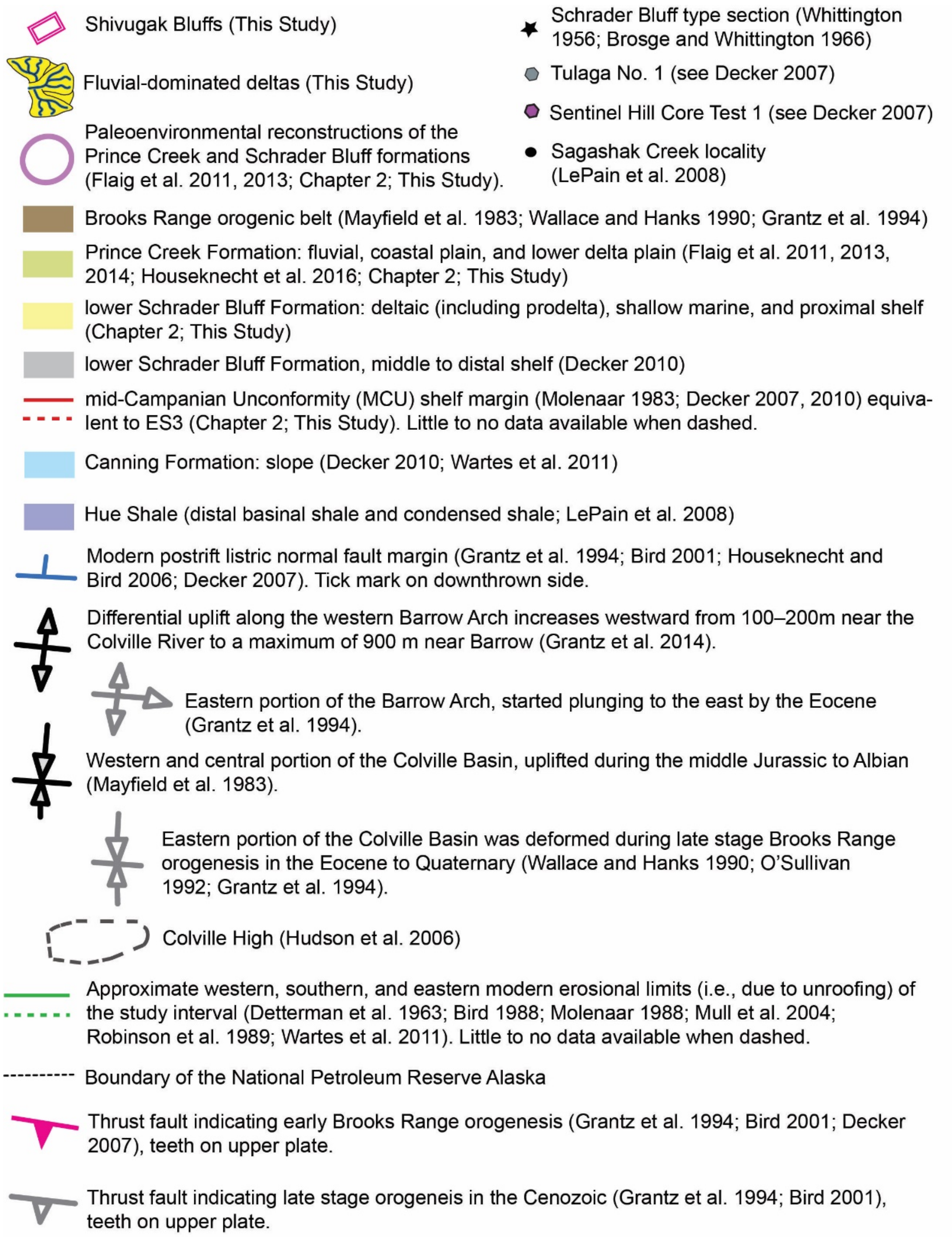


Figure 3.20. Key for paleogeogrpahic map in Figure 3.19.

including medial-delta-front deposits overlain by distal, medial, and proximal DMBs (SB-2, 0–4.5 m and 18–22 m, Appendix A). A significant erosion surface truncates the top of the youngest DMB complex (SB-2 at 22 m) and is referred to as erosion surface 0 (ES0; Figs. 3.4, 3.15, 3.17). ES0 is draped with a layer of outsized chert, quartz, and quartzite pebbles to cobbles up to 10 cm in diameter encased in mudstone (Fig. 3.15). The presence of ES0, combined with the overlying outsized clasts likely sourced from updip fluvial systems (cf. van der Kolk et al. 2015), suggests that this is a sediment bypass surface (Fig. 3.17). A 40-m-thick mudstone succession that overlies this surface is interpreted as PD mudstone (SB-2, 22–54 m; SB0 22–30 m; Appendix A).

Overlying the 40-m-thick PD succession is a ~60-m thick, sand-dominated bluff comprising three successions in ascending order: 1) HCS sheet sandstones (DHCS), DDMBs, MDMBs, LTDCs, subaqueous to subaerial HTDCs, PS, and IDB deposits (SB1B, 0–26 m, Fig. 3.5, Appendix A); 2) distal, medial, and proximal DMBs truncated by HTDCs, and IDB deposits (SB1B, 26–40 m, 14 m thick); and 3) MDMBs overlain by DDMB complexes with abundant truncation surfaces, PS interbedded with MDMB, and lower delta plain fines (paleosols, crevasse splays or levees, and swamp deposits) (SB1B, 40–54 m, 14 m thick). The numerous truncation surfaces and the high degree of amalgamation in the 3rd succession indicate cannibalization of the delta front by the river-dominated deltaic system (Ahmed et al. 2014). The top of the 3rd succession of DMBs coarsen or fine upwards laterally between SB0.3 and SB1B measured sections; the interval is capped everywhere by a 7-m-thick succession of meandering distributary channels and lower delta-plain deposits (FA-I) that extend across measured sections SB0.3 (19.5–24.5 m), SB1B (47.5–54 m), and SB2 (0–7 m) (Appendix A).

Overlying the lower delta plain deposits in SB2 are MDMB complexes (SB2, 8–16 m, and 8-m thick) and MDF and PD deposits (SB2, 24–34 m, 10-m thick). The base of SB3 contains storm-modified MDF and IDB deposits (0–5.5 m) that are overlain by a relatively thick wave-modified, MDMB succession (9–19.5 m). Interbedded DDF, MDF, DDMBs, HTDCS, and, in one interval, a rare pedogenically modified horizon with rhizoliths (SB4 29 m) overlie wave-modified MDMB complexes (i.e., SB3 at 21.5 m; SB4 at 10 m; SB4 at 30.5 m). Stratigraphically above 42.5 m in SB4, SHF deposits are interbedded with DDF, PD, and PDTDCs and levees (SB4, 44.5–59.5 m, 19 m thick). This interval is capped by 17 m of organic-rich, proximal shelf mudstone (SB4, 59.5–75.5 m; SB5A, 0–9 m). A succession comprising PD, IDB, MDMB, and DDMB deposits overlie proximal shelf deposits in SB5A (9.5–36 m; Appendix A; Fig. 3.4). A flooding surface at 36 m separates the DMB complex (SB5A, 9.5 to 36 m) from overlying PD (SB5A, 36–47 m), subaqueous PDTDCs (SB5A, 0.25–0.6 m thick), IDB (SB5A, 47–48 m, 1-m thick), DDF (SB5A, 48–53 m, 5-m thick), and IDB (SB5A, 53–57 m, 4-m thick) deposits. For a detailed description of the stratigraphy that overlies this interval see van der Kolk et al. (2015).

DISCUSSION

EVIDENCE FOR RIVER-DOMINATED DELTAS

Deltaic successions are typically categorized into the tripartite classification system containing river-, wave-, and tide-dominated end members based on modern deltaic geomorphology (Galloway 1975; Bhattacharya 2010), seismic geomorphology (Roberts et al. 2004), wireline well logs (Coleman and Prior 1982), the relative percentages of diagnostic sedimentary structures and architectures preserved in the rock record, or they are placed into some intermediate categorization between these end members (Coleman and Wright 1975; Galloway 1975; Bhattacharya and Walker 1992). Here we examine the sedimentary structures and architectural elements of the Schrader Bluff and Prince Creek fms at Shivugak Bluff to best classify the type of ancient deltaic succession exposed there.

Paleoenvironment, Facies, and Grain Size Trends.—When considering the entirety of 532 m of outcrop at Shivugak Bluffs, 17 % (93.8 m) of strata are interpreted as coastal plain deposits, 79 % (427.8 m) as deltaic deposits, and 4 % (20.4 m) as proximal shelf deposits (Fig. 3.17; Table 3.3; van der Kolk et al. 2015). The 336 m of lower Schrader Bluff Fm examined in this study comprises 47 % sand (Appendix A), whereas the overlying 196 m—previously documented from the lower Schrader Bluff Fm (SB5 to SBPC1B < 119 m; Fig. 3.17; van der Kolk et al. 2015)—comprises only 32% sand. Sand-dominated deltas in the lower 336 m have proximal delta fronts built entirely of DMB and TDC complexes with minor storm-wave influence (Figs. 3.7, 3.9, 3.11, 3.12). In contrast mud-rich, river-dominated deltas identified in the upper 196 m have a higher percentage of siltstone and mudstone between isolated sheet bedsets, and rarely contain DMBs in proximal delta fronts successions (van der Kolk et al. 2015). Mud-rich deltaic successions lack MDMB, DDMB, and LTDCS, but comprise abundant hyperpycnites sheet sandstones and subaqueous PDTDCs (van der Kolk et al. 2015). There is a lithologic change between measured sections SB5A and SB5 due to a decrease in sandstone abundance, and noticeable lack of sandy DMBs and MDF found in the stratigraphy above SB5 (Figs. 3.4, 3.17; Appendix A; van der Kolk et al. 2015). Regardless, the 196 m of strata at the top of Shivugak Bluffs record deposits of a muddy, river-dominated delta. We suggest that the change from sand-rich to mud-rich deltaic stratigraphy in the lower Schrader Bluff Fm at Shivugak Bluffs reflects a change from active sedimentation to a lack of sand in the sediment supply, possibly related to an upstream avulsion and temporary delta lobe abandonment. This is an autogenic mechanism also invoked for grain size variability within the upper 196 m (van der Kolk et al. 2015).

DMB-TDC complexes (Fig. 3.16) are distinguishable architectural elements in river-dominated deltas (Olariu and Bhattacharya 2006; Ahmed et al. 2014), and are dominantly built by traction- and inertia-flows, including hyperpycnal, and hypopycnal processes typical of turbulent jet plume deposition (Wellner et al. 2005). At Shivugak Bluffs stacking of multiple DMB-TDC complexes have a maximum cumulative thickness of ~108 m (21 % of total stratigraphy, Fig. 3.17), and are dominated by sedimentary structures and geometries consistent with turbulent jet plume deposition by rivers. The exception to this is 19.1 m of strata (4 % of total stratigraphy, Fig. 3.17) that include symmetric wave-ripples, SCS, or HCS, indicating storm-wave reworking (Appendix A; Table 3.2). Traction flows, hyperpycnites, and hypopycnites are also depositional elements in MDF, DDF, PD and PDTDC successions (Fig. 3.16), indicating that the lower Schrader Bluff Formation is predominantly built by traction- and inertia-driven processes typically associated with river-dominated deltas (Table 3.2; Fig. 3.16).

Similar to previous investigations, lenticular and flaser bedding in IDB deposits (7.1 % of total stratigraphy; Fig. 3.17) and IHS in small sinuous channels (1.9% of total stratigraphy; Fig. 3.17) at Shivugak Bluffs are sedimentary features suggestive of minor tidal influence (e.g., Elliot 1974; Thomas et al. 1987; Phillips 2003; Bhattacharya 2010; Flaig et al. 2011; van der Kolk et al. 2015). No other sedimentary structures typically associated with waves or tides (herringbone cross-stratification, double mud drapes, mud rip-ups, etc.) have been documented at Shivugak Bluffs. Small sinuous distributary channels and associated lower delta plain fines overlying DMB complexes in SB0.3 and SB1 reinforce that the Rogers Creek and Barrow Trail mbrs of the lower Schrader Bluff Fm are best classified as a deltaic system (Bhattacharya 2010; Olariu et al. 2010; van der Kolk et al. 2015).

DMB and TDC Complexes.—Such key architectural elements as DMBs and subaerial to subaqueous TDCs in river-dominated delta-front successions remain poorly understood with regard to mouth bar and channel variability (e.g., Bates 1953; Wright 1977; Olariu and Bhattacharya 2006; Ahmed et al. 2014). Elements within DMB-TDC complexes remain poorly documented, and deltaic terminology can be confusing and ambiguous (Ahmed et al. 2014). This investigation builds off previous models and describes MDMB, and DDMB complexes (Fig. 3.16) and suggests new terminology for ancient TDC networks found in outcrops (HTDC, LTDC, and PDTDC).

DMB complexes in SB1A, SB1B and SB5A record different phases of river-flood dominated deltaic sedimentation. Highly amalgamated MDMBs with abundant truncation surfaces indicate zones of mouth bar cannibalization, whereas thick (up to 2.5 m) and complete MDMBs record adequate accommodation and water column depth for preservation of complete mouth bars. Compensationally stacked DMBs and associated subaqueous TDC complexes are typical of river-mouth discharge dispersal and accumulation patterns in river-dominated deltas near the mouth of rivers near flood stage (Wellner et al. 2005; Straub et al. 2009; Hofmann et al. 2011; Ahmed et al. 2014; Flaig et al. 2016). Rooted DMBs indicate subaerial exposure that followed shallow-water deposition (Baganz et al. 1975; Hasiotis 2002, 2007).

Some DMBs at Shivugak Bluffs are associated with and incised into by channel-form structureless sandstones interpreted as subaqueous LTDCs (Fig. 3.11). Common LTDCs suggest high-sediment discharge from sediment-laden water, and possibly a sediment-choked distributary system similar to what has been described from modern environments and from the ancient rock record in the Ferron Sandstone (Mulder and Syvitski 1995; Bhattacharya 2010; Ahmed et al. 2014). Distributary channels (Fig. 3.6) of the Prince Creek Fm, similar to those interpreted to have fed these deltas, have been described as containing a high-suspended sediment load (Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015). High-suspended sediment load distributary channels are interpreted to have recurrently produced hyperconcentrated flows (Flaig et al. 2014). This high sediment load would have been delivered to the delta front. Clean, confined LTDCs and unconfined HTDCs are also associated with medial and distal DMBs, MDF, and in some intervals are reworked by HCS (Figs. 3.11–3.13).

Satellite imagery indicate that modern river-dominated deltas notably have tens to hundreds of TDCs, compared with tide-dominated deltas that have a maximum of 10–20 TDCS, and wave-dominated deltas that have 1–2 TDCs (Olariu and Bhattacharya 2006). Although TDCs account for a relatively small percentage of the overall stratigraphy at Shivugak Bluffs, when found they occur as numerous channels along the same stratigraphic horizon (van der Kolk et al 2015), as do fixed (anastomosed?) channels in the Prince Creek Fm (Flaig et al. 2011). Although we cannot say for certain that these tiered channels were all active at the same time, this would be consistent with the high abundance of active distributaries and TDCs observed in modern river-dominated deltaic systems. Sharp-based DMB complexes similar to those detailed here have been described from modern shallow-water, river-dominated deltas, such as the Volga (siltstone to very fine sandstone) and Burdekin River deltas (very fine to fine sandstones up to 4-m thick; Kroonenberg et al. 1997; Overeem et al. 2003; Fielding et al. 2005a, 2005b), and from the ancient rock record, for example in the Ferron Sandstone (Zhu 2010; Ahmed et al. 2014). The lower Schrader Bluff Fm also contains fining upward DMB complexes

(SB1B, 45–47.75 m) similar to the flood-related processes described for the Burdekin River Delta (Fielding et al. 2005a, 2005b). We interpret the combination of DMBs and TDCs as proximal delta front environments that are part of Prince Creek and Schrader Bluff fms clinoform topsets (Figs. 3.16, 3.17), which is consistent with previous investigations of river-dominated deltas described elsewhere (Olariu and Bhattacharya 2006; Olariu et al. 2010; Ahmed et al. 2014; Flaig et al. 2016).

At Shivugak Bluffs, DMBs also truncate subaqueous TDCs or fill in and drape basal erosion surfaces cut by TDCs (SB1B). Similar relationships between DMBs and TDCs have been described in ancient river-dominated deltas in the Upper Cretaceous (Turonian) Ferron Sandstone (Zhu 2010; Ahmed et al. 2014), the Panther tongue of the Star Point Fm (Olariu and Bhattacharya 2006) and the Permian Mackellar Fm of Antarctica (Flaig et al. 2016). Subaqueous TDCs have been documented to extend as far downdip as prodelta environments (van der Kolk et al. 2015), but siltstone levees described in SB4 (50.55–51.80 m) lateral to PDTDCs have not been previously documented at Shivugak Bluffs. Previous studies showed that: (1) rivers of the Prince Creek Fm were suspended load rivers, with this suspended sediment derived from clay- and ash-rich floodplains (Flaig et al. 2011, 2013, 2014; van der Kolk et al 2015); (2) these suspended load rivers were the appropriate size and had the appropriate discharge to regularly produce hyperpycnites (van der Kolk et al. 2015); and (3) some deltas were mud rich (van der Kolk et al. 2015). Studies elsewhere show that fine-grained deltaic systems in general have complex deltaic morphologies (e.g., birdsfoot) with more abundant distributary channels and high rugosity at the coastline compared to sandy counterparts (Edmonds and Slingerland 2010; Geleynse et al. 2011). Field-based and numerical–computational models indicate that depositional settings with increased silt-mud concentrations exhibit more elongate and sinuous planview deltaic geometries and that TDCs extend much further from the shoreline (Orton and Reading 1993; Edmonds and Slingerland 2010; Geleynse et al. 2011). Shivugak Bluffs contains abundant DMBs and numerous instances of TDCs that extend into the delta front and prodelta.

We interpret the fluvio-deltaic system of the Prince Creek–Schrader Bluff fms as a river-dominated deltaic system based on the abundance of DMBs, TDCs, and hyperpycnites along with a scarcity of wave- and tide-dominated sedimentary structures and associated architectural elements.

POTENTIAL DRIVERS FOR RECURRING RIVER FLOODS, PALEOGEOGRAPHY, AND PRESERVATION

Deposits of river-flood origin can be identified by strata containing such high-energy flows as cohesionless debris flows or high-density turbidity flows (i.e., hyperpycnites) in lower delta-plain, delta-front, and prodelta environments (García-García et al. 2011). Evidence for recurring river floods (fluctuating discharge) is relatively common in both the Schrader Bluff and Prince Creek fms. Previous studies identifying fluctuating discharge in the Prince Creek and Schrader Bluff fms include: 1) IHS and ubiquitous roots in river channels interpreted to reflect a combination of tidal influence and seasonal discharge (Flaig et al. 2011); 2) floodplains dominated by crevasse splays and crevasse-splay complexes indicative of frequent levee breaches

(Flaig et al. 2011); 3) macro- and micro-scale characteristics of paleosols that suggest repeated wetting and drying on floodplains (Flaig et al. 2013); 4) recurring hyperconcentrated flows suggesting repeated clay- and ash-rich floods that overtopped levees and spilled onto floodplains (Flaig et al. 2014); 5) hyperpycnites and TDCs on the delta front to prodelta suggesting frequent underflows delivered by distributaries with the appropriate size and discharge to recurrently produce hyperpycnites (van der Kolk et al 2015); and 6) isotopic evidence from invertebrate shells for seasonal fluctuations in discharge (Suarez et al., 2016) and from vertebrate teeth and pedogenic siderite for an intensified hydrological cycle and latent heat transfer to the poles (Suarez et. al, 2013).

Seasonal discharge (flashiness) has been proposed as a mechanism for repeated river flooding and alternating wetting and drying on the lower delta plain of the Prince Creek Fm (Flaig et al. 2011, 2013, 2014), with the seasonal discharge possibly related to a polar light regime and snowmelt in the ancestral Brooks Range (Herman and Spicer 2010). Although no evidence of cryoturbation or ground ice has been found in Late Cretaceous sediments or paleosols of the Prince Creek Fm, seasonality is evident from ring patterns in fossilized wood (Spicer et al. 1992; Spicer 2003). Elevations likely exceeded 1500 m in the Brooks Range, with mean annual temperatures below 0° C at higher elevations (Spicer 2003) likely resulting in seasonal ice and snow (Spicer and Parrish 1990b; Fiorillo et al. 2009). High-discharge events that delivered floodwaters to deltas may have been generated by seasonal snowmelt in the Brooks Range.

A second explanation for recurring floods may have been seasonal storms or extreme variability in discharge events (e.g., Fielding et al. 2006). Previously documented storm-flood deltas contain abundant hyperpycnites, sheet sandstones, sinuous subaqueous channels in delta front and prodelta environments (e.g., García-García et al. 2011), and common well-developed, sharp-based, coarse-grained mouth bars (Fielding et al. 2005a, 2005b). Deltaic successions at Shivugak Bluffs include a 60-m thick succession of sandy DMB-TDC complexes and intervals with isolated hyperpycnite sheet sandstone encased in hypopycnite mudstone and siltstone, indicating turbulent sediment-laden flows. Subaqueous channels are found in delta-front and prodelta environments and in shallower environments HTDCs are rooted, indicating flashy, seasonal discharge or exceptional discharge events (cf. Flaig et al. 2011, 2014). Rodriguez et al. (2000) documented episodic and evolving growth of channel mouth bar sediments deposited above distal mouth bar sediments as a result of the 1965 and 1992 flooding events along the New Brazos Delta in Texas. During multiple storm events, channel mouth bars formed, which became enlarged and back-bar lagoons developed due to the protection of seaward positioned DMBs (Rodriguez et al. 2000). Well-developed, amalgamated DMB-TDC complexes are common at Shivugak Bluffs (Fig 3.11, Appendix A). LTDCs are interpreted to record high-sediment discharge events. DMBs can be interbedded with storm sheet sandstones. Discrete bioturbated intervals with high ii in distal distributary mouth bar complexes, medial delta front (Fig. 3.13), distal delta front, and prodelta deposits (Fig. 3.14B) may represent relatively quiescent intervals between river floods (e.g., Jackson et al 2016). DMBs and HTDCs transition laterally into wave-reworked deposits (Fig. 3.12). The New Brazos Delta in Texas exhibited penecontemporaneous modification by storm waves along the coastline during flooding events (Rodriguez et al. 2000). At Shivugak Bluffs, 15–19 % of the DMB-TDCs complexes, notably DDMBs, MDMBs, and LTDCs are laterally HCS and SCS or are interbedded with HCS storm sheets (Figs. 3.4, 3.17). Strata at Shivuagk Bluffs lack coarse-grained, cohesionless debris flows often associated with hyperpycnites (García-García et al. 2011). This is likely a product of the fine-grained nature of the sediment available to be delivered to the deltas (Flaig et al. 2011, 2013, 2014; van der Kolk et al. 2015). Deltas at Shivugak Bluffs have numerous characteristics similar to deltas characterized as storm-flood, river-dominated deltas and are, therefore, classified as such. This would suggest that multiple storms delivered rainfall to the Brooks Range, coastal plain, and lower delta plain, and are an alternative mechanism to seasonal snowmelt that could have driven the recurring flooding events recorded in strata at Shivugak Bluffs.

In order to preserve a river-dominated deltaic succession along the Arctic Ocean shoreline during the Late Cretaceous an embayed area within the Colville Basin is interpreted and presented in a paleogeographic map in Figure 3.19 (see Fig. 3.20 for key). The northern margin of the Colville Basin, known as the Barrow Arch, is a product of multiple Jurassic through Cretaceous tectonic events rather than a single episode of folding or upwarping (Grantz et al. 1994; Houseknecht and Bird 2006). Coeval strata of the lower Schrader Bluff Formation downlaps, thins, and coalesces with similar aged basinal condensed shale northeastward into the low-accommodation area associated with the Barrow Arch (Bird 1989; Houseknecht and Bird 2001; personal communication, D. Houseknecht, United States Geological Survey, 2016). Several seismic lines depict thick Brookian stratigraphy that does not appear to be affected by the western Barrow Arch (Houseknecht and Bird 2011); however; reactivation of either the Barrow Arch, or a structural feature known as the Colville High (Hudson et al. 2006), or a combination of these structures with the presence of older paleoshorelines (e.g. Nanushuk and Tuluvak fms) may have caused a large embayment within the Colville Basin during deposition of the lower Schrader Bluff Fm. Regionally the lower Schrader Bluff Formation thins to the north, potentially reflecting reduced accommodation in that direction during the Santonian to mid-Campanian (see A-A' in Herriott et al. 2015) or perhaps an increase in accommodation to the south related to the Colville Basin foredeep during deposition of the lower Schrader Bluff Fm (Figs. 3.19, 3.20).

SEQUENCE STRATIGRAPHY

Accommodation succession sets (Neal and Abreu 2009) were assigned to depositional sequences at Shivugak Bluffs (Figure 3.17). Santonian−Campanian deposits of the lower Schrader Bluff Fm overly a regional flooding surface located above the Tuluvak and Seabee fms that are not exposed at Shivugak Bluffs (Mull et al. 2004; Decker 2007, 2010). The basal lower Schrader Bluff Fm at Shivugak Bluffs includes a 4-m-thick DMB complex, overlain by 13 m of PD mudstone, and another 4-m-thick DMB complex overlain by a 40-m-thick prodelta succession (Fig. 3.17). The two DMB successions shoal upward relative to one another and are interpreted as the first progradational-aggradational (PA1) pulse of the lower Schrader Bluff Fm (Fig. 3.17; SB-2 in Appendix A). An erosional surface truncates the top of the DMB in SB-2 at 22 m (ES0), and ES0 is overlain by anomalous pebble and cobble clasts encased in mudstone (see Fig. 3.15), indicating a drop in sea level, and sediment bypass surface that truncates and overlies PA1 (Fig. 3.17). Along the ES0 surface, SB1 and FS1 are grouped as conformable surfaces (SB1-FS1; Fig. 3.17). SB1-FS1 is overlain by a 40-m-thick prodeltaic succession interpreted as having a maximum flooding surface (MFS1) and the initial aggradational phase of the thinnest aggradational–progradational–degradational (part of APD1) succession set at Shivugak Bluffs. Above the 40-m-thick PD succession is a ~ 60-m-thick sandstone succession that represents the progradation and aggradation phase of APD1, and is recorded in measured sections SB0, SB0.3, SB1A, and SB1B (Fig. 3.17; Appendix A). Sequence boundary two-flooding surface two (SB-FS2) occurs above meandering channel and crevasse splay deposits, and paleosols in measured section SB2. Lower delta plain deposits are not encountered again at Shivugak Bluffs until ~445 m, below ES1 in measured section SBPC1 (Fig. 3.17).

Overlying SB2-FS2 is ~175 m of back-stepping, deltaic parasequences grouped into a retrogradational (R) succession set (R1). MDF, DDF, and PD deposits are recurrently deposited above DMB complexes, forming at least four back-stepping parasequences (see measured sections SB2, SB3 and SB4). These parasequences are ultimately transgressed by SHF deposits (SB4 at 42.5 m and 57.5 m). The second maximum flooding surface (MFS2) is interpreted to occur within the thickest succession of SHF deposits, which is also the maximum transgressive surface (Posamentier and Allen 1999) based on SHF deposits being the most seaward depositional environment exposed at Shivugak Bluffs.

The start of APD2 begins at ~280 m in the composite section (Fig. 3.17) with the return of MDMB and DDMB complexes (see measured section SB5A, 9.5–36 m). The basal parasequence in APD2 contains the last succession of MDMB and DDMBs exposed at Shivugak Bluffs. The overlying deltaic sequences in APD2 (> 57 m in SB5A), and the rest of the stratigraphy are detailed in van der Kolk et al. (2015) and summarized here. APD2 is generally muddier than APD1. Strata in SB5 and younger strata higher in the succession have muddier proximal delta front deposits than underlying sequences, and sandstone beds tend to consist of relatively thin, discrete event beds interpreted as hyperpycnites (van der Kolk et al. 2015) instead of relatively thick DMB complexes (Fig. 3.17). DDF deposits, TDCs encased in PD deposits, and IDBs become more abundant (van der Kolk et al. 2015). IDBs shoal upward and become subaerially exposed, resulting from the abandonment of the deltaic system or delta lobe (van der Kolk et al. 2015). IDBs are overlain by paleosols, crevasse splays, and distributary channels. In SBPC1A at 45 m, an erosional surface (ES1) and anomalous pebbles indicate a moderate drop in relative sea level and is, therefore, interpreted as a sediment bypass surface similar to ES0. ES1 is interpreted as the end of the APD2 and is marked as SB3-FS3 (Fig. 3.17).

A thick, floodbasin-lake succession overlies SB3-FS3 (SBPC1 48.5 to 69 m) at ~445 m and is interpreted as the base of the second retrogradational succession set (R2; Fig. 3.17). At SBPC1A, marine deposits above ~470 m contain Ph, indicating a significant marine flooding surface. This marine flooding event is interpreted to continue into the subsurface for more than 50 km (32 miles) from Shivugak Bluffs based on the high-gamma response in the Itkillik Unit 1 and Tulaga No. 1 wells, with picks provided by Paul Decker (pers. communication, Alaska Division of Oil And Gas 2015) and Bird (2006). This flooding surface is below what is commonly referred to as the mid-Campanian Unconformity (MCU of Decker 2007; 2010) and is the last pulse of the lower Schrader Bluff Fm deltas at Shivugak Bluffs. R2 is overlain by paleosols, swamp, swamp margin, crevasse splay or levee, and small sinuous, meandering, and braided channel deposits interpreted as the second PA cycle (PA2; Fig. 3.17). ES2 truncated the top of a meandering channel and ES3 is at the base of a braided channel (Chapter 2). ES1, ES2, and ES3 are interpreted as the Campanian composite unconformity (CU) by van der Kolk et al. (2015), and down depositional dip these three unconformities become a Composite Sequence Boundary (Fig. 3.17; McCarthy and Plint 1998). In the subsurface, this Composite Sequence Boundary is mapped as the MCU, which is correlative with ES3 in this proximal setting.

IMPLICATIONS FOR RESERVOIR MODELERS

Although we examined a laterally extensive outcrop belt and do not have the complete plan-view perspective of this river-dominated deltaic depositional system at Shivugak Bluffs, we present a depositional model that is atypical of what many have interpreted for paleoenvironments and stacking patterns of Schrader Bluff Fm in northern Alaska (Fig. 3.16). Historically, the Schrader Bluff Fm has been interpreted as wave-dominated shoreface successions (Flores et al. 2007b; LePain et al. 2008). The overall geometries and internal architectural elements are markedly different between river-dominated deltas (lobes) and wave-dominated shorefaces (sheets), or wave-dominated deltas (mixed lobes and sheets). Shoreface environments typically include foreshore, upper shoreface, lower shoreface, and offshore components dominated by sand, silt, and mud that include such sedimentary structures as low angle planar lamination, trough cross stratification, SCS, HCS, symmetrical ripple cross lamination, and interbedded silt and mud (e.g., Bhattacharya and Walker 1992; Bhattacharya 2010). Wave-dominated deltas have some similar characteristics and also include channels (Boyd et al. 1992). In contrast, sand-prone, river-dominated deltas at Shivugak Bluffs contain distributary channels and floodplains, abundant DMB-TDC complexes, MDF, DDF, IDBs, PD, PDTDCs, and rare DHCS and DSCS (Figs. 3.6–3.16). A river-dominated delta interpretation invokes a much different gross-depositional-environmental map (Fig. 3.16) when modeling the Schrader Bluff and Prince Creek fms as potential reservoirs in the subsurface.

The best reservoir sandstones in the lower Schrader Bluff Fm at Shivugak Bluffs are within DMB-TDC complexes (up to 60-m thick) in APD1 (Figs. 3.7, 3.9, 3.11, 3.17), and DMB complexes and MDF deposits in R1. MDF sandstones with subordinate mudstone interbeds in R1 have the highest ii, which potentially increases permeability of reservoir sandstones. MDF deposits (Fig. 3.13) lack the internal architectural and lateral variability of DMBs, and may prove to be more laterally extensive as reservoirs than DMB complexes.

The combination of lobate and compensationally stacked DMB architectures, sigmoidal and trough cross-stratification in MDMBs, truncating TDCs infilled with trough cross-stratification, erosional bounding surfaces (e.g., recurring cannibalization of the deltaic system), and rare overprinting of HCS makes paleoenvironmental interpretation challenging, even along these laterally extensive outcrop belts. Facies and environments exhibit dramatic changes laterally in this dynamic depositional system. DMBs could easily be mistaken as HCS in core due to the draping nature of compensationally stacked DMBs. Care must be used when evaluating similar environments in cored intervals and making predictions about reservoir geometries.

CONCLUSIONS

The 532 m-thick continuous succession at Shivugak Bluffs comprises river-dominated deltas that are of value to workers who model clinoform-topset and deltaic systems, high-latitude greenhouse depositional systems, and Alaska North Slope hydrocarbon reservoirs. This manuscript provides the first detailed sedimentologic and sequence stratigraphic analysis of sand-dominated proximal deltaic environments of the lower Schrader Bluff and Prince Creek fms at Shivugak Bluffs. The main conclusions of this outcrop-based analysis in the National Petroleum Reserve–Alaska are;

1. Relatively sand-rich deltas in the Rogers Creek and Barrow Trail mbrs of the lower Schrader Bluff Fm are constructed predominantly of progradational and retrogradational DMB-TDC complexes and MDF deposits with abundant hyperpycnites and minor HCS and SCS, indicating river-dominated deltas with minor wave influence.
2. Relatively mud-rich, river-dominated deltas in the Sentinel Hill Mbr are composed of hyperpycnite-dominated sheet sandstones interbedded with siltstone or mudstone in PDF and DDF deposits with minor DMBs, and a relative lack of MDMB-DDMB-TDC complexes and MDF deposits found in the lower 336 m.
3. The fining upward succession at Shivugak Bluffs—representing an evolving sand-rich to mud-rich deltaic system—is likely due to a reduction in sand within the sediment supply caused by autogenic processes (i.e., lobe abandonment or avulsion).
4. DMB-TDC complexes with abundant erosion surfaces, hyperpycnites, and minor wave influence record deltaic cannibalization and variable discharge related to seasonal snowmelt, river floods by storm events, or a combination of both.

5. Shivugak Bluffs is interpreted as having two PA, two APD, and two R accommodation succession sets. ES1, ES2 and ES3 become a composite sequence boundary down depositional dip.
6. From a reservoir perspective, DMB-TDC complexes and MDF deposits in sand-rich portions of river-dominated deltas are the thickest and most continuous reservoirs at Shivugak Bluffs.

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CHAPTER 4 – A SEDIMENTOLOGIC ANALYSIS OF RIVER- VS. WAVE-DOMINATED DELTAS: THE LOWER SCHRADER BLUFF FORMATION (ARCTIC ALASKA) AND BLACKHAWK FORMATION (UTAH)[3]

ABSTRACT

Deltaic deposits of the Upper Cretaceous (Santonian–Campanian) Rogers Creek Member of the lower Schrader Bluff Formation, deposited at ~ 80 to 83° N along the paleo-Arctic Ocean margin, are compared to the lower and middle Campanian Kenilworth and Grassy members of the Blackhawk Formation, deposited at ~ 42° N along the margin of the Western Interior Seaway. A detailed analysis of sandbodies that range from 34–37-m thick and ~ 200-m wide illustrates how two discernibly different depositional systems could potentially be mistaken as the same type of system if interpretations were based solely on cored intervals. Stratal architectures and sedimentology indicate that there are significant and quantifiable differences between these depositional systems. The stratigraphic architecture of Rogers Creek Member includes amalgamated distributary-mouth-bar and subaqueous terminal-distributary-channel complexes (54%) with minor swaley and hummocky cross-stratified, wave-reworked deposits (46%). This succession is compared with the Kenilworth and Grassy members that exhibit dominantly swaley and hummocky cross-stratified intervals (75–81%) with minor channel complexes (14–25%). Results indicate that the Rogers Creek Member at Shivugak Bluffs is a river-dominated delta with minor wave-influence,

[3]This chapter is intended for future publication in Sedimentology.

whereas both members of the Blackhawk Formation contain wave-dominated deltaic successions. Architecturally, the Rogers Creek Member forms highly amalgamated DMB-TDC complexes that stack compensationally, and the Kenilworth and Grassy members are dominated by relatively continuous amalgamated HCS and SCS tabular beds and bedsets punctuated by muddy or thin-bedded intervals with lenticular or wavy laminations. Trace fossils assemblages are similar; however the tracemakers producing high ichnofabric indices are significantly different. Common interdistributary facies between the DMB-TDC complexes, which are inferred to have lobate geometries in the river-dominated deltaic systems, suggests that the Rogers Creek Member would contain complex reservoirs. Continuous shoreface deposits along strike, typical of wave-dominated deltaic and shoreline systems, suggests that the Blackhawk Formation would contain simple homogeneous reservoirs. Although one would expect that the high-latitude greenhouse depositional systems of the Arctic Ocean would generate more wave-dominated stratigraphy, observations from the Rogers Creek Member are counterintuitive, suggesting deposition in a protected embayment within the Arctic Ocean due to the preservation of predominantly river-generated deltaic strata.

INTRODUCTION

The Book Cliffs in the Uinta Basin of eastern Utah contain some of the best outcrop exposures of Upper Cretaceous marine to continental strata deposited along the Western Interior Seaway (WIS), an epeiric or epicontinental seaway that extended north to south across Cretaceous North America (Van Wagoner et al., 1991). The combination of sparse vegetation, open road access, and extensive rock exposures—both along depositional strike and dip—allow researchers easy access to study strata in detail. Facies, paleoenvironments, stratal architectures, paleogeography, and sequence stratigraphy of the Book Cliffs are well documented (Van Wagoner et al., 1990, 1991; Kauffman & Caldwell, 1993; Pattison et al., 2007; Blakey & Ranney, 2008; Fillmore, 2011). The Book Cliffs are frequented by university classes for educational purposes, and are considered outcrop analogues for oil-field-scale shoreface, deltaic, and coastal-plain fluvial-distributive reservoir systems around the world, including Arctic Alaska reservoirs (Van Wagoner et al., 1990, 1991; O'Byrne and Flint, 1993; Corbett et al., 1994; Pattison et al., 2007). Epicontinental seas similar to the WIS actually make up a small percentage of Earth's surface area today (e.g., Gulf of Carpentaria, Hudson Bay, Baltic Sea; Algeo et al., 2008; Harries, 2009), but were more common during greenhouse periods in Earth history (e.g., Cretaceous; Blakey & Ranney, 2008) when there was less ice at the poles and sea level was significantly higher. The WIS could, therefore, be considered as an anomalous phenomenon, and not the norm, compared to extensive passive margin shelves common today and in the past (e.g., Miall, 1984; Blakey & Ranney, 2008). Despite epicontinental seas comprising a small fraction of the world's ocean systems through geologic time, researchers who study fluvio-deltaic or shallow marine successions are often tasked with placing their study in a context relative to strata and depositional processes described from the WIS (e.g., Flaig et al. 2016).

This study explores whether two well-exposed, well-documented, and commonly visited intervals in the Book Cliffs—the Kenilworth and Grassy members of the Blackhawk Formation (O'Byrne & Flint, 1993, 1995, 1996; Taylor & Lovell, 1995; Eide et al. 2014)—should be used as an outcrop analogue for subsurface viscous- to heavy-oil reservoirs of the Upper Cretaceous (Santonian–Campanian) Schrader Bluff Formation in the Colville Basin of Arctic Alaska (Fig. 4.1). In this comparison, outcrops of near-coeval progradational deltaic successions (~ 4,135 km apart) were studied for their ichnology, bedforms, facies-stacking patterns, and stratal architecture. The Kenilworth and Grassy members of the Blackhawk Formation, widely recognized as wave-dominated deltaic successions, are compared to the Rogers Creek Member of the lower Schrader Bluff Formation (Fig. 4.2; Pattison, 1995; Taylor and Lovell, 1995; Hampson, 2000; Chapter 3), a stratigraphic succession historically interpreted as wave-dominated but recently reinterpreted as river-dominated deposits. Although the Rogers Creek Member of the lower Schrader Bluff Formation was recently interpreted to contain predominantly river-dominated delta deposits, wave influence was also documented along the delta front (Chapter 3). We, therefore, compare the most wave-influenced portion of the lower Schrader Bluff Formation to the Kenilworth and Grassy members of the Blackhawk Formation. All three successions contain channels at the top, suggesting that each should be considered deltaic successions (O'Byrne & Flint, 1993, 1995, 1996; Eide et al., 2014; Chapter 3).

Maximum sandbody widths and thicknesses of both river- and wave-dominated environments commonly overlap (Reynolds 1999). A major concern for subsurface workers is the difficulty of identifying swaley and hummocky cross-stratification (SCS, HCS) in core, which are considered abundant in storm-wave-dominated deltaic systems (Bhattacharya & Walker, 1992; Bhattacharya & Giosan, 2003). Another issue is that parallel laminasets in such wave-produced sedimentary structures as SCS and HCS dip at similar angles to parallel-laminasets that comprise topsets, foresets and bottomsets in distributary mouth bars of river-dominated deltas (e.g., Corbett et al., 1994; Chapter 3). Recent studies describe a variety of inertia- and traction-dominated sedimentary structures in distributary mouth bars, with the most relevant to this study being parallel-laminated topsets, foresets, and bottomsets formed by hyperpycnites (inertia-dominated jet plumes related to dense underflows; e.g., Wright, 1977; Wellner et al., 2005; Ahmed et al., 2014; Chapter 3).

Bedforms are direct indicators of significantly different deltaic systems with considerably different plan-view geometries (Bhattacharya & Walker 1992; Bhattacharya 2010). In plan view and cross section, wave-dominated deltas have arcuate to cuspate margins with smooth-fronted lobes that have either symmetric, asymmetric, or deflected geometries based on the interplay of river sediment and longshore-current-transport rates (e.g., Bhattacharya and Giosan, 2003; Bhattacharya, 2010). River-dominated deltas are more complex three dimensionally (3D) and have point-sourced lobate or elongate morphologies (e.g., Olariu and Bhattacharya 2006; Bhattacharya, 2010). Sediment-dispersal patterns would vary for these two different deltaic depositional models; the best reservoir sands would likely be orientated along strike in wave-dominated deltas, and alternatively would have more complex geometries that vary significantly along strike and dip due to sediment dispersal patterns for river-dominated deltas. The goals of this research are, therefore, to compare and contrast outcrop exposures of a river-dominated, wave-modified deltaic system of Arctic Alaska to wave-dominated deltaic systems in Utah in order to: 1) determine variations in facies and ichnology; 2) document similarities and differences between bedforms and stratal architectures produced by different processes; and 3) examine the usefulness of using the Kenilworth and Grassy members of the Blackhawk Formation as an analogue for reservoirs of the Schrader Bluff Formation.

GEOLOGIC SETTING

CRETACEOUS PALEO-ARCTIC OCEAN

The Late Cretaceous Arctic Ocean is thought to have been ice-free during the summer months, with only intermittent sea ice in the winter (Parrish et al., 1987; Zakharov et al., 1999; Miller et al., 2005; Davies et al., 2009). The Colville Foreland Basin formed adjacent to the Amerasia Basin, and was a sub-basin of the Arctic Ocean during the Cretaceous–Miocene (Embry & Dixon, 1990; Decker, 2010; Houseknecht & Bird, 2011). The Colville Basin formed as a result of loading by northward duplexing allocthons created by crustal thickening related to southward-dipping subduction of the continental Arctic Alaska terrain beneath the continental Angayuchum terrain (Moore et

Figure 4.1. Paleogeographic map of North America during the Late Cretaceous (~ 85 Ma) including the Western Interior Seaway and connection with the Arctic Ocean (© Ron Blakey, Colorado Plateau Geosystems, Inc.). Star notes the approximate location of the Alaska study area, and the square notes the approximate location of study areas in Utah. The Blackhawk Formation was deposited at ~ 46° N (Kauffman and Caldwell 1993; Hampson 2010) and the Schrader Bluff Formation was deposited at ~ 83 to 84° N (Spicer and Parrish 1990a, 1990b; Spicer and Herman 2010; Flaig et al. 2011; Chapter 3). Dashed lines indicate approximate location of 20 and 40° paleolatitudes from (Couillard and Irving 1975; Torsvik et al. 2012).

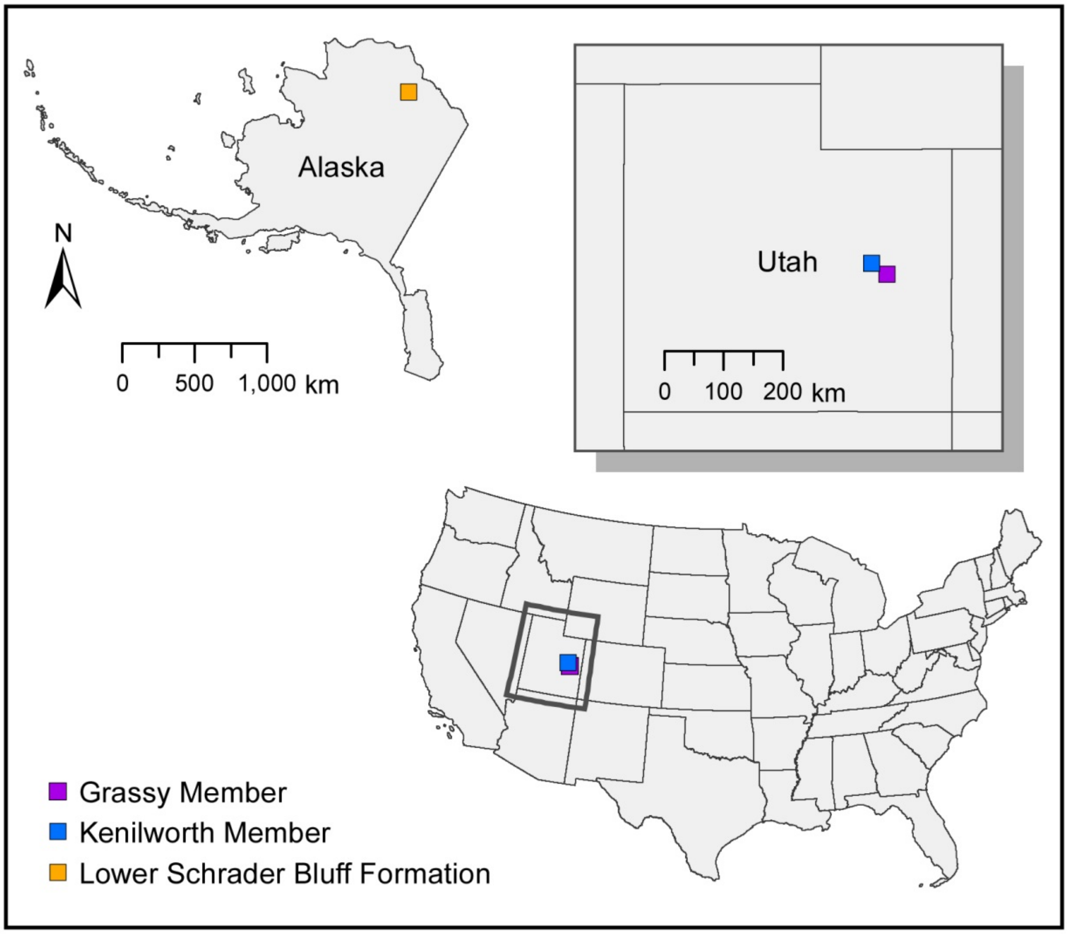


Figure 4.2. Map of the continental United States, Alaska and Utah showing locations of the study areas for the Schrader Bluff Formation in Alaska and the Kenilworth and Grassy members of the Blackhawk Formation in Utah.

al., 1994). The Colville Basin is bounded to the south by the Brooks Range fold and thrust belt and to the north by the Barrow Arch rift shoulder (Bird, 2001). Sediments (> 8-km thick) sourced predominantly from the Chukchi platform that filled the basin axially from the west to east are known formally as the Brookian tectonostratigraphic megasequence (Moore et al., 1994; Houseknecht et al. 2009; Hubbard et al., 1987). The longest occurring clastic wedge within the Brookian megasequence includes deltaic, shallow marine, and shelf deposits of the Santonian–Paleocene Schrader Bluff Formation (Fig. 4.3; Decker, 2010). The Schrader Bluff Formation is the shallow marine component of this clastic wedge (Fig. 4.3; Mull et al., 2003; Decker, 2007, 2010; Chapter 2). The Schrader Bluff Formation is informally divided into lower, middle and upper units and the lower Schrader Bluff Formation is further divided into the Rogers Creek, Barrow Trail and Sentinel Hill members (Gyrc et al., 1951, 1956; Whittington, 1956; Mull et al., 2003; Chapter 2, Chapter 3). Each member is poorly constrained chronostratigraphically; however, the occurrence of *Inoceramus (Sphenoceramus*) *patootensis* and microfauna in the lower Schrader Bluff Formation suggests deposition during the Santonian–late Campanian (Jones & Gyrc, 1960; Detterman et al., 1963; Mull et al., 2003; Flores et al., 2007a, b; LePain et al., 2008; Decker, 2010). This study focuses on the Rogers Creek Member of the lower Schrader Bluff Formation.

Between the Arctic Alaska geographic markers of Umiat and Ocean Point, the orientation of the Late Cretaceous paleoshelf edge in the Colville Basin trended generally from N–S (Houseknecht & Schenck, 2009; Decker, 2010). Extensive N–S trending outcrop exposures of Santonian−Maastrichtian strata along the Colville River provide insight into the most proximal settings preserved within the Colville Basin clinoform-topset system. At the eastern boundary of the National Petroleum Reserve−Alaska, the southern tip of these extensive outcrop exposures includes the lower Schrader Bluff Formation at Shivugak Bluffs (Chapters 2, 3). Extensive sedimentologic and stratigraphic analyses were recently conducted on an 11-km long, SW−NE trending outcrop belt (~ 90- to 120-m high) at Shivugak Bluffs. Results indicate that the lower Schrader Bluff Formation at Shivugak Bluffs comprise recurring northward-dipping, river-dominated delta lobes and thick interdistributary bays suggesting pronounced and compensationally stacked lobate deltaic morphologies along the Late Cretaceous Arctic shoreline (Chapter 2, 3). The marine succession is interbedded with lower delta plain fines and distributary channels of the Prince Creek Formation (Flaig, 2010; Flaig et. 2011, 2013, 2014). The interval within the Rogers Creek Member described herein includes the most wave-modified succession within the overall river-dominated deltaic system at Shivugak Bluffs (Chapter 2, 3).

CRETACEOUS WESTERN INTERIOR SEAWAY

The WIS was a N–S trending epeiric seaway that extended across North America and connected the Arctic Ocean to the Gulf of Mexico during the Late Cretaceous (see Fig. 4.1; Schröder-Adams, 2014). This epeiric sea filled the North American Cordilleran foreland basin that formed by short-wavelength, thrust-sheet loading and long wavelength subduction, related to subsidence along the western margin of North

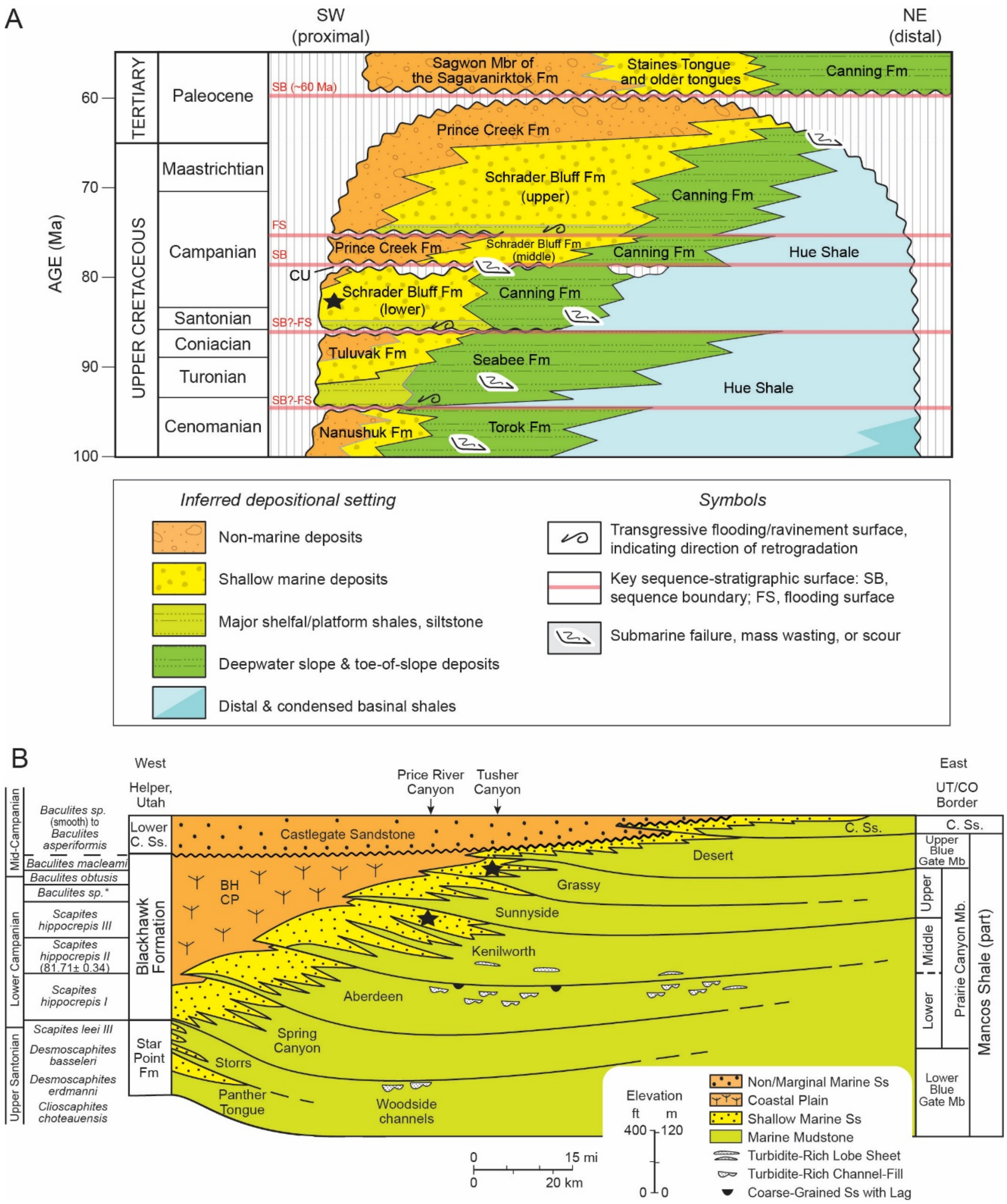

A
SW (proximal)
NE (distal)
AGE (Ma)
TERTIARY
UPPER CRETACEOUS
Paleocene
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
60
70
80
90
100
Sagwon Mbr of the Sagavanirktok Fm
Staines Tongue and older tongues
Canning Fm
SB (~60 Ma)
Prince Creek Fm
Schrader Bluff Fm (upper)
Canning Fm
FS
SB
Prince Creek Fm
Schrader Bluff Fm (middle)
Canning Fm
Hue Shale
CU
Schrader Bluff Fm (lower)
Canning Fm
SB?-FS
Tuluvak Fm
Seabee Fm
Hue Shale
SB?-FS
Nanushuk Fm
Torok Fm
Inferred depositional setting
Non-marine deposits
Shallow marine deposits
Major shelfal/platform shales, siltstone
Deepwater slope & toe-of-slope deposits
Distal & condensed basinal shales
Symbols
Transgressive flooding/ravinement surface, indicating direction of retrogradation
Key sequence-stratigraphic surface: SB, sequence boundary; FS, flooding surface
Submarine failure, mass wasting, or scour
B
West
Helper, Utah
Price River Canyon
Tusher Canyon
East
UT/CO Border
Mid-Campanian
Lower Campanian
Upper Santonian
Baculites sp. (smooth) to Baculites asperiformis
Baculites macleami
Baculites obtusis
Baculites sp.*
Scapites hippocrepis III
Scapites hippocrepis II (81.71± 0.34)
Scapites hippocrepis I
Scapites leei III
Desmoscaphites basseleri
Desmoscaphites erdmanni
Clioscaphites choteauensis
Lower C. Ss.
Blackhawk Formation
Star Point Fm
Castlegate Sandstone
C. Ss.
BH CP
Desert
Grassy
Sunnyside
Kenilworth
Aberdeen
Spring Canyon
Storrs
Panther Tongue
Woodside channels
C. Ss.
Upper Blue Gate Mb
Upper
Middle
Lower
Prairie Canyon Mb.
Mancos Shale (part)
Lower Blue Gate Mb
Elevation
ft m
400 120
0 0
0 15 mi
0 20 km
Non/Marginal Marine Ss
Coastal Plain
Shallow Marine Ss
Marine Mudstone
Turbidite-Rich Lobe Sheet
Turbidite-Rich Channel-Fill
Coarse-Grained Ss with Lag

Figure 4.3. Lithostratigraphic diagrams showing the stratigraphy of Alaska and Utah. A) The lower Schrader Bluff Formation (Fm) deposited in the Colville Basin in Arctic Alaska (modified from Decker 2010; Chapter 2). B) Spring Canyon, Aberdeen, Kenilworth, Sunnyside, Grassy and Desert members of the Blackhawk Formation bounded below by the Storrs Member (Mbr) of the Star Point Sandstone and above by Castlegate Sandstone (C. Ss.), deposited in the North America foreland basin (after Hampson 2000). Several ammonite biozones and radiometric dates from this stratigraphic interval in east-central Utah have been defined (Young, 1955; Gill and Hail, 1975; Obradovich, 1993; Cole et al. 1997; Hampson 2010). Abbreviations are CU = Campanian Unconformity (Chapter 2), BH CP = Blackhawk Formation coastal plain.

America, and development of the Sevier Orogenic Belt and associated fold and thrust belt (Kauffman & Caldwell, 1993; Liu & Nummedal, 2004; Hampson, 2010). This asymmetric foreland basin filled transversally from west to east with sediments eroded from the Sevier orogenic belt to the west (Kauffman & Caldwell, 1993; DeCelles & Coogan, 2006). In central Utah and western Colorado a locally broad embayment, often referred to as the Utah Bight, formed along the N–S trending western coastline (Zapp & Cobban, 1960; McGookey et al., 1972; Franczyk et al., 1992; Hampson, 2010). In this area, the Blackhawk Formation and Castlegate Sandstone form a single clastic wedge that thins basinward into the Mancos Shale, which records the deepest deposits within the foreland basin (Fig. 4.3B; Young, 1955).

The Blackhawk Formation is part of the Mesa Verde Group and contains (from oldest to youngest) the Spring Canyon, Aberdeen, Kenilworth, Sunnyside, Grassy, and Desert members (Fig 4.3B; Speiker, 1931; Balsley, 1980). The Blackhawk Formation in east-central Utah was deposited during the lower and middle Campanian (Fig. 4.2B; Hampson, 2000). Molluscan fossil zones and radiometric ages compiled for strata in the WIS and ages for members of the Blackhawk Formation are summarized in Figure 4.3B (Cobban et al., 2006; Gradstein et al., 2012; Merewether et al., 2015). This study focuses specifically on the Kenilworth and Grassy members within the Blackhawk Formation, which include some of the most well-documented, wave-dominated coastlines in the rock record (e.g., Swift et al., 1987; O'Byrne & Flint, 1993, 1995; Eide et al., 2014).

The Kenilworth Member dominantly comprises strandplains, supplied by longshore drift, and shoreline orientations generally trended NNW–SSE (Young, 1955; Gill & Hail 1975; Taylor & Lovell 1991, 1995; Cole et al., 1997; Pattison, 1994a, b, 1995; Hampson, 2010). This study focuses on the fourth parasequence of the Kenilworth Member (KPS4) of Taylor and Lovell (1995), equivalent to the seventh and eighth parasequences (KPS 7, KPS 8) of Pattison (1995). For purposes of this study, we refer to this stratigraphic interval as KPS4. This interval ranges from 15–36-m thick (21 m average) from Price River Canyon to Battleship Mesa, based on LIDAR (light detection and ranging scanner; Eide et al. 2014). KPS4 is capped by coastal plain-lagoonal deposits (up to ~ 5.5-m thick), with fluvial distributary channels (3–8-m thick) that are ultimately overlain by a transgressive lag (Eide et al., 2014). Fluvial distributary channels had orientations subparallel to depositional dip and intermittently fed wave-dominated deltas (~ 1-km wide) of KPS4 along strike (Eide et al., 2014). One of the only wave-dominated deltas preserved in KPS4 is in Price River Canyon (Eide et al., 2014), and this interval contains the stratigraphic succession explored further in this study.

Shoreline orientations for the Grassy Member were N–S or NNE–SSW, based on paleocurrents from shore-subparallel, trough- and tabular-cross-sets interpreted as barrier island deposits (O'Byrne & Flint, 1993, 1995, 1996). The Grassy Member has been subdivided into four parasequences (GPS1-4) between Woodside and Hatch Mesa localities (O'Byrne & Flint, 1993, 1995, 1996). The upper bounding surface of the Grassy Member comprises either: (1) sphaerosiderite-rich marker beds indicative of fresh- to brackish water interaction; (2) thin, 0.1–2-m-thick paleosols interpreted as interfluve deposits; or (3) carbonaceous shale, asymmetric ripples, or symmetric ripples and parallel lamination interpreted as lagoonal deposits (O'Byrne & Flint, 1993, 1995, 1996). One of the best outcrop exposures that contains HCS in the Grassy Member is in a NW–SE trending canyon off of Tusher Canyon (Ciametti et al., 1995), and this interval is explored further in this study.

VARIATIONS OF GEOLOGIC AND PALEOGEOGRAPHIC SETTINGS

The Colville Basin, which formed along the paleo-Arctic Ocean (Moore et al., 1994) presents a much different geologic setting from that of the Cretaceous WIS (Balsley, 1982). The Colville foreland basin filled predominantly axially (Hubbard et al., 1987; Moore et al., 1994; Houseknecht et al., 2009) from sediments sourced from paleotopographic highs of the Chukotka borderland magmatic belt, the ancestral Wrangel–Herald thrust belt, and the Brooks Range orogenic belt (McMillen 1991; Houseknecht et al. 2009; Houseknecht and Bird 2011). The Sevier Foreland Basin filled predominantly via transverse flow from erosion of the nearby Sevier mountain belt (Fouch et al., 1983). The distance from sediment source-to-sink was up to three times longer in the Colville Basin of Alaska compared to the WIS. The paleo-Arctic Ocean is also thought to have had larger fetch dimensions (Fig. 4.1), was deeper than the WIS, and had a significant shelf-slope break. The WIS had a very long N–S trending fetch over 5,000-km long (Kauffman and Caldwell 1993). Waves generated by storms are controlled by wind speed, storm duration, fetch length, water depth and shape of the ocean floor

(Komar, 1998; McInnes et al. 2003; Yang et al. 2006). The lower Schrader Bluff Formation preserves a 546-m thick river-dominated deltaic succession suggesting deposition in an embayed portion of the Arctic coastline that dampened wave processes (Chapters 2, 3). Local paleotopography or such active structural features as the Barrow Arch and Brooks Range may have contributed to an embayed, protected shoreline for deposition of the Schader Bluff Formation (Chapters 2, 3). Many studies have described portions of the Blackhawk Formation as being deposited in the Utah Bight (Zapp & Cobban, 1960; McGookey et al., 1972; Franczyk et al., 1992; Hampson, 2010). All three successions compared in this investigation were deposited in the Late Cretaceous (spanning from Santonian to Campanian); however, constraining sedimentation rates using absolute age control for each interval is problematic.

METHODS

A total of three stratigraphic successions were measured, one at each of three localities, SB1, KPS4, and GPS1-4 using standard sedimentologic techniques (Figs 4.4–4.6). These localities include: 1) a 37-m-thick succession in the lower Schrader Bluff Formation on the North Slope of Alaska (Fig. 4.5); 2) a 36-m-thick succession in the Kenilworth Member of the Blackhawk Formation; and 3) a 34-m-thick succession in the Grassy Member of the Blackhawk Formation (Fig. 4.6). Data includes grain size, sedimentary structures, surfaces, flora, fauna, and trace fossils. Gigapixel photo panoramas were recorded using a GigaPan EPIC Pro System and Nikon D-800 digital camera and 200-400 mm Nikkor lens. Panoramas were used to assess lateral and vertical facies relationships and examine stratigraphic architectures for data collected at each measured section. A facies analyses was conducted for each measured section (Table 4.1, 4.2, 4.3). Facies abundances and percentages were tabulated for each locality (Table 4.2). Ichnotaxa were assigned based on architecture, surficial morphologies, and infill patterns (e.g., Hasiotis and Mitchell, 1993; Bromley, 1996). Ichnofabric indices (ii) were logged using the classification scheme of Droser and Bottjer (1986). Trace-fossil assemblages are displayed adjacent to the stratigraphic columns, listed in the text based on order of abundance (Figs. 4.5, 4.6), and are summarized in alphabetical order in Table 4.4.

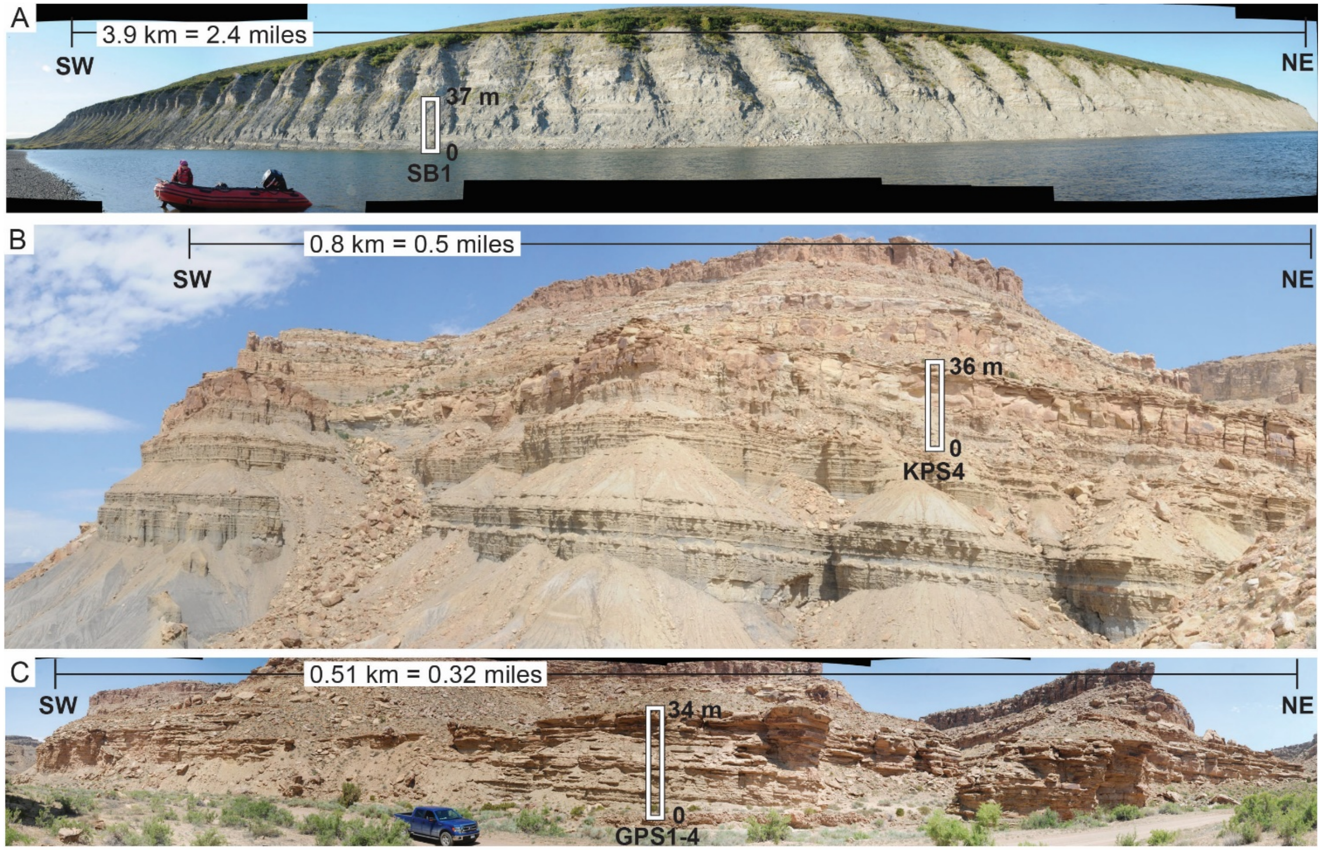


Figure 4.4. Photomosaics showing the location of each measured stratigraphic section in the following outcrop intervals: A) the lower Schrader Bluff Formation along the Colville River in Alaska shown in Figure 4.5, B) the Kenilworth Member of the Blackhawk Formation within Price River Canyon in Utah shown in Figure 4.6, and C) the Grassy Member of the Blackhawk Formation within Tusher Canyon in Utah shown in Figure 4.6.

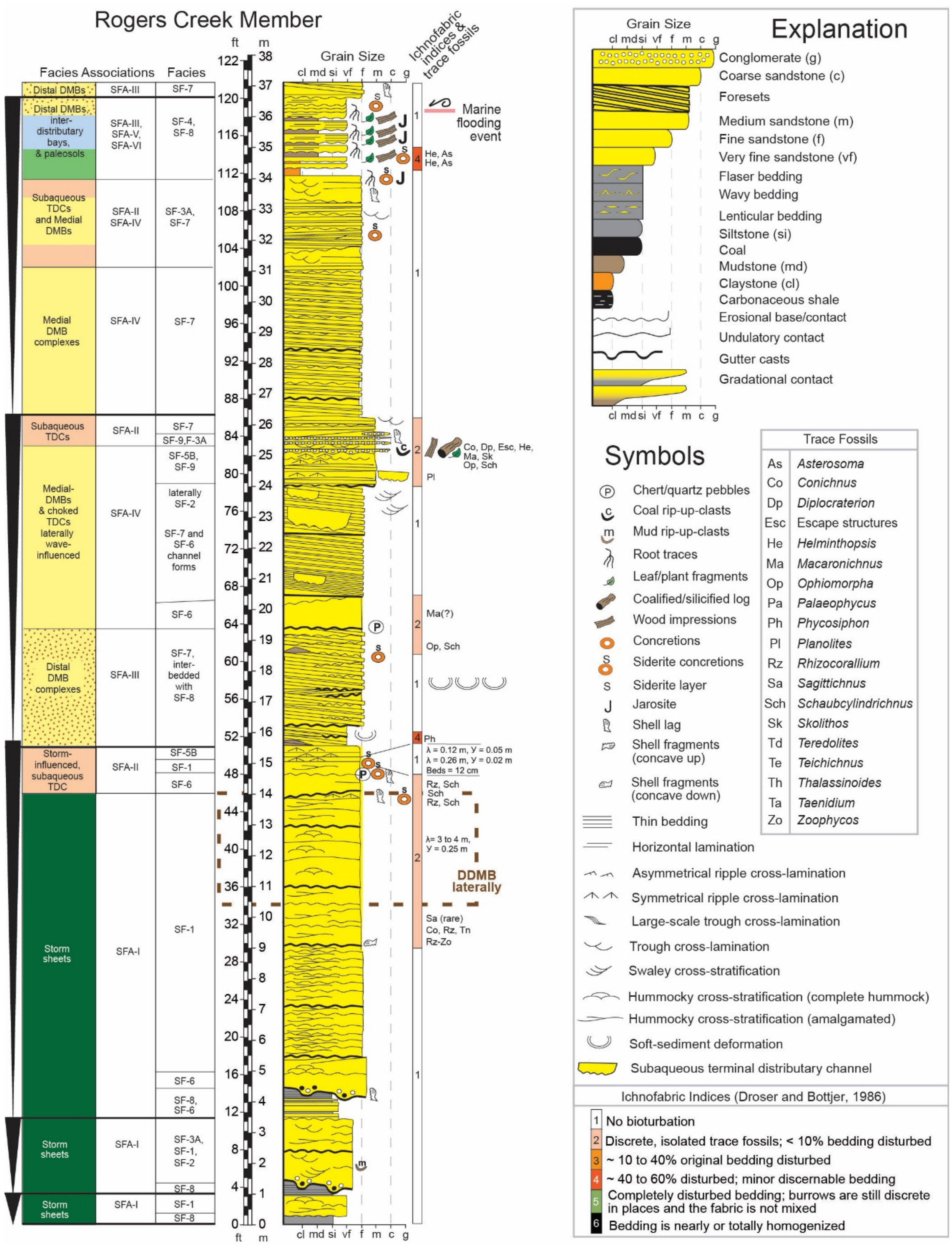
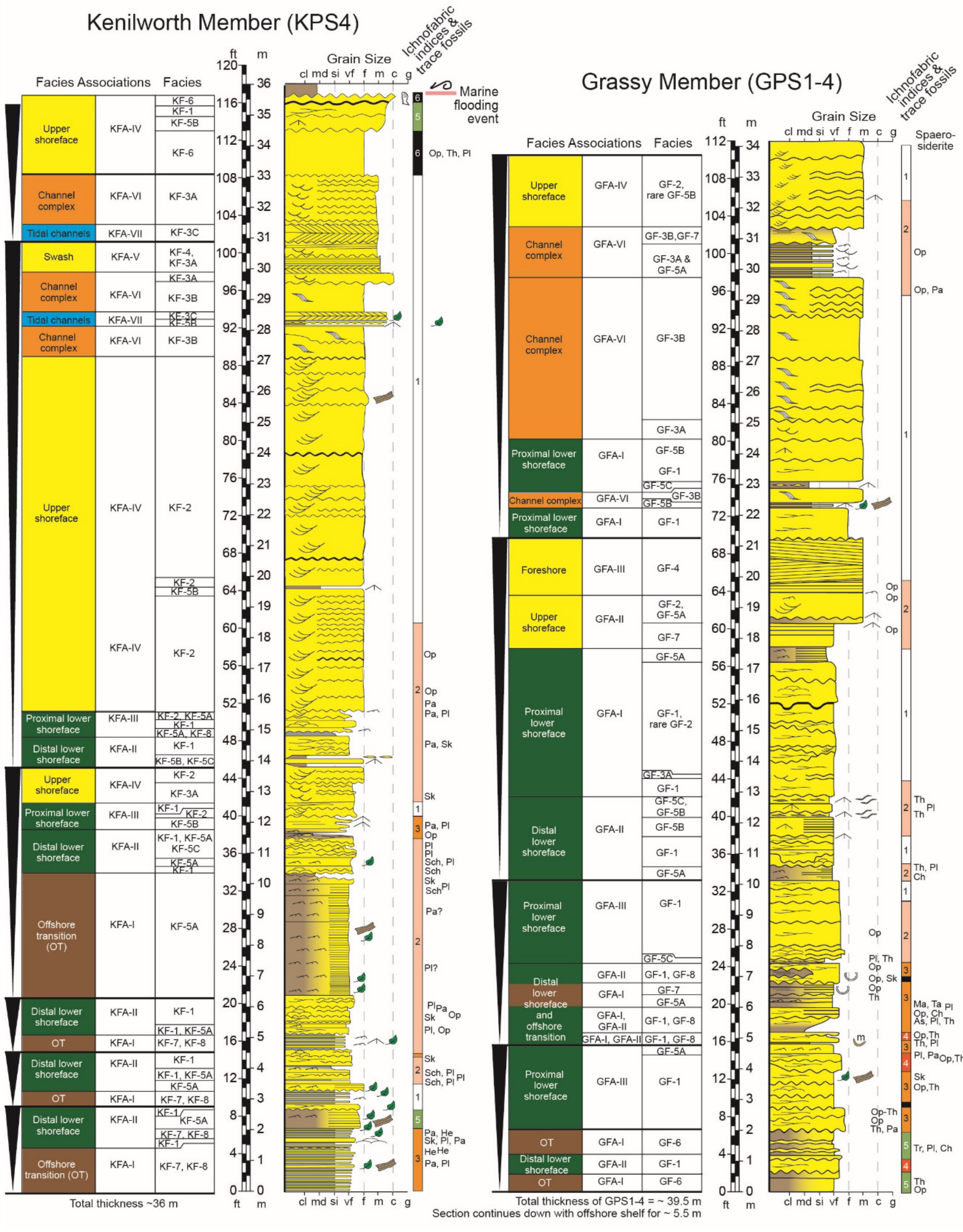

Rogers Creek Member
Facies Associations
Facies
ft
m
Grain Size
cl md si vf f m c g
Ichnofabric indices & trace fossils
Distal DMBs
SFA-III
SF-7
Distal DMBs, inter-distributary bays, & paleosols
SFA-III, SFA-V, SFA-VI
SF-4, SF-8
Marine flooding event
He, As
He, As
Subaqueous TDCs and Medial DMBs
SFA-II SFA-IV
SF-3A, SF-7
Medial DMB complexes
SFA-IV
SF-7
Subaqueous TDCs
SFA-II
SF-7
SF-9,F-3A
Co, Dp, Esc, He, Ma, Sk Op, Sch
Pl
Medial-DMBs & choked TDCs laterally wave-influenced
SFA-IV
SF-5B, SF-9
laterally SF-2
SF-7 and SF-6 channel forms
SF-6
Ma(?)
Op, Sch
Distal DMB complexes
SFA-III
SF-7, inter-bedded with SF-8
Ph
λ = 0.12 m, У = 0.05 m
λ = 0.26 m, У = 0.02 m
Beds = 12 cm
Storm-influenced, subaqueous TDC
SFA-II
SF-5B
SF-1
SF-6
Rz, Sch
Sch
Rz, Sch
λ= 3 to 4 m, У = 0.25 m
DDMB laterally
Storm sheets
SFA-I
SF-1
Sa (rare)
Co, Rz, Tn
Rz-Zo
SF-6
SF-8, SF-6
Storm sheets
SFA-I
SF-3A, SF-1, SF-2
SF-8
Storm sheets
SFA-I
SF-1
SF-8
Explanation
Grain Size
Conglomerate (g)
Coarse sandstone (c)
Foresets
Medium sandstone (m)
Fine sandstone (f)
Very fine sandstone (vf)
Flaser bedding
Wavy bedding
Lenticular bedding
Siltstone (si)
Coal
Mudstone (md)
Claystone (cl)
Carbonaceous shale
Erosional base/contact
Undulatory contact
Gutter casts
Gradational contact
Symbols
Chert/quartz pebbles
Coal rip-up-clasts
Mud rip-up-clasts
Root traces
Leaf/plant fragments
Coalified/silicified log
Wood impressions
Concretions
Siderite concretions
Siderite layer
Jarosite
Shell lag
Shell fragments (concave up)
Shell fragments (concave down)
Thin bedding
Horizontal lamination
Asymmetrical ripple cross-lamination
Symmetrical ripple cross-lamination
Large-scale trough cross-lamination
Trough cross-lamination
Swaley cross-stratification
Hummocky cross-stratification (complete hummock)
Hummocky cross-stratification (amalgamated)
Soft-sediment deformation
Subaqueous terminal distributary channel
Trace Fossils
As Asterosoma
Co Conichnus
Dp Diplocraterion
Esc Escape structures
He Helminthopsis
Ma Macaronichnus
Op Ophiomorpha
Pa Palaeophycus
Ph Phycosiphon
Pl Planolites
Rz Rhizocorallium
Sa Sagittichnus
Sch Schaubcylindrichnus
Sk Skolithos
Td Teredolites
Te Teichichnus
Th Thalassinoides
Ta Taenidium
Zo Zoophycos
Ichnofabric Indices (Droser and Bottjer, 1986)
1 No bioturbation
2 Discrete, isolated trace fossils; < 10% bedding disturbed
3 ~ 10 to 40% original bedding disturbed
4 ~ 40 to 60% disturbed; minor discernable bedding
5 Completely disturbed bedding; burrows are still discrete in places and the fabric is not mixed
6 Bedding is nearly or totally homogenized

Figure 4.5. Measured section from the Rogers Creek Member of the lower Schrader Bluff Formation showing storm sheets, storm-influenced high width-to-depth terminal distributary channels (HTDCs), distal and medial distributary mouth bars (MDMBs and DDMBs), pedogenically modified HTDCs and interdistributary bays interbedded with paleosols (PS) deposits at Shivugak Bluffs (see measured section SB1in Chapter 3). Explanation is included for all measured sections.



Kenilworth Member (KPS4)
Facies Associations
Facies
ft
m
Grain Size
cl md si vf f m c g
Ichnofabric indices & trace fossils
Marine flooding event
Upper shoreface
Channel complex
Tidal channels
Swash
Proximal lower shoreface
Distal lower shoreface
Offshore transition (OT)
OT
KFA-IV
KFA-VI
KFA-VII
KFA-V
KFA-III
KFA-II
KFA-I
KF-6
KF-1
KF-5B
KF-3A
KF-3C
KF-4, KF-3A
KF-3B
KF-2
KF-5A
KF-5C
KF-7, KF-8
Total thickness ~36 m
Grassy Member (GPS1-4)
Spaero-siderite
Foreshore
Distal lower shoreface and offshore transition
GFA-IV
GFA-VI
GFA-I
GFA-III
GFA-II
GF-2, rare GF-5B
GF-3B,GF-7
GF-3A & GF-5A
GF-3B
GF-3A
GF-5B
GF-1
GF-5C
GF-4
GF-2, GF-5A
GF-7
GF-5A
GF-1, rare GF-2
GF-1, GF-8
GF-6
Total thickness of GPS1-4 = ~ 39.5 m
Section continues down with offshore shelf for ~ 5.5 m

Figure 4.6. Two measured sections from the Blackhawk Formation including: parasequence 4 in the Kenilworth Member (KPS4) located east of Woodside, Utah in Price River Canyon and parasequences 1–4 in the Grassy Member (GPS1-4) located in Tusher Canyon northeast of Green River, Utah. Deposits include offshore transition, distal lower shoreface, proximal lower shoreface, upper shoreface, channel complexes, swash/foreshore and tidal channels. See explanation for symbols in Figure 4.5.

Table 4.1. Summary of facies in the Rogers Creek Member of the lower Schrader Bluff Formation (SF) and those in the Kenilworth (KF) and Grassy (GF) members of the Blackhawk Formation.

Sedimentary Structures	**Facies ID**	**Grain Size**	**Lamina, laminaset, or Bed Thickness (m)**	**Bed or bedset Thick ness (m)**	**Contacts**	**Notes**
Hummocky cross-stratification	**SF-1**	Very fine to fine-grained sandstone	0.10 to 0.50	0.5 to 2.0	Basal Erosional to gradational Upper Grad ational to erosional	Wavelength ranges from 0.7 to 4.0 m (n= 3); laterally massive to trough cross-stratified. Rare Plant material and wood impressions
	KF-1	Very fine sandstone	0.05 to 0.50	0.2 to 0.7	Basal Erosional to sharp Upper Erosional, sharp to gradational	Wavelength ranges from 0.3 to 5.8 m (n = 6); laterally and locally massive.
	GF-1	Very fine to upper very fine sandstone	0.10 to 0.60	0.20 to 2.0	Basal Erosional to gradational Upper Erosive to gradational	Wavelength ranges from 0.2 to 6.4 m (n = 9).
Swaley cross-stratification	**SF-2**	Medium-grained sandstone	0.15 to 0.75	0.45 to 2.0	Basal Undulatory to erosional Upper Erosional	Rare shell detritus and mud rip-ups.

Table 4.1 (continued)

	KF-2	Very fine to fine sandstone	0.15 to 0.50	0.5 to 3.25	Basal Erosional Upper Erosional, undulatory, to sharp
	GF-2	Very fine to medium sandstone	0.3 to 0.75	0.3 to 2.5	Basal Erosional Upper Erosional to gradational
Trough cross-stratification or planar cross beds	**SF-3A**	Trough-shaped, trough or planar cross-bedding in fine to medium sandstone	0.05 to 0.30	0.05 to 0.9	Basal Erosional to sharp Upper Erosional to sharp
	KF-3A	Very fine to coarse trough cross-stratified sandstone	0.10 to 0.25	0.10 to 1.5	Basal Erosional Upper Erosional, undulatory, to sharp
	GF-3A	Very fine to upper very fine trough cross-stratified sandstone	0.08 to 0.50	0.08 to 0.5	Basal Erosional to sharp Upper Erosional to sharp
Large-scale trough cross stratification (dunes > 0.6 height)	**KF-3B**	Fine sandstone	0.6	0.50 to 1.0	Basal Erosional Upper Sharp to erosional

Table 4.1 (continued)

	GF-3B	Very fine to medium sandstone	0.10 to 1.50	0.45 to 1.75	Basal Erosional to sharp Upper Erosional to sharp	
Herringbone cross-stratification	**KF-3C**	Fine to medium sandstone	0.10 to 0.15	0.20 to 0.6	Basal Erosional to sharp Upper Erosional to sharp	
Low-angle, planar lamination to planar lamination	**SF-4**	Very-fine to coarse-grained sandstone	0.003 to 0.01	0.20 to 0.40	Basal Erosional to sharp Upper Sharp	Rare rhizoliths.
	KF-4	Fine to medium sandstone	0.05-0.10	0.10 to 0.25	Basal Erosional to sharp Upper Erosional to sharp	
	GF-4	Medium sandstone	0.05 to 0.50	1.65	Basal Erosional to sharp Upper Erosional to sharp	
Asymmetric ripple-lamination	**KF-5A**	Muddy, very fine to clean, fine sandstone	0.05 to 0.10	0.15 to 2.4	Basal Sharp Upper Erosional to sharp	Abundant wood and plant fragments.
	GF-5A	Mudstone, very fine to medium sandstone	0.05 to 0.10	0.05 to 0.5	Basal Sharp to Gradational Upper Erosional, sharp to gradational	
Symmetric ripple-lamination	**SF-5B**	Very fine to medium sandstone	0.05	0.5		Rare bedform
	KF-5B	Very fine to medium sandstone	0.05 to 0.14	--	Basal Gradational to erosional Upper	

Table 4.1 (continued)

					Erosional	
	GF-5B	Very fine to medium sandstone	0.01 to 0.1	0.60	Basal Erosional Upper Erosional to sharp	
Lenticular- and wavy-beds	**KF-5C**	Mudstone and very fine to medium sandstone	0.01 to 0.05	0.05 to 0.2	Basal Sharp to gradational Upper Erosional to sharp	
Flaser-, wavy-, lenticular bedding	**GF-5C**	Mudstone and very fine sandstone	0.01 to 0.03	0.12 to 0.20	Basal Sharp to erosional Upper gradational	
Thick to very thick bedded, massive or highly bioturbated, sandstone	**SF-6**	Fine sandstone	0.5 to 1.0	1.00	Basal Erosional Upper Erosional	Massive
	KF-6	Fine sandstone	0.3 to 1.5	0.3 to 1.5	Basal Erosional Upper Erosional to sharp	Bioturbation index = 5 to 6.
	GF-6	Muddy very fine sandstone	0.12 to 0.60	0.80	Basal Erosional to gradational Upper Erosional, sharp to gradational	Bioturbation index = 5 to 6.

Table 4.1 (continued)

Very thin to thick beds, often intralaminated and dipping	**SF-7**	Very fine to medium sandstone	0.2 to 0.4	0.2 to 2.75	Basal Sharp Upper Erosional to sharp	
Laminated or massive, very-	**KF-7**	Very fine sandstone	0.01 to 0.06	0.40 to 1.35	Basal Sharp Upper Erosional to sharp	
	GF-7	Muddy very fine sandstone	0.001 to 0.1	0.12 to 0.7	Basal Erosional Upper Erosional	
Massive, ripple laminated	**SF-8**	Siltstone, mudstone, or claystone	0.05 to 0.25	0.05 to 0.5	Basal Sharp Upper Erosional	Common: rhizoliths.
Massive, laminated, or ripple-lamination	**KF-8**	Siltstone, mudstone, or carbonaceous shale	0.03 to 0.10	0.40 to 1.35	Basal Sharp Upper Erosional	Abundant wood and plant fragments.
Massive to laminated	**GF-8**	Mudstone	0.001 to 0.010	0.05 to 0.2	Basal Erosional to sharp Upper Erosional to sharp	
Thin beds	**SF-9**	Pebble conglomerate	0.1	0.5	Basal Erosional Upper Erosional	

Table 4.2. Total thickness of lithology, sedimentary structures and calculated percentages for the Rogers Creek Member of the lower Schrader Bluff Formation and the Kenilworth and Grassy Members of the Blackhawk Formation.

Rogers Creek Member, lower Schrader Bluff Formation		**Total Measured**	**Calculated Percentage**
Lithology	**Sedimentary Stuctures**	**(m)**	**(%)**
Very fine- to fine-grained sandstone	Hummocky cross-stratification (SF-1)	11.2	31
Medium-grained sandstone	Swaley cross-stratification (SF-2)	0.5	1
Fine-grained sandstone	Trough cross-stratification (SF-3A)	2.4	7
Very fine- to coarse-grained sandstone	Planar lamination (SF-4)	0.8	2
Very fine- to medium-grained sandstone	Symmetric ripple-lamination (SF-5B)	1.5	4
Fine-grained sandstone	Massive sandstone (SF-6)	2.6	7
Very fine- to medium-grained sandstone	Very thin to thick beds, often intralaminated and dipping 25 degrees or less (SF-7)	14.6	41
Siltstone, mudstone, or claystone	Massive to laminated (SF-8)	2.3	6
Pebble conglomerate	Lenticular, trough cross-stratification (SF-9)	0.4	1
	Sum	36.0	100

Kenilworth Member, Blackhawk Formation		**Total Measured**	**Calculated Percentage**
Lithology	**Sedimentary Stuctures**	**(m)**	**(%)**
Very fine-grained sandstone	Hummocky cross-stratification (KF-1)	4.3	12
Very fine- to fine-grained sandstone	Swaley cross-stratification (KF-2)	12.2	33
Very fine- to coarse-grained sandstone	Small-scale trough cross stratification (KF-3A)	2.5	7

Table 4.2 (continued)

Fine-grained sandstone	Large-scale trough cross-stratification (K-3B)	2.0	5
Fine- to medium-grained sandstone	Herringbone cross stratification (KF-3C)	1.1	3
Fine- to medium-grained sandstone	Low-angle, planar laminations (KF-4)	0.6	2
Muddy, very fine- to clean, fine-grained sandstone	Asymmetric ripple lamination (KF-5A)	5.7	16
Very fine- to medium-grained sandstone	Symmetric wave ripples (KF-5B)	1.4	4
Mudstone and very fine-grained sandstone	Very thin to medium lenticular laminae (KF-5C)	0.2	1
Fine-grained sandstone	Bioturbated intervals with high ii (KF-6)	1.6	4
Very fine-grained sandstone	Massive, laminated, very thin to thin bedding (KF-7)	1.9	5
Siltstone, mudstone, or carbonaceous shale	Massive to laminated (KF-8)	3.0	8
	Sum	36.5	100

Grassy Member, Blackhawk Formation		**Total Measured**	**Calculated Percentage**
Lithology	**Sedimentary Stuctures**	**(m)**	**(%)**
Very fine- to upper very fine-grained sandstone	Hummocky cross-stratification (GF-1)	13.75	40
Very fine- to medium-grained sandstone	Swaley cross-stratification (GF-2)	3.60	11
Very fine- to upper very fine-grained sandstone	Small-scale trough cross stratification (GF-3A)	1.50	4
Very fine- to medium-grained sandstone	Large-scale trough cross-stratification (GF-3B)	5.60	16
Medium-grained sandstone	Low-angle, planar laminations (GF-4)	1.75	5
Mudstone and very fine- to medium-grained sandstone	Asymetric ripple lamination (GF-5A)	2.70	8
Very fine- to medium-grained sandstone	Symmetric wave ripples (GF-5B)	1.80	5
Mudstone and very fine-grained sandstone	Lenticular laminae (GF-5C)	0.90	3

Table 4.2 (continued)

Muddy, very fine-grained sandstones	Bioturbated muddy very fine sandstones (GF-6)	1.40	4
Muddy, very fine-grained sandstone	Massive, laminated to very thin to thin bedding (GF-7)	0.50	1
Mudstone	Massive to laminated (GF-8)	0.50	1
	Sum	34.0	100

Table 4.3. Facies associations of the Rogers Creek Member of the Schrader Bluff Formation (SFA) and the Kenilworth Member (KFA) and Grassy Member (GFA) in the Blackhawk Formation.

Depositional Environments		Facies Association (FA)	Facies ID	Occurrence of Facies Association
Wave-modified, river-dominated delta	**Storm Sheets**	SFA-I	SF-1, SF-8	
	Subaqueous to subaerial terminal distributary channels	SFA-II	SF-3A, SF-6, SF-1, SF-5B, SF-7, and SF-9	Associated with distributary mouth bar complexes.
	Distal distributary mouth bar complex	SFA-III	SF-7 and SF-8	Found below medial distributary mouth bars (SFA-IV).
	Medial distributary mouth bar complex	SFA-IV	SF-7, SF-6, SF-3B	Found above distal distributary mouth bars (SFA-III).

Table 4.3 (continued)

	Interdistributary Bay		SFA-V	SF-8, SF-6	Found above or in between DMB-TDC complexes
Coastal plain	**Paleosols**		SFA-VI	SF-8A, SF-7	Forming above DMB-TDC complexes
	Crevasse splays or levees		SFA-VII	SF-4B, SF-9	Associated with paleosols (SFA-VI)
Wave-dominated delta	**Offshore Transition**		KFA-I	KF-7, KF-8, KF-5A, KF-5B	Associated with KFA-II or found below KFA-III deposits.
			GFA-I	GF-6, GF-7, GF-8	Associated with GFA-II deposits or found below GFA-III deposits.
	Delta Front	**Distal lower shoreface**	KFA-II	KF-1, KF-5A	Typically encased in offshore transition.
			GFA-II	GF-1, GF-5A, GF-5B, GF-5C	Typically encased in offshore transition deposits or below proximal lower shoreface deposits.
		Proximal lower shoreface	KFA-III	KF-1, KF-5A, KF-5B, KF-5C, KF-6	Found below KFA-IV deposits.

Table 4.3 (continued)

		GFA-III	GF-1, GF-2, GF-5A, GF-5B, GF-3A. Rare GF-5C.	Found above GFA-II or GFA-I deposits.
	Upper shoreface	KFA-IV	KF-2, KF-3A, and KF-5B	Found above KFA-III deposits.
		GFA-IV	GF-2 and GF-5A rare GF-5B	Found above GFA-III and below GFA-V and GFA-VI deposits.
	Foreshore	KFA-V	KF-4, KF-3A	Associated with channels (KFA-VI and KFA-VII)
		GFA-V	GF-4	Above upper shoreface deposits (GFA-IV), but rare.
Channel complexes	**Fluvial channels (Hampson, 2012)**	KFA-VI	KF-3B, KF-3A	Found above upper shoreface (KFA-IV) deposits.
	Tidal influenced channels and tidal flats (Hampson, 2012)	KFA-VII	KF-3C, rare KF-5C	Associated with channel complex (KFA-VI).
	Tidal Inlets (O'Byrne and Flint, 1993)	GFA-VI	GF-3B. Rare GF-3A, GF-5A, GF-5B, and GF-7	Found above proximal lower shoreface (GFA-III) and upper shoreface (GFA-IV) deposits.

Table 4.4. Summary of trace-fossil assemblages and ichnofabric indices (ii) in the lower Schrader Bluff and Blackhawk formations.

Strata	Alphabetized Trace Fossil Assemblage	Total Trace Fossils Identified	Ichnofabric Indices
Rogers Creek Member, lower Schrader Bluff Formation	*Astersoma*, *Conichnus*, *Diplocraterion*, Escape Structures, *Helminthopsis*, *Machronichnus* (?), *Ophiomorpha*, *Phycosiphon*, *Planolites*, *Rhizocorallium*, *Sagittichnus*, *Schaubcylindrichnus*, *Skolithos*, *Taenidium*, *Zoophycus*	15	Mostly discrete, isolated trace fossils (ii = 2) with the exception of abundant *Helminthopsis* and *Phycosiphon* (ii = 4).
Kenilworth Member, Blackhawk Formation	*Helminthopsis*, *Paleophycus*, *Planolites*, *Ophiomorpha*, *Thalassinoides*, *Schaubcylindrichnus*, *Skolithos*	7	Discrete, isolated trace fossils to moderately bioturbated (ii = 2 to 3) include *Helminthopsis*, *Ophiomorpha*, *Paleophycus*, *Paleophycus*, *Planolites*, *Schaubcylindrichnus*, and *Skolithos*. Completely disturbed to completely homogenized (ii = 5 to 6) include layers with *Ophiomorpha*, *Thalassinoides*, and *Planolites*.

Table 4.4 (continued)

Grassy Member, Blackhawk Formation	*Asterosoma*, *Chondrites*, *Ophiomorpha*, *Paleophycus*, *Planolites*, *Thalassinoides*, *Schaubcylindrichnus*, *Machronichnus*, *Taenidium*	9	Discrete, isolated trace fossils (ii= 2) *Chondrites*, *Ophiomorpha*, *Paleophycus* *Thalassinoides*. Moderate to abundant (ii = 3 to 4) includes *Thalassinoides*, *Planolites*, *Schaubcylindrichnus*, *Chondrites*, *Machronichnus*, *Asterosoma*, and *Taenidium*. Completely disturbed to nearly homogenized (ii = 5 to 6) include *Ophiomorpha*, *Thalassinoides*,and *Chondrites*.
Summary of Kenilworth and Grassy Members from the Blackhawk Formation	*Asterosoma*, *Chondrites*, *Helminthopsis*, *Machronichnus*, *Ophiomorpha*, *Paleophycus*, *Planolites*, *Thalassinoides*, *Schaubcylindrichnus*, *Skolithos*,*Taenidium*	11	--

ROGERS CREEK MEMBER, LOWER SCHRADER BLUFF FORMATION

Description.—A 37-m-thick succession comprises 40.4% planar-laminated, thin-bedded very fine- to medium-grained sandstone (SF-7) and rare mudstone (SF-8) that form tabular bedsets with 5–25° dipping foresets (0.2–2.5-m thick) (Fig. 4.7). A maximum of 30.9% of the succession comprises HCS very fine- to fine-grained sandstone (SF-1; Fig. 4.8). Less abundant facies include 7.1 % massive sandstone (SF-6), 6.6% massive to laminated siltstone, mudstone or carbonaceous shale (SF-8; Fig. 4.7D); 6.5% small-scale trough cross-stratification (SF-3A), 4% symmetric ripple lamination (SF-5B); 2.1% planar laminated sandstone (SF-4), 1.4% SCS (SF-2); and 1% pebble conglomerate (SF-9).

Interpretation.—The Rogers Creek Member of the lower Schrader Bluff Formation at Shivugak Bluffs records an overall progradational succession of a river-dominated delta (Chapter 3). Planar-laminated foresets that form tabular bedsets represent medial and distal distributary mouth bars (DMBs). DMBs are associated with trough cross-stratified or massive channel fills, interpreted as subaqueous TDCs, and together these form 8–10-m-thick, amalgamated DMB-TDCs complexes that stack vertically to form cliff walls at least 55-m thick (Fig. 4.7C; Chapter 3). Medial DMBs (SFA-IV) generally have steeper dipping foresets (up to 25°), whereas distal DMBs (SFA-III) typically have shallower dipping foresets (< 10°) and may contain siltstone and mudstone interbeds (Fig. 4.7E; Chapter 3). Distal DMBs also have localized intervals of soft-sediment deformation (0.5-m thick; Fig. 4.7E). Undulating deformed layers likely formed due to density variations when saturated intervals were deformed by denser, rapidly deposited sediment (Anketell et al., 1970; Owen et al., 2011).

DMB-TDC complexes (see Fig. 4.5) overlie or are interbedded with HCS beds overlain by symmetric ripple laminated beds (see 15 m interval at Fig. 4.5, 4.7B; Fig. 4.). HCS intervals represent wave-reworked DMB-TDCs and/or storm sheets (Chapter 3) and symmetric ripples indicate waning flow (Cheel and Leckie 1993; Gani and Bhattacharya 2007; Chapter 3). Massive to HCS sandbodies in this part of the Rogers Creek Member (Figure 4.5) have subtle gutter casts associated with the basal erosional surface (Fig. 4.8C). Gutter casts are laterally connected by thick beds, are shallowly rounded, and infilled with matrix-supported basal lags (Myrow, 1992). Invertebrate-shell- and black-chert-pebble lags are common in gutter casts and along wave-cut erosion surfaces interpreted as first-order truncation surfaces in HCS (Dott and Bourgeois, 1982) (Fig. 4.8C). In the Rogers Creek Member, TDCs may also contain logs, black-chert pebbles, invertebrate shell debris, and mud-rip-up clasts (Chapter 3). Shell hash and debris are common and contain inoceramid pelecypods or other thin-walled bivalves, and rare gastropods (Fig. 4.8C).

Subaqueous TDCs in the lower Schrader Bluff Formation comprise single- or multistory lensoidal or sheet-forming sandbodies (Chapter 3). TDCs likely formed in subaqueous to subaerial environments, owing to the presence of marine trace-fossil assemblages or jarosite- and siderite-lined rhizoliths (see Fig. 4.7A; Chapter 3). A DMB-TDC complex at the 34-m level is rooted and pedogenically modified, indicating subaerial exposure (see Figs. 4.5, 4.7A). This interval is overlain by mudstone containing

Asterosoma and *Helminthopsis* (see Fig. 4.7D), suggesting original deposition in a shallow interdistributary bay (Chapters 2, 3).

KENILWORTH MEMBER, BLACKHAWK FORMATION

Description.—A 36-m-thick measured succession (Fig. 4.9) comprises 33% SCS (KF-2; Fig. 4.9D), 16% asymmetric ripple lamination in very fine- to fine-grained sandstone (KF-5A); 12% HCS (KF-1; Fig. 4.9E); 8% massive to laminated siltstone, mudstone or carbonaceous shale (KF-8); and 7% small-scale trough cross-stratification (KF-3A). Less abundant bedforms include massive, laminated, or very thin- to thin-bedded very fine sandstone (5%; KF-7; see Tables 4.1, 4.2); symmetric wave ripple lamination (2%; KF-5B; Fig. 4.9C); and lenticular mudstone with very fine sandstone (1%; KF-5C).

Interpretation.—KPS4 within the Kenilworth Member represents a progradational cycle recording a wave-dominated deltaic system (see Fig. 4.6). The upper 9 m of KPS4 includes 6-m-thick, small- and large-scale trough cross-stratification (KF-3A and KF-3B), interbedded with herringbone cross-stratification (KF-3C; Fig. 4.9A) and low-angle planar lamination (KF-4). This 6-m-thick succession is interpreted as tidally influenced fluvial channels and swash (KFA-V) deposits, and this is consistent with previous investigations; however, it likely represents an interval down depositional dip (Eide et al. 2014). At the 33-m level, the channel complex is overlain by a 3-m-thick interval of sandstone interpreted as upper shoreface based on grain size, but is strongly overprinted by *Ophiomorpha, Thalassinoides*, and *Planolites* (Fig. 4.9B) and reworked by HCS (see Fig. 4.6). The lower 27 m of KPS4 represents proximal delta-front deposits of a wave-dominated delta, which also resembles a prograding non-deltaic shoreface typical of wave-dominated delta fronts (Walker & Plint 1992; Dominguez 1996; Bhattacharya and Giosan 2003). These proximal delta-front deposits are separated, based on sedimentary structures, into classic swash and upper and lower shoreface subdivisions, using the shoreface terminology of Bhattacharya and Walker (1992) for wave-dominated or wave-influenced deltas (see Fig. 4.6; Table 4.6; Walker & Plint 1992; Bhattacharya and Giosan 2003; Bhattcharya 2010). SCS intervals are interpreted as upper shoreface (KFA-IV) deposits, HCS intervals indicate proximal lower shoreface (KFA-III), isolated HCS beds in muddy sandstone are distal lower shoreface (KFA-II), and muddy sandstone or siltstone–very fine sandstone interbeds represent the offshore transition (KFA-I; Elliot 1978; Eide et al. 2014).

GRASSY MEMBER, BLACKHAWK FORMATION

Description.—The upper 34-m of 39.5 m thick succession in Tusher Canyon (Fig. 4.10) comprises 40% HCS (GF-1; see Fig. 4.6; Tables 4.1, 4.2), 16% large-scale, trough cross-stratification (GF-3B), 11% SCS (GF-2), and 8% asymmetric ripple lamination (GF-5A). Less abundant sedimentary structures include low-angle planar laminated sandstone (5%; GF-4); symmetric ripple lamination (5%; GF-5B); small-scale, trough cross-stratification (4%; GF-3A); lenticular mudstone and very fine sandstone (3%; GF-5C); massive or laminated very thin- to thin-bedded muddy, very fine sandstone (1%; GF-7); and massive to laminated mudstone (1%; GF-8). The interval between 6.5

and 7 m has abundant soft sediment deformation (Fig. 4.10C). Exceptional examples of nested gutter casts are present at ~16 m (Fig. 4.10E). Gutter casts commonly are laterally discrete, deeply rounded, and have a structureless infill (e.g., Myrow, 1992). Trace-fossil assemblages are summarized in Table 4.4, but *Ophiomorpha* that produce high ii (4–6; Droser & Bottjer 1986) are located at 2.75, 4.00, 5.00, and 6.75 m (see Fig. 4.6, 4.10D).

Interpretation.—GPS1–GPS4 within the Grassy Member represents an ~ 39.5-m-thick overall progradational cycle recording the vertical transition from offshore transition through distal lower shoreface, proximal lower shoreface, upper shoreface, and foreshore (swash) environments (see Figs. 4.2, 4.6). At ~ 39.5 m within GPS4, sphaerosiderite concretions indicative of fresh- to brackish water interaction in upper shoreface deposits (O'Byrne et al. 1995) is interpreted as the top of the parasequence. Below the sphaerosiderite interval, a < 7-m-thick channel complex (Fig. 4.10A) is associated with SCS, including small- and large-scale, trough cross-stratification and a few interbeds with asymmetric and symmetric ripple laminations (GF-5A and GF-5B) or rare lenticular laminated mudstone (GF-5C). These channels and mudstones have previously been interpreted as tidal inlets and lagoonal deposits (O'Byrne and Flint, 1993). Similar to previous studies of the Kenilworth Member (Pattison 1995, Taylor and Lovell 1995; Hampson 2000), this study uses the term distal lower shoreface to distinguish isolated HCS beds encased in fairweather deposits from amalgamated HCS intervals in proximal lower shoreface. Distal and proximal lower shoreface, upper shoreface, foreshore, and channel complexes are interpreted as delta-front deposits within a wave-dominated delta.

RESULTS

Delta-front deposits in the lower Schrader Bluff Formation are compared to delta-front deposits in the Blackhawk Formation (Eide et al., 2014; Chapter 3). Calculated percentages of wave, river, and tide-generated strata are summarized in Table 4.5. In this comparative analysis, HCS, SCS, symmetric ripple-laminated beds, plane parallel-laminated beds (swash), and small trough cross-stratification associated with either HCS or SCS are included as wave-generated strata (Table 4.5). Plane parallel-laminated foresets of distal and medial DMBs, and TDCs in the lower Schrader Bluff Formation are included as river-generated deltaic strata (Table 4.5). Small- to large-scale trough cross-stratified beds and bedsets that form channel complexes in the Kenilworth and Grassy members of Blackhawk Formation are included as river-generated deltaic strata. Herringbone cross-stratified beds (1.3 m thick) in the Kenilworth Member are included as tide-generated strata. Results indicate that wave-modified strata in the Kenilworth (KPS4) and Grassy (GPS1-4) members range from 75–81%, and that wave-modified strata within the most wave-influenced succession of the lower Schrader Bluff Formation comprise 46% of strata (Table 4.5; Fig. 4.11). The lower Schrader Bluff Formation has the most river-dominated strata (54%), followed by the GPS1-4 (25%), and KPS4 (14%). The Kenilworth Member is the only locality in this investigation with significant tide-generated strata (5%).

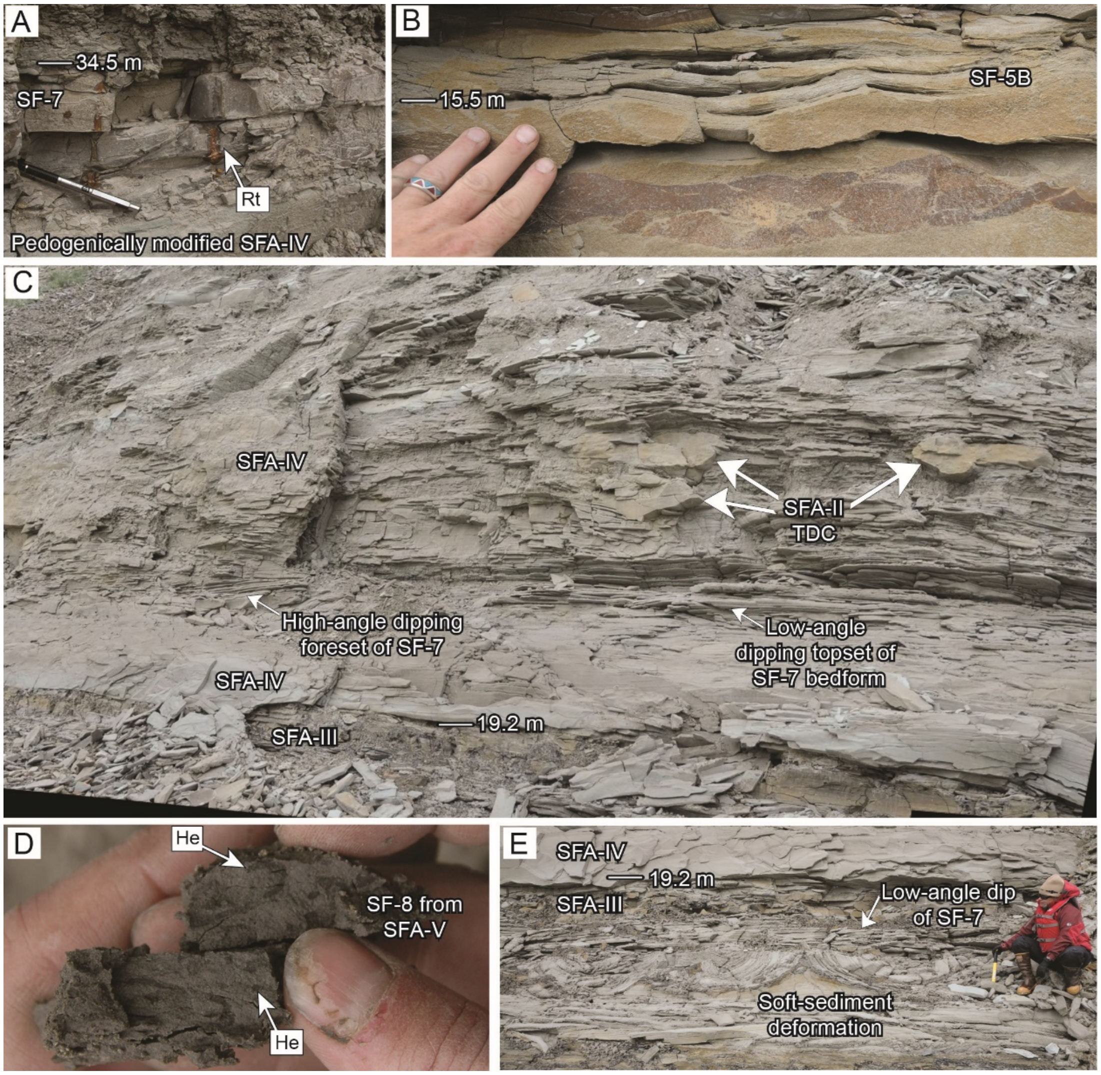


Figure 4.7. Photographs of the lower Schrader Bluff Formation: A) pedogenically modified distributary mouth bars (DMBs) in SFA-IV, B) symmetric wave ripples (SF-5B; Fig. 4.5), C) distal DMBs (SFA-III) overlain by medial DMBs (SFA-IV), note topsets and foresets (SF-7) of DMBs in SFA-IV that are truncated by terminal distributary channels (SFA-II), D) *Helminthopsis* in SF-8 from interdistributary bay (SFA-V) deposits, and E) soft-sediment deformation load structures in SF-7 within SFA-III.

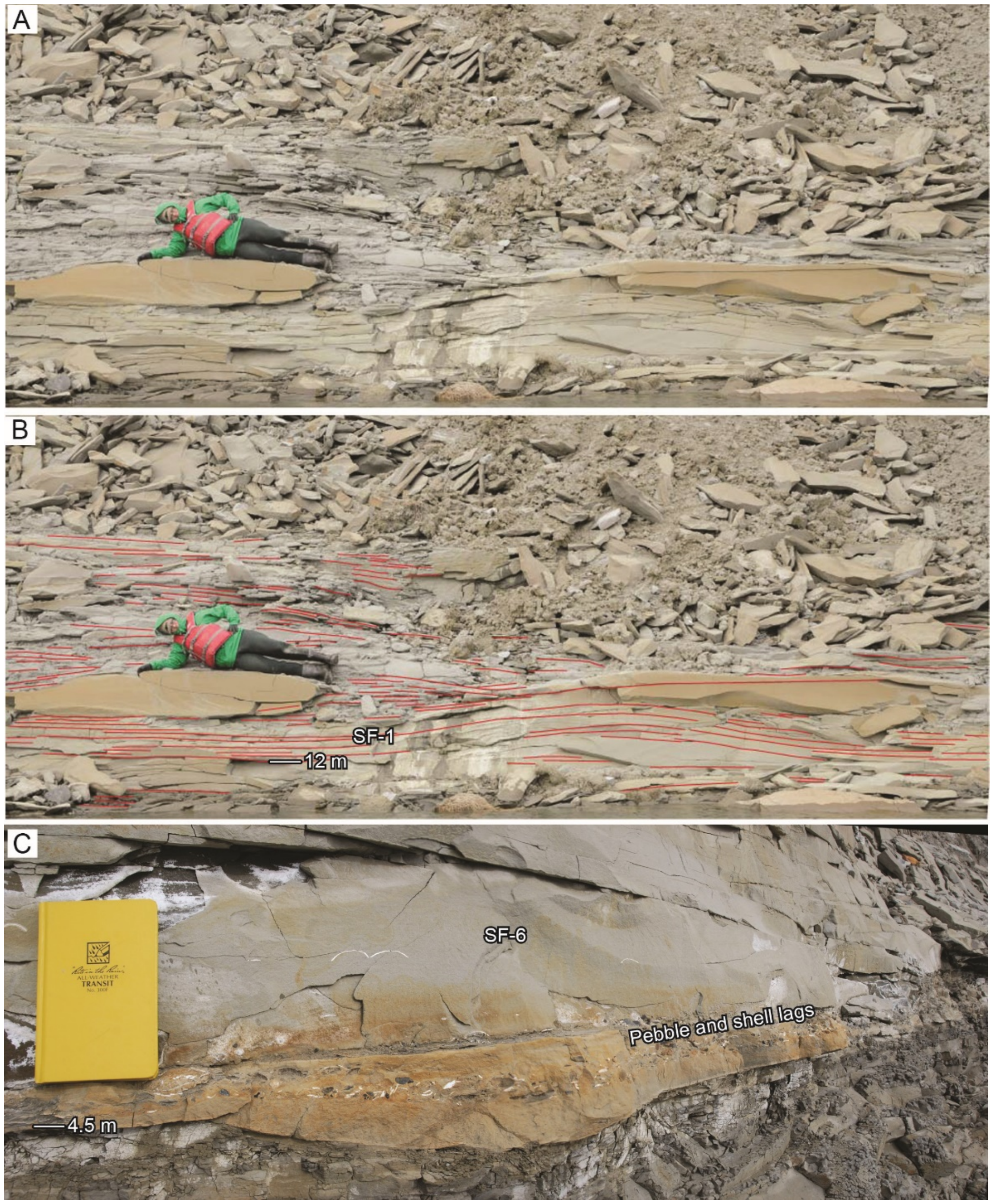


Figure 4.8. Photographs of the lower Schrader Bluff Formation: A) hummocky cross-stratification (SF-1) in distal distributary mouth bar complexes (SFA-III), B) line drawing of A, and C) shallow gutter cast with pebble and shell lags.

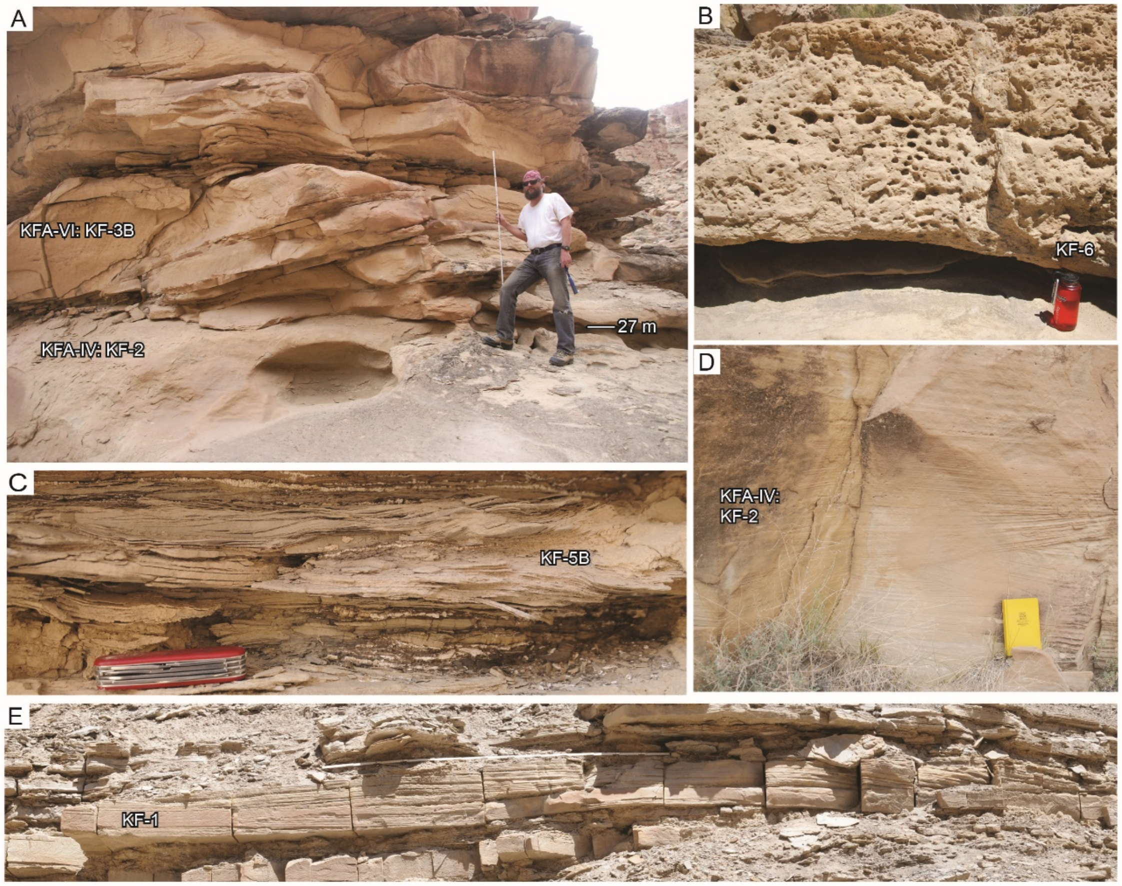


Figure 4.9. Sedimentary structures in the Kenilworth Member of the Blackhawk Formation in Utah. Refer to measured section in Figure 4.6. A) Large-scale trough cross-stratification (KF-3B) forming a channel complex (KFA-VI) that erodes into upper shoreface (KFA-IV) deposits in KPS4. B) Bioturbated sandstone (KF-6) with a bioturbation index of 5–6 (Fig. 4.5; Droser and Bottjer 1986). C) Symmetric (wave) ripple-lamination (KF-5B). Pocket knife is 9 cm long. D) Swaley cross-stratification (KF-2). Field book is 12.0 cm wide and 19.5 cm long. E) Over 4 meter wide hummock in hummocky cross-stratification (KF-1) with a 2-m-long measuring stick for scale.

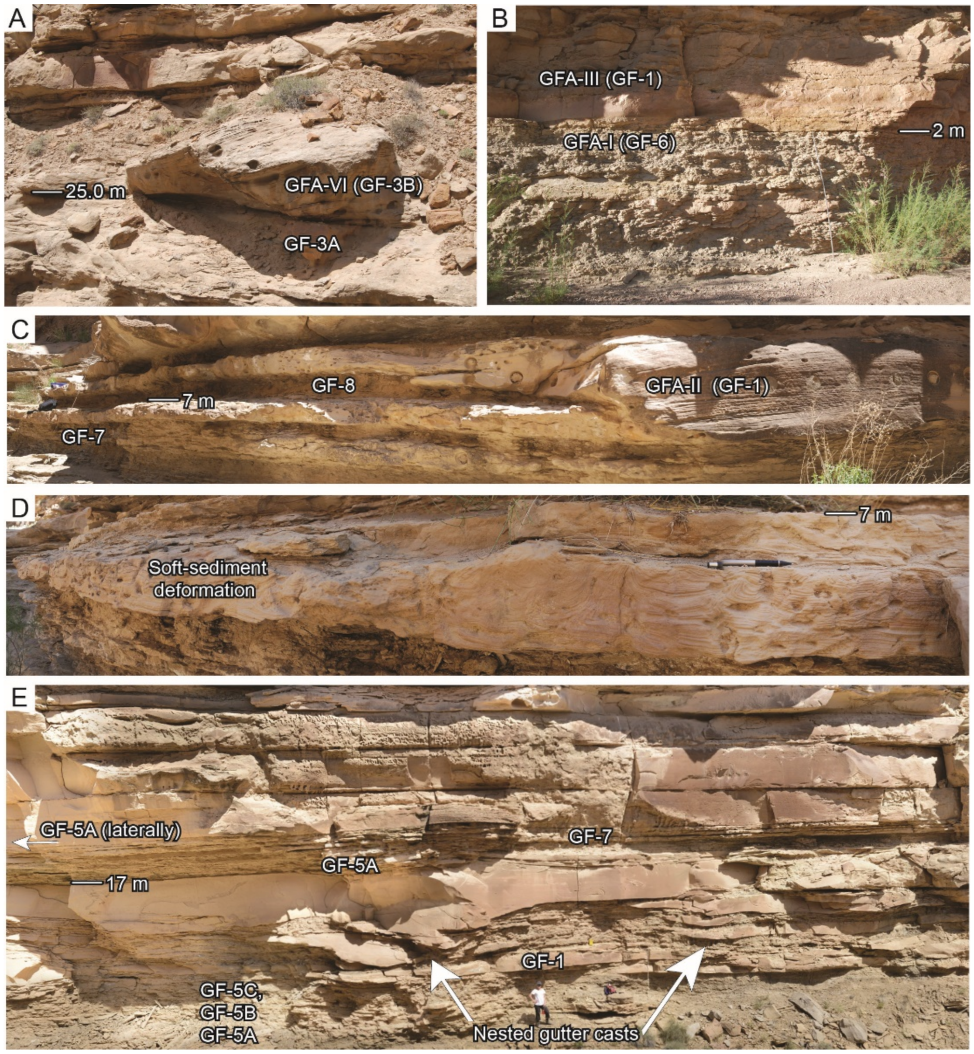


Figure 4.10. Sedimentary structures in the Grassy Member of the Blackhawk Formation in Utah. Refer to measured section in Figure 4.6. A) Large-scale trough cross-stratification (GF-3B) interpreted as a channel complex near 25 m in GPS4 (Fig. 4.6). B) Sharp-based contact between offshore transition (GFA-1) and proximal lower shoreface (GFA-III) deposits at 2 m in GPS4. C) A marker bed of HCS (GF-1) at 7 m interpreted as proximal lower shoreface (GFA-III). D) Soft-sediment deformation exposed in the bed immediately below 7 m in C. E) Multiple storm event beds and nested gutter casts with a geologist 1.5 m tall for scale.

Table 4.5. Total thickness of depositional processes interpreted as river-, wave-, and tide dominated as well as shelf and coastal plain in the Schrader Bluff Formation, Kenilworth and Grassy Members of the Blackhawk Formation.

Rogers Creek Member, Schrader Bluff Formation Depositional Environments (see Fig. 4.5)		**Inclusive Facies**	**Total Measured (m)**	**Calculated Percentage of Facies Associations (%)**	**Calculated Percentage Tripartite Processes (%)**	**Active Processes (see Fig 4.11)**
Rooted Horizons and Interdistributary Bay		SF-4, SF-8	2.75	7	--	--
Proximal delta front	**Distributary mouth bars and terminal distributary channels**	SF-7, SF-9, SF-8, SF-6, (0.25 m), SF-3A (1.8 m)	18.5	50	54	**River**
	Storm Sheets	SF-1, SF-2, SF-5B, SF-6, SF-8, SF-3A	15.5	42	46	**Wave**
	Sum		36.75	100	100	

Kenilworth Member, Blackhawk Formation Depositional Environments (see Fig. 4.6)	**Inclusive Facies**	**Total Measured (m)**	**Calculated Percentage of Facies Associations (%)**	**Calculated Percentage Tripartite Processes (%)**	**Active Processes (see Fig 4.11)**

Table 4.5 (continued)

	Tidal channels	KF-3C, KF-5C	1.30	4	5	**Tide**
	Subaqueous Channel Complexes	KF-3A (2 m), K-3B	4.00	11	14	**River**
Delta front	**Swash**	KF-4, KF-3A	0.90	3	81	**Wave**
	Upper Shoreface	KF-2, KF-3A (0.75 m), KF-6,	15.20	42		
	Proximal Lower Shoreface	KF-1, KF-2, KF-5B (4 m)	1.70	5		
	Distal Lower Shoreface	KF-1, KF-5A, KF-7, KF-8	6.00	17		
Offshore Transition		KF-7, KF-8, KF-5A	6.90	19	--	--
		Sum	36.00	100	100	

Grassy Member, Blackhawk Formation Depositional Environments (see Fig. 4.6)		**Inclusive Facies**	**Total Measured (m)**	**Calculated Percentage of Facies Associations (%)**	**Calculated Percentage Tripartite Processes (%)**	**Active Processes (see Fig 4.11)**
Delta front	**Subaqueous Channel Complexes**	GF-3A, GF-3B, GF-7, GF-5A	7.75	23	25	**River**
	Swash	GF-4	1.75	5	75	**Wave**
	Upper Shoreface	GF-2, GF-5A, GF-7, rare GF-5B	3.60	11		

Table 4.5 (continued)

	Proximal Lower Shoreface	GF-1, rare GF-2 and GF-3A	12.85	38		
	Distal Lower Shoreface	GF-1, GF-5C, GF-5B	5.85	17		
Offshore Transition		GF-6, GF-7, GF-5A	2.20	6	--	--
		Sum	34.00	100	100	

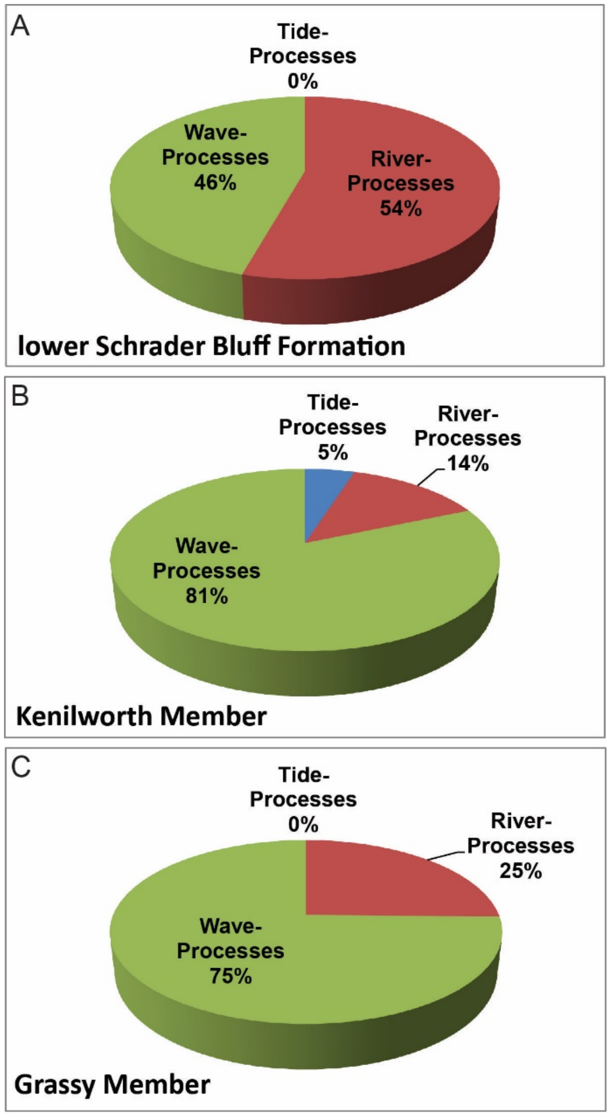


Figure 4.11. Percentages of facies and facies associations were calculated for river-, wave- and tide-dominated processes for the lower Schrader Bluff Formation (A), Kenilworth Member of the Blackhawk Formation (B), and Grassy Member of the Blackhawk Formation (C).

DISCUSSION

COMPARISON OF FACIES, ICHNOLOGY, AND ENVIRONMENTS OF DEPOSITION ALONG DELTA FRONTS

The Rogers Creek Member of the lower Schrader Bluff Formation (Fig. 4.5) is dominantly composed of inclined, planar-laminated, very fine- to medium-grained sandstone (SF-7; 41%; Table 4.2) interpreted as medial and distal DMBs (Table 4.3). The base of this succession, however, mostly comprises HCS (SF-1; maximum of 31%; Table 4.2) very fine- to fine-grained sandstone interpreted as wave-modified proximal delta-front deposits or storm sheets (Table 4.3; Chapter 3). Bioturbated intervals include mostly discrete, isolated trace fossils with the exception of *Helminthopsis* and *Phycosiphon* in mudstone layers (ii = 4; Table 4.4). Proximal delta-front deposits of the Rogers Creek Member are interpreted as a river-dominated (54%), wave-modified (46%) deltaic system (Table 4.5).

The upper succession of KPS4 within the Kenilworth Member of the Blackhawk Formation (Fig. 4.6) is dominantly composed of SCS, very fine- to fine-grained sandstone (KF-2; 33%; Table 4.2), interpreted as upper shoreface (Table 4.3). Asymmetric ripple lamination (KF-5A) in muddy sandstone, which also includes undifferentiated rippled intervals due to bioturbation (ii =2–5), account for 16% of strata in the KPS4 and are interpreted as offshore transition (19%; Table 4.5).The third most important facies in KPS4 is HCS (KF-1; 12%; Table 4.2), interpreted as distal and proximal lower shoreface (Fig. 4.6; Table 4.5). Discrete, isolated trace fossils and moderately bioturbated (ii = 2–3) strata are dominantly associated with offshore transition and lower shoreface deposits (Fig. 4.6). A bed at ~ 2 m has ii5, and strata above 33 m near the upper parasequence boundary has ii5–6. Delta-front deposits are subdivided into swash, and upper and lower shoreface in KPS4. KPS4 is interpreted as a wave-dominated deltaic system due the abundance of wave-generated strata (81%) and relatively minor river- (14%) and tide-generated deposits (5%) preserved in the system (Table 4.5; Figure 4.11).

GPS1-4 within the Grassy Member of the Blackhawk Formation (Fig. 4.6) is dominantly composed of HCS (GF-1; 40%; Table 4.2), interpreted as proximal lower shoreface (38%) and distal lower shoreface (17%; Table 4.5). The second significant facies includes large-scale trough cross-stratification (GF-3B; 16%), interpreted as subaqueous channel complexes based on the occurrence of *Ophiomorpha* and *Palaeophycus* (Fig. 4.6). SCS (GF-2; 11%; Table 4.2), is the third abundant facies in GPS1-4 and is interpreted as upper shoreface (5%). Distal and proximal lower shoreface, upper shoreface and swash deposits account for 75% of wave-generated strata in delta-front deposits within GPS1-4 (Table 4.5). Bioturbated intervals include mostly discrete, isolated trace fossils (ii2), but the succession is moderately to highly bioturbated (ii3–6) in the offshore transition and lower shoreface intervals near the base of the succession (0–7 m; Fig. 4.6). Delta-front deposits in the Grassy Member are also interpreted as wave-dominated deltaics (75%) with minor river-generated deltaic deposits (25%; Table 4.5; Fig. 4.11).

The Utah localities typically contain abundant *Ophiomorpha*, whereas high-latitude successions in Alaska generally lack *Ophiomorpha* but contain abundant *Helminthopsis* and *Phycosiphon* (vermiform) burrows (Table 4.4). Abundant *Ophiomorpha* within the Blackhawk Formation indicate that the Cretaceous WIS supported large populations of shrimp. Present-day latitudinal distributions of callianassid shrimp (Decapoda: Axiidea) show greater diversity from 30–40°N and 20–30°S, and are not present in latitudes > 70°N and > 50°S (e.g., Dworschak 2000, 2005; Goldring et al. 2004; Kneer et al., 2013). The rare occurrence of *Ophiomorpha* in Alaska deposits does suggest that the Arctic Ocean would have been warm enough to sustain shrimp populations. Shrimp populations may have been less prolific due to frequent freshwater and sediment influx into the marine system (Jackson et al., 2016), since the lower Schrader Bluff Formation is interpreted as a river-dominated, wave-influenced delta (Chapter 2, 3).

COMPARISON OF BEDFORMS AND STRATAL ARCHITECTURES

At first glance, low-angle, planar laminations in topsets, foresets, and bottomsets that form simple to amalgamated DMB complexes could easily be confused with HCS and SCS intervals (Fig. 4.12). Although similar HCS wavelengths and bedform thicknesses were recorded for both the Schrader Bluff Formation and the Kenilworth and Grassy members of the Blackhawk Formation (see Table 4.1 notes), the angles of the HCS bedforms appear greater (~ 5–10°; Fig. 4.8A, B) in the Schrader Bluff Formation and are generally less in the Blackhawk Formation < 5° ; Fig. 4.9E). Planar-laminations in DMBs in the lower Schrader Bluff Formation in this study are < 15° (can be up to 25° in Chapter 3), and SCS in the Blackhawk Formation generally dips < 10°. From the examination of outcrop exposures, most of these bedforms have similar dips and may be difficult to distinguish from one another in core (Fig. 3.12). HCS–SCS laminae thicken into the swale, whereas foresets in planar and trough cross-strata intervals in TDCs, and foresets in distributary mouth bars thin toward the basal surface (Harms et al. 1975; Reineck & Singh 1980; Ahmed et al. 2014). The best ways to distinguish mouth-bar deposits from HCS and SCS in these outcrops include: 1) mouth bars exhibit tripartite proximal, medial, distal gradation from troughs, to high-angle, to low-angle bedforms whereas HCS have domal symmetrical to asymmetric sedimentary structures (Dott & Bourgeois, 1982); and 2) HCS are generally 0.5-m-thick bedforms, whereas DMBs can have foresets up to 2.5 m that may be more similar to SCS intervals.

Erosional surfaces within amalgamated HCS beds and TDCs in the lower Schrader Bluff Formation commonly have shell, pebble, log, and peat or mud rip-cup clasts. Investigators have noted the general lack of shell and lag debris, even at major sequence boundaries in the Grassy Member (O’Byrne and Flint 1993). Major sequence boundaries in the Blackhawk Formation are commonly noted by an increase in grain size, such as evidence of coarse or very coarse fluvial sandstones above major erosional surfaces (O’Byrne and Flint 1993), with the exception of shell debris and shark teeth interpreted as a transgressive lag at the top of KPS4 (Pattison, 1995; Pattison et al. 2007).

Architecturally, DMB-TDC complexes in the Rogers Creek Member of the Schrader Bluff Formation form highly amalgamated disrupted tabular beds and compensationally stacked bedsets in outcrop (Fig. 4.12). Even the most continuous and resistant tabular bedsets in this succession, interpreted as multistory TDCs, laterally becomes HCS (see 14–15.5 m in Fig. 4.5; Chapter 3). The Rogers Creek Member contains the thickest amalgamated HCS intervals (~ 4–5.5 m thick; Chapter 2) at Shivugak Bluffs interpreted as wave-modified DMBs or storm sheets (Chapter 3). The thickness of HCS intervals depicted herein (Fig. 4.5) are a maximum for measured sections in the Rogers Creek Member. Laterally to these HCS deposits at the same stratigraphic level are distal DMBs (SFA-III) and TDCs (SFA-II), and these architectural elements are more representative of that outcrop interval (Fig. 4.5; Chapter 3). HCS intervals are intermittent at best at Shivugak Bluffs, likely due to the orientation of river discharge (e.g., DMB lobes in Chapter 3) relative to the propagation of waves along the shoreline (Komar, 1998).

Architecturally, the Kenilworth and Grassy members are dominated by amalgamated HCS and SCS tabular beds and bedsets punctuated by laterally continuous muddy or thin-bedded intervals with lenticular or wavy laminations between HCS and SCS that represent waning-flow or fairweather deposits (Hamblin & Walker 1979; Eide et al. 2014). The lower Schrader Bluff Formation generally lacks waning-flow indicators (ripples) or fairweather-generated deposits (mudstone and siltstone; Fig. 4.6). Amalgamated DMBs in the lower Schrader Bluff Formation look similar to thick SCS bedsets between 15.5 and 27 m in the Kenilworth Member (Figs. 4.6, 4.12). Out of the three localities, the Kenilworth Member preserves the thickest SCS interval, interpreted as the thickest upper shoreface deposits (Fig. 4.6, 4.12). The Grassy Member has the most HCS deposits; interpreted as proximal and distal lower shoreface deposits that were divided similarly to KPS4 (Fig. 4.6; Table 4.3). The Rogers Creek Member of the Schrader Bluff Formation contains the least HCS and SCS and is dominated by DMB-TDC complexes.

IMPLICATIONS FOR RESERVOIR MODELERS

Of the 546 m of continuous, vertical strata of lower Schrader Bluff and Prince Creek formations at Shivugak Bluffs, only 4% of the total section (19.1 m, Chapter 3) includes HCS, SCS, or symmetric wave-ripples indicative of wave-reworked deposits (Chapter 3). The Schrader Bluff Formation was initially hypothesized to contain a higher abundance of HCS, based on the greater fetch area of the paleo-Arctic Ocean, and increased potential for storms to generate HCS under greenhouse conditions within a high-latitude setting (e.g., Ito et al., 2001; McCabe et al., 2001; Stutz & Pilkey, 2011). Wave-influenced to wave-dominated paralic environments are commonly described for the Schrader Bluff Formation in the Colville Basin (Phillips, 2003; LePain et al., 2008), and the lower Schrader Bluff Formation at Shivugak Bluffs was previously interpreted as wave-dominated, shoreface environments (Flores et al., 2007a, b). Although this study documents wave-processes at Shivugak Bluffs, they are only a minor component; the succession comprises mainly river-dominated deltaic deposits that include truncated DMBs and amalgamated DMB-TDC complexes suggestive of high sedimentation rates and flashy discharge in a fluvial dominated deltaic system (e.g., Flaig et al., 2014; Chapters 2, 3). River-dominated deltas typically form complex reservoirs as DMB lobes form irregular deltaic margins since they are on average twice as long as they are wide (Reynolds, 1999). The sand-prone succession of the lower Schrader Bluff Formation comprises inertia- and traction- driven deposits that form DMB-TDC complexes (hyperpycnites generated from jet-plume sedimentation; Chapter 3), which likely created delta fronts with high rugosity. From a reservoir-modeling perspective, DMB-TDC complexes in the interval presented herein are the thickest and most continuous reservoir intervals in the Rogers Creek Member at Shivugak Bluffs. Barriers and baffles to reservoir flow would include fine-grained intervals within interdistributary bay, distal delta-front, and prodelta deposits that often form between compensationally stacked DMBs and/or interdistributive portions of the delta (Chapters 2, 3). Out of the sand-prone ~ 296 m-thick succession preserved at Shivugak Bluffs (Chapter 3), muddier interdistributary bay, distal delta-front, and prodelta strata make up 44.5% of the stratigraphic interval.

The Blackhawk Formation is a classic outcrop analog for wave-dominated, deltaic-shoreface reservoirs (Pattison, 1995; Taylor & Lovell, 1995; Hampson, 2000; Pattison et al., 2007). In this investigation delta-front deposits of the Blackhawk Formation include lower and upper shoreface, swash, and tidal inlets or tidally influenced distributary channels (Fig. 4.6). The Blackhawk Formation is dominated by 75–81% wave-generated strata (HCS, SCS, symmetric ripples, etc.), and has substantially less river-flood generated strata (14–25%; small- and large-scale trough cross-stratification; Fig. 4.11). In contrast, even in the most wave-dominated scenario (~ 46%), the Schrader Bluff Formation comprises ~ 54% river-generated deltaic strata. Wave-dominated deltas are different in plan view from river-dominated deltas in that they have arcuate to cuspate margins with smooth-fronted lobes that have either symmetric, asymmetric, or deflected geometries based on the interplay of river sediment and longshore-current-transport rates (e.g., Bhattacharya & Giosan, 2003; Bhattacharya, 2010). From a reservoir-modeling perspective the best reservoirs in the Kenilworth and Grassy members are within the upper successions of the wave-dominated delta front (i.e., swash, upper shoreface, and proximal lower shoreface), since these intervals often clean upward due to high-energy wave reworking (Reynolds, 1999). Barriers and baffles to reservoir flow would include muddy intervals within the offshore transition and shelf deposits. Lagoon and coastal plain fines would also decrease reservoir potential in the Blackhawk Formation.

The Utah and Alaska case studies would certainly generate two significantly different depositional models portrayed differently on paleogeographic reconstructions. These contrasting models and plan-view morphologies of these deltaic systems would affect common risk segment (CRS) maps that are often generated for play fairway analyses (Fraser, 2010). The Alaska and Utah reservoirs systems would also differ in the

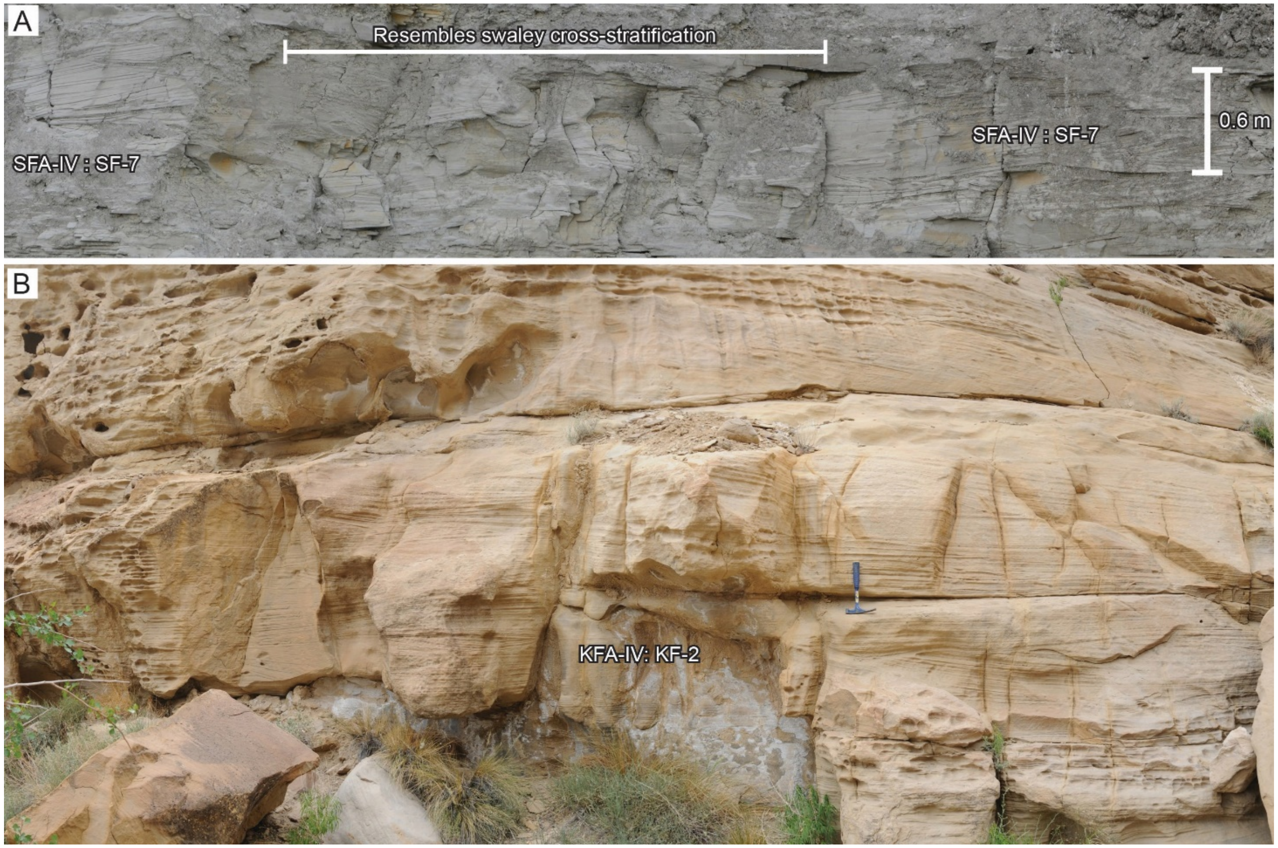


Figure 4.12. Similarities between distributary mouth bar (DMB) complexes and swaley cross-stratified (SCS) intervals. A) An example of inclined foresets interpreted as medial DMBs (SFA-IV) in the lower Schrader Bluff Formation at Shivugak Bluffs. B) An example of SCS (KF-2) interpreted as upper shoreface deposits (KFA-IV) in the Kenilworth Member of the Blackhawk Formation in Price River Canyon.

type and distribution of reservoir heterogeneities. A better outcrop analog for the Schrader Bluff Formation in the WIS might be the Ferron Notom Delta, which has been interpreted as a river-dominated delta with DMB complexes and moderate wave influence (see Gardner, 1993; Ahmed et al., 2014; Li et al., 2011; Li et al., 2015).

CONCLUSIONS

Near coeval successions (34–37-m-thick) in Alaska and Utah were evaluated for facies, facies associations, ichnology and stratal architecture in outcrop transects. The Rogers Creek Member of the lower Schrader Bluff Formation at Shivugak Bluffs in Arctic Alaska is interpreted as a river-dominated deltaic system (54%) with minor storm-wave influence (46%). The Kenilworth and Grassy members of the Blackhawk Formation in the Book Cliffs, Utah, are interpreted as wave-dominated deltaic systems (75–81%). These classic wave-dominated intervals in the Blackhawk Formation, located ~ 4,135 km from Alaska, are interpreted to be a poor outcrop analog for the Schrader Bluff Formation reservoir system. This study does, however, provide a thorough comparison between wave-dominated and river-dominated deltaic faces and architectures in ancient outcrops. The key points of this investigation include:

1. River-dominated, proximal delta-front deposits of the lower Schrader Bluff Formation comprise DMB-TDC complexes interbedded with HCS-SCS storm sheets. Wave-dominated proximal delta-front deposits of the Kenilworth and Grassy Members of the Blackhawk Formation in the Book Cliffs, Utah, comprise lower shoreface, upper shoreface, swash, and channel complexes.

2. Planar laminations in DMBs and TDCs could be mistaken for planar laminations in HCS and SCS. DMB-TDC complexes could be lumped as HCS or SCS intervals, especially if there are minor remnants of HCS and SCS in the depositional system, but the geometries of these environments are very different.
3. From a reservoir perspective, river-dominated deltaic systems likely present more complicated reservoirs than those of wave-dominated deltaic and shoreline systems. Although some facies may be similar, and certain environments and processes overlap (channels, wave-modification) the bulk of the stratigraphy in each delta type formed by significantly different processes (e.g. planar lamination in DMBs versus HCS), and the resultant reservoirs would have significantly different geometries.

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CHAPTER 5 –DISSERTATION CONCLUSIONS

This dissertation is the first to provide a high-resolution sedimentologic, stratigraphic, and ichnologic outcrop analysis of the ~ 532 m-thick composite stratigraphic succession of the lower Schrader Bluff–Prince Creek formations (fms) at Shivugak Bluffs on the North Slope of Alaska (Chapter 2). This research is also the first detailed investigation of sand- and mud-dominated deltaic environments of the Rogers Creek, Barrow Trail, and Sentinel Hill members (mbrs) of the lower Schrader Bluff Fm (Chapter 3). Research results herein are important to workers who model: 1) Alaska North Slope hydrocarbon reservoirs; 2) high-latitude greenhouse depositional systems; and 3) clinoform-topset deltaic systems. A comparison of river-dominated deltas in the lower Schrader Bluff Fm deposited along the margin of the paleo-Arctic Ocean to wave-dominated deltaic systems of the Blackhawk Fm deposited along the margin of the Western Interior Seaway, provides sedimentological contrasts between high-latitude vs mid-latitude paralic systems in a greenhouse setting, as well as contrasting styles of wave interaction with deltaic systems (Chapter 4). The following sections summarize the main conclusions of each chapter in the dissertation and major implications of this research.

CHAPTER 2

- Analysis of the deltaic-to-fluvial transition from the Cretaceous lower Schrader Bluff Fm into the Prince Creek Fm at Shivugak Bluffs combines sedimentologic and ichnologic observations, including the occurrence of rhizoliths, rhizocretions, mottling, and paleosols, to distinguish between marine and continental deposits and construct a depositional model for this system.

- Floodbasin environments including lakes, swamps, crevasse splays, and other overbank deposits, most of which contain varying degrees of pedogenic modification (i.e., paleosols), record deposition in a continental setting.
- Distributary channels in the Prince Creek Fm were adequate in size (i.e., measured depth, width, area) and had the appropriate sediment discharge to routinely produce hyperpycnal plumes. The muddy deltaic system of the lower Schrader Bluff Fm includes abundant sheet sandstones and channel forms, interpreted as hyperpynites and subaqueous terminal distributary channels.
- Three significant erosion surfaces (ES1, ES2 and ES3) at Shivugak Bluffs are interpreted as the outcrop expression of a composite unconformity. Down depositional dip this unconformity is mapped as the boundary between lower and middle Schrader Bluff fms in the subsurface.

CHAPTER 3

- The Rogers Creek Mbr is a ~ 120-m thick progradational package comprising prodelta and distributary mouth bar (DMB)–terminal distributary channel (TDC) complexes with minor hummocky cross-stratified storm sheets interpreted as river-dominated deltas (81 %) with minor wave-influence (13%). The Rogers Creek Mbr is capped by deposits representing sinuous (meandering) channels, crevasse-splays and levees, paleosols, and swamps (6%).

- The Barrow Trail Mbr is a ~ 150 m-thick retrogradational package comprising DMB-TDC complexes, medial and distal delta front, and prodelta deposits interpreted as river-dominated deltas with minor wave-influence (4%).
- The Sentinel Hill Mbr is a ~ 250-m thick progradational succession comprising mud-rich, river-dominated delta deposits. Proximal- and distal-delta fronts are composed of hyperpycnite-dominated sheet sandstone interbedded with siltstone or mudstone with minor distributary mouth bars (DMBs). Paleoenvironments include proximal shelf, prodelta, distal and proximal delta front, as well as interdistributary bays, terminal distributary channels, mouth bars, floodbasins, low-sinuosity, high-sinuosity, and downstream-accreting channels. The Sentinel Hill Mbr lacks medial delta front, medial distributary mouth bar (MDMB), distal distributary mouth bar (DDMB), and TDC complexes that are present in the Rogers Creek and Barrow Trail Mbrs.
- The outcrop at Shivugak Bluffs preserves an overall fining upward succession of sand-rich to mud-rich deltaic deposits. The reduction in sand within the sediment supply was likely driven by autogenic processes (i.e., lobe abandonment or avulsion).
- The Rogers Creek, Barrow Trail, and Sentinel Hill mbrs of the lower Schrader Bluff Fm at Shivugak Bluffs is placed within accommodation succession sets to establish a sequence stratigraphic framework. The sequence stratigraphic framework of these deposits contains having two PA, two APD, and two R accommodation succession sets. ES1, ES2 and ES3 become a composite sequence boundary down depositional dip.

- From a reservoir perspective, DMB-TDC complexes and MDF deposits in sand-rich portions of river-dominated deltas are the thickest and most continuous reservoirs in the lower Schrader Bluff Fm at Shivugak Bluffs.

CHAPTER 4

- The most wave-influenced interval at Shivugak Bluffs is within the Rogers Creek Mbr of the lower Schrader Bluff Fm. This 37-m-thick interval is compared to 36- and 34-m-thick wave-dominated intervals within the Kenilworth and Grassy mbrs of the Blackhawk Formation in the Book Cliffs, Utah. The Rogers Creek Mbr is interpreted as a river-dominated deltaic system (54%) with minor storm-wave influence (46%) and mbrs of the Blackhawk Fm are interpreted as wave-dominated deltaic systems (75–81%). The Blackhawk Fm, based on this analysis, is a poor outcrop analog for the Schrader Bluff Fm reservoir system.
- River-dominated, proximal delta-front deposits of the lower Schrader Bluff Fm comprise DMB-TDC complexes interbedded with HCS-SCS storm sheets. Wave-dominated proximal delta-front deposits of the Kenilworth and Grassy mbrs of the Blackhawk Fm in the Book Cliffs, Utah, comprise lower shoreface, upper shoreface, swash, and channel complexes.
- Planar-laminations in DMBs and TDCs could be mistaken for planar-laminations in HCS and SCS. DMB-TDC complexes could be lumped as HCS or SCS intervals, especially if there are minor remnants of HCS and SCS in the depositional system, but the geometries of these environments are very different.

- From a reservoir perspective, river-dominated deltaic systems likely present more complicated reservoirs than those of wave-dominated deltaic and shoreline systems. Although some facies may be similar, and certain environments and processes overlap (channels, wave-modification) the bulk of the stratigraphy in each delta type formed by significantly different processes (e.g. planar-lamination in DMBs versus HCS), and the resultant reservoirs would have significantly different geometries.

MAJOR IMPLICATIONS

Architectural Elements in Sand-Rich vs. Mud-Rich Deltaic Systems.— Shivugak Bluffs are a world-class outcrop belt that uniquely preserves a continuous vertical succession of the transition from sand- to mud-rich deltaic systems. The vertical and lateral nature of these strata provides a unique perspective on the evolution of a small piece (2–4 km) of a large deltaic system (~542-m thick). The change from sand- to mud-rich deltas is interpreted as to result from autogenic processes, whereas major erosion surfaces along the delta are likely allogenic in nature. Results indicate that the lower Schrader Bluff Fm at Shivugak Bluffs comprises recurring northward-dipping, river-dominated delta lobes and thick interdistributary bays, suggesting pronounced digitate and lobate deltaic morphologies along the Late Cretaceous Arctic shoreline. This is particularly important because of the lack of published data, in general, on prograding muddy deltaic systems and the architectural elements within them. New nomenclature is proposed for TDCs, and this is one of the first examples of subaqueous TDCs described from muddy prodelta environments. The Sentinel Hill Mbr of the lower Schrader Bluff

Fm preserves embayed muddy environments, but the preservation of sandy river-dominated deltas and the general lack of wave reworking indicate a significant amount of protection of delta lobes, in order to preserve the primary river-flood processes. The Barrow Arch along the northern edge of the Colville Basin may have acted as a paleohigh and exerted a paleogeographic control on deposition, protecting deltaic systems during deposition of the lower Schrader Bluff Fm. Similarly, river-dominated deltas from the Cretaceous WIS, such as the Panther Tongue of the Star Point Fm, are interpreted to have been deposited in a large embayment or bight in the WCIS.

Deltaic versus Shoreface Depositional Systems in the Schrader Bluff Fm.— The Schrader Bluff Fm has historically modeled in outcrop and in the subsurface as a series of stacked shoreface successions with sedimentary structures and geometries controlled by wave action. Strata described at Shivugak Bluffs herein provide new evidence of deltaic geometries and added complexities for coastal strata of the Schrader Bluff Fm. Investigators that discover discrepancies between subsurface data and their depositional models along coastlines with mixed river- and wave-processes may want to assess if this is a product of wave-modified, river-dominated deltaic systems versus a wave-dominated deltaic or shoreface system. The Schrader Bluff Fm is commonly interpreted to contain top-truncated, shoreface successions that lack upper shoreface, foreshore, and continental deposits. Results from this dissertation suggest that a deltaic system could be an alternative interpretation for this stratigraphy. River-dominated deltas of the Schrader Bluff Fm are interpreted as lobate geometric features that are internal and laterally complex with high rugosities due to the presence of DMB-TDC complexes. Stacked mouth bar complexes, TDCs, and medial delta front sandstone are potentially good reservoirs, but they have different geometries than stacked shoreface successions, which are sheetlike. Modelers of North Slope reservoir systems should take all of this information into account, not only when modelling the Schrader Bluff Fm, but also other prograding clastic wedges in the Colville Basin (e.g. Nanushuk-Torok). The recognition of two very different depositional models that share sedimentary structures with similar characteristics (e.g., low-angle planar laminated sandstone, HCS) can easily be applied to other basins modelling similar deltaic and shoreface systems with sparse, disconnected datasets.

Recognition of a Composite Unconformity and Composite Sequence Boundary.—The mid-Campanian Unconformity (mCU) has regionally been mapped in the subsurface on the North Slope, and Shivugak Bluffs represents the only known outcrop expression of it in Arctic Alaska. In outcrop, three possible erosion surfaces were candidates for the mCU at Shivugak Bluffs (ES1, ES2, and ES3). The mCU, renamed the Campanian Unconformity (CU) herein, is interpreted as a composite unconformity in an updip location. Wireline-well-log interpretations suggest that ES3 is correlative to the previously mapped mCU near Shivugak Bluffs. ES1, ES2, and ES3, however, likely become conformable downdip and are interpreted as composite sequence boundary at locations downdip from Shivugak Bluffs.

River- versus Wave-Dominated Deltaic Systems.—Previous investigations of the lower Schrader Bluff Fm have mistakenly interpreted the succession at Shivugak Bluffs as deposits of wave-dominated shoreface environments (Flores et al. 2007a, b). Those working the subsurface in Arctic Alaska have used the Book Cliffs of eastern Utah as a potential outcrop analog for northern Alaska reservoirs. This dissertation tested whether the Kenilworth and Grassy mbrs of the Blackhawk Fm in Utah are the appropriate analog for the Rogers Creek Mbr of the lower Schrader Bluff Fm. Results indicate that the Blackhawk Fm is not a good reservoir analog, as the Blackhawk Fm comprises 75–81% wave-dominated sedimentary structures, whereas the maximum wave-dominated interval in the lower Schrader Bluff Fm comprises ~46 % wave-dominated structures. This dissertation illustrates how DMB-TDC complexes can be mistaken for HCS and SCS intervals, and cautions those working mixed wave- and river-dominated intervals in outcrop and in core.

APPENDICES

APPENDIX A. MEASURED SECTIONS FROM SHIVUGAK BLUFFS FROM CHAPTER 3. SEE SUPPLEMENTAL FILES.

APPENDIX B. DIGITAL COPIES OF PHD MEDIA COVERAGE. SEE SUPPLEMENTAL FILES.

APPENDIX C. DIGITAL COPY OF DISSERTATION. SEE SUPPLEMENTAL FILES.

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CHAPTER 5 REFERENCES

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VITA

Dolores Ann van der Kolk was born near Seattle, Washington, to Patricia and Jan van der Kolk. She was raised in Orange County, California, and discovered geology at a young age while camping with her family in the high desert, now known as Death Valley National Park. She graduated from Foothill High School in Santa Ana, California, in June 1997 and finished her first semester at California State University, Fullerton, before turning 18 years old. During her undergraduate career, she took advantage of several summer research opportunities including: SUNY Stony Brook's Center for High Pressure Research in 1999, Keck Geology Consortium's Mars Project held at Goddard Space Flight Center in 2000, and Rice University's aqueous geochemistry lab in 2001. She wrote her undergraduate senior thesis on the Goldstein Peak Formation, a metamorphic roof pendant, in the western foothills of the Sierra Nevada Mountains, California. Dolores obtained a Bachelor of Science degree in geology from California State University, Fullerton, in 2002.

Between 2002 and 2005, Dolores executed environmental and geotechnical investigations in the Los Angeles Basin with URS Corporation and Earth Tech, two large engineering firms. In August 2005, Dolores moved to Alaska and enrolled in the graduate program at the University of Alaska Fairbanks. By January 2006, she was employed as an Energy Intern by the Division of Geological & Geophysical Surveys (DGGS) that financially supported the helicopter-based fieldwork she carried out in the Arctic National Wildlife Refuge for her master's research. In 2006 and 2007, she worked as a field assistant for Dr. Peter Flaig during his dissertation research along the Colville River in the National Petroleum Reserve–Alaska. Dolores and Peter also conducted helicopter-supported fieldwork for the DGGS on state land along the Toolik River in 2007. In 2008, Dolores and Peter worked as contract geologists for FEX, L.P., a subsidiary of Talisman Energy; during this time they continued their northern Alaska fieldwork and led a field trip for FEX and Talisman employees along the Toolik, Sagavanirktok and Ivishak

Rivers. While conducting fieldwork along the Sagavanirtok River in 2008, they decided that Sagwon Bluffs would be a great candidate for the first ground-based LiDAR survey in northern Alaska. In 2009, in collaboration with the Quantitative Clastics Laboratory at the Bureau of Economic Geology, Dolores and Peter piloted a LiDAR survey of Sagwon Bluffs with helicopter-support from the United States Geological Survey. Dolores entered the PhD program at the University of Texas at Austin in the fall of 2009, and earned her master's degree from the University of Alaska Fairbanks, in the spring of 2010. After looking at the fluvial-coastal plain deposits of the Prince Creek Formation, as Peter's field assistant, Dolores wanted to investigate the coeval shallow-marine deposits of the Schrader Bluff Formation that she and Peter had boated past in previous field seasons. Dolores and Peter married in Talkeetna, Alaska on November 11, 2011.

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This dissertation was typed by Dolores van der Kolk.