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**SEDIMENTOLOGY, STACKING PATTERNS, AND  
DEPOSITIONAL SYSTEMS IN THE MIDDLE ALBIAN–  
CENOMANIAN NANUSHUK FORMATION IN OUTCROP,  
CENTRAL NORTH SLOPE, ALASKA**

by  
David L. LePain, Paul J. McCarthy, and Russell Kirkham



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## CONTENTS

Abstract .....	1
Introduction .....	2
Regional geologic framework .....	4
Facies .....	8
Facies 1—Laminated clay shale .....	9
Facies 2—Silty shale .....	11
Facies 3a—Silty shale and ripple cross-laminated sandstone .....	11
Facies 3b—Ripple cross-laminated sandstone with minor silty shale .....	11
Facies 4—Carbonaceous mudstone and coal .....	11
Facies 5—Blocky sideritic mudstone .....	13
Facies 6—Platy Argillaceous mudstone with plant fragments .....	13
Facies 7—Bioturbated silty shale, siltstone, and sandstone .....	14
Facies 8— <i>Skolithos</i> - and <i>Thalassinoides</i> -bearing sandstone and mudstone .....	17
Facies 9a—Bioturbated hummocky cross-stratified sandstone .....	17
Facies 9b—Amalgamated hummocky cross-stratified sandstone .....	19
Facies 10—Swaley cross-stratified sandstone .....	19
Facies 11—Small-scale trough cross-bedded sandstone .....	20
Facies 12—Medium- to large-scale trough cross-bedded sandstone .....	20
Facies 13—Apparently structureless sandstone .....	20
Facies 14—Plane-parallel laminated sandstone .....	22
Facies 15—Medium- to large-scale planar cross-bedded sandstone .....	22
Facies 16—Sigmoidally cross-bedded sandstone .....	22
Facies 17—Argillaceous siltstone and sandstone .....	24
Facies 18—Granule and pebble conglomerate .....	24
Facies associations .....	25
Facies Association 1—Offshore .....	25
Facies Association 2—Storm-influenced shoreface .....	26
Facies Association 3—Distributary channel mouth bar .....	35
Facies Association 4—Tidal inlet .....	36
Facies Association 5—Bayfill—estuarine .....	36
Facies Association 6—Crevasse channel .....	38
Facies Association 7—Crevasse delta .....	40
Facies Association 8—Sandy fluvial sheet .....	40
Facies Association 9—Conglomeratic fluvial sheet .....	41
Facies Association 10—Alluvial floodbasin .....	41
Facies association stacking patterns .....	41
Southern outcrop belt .....	42
Tuktu Bluff .....	42
Kanayut River .....	42
Arc Mountain .....	42
Marmot syncline (Slope Mountain) .....	44
Northern outcrop belt .....	44
Rooftop Ridge .....	44
Ninuluk Bluff .....	46
Colville Incision .....	46
Depositional systems .....	47
Sequence stratigraphy of the Nanushuk Formation .....	51
Previous sequence stratigraphic interpretations .....	51
Present study .....	52
Controls on facies stacking patterns and sequence development .....	54
Conclusions .....	55
Acknowledgments .....	55
References cited .....	55

## FIGURES

Figure 1.	Shaded-relief map of northern Alaska showing approximate outline of the Nanushuk outcrop belt .....	2
2a.	Generalized stratigraphic column for the Brookian and Beaufortian megasequences .....	3
2b.	Generalized cross-section across the Colville basin .....	3
3.	Geologic map of the foothills belt between the Trans-Alaska Pipeline corridor and the Killik River, showing the distribution of stratigraphic units in the study area .....	5
4.	Generalized stratigraphy of the Nanushuk Formation in the south-central North Slope, showing major facies recognized by Huffman and others (1985).....	6
5.	Diagrams of paleogeographic reconstruction for the central and western Colville basin during middle to late Albian time and late Albian to Cenomanian time .....	7
6.	Simplified diagram showing the range of facies and facies complexity typically encountered in deltaic depositional systems .....	9
7.	Outcrop photographs showing typical outcrop expression of selected Nanushuk facies. Photographs are tied to the measured sections included in Appendix A. ....	12
8.	Outcrop photographs showing field expression of facies associations recognized in the Nanushuk Formation .....	26
9a.	Segment of measured section through the proximal offshore association (FA1) .....	29
9b.	Segment of measured section through offshore deposits (FA1) that grades up-section to deposits of shoreface association .....	30
10a.	Segment of measured section through distal shoreface facies association (FA2) .....	31
10b.	Segment of measured section through two shoreface facies associations (FA2) and a distributary channel association (FA3).....	32
10c.	Segment of measured section through the upper part of a bayfill–estuarine succession (FA5) to open marine facies associations (FA1 and FA2).....	33
10d.	Segment of measured section through a tidal inlet (FA4) and bayfill–estuarine succession (FA5) that is overlain by proximal shoreface deposits (FA2) .....	34
11a.	Segment of measured section through a proximal shoreface (FA2), distributary mouth bar (FA3), distributary channel (FA3) successions that are overlain by bayfill–estuarine (FA5) deposits .....	37
11b.	Segment of measured section through bayfill–estuarine (FA5) succession, fluvial sandy sheet (FA8), and alluvial floodbasin deposits (FA10).....	38
11c.	Segment of measured section through bayfill–estuarine (FA5) deposits .....	39
12a.	Strike-oriented stratigraphic cross-section from Tuktu Bluff to Marmot syncline (Slope Mountain), showing facies association stacking patterns.....	in envelope
12b.	Combination dip- and strike-oriented stratigraphic cross-section from the Kanayut River to the Colville Incision.....	in envelope
13.	Measured sections through firmgrounds developed in transgressive deposits above shoreface successions and photographs illustrating some aspects of both .....	43
14.	Segment of measured section through a shoreface succession that is truncated by an erosion surface interpreted as a subaerial unconformity .....	45
15.	Block diagrams summarizing delta style inferred from facies and facies associations recognized in the Nanushuk from the south-central North Slope .....	48

## TABLE

Table 1.	Summary of facies recognized in the Nanushuk Formation in outcrop, east-central North Slope, Alaska .....	10
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## APPENDICES

### APPENDIX A MEASURED STRATIGRAPHIC SECTIONS

Table A1.	Location Information for Measured Sections .....	61
Figure 1.	Ninuluk Bluff.....	62
	2. West Colville Incision.....	63
	3. Tuktu Bluff.....	63
	North Tuktu Bluff .....	64
	4. Big Bend of Chandler River .....	64
	5. Kanayut River.....	65
	6. Arc Mountain.....	65
	7. Rooftop Ridge.....	66
	8. Slope Mountain.....	67

### APPENDIX B BIOSTRATIGRAPHIC CONTROL

Tuktu Bluff .....	69	
Kanayut River .....	69	
Arc Mountain.....	69	
Marmot Syncline (Slope Mountain) .....	69	
Rooftop Ridge.....	69	
Ninuluk Bluff.....	70	
Table B1.	Summary of palynologic and foraminifera samples tied to measured stratigraphic sections of the Nanushuk Formation in the central North Slope, Alaska .....	71
	B2. Summary of macrofossils specimens collected from the Nanushuk Formation as part of this study.....	75

# SEDIMENTOLOGY, STACKING PATTERNS, AND DEPOSITIONAL SYSTEMS IN THE MIDDLE ALBIAN–CENOMANIAN NANUSHUK FORMATION IN OUTCROP, CENTRAL NORTH SLOPE, ALASKA

Version 2

by

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## Abstract

Detailed study of middle Albian to late Cenomanian strata of the Nanushuk Formation in the south-central North Slope allow recognition of 20 facies. These facies combine to form ten facies associations, including (1) offshore–prodelta, (2) storm-influenced shoreface, (3) distributary channel and mouth-bar successions, (4) tidal inlet, (5) bayfill–estuarine, (6) crevasse channel, (7) crevasse splay, (8) sandy fluvial channel fill, (9) conglomeratic fluvial sheet, and (10) alluvial floodbasin successions. Facies associations 1, 2, and 3 record deposition in open marine settings; facies associations 4 and 5 record deposition in open marine and marginal-marine settings; facies associations 6 and 7 are interbedded in both marginal-marine and nonmarine deposits of the bayfill–estuarine association and alluvial floodbasin associations, respectively; facies associations 8, 9, and 10 record deposition in nonmarine settings. The abundance of storm-wave-generated structures, such as hummocky and swaley cross-stratification in marine deposits, demonstrates deposition in high-energy, storm-wave-modified deltas and associated inter-deltaic shoreface settings.

The spatial arrangement of marine and nonmarine facies associations in the study area defines an asymmetric formation-scale progradational–retrogradational stacking pattern that is in agreement with previous regional studies. Our data suggest the following refinements on this regional theme. Stacking patterns in middle to late Albian marine strata along the south side of the Nanushuk outcrop belt indicate deposition in an accommodation-dominated setting in which sediment supply roughly kept pace with subsidence, resulting in thick shoreface and delta front parasequences. Marine and marginal-marine strata in this part of the Nanushuk comprise a thick progradational succession. The paucity of erosional sequence boundaries in this area suggests that times of negative accommodation were rare and most sediment was trapped in coastal plain and nearshore settings.

Stacking patterns in Cenomanian-aged strata at the top of the Nanushuk, along the north side of the outcrop belt, suggest the presence of at least two sharp-based shoreface successions at Ninuluk Bluff, and two incised valley-fill successions at a location approximately midway between Ninuluk Bluff and Umiat. Poor biostratigraphic resolution and a lack of outcrop continuity preclude correlation between these two locations, other than the Nanushuk–Seabee contact. These features suggest deposition in an accommodation-limited setting punctuated by times of negative accommodation when erosional sequence bounding unconformities developed. It is unclear whether this change from accommodation-dominated to accommodation-limited regimes was a function of position within the basin or to changing basin tectonics. Regional facies relations demonstrate that marine and marginal-marine strata at the top of the Nanushuk in this area comprise a relatively thin retrogradational succession that culminated in regional flooding of the Nanushuk shelf and coastal plain and the establishment of outer shelf water depths in which clay shales of the basal Seabee Formation were deposited. The original southern extent of Cenomanian–Turonian transgressive deposits in this area is unknown.

Rhythmically alternating alluvial floodbasin and fluvial sand and conglomerate bodies characterize the upper part of the Nanushuk along the south side of its outcrop belt. It is unclear whether this stacking pattern resulted from autocyclic processes or from base level falls associated with times of negative accommodation; however, we infer an erosional sequence-bounding unconformity at the base of each fluvial sand body. The abrupt northward pinchout of coarse-grained fluvial facies associations a short distance north of the southern edge of the Nanushuk outcrop belt is attributed to rapid decline in fluvial gradients and bifurcation of fluvial feeder channels (abrupt decline in flow competence) as channels entered the delta plain. Limited biostratigraphic control and poor outcrop continuity make detailed correlations difficult to impossible and hamper efforts to erect a detailed sequence stratigraphic framework for the Nanushuk in outcrop. We suggest that subsidence resulting from compaction was a significant control on stacking patterns in marine strata observed along the south side of the outcrop belt and that eustasy exerted significant control on patterns recognized in Cenomanian strata on the north side of the outcrop belt.

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## INTRODUCTION

Recent exploration activity on the North Slope has focused on Cenomanian through Turonian topset and deepwater strata associated with a shelf margin ~30 km east of the Colville River (fig. 1). This activity has resulted in discovery of two oil fields in Cenomanian-age lowstand turbidites (Tarn and Meltwater) that involve stratigraphic traps in slope and base-of-slope deposits (Houseknecht and Schenk, 2005). Other exploration objectives include stratigraphic traps in topset strata of the Nanushuk Formation. In spite of this interest, little is known about sand partitioning between alluvial, shelf, and deeper water facies associated with Cenomanian and older strata west and south of the Cenomanian–Turonian shelf margin.

A detailed stratigraphic framework for the Nanushuk Formation (fig. 2A) in outcrop provides information relevant to understanding sand partitioning between nonmarine and basinal environments in Albian through Cenomanian time. Albian to Cenomanian alluvial and shallow-marine strata of the Nanushuk, together with coeval and older outer-shelf, slope, and basinal strata of the Torok Formation fill the western two-thirds of a large east–west-trending foreland basin (see Molenaar, 1988). Sand in deepwater strata of this age had to pass through nonmarine and shallow-marine depositional systems depositionally updip in the Nanushuk Formation. In addition, sand-rich Nanushuk strata represent exploration

targets in their own right. Umiat field, discovered during World War II but never developed, contains ~70 mmb of technically recoverable oil in delta-front sands of the Nanushuk Formation (Molenaar, 1982). Recent discovery of the Qannik pool in a 25-ft-thick shelf-margin sand body above Alpine field in the Colville delta is the first Nanushuk reservoir to be developed (D. Houseknecht, oral. commun.).

Many advances have been made in our understanding of depositional systems and basin-fill patterns since the late 1970s when the Nanushuk was first examined in detail. Chief among them is a vastly improved ability to recognize storm-generated sedimentary structures and facies sequences in shallow marine siliciclastic depositional systems (for example, Harms and others, 1975; Dott and Bourgeois, 1982; Walker and others, 1983, to name only a few). During this same period the advent of seismic stratigraphy helped spur a revolution in sequence stratigraphy (Vail and others, 1977; Posamentier and others, 1988; Posamentier and Vail, 1988). These complementary stratigraphic methods have provided new tools for evaluating the large- and small-scale stratal patterns preserved in sedimentary basins in a chronostratigraphic framework.

In this report we present a detailed facies analysis that focuses on marine and marginal-marine strata in the eastern third of the Nanushuk outcrop belt. The analysis incorporates recent advances in our understanding

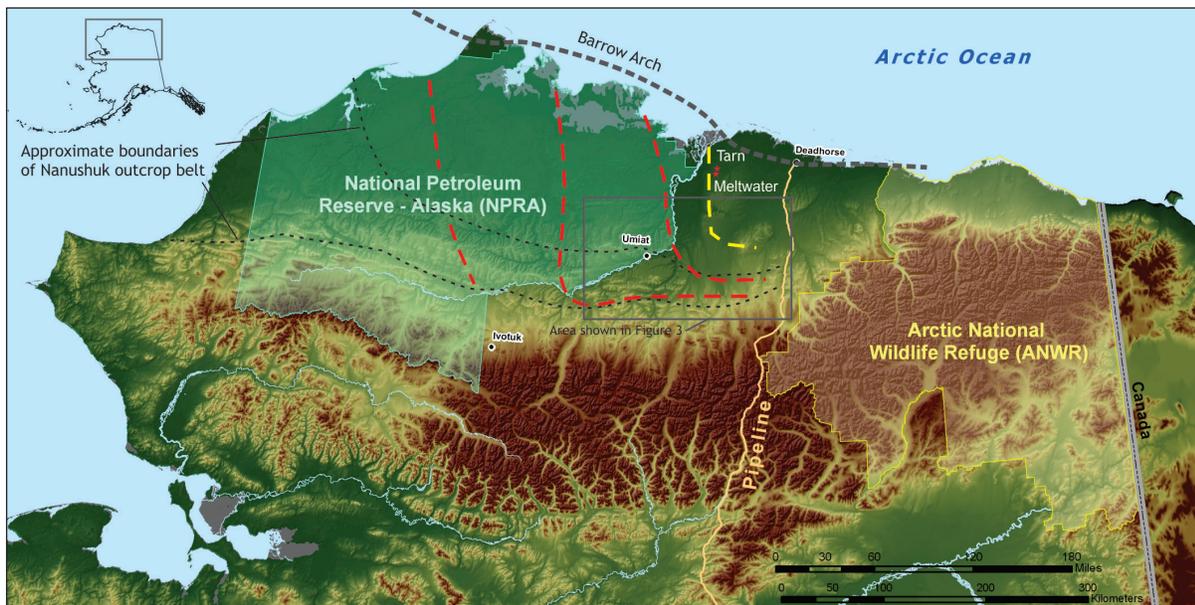


Figure 1. Shaded-relief map of northern Alaska, showing approximate outline of the Nanushuk outcrop belt, subsurface trace of the Barrow arch, and selected Nanushuk shelf margin positions (dashed red lines). The ultimate Nanushuk shelf margin is shown by the dashed yellow line. The black rectangle outlines the area shown in figure 3. The outline of the Nanushuk outcrop belt was modified from Huffman and others (1985); Nanushuk shelf margin positions were taken from Houseknecht and Schenk (2001).

Figure 2A. Generalized stratigraphic column for the Brookian and Beaufortian megasequences. Brookian clastic rocks were derived from sources in the ancestral Brooks Range to the south and southwest and record development of a major orogenic belt preserved in the present-day Brooks Range. Beaufortian strata were derived from northern sources and record extensional events that ultimately led to the rift opening of the oceanic Canada Basin.

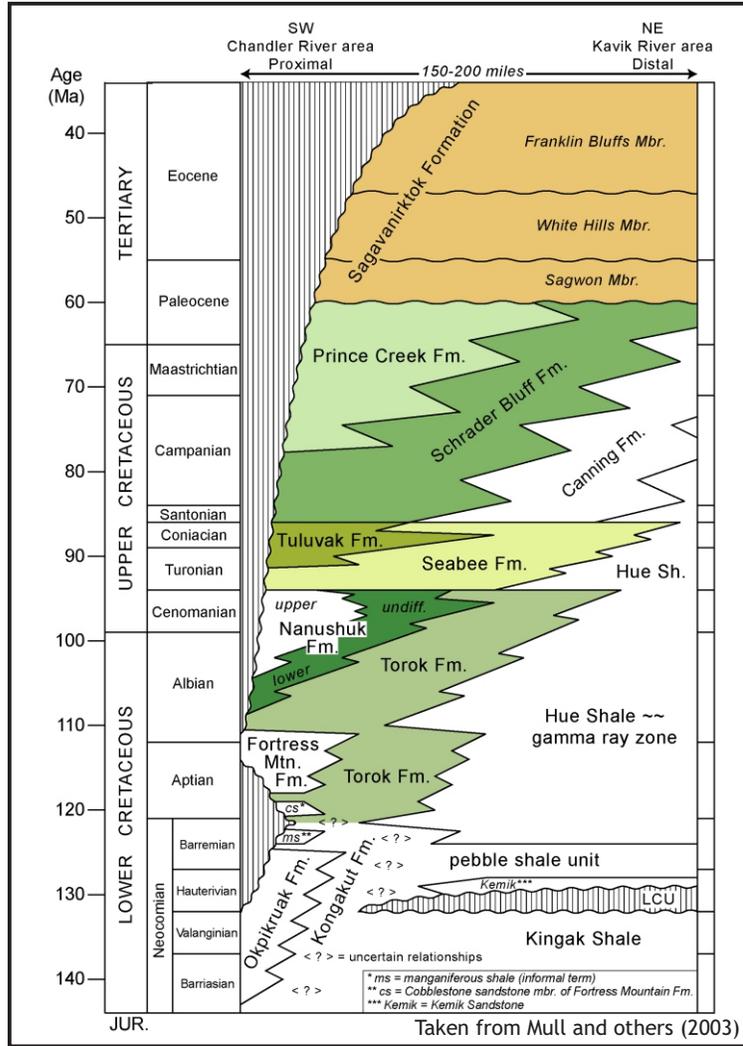
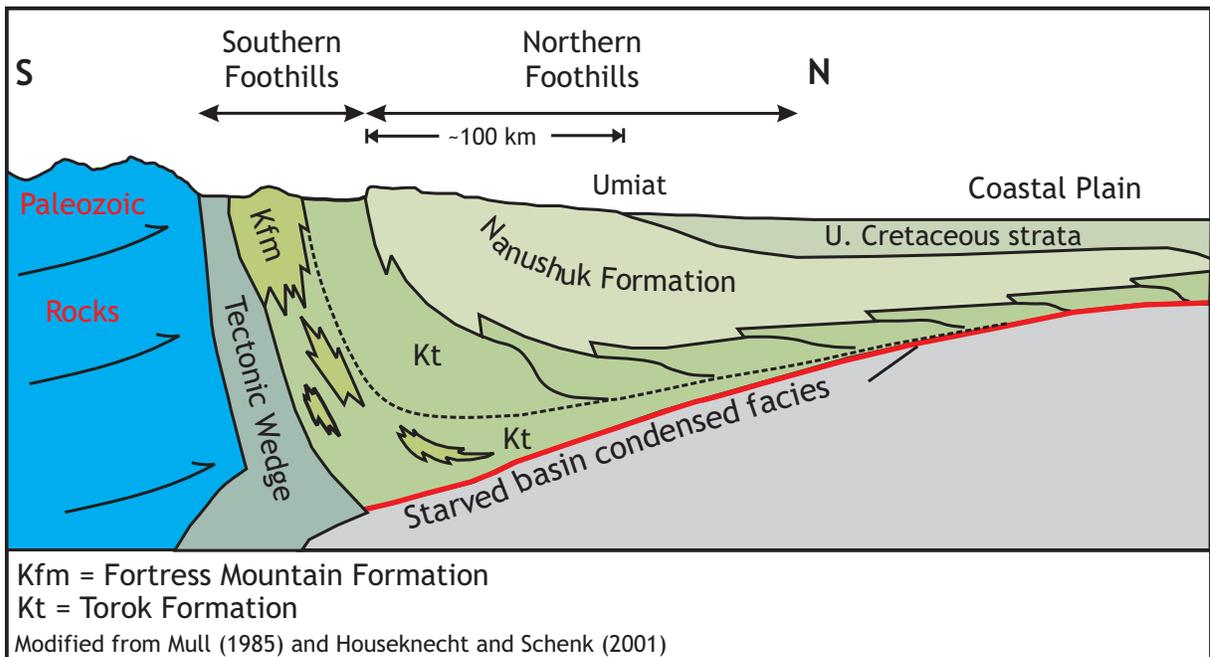


Figure 2B. Generalized cross-section across the Colville basin. Line of section starts at the coast north of Tarn field and extends south-southwest through Umiat to the mountain front (see fig. 1).



of depositional processes operating in these settings. Through detailed facies analysis we document the degree to which Nanushuk shorezone depositional systems were influenced by storm waves. We document facies stacking patterns and develop a sequence stratigraphic framework for the Nanushuk over the eastern third of its outcrop belt. Our sequence stratigraphic framework is incomplete and speculative because of limited outcrop continuity and limited biostratigraphic control. Our treatment of nonmarine Nanushuk facies is cursory and interested readers are referred to Finzel (2004) for more detailed information on nonmarine facies in the central part of the study area.

This study incorporates detailed measured stratigraphic sections from ten outcrop locations. Measured sections from eight of these locations (fig. 3) are presented in Appendix A. The study area extends from the Chandler River and Ninuluk Bluff in the west to the Sagavanirktok River in the east (figs. 1 and 3). Stratigraphic sections were measured using a Jacob's staff equipped with a clinometer. Bed thickness, grain size, grain sorting, sedimentary structures, body fossils, and trace fossils were described. Degree of bioturbation was estimated using the ichnofabric index developed by Droser and Bottjer (1986). An ichnofabric index of 1 corresponds to unbioturbated strata and is reported as III; an ichnofabric index of 6 corresponds to thoroughly burrow-mottled strata with no recognizable discrete traces and is reported as II6. Biostratigraphic control obtained during the course of this study is summarized in Appendix B. Important biostratigraphic information from various published sources is also included in Appendix B. The revised formation nomenclature of Mull and others (2003) is used in this report. Formation and member names of former usage are used only where they add to our understanding of stratigraphic relations.

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## REGIONAL GEOLOGIC FRAMEWORK

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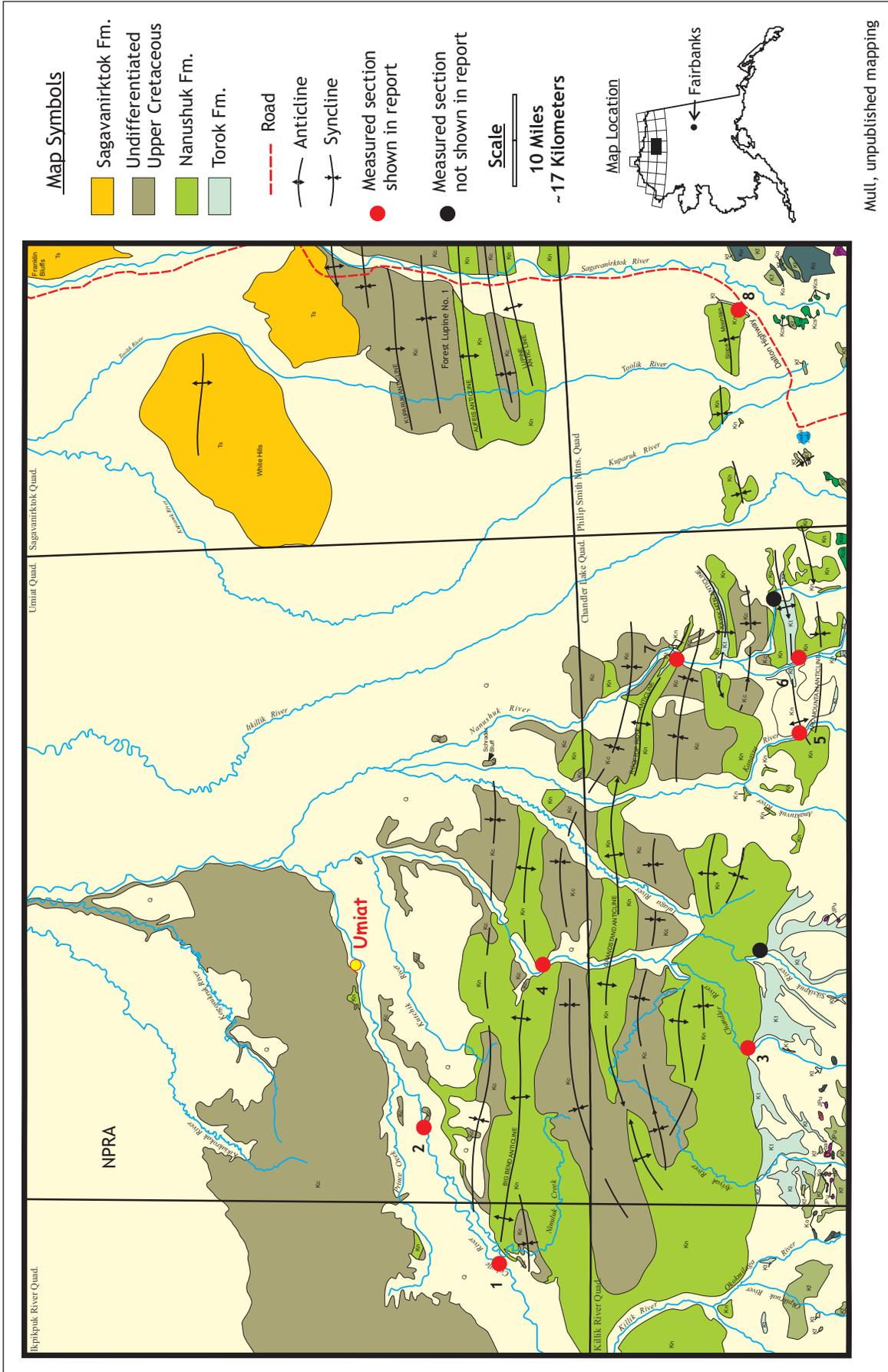
The Nanushuk Formation and coeval outer-shelf, slope, and basinal deposits of the upper Torok Formation fill the western two-thirds of a large Mesozoic–Cenozoic peripheral foreland basin (figs. 1 and 2A and B). The basin is east–west trending and extends from approximately the Alaska–Yukon border in the east to the Chukchi Sea coast in the west, and continues offshore to the Herald arch (Bird and Molenaar, 1992). The onshore part of the basin, referred to as the Colville basin, is bounded on its north side by the Barrow arch (figs. 1 and 2B). The Barrow arch is a subsurface high that coincides approximately with the present-day north coast of Alaska, from Point Barrow to the Canning River (fig. 1), and represents a rift shoulder formed when Arctic Alaska separated from a northern landmass (present-day

coordinates) in Neocomian (Valanginian–Hauterivian) time (Bird and Molenaar, 1992). The basin is bounded on its south side by the Brooks Range (figs. 1 and 2B), an east–west-trending, north-vergent (present-day coordinates) fold and thrust belt (Moore and others, 1994). The fold and thrust belt consists of a thick stack of far-traveled allochthons emplaced northward during Neocomian time (Roeder and Mull, 1978; Mull, 1985; Mayfield and others, 1988a and b), in part contemporaneous with rifting to the north (Bird and Molenaar, 1992; Moore and others, 1994). The foreland basin formed in response to the load imposed by these allochthons (Mull, 1985; Mayfield and others, 1988a and b) and was subsequently filled by detritus shed from them.

Widespread uplift and exhumation in the hinterland of the Brooks Range between 135 Ma and 95 Ma (Blythe and others, 1996; O'Sullivan, and others, 1997) resulted in a flood of clastic sediments entering the foreland basin from the south and southwest starting in late Neocomian to Aptian time. These sediments include Barremian(?) to early Albian deepwater through nonmarine deposits of the Fortress Mountain Formation and coeval deepwater strata of the Torok Formation, and fluvial–deltaic–shelf strata of the early Albian to late Cenomanian Nanushuk Formation and coeval deeper water strata of the Torok Formation (figs. 2A and B and 3; Molenaar, 1985, 1988; Mull, 1985).

The Nanushuk Formation and upper part of the Torok Formation (herein referred to as the upper Torok Formation, or upper Torok) are present throughout the northern foothills belt and subsurface of the central and western North Slope coastal plain. Collectively these two units record the change from an underfilled foreland basin to an overfilled basin by the end of late Albian time, when Nanushuk strata overtopped the Barrow arch (Molenaar, 1985). This change can be attributed to the enormous volume of clastic sediments shed into the basin from the west and southwest, resulting from widespread uplift in the hinterland (noted above), and to an episode of basin uplift in Albian time (Cole and others, 1997).

The Nanushuk Formation is a succession of complexly intertonguing marine and nonmarine strata interpreted as marine shelf, deltaic, strandplain, fluvial, and alluvial overbank deposits (figs. 4 and 5; Fisher and others, 1969; Ahlbrandt and others, 1979; Huffman and others, 1985, 1988; Molenaar, 1985, 1988). Thickness estimates for the unit range from 2,750 m in coastal exposures along the Chukchi Sea in the west (Ahlbrandt and others, 1979) to a zero edge ~75 km east of Umiat and in the area of the present-day Colville delta (fig. 1). The present-day distribution of the Nanushuk is limited to the northern foothills belt and coastal plain where it consists of a lower, dominantly marine succession of intertonguing shallow-marine shale, siltstone, and sandstone (Tuktu and Grandstand Formations of former usage) that grades



Mull, unpublished mapping

Figure 3. Geologic map of the foothills belt between the Trans-Alaska Pipeline System corridor and the Killik River, showing the distribution of major Cretaceous and Tertiary stratigraphic units in the study area. Key to units: Torok Formation (KT) shown as sage green; Nanushuk Formation (Kn) shown as pea green; undifferentiated upper Cretaceous units (Kc) shown as light gray-brown; and Tertiary Sagavanirktok Formation (Ts) shown as yellow-orange. Numbered and unnumbered dots correspond to locations of measured stratigraphic sections obtained during this study. Numbered red dots show locations of measured sections included in this manuscript. Location names: 1. Ninuluk Bluff; 2. Colville incision; 3. Tuktu Bluff and North Tuktu Bluff (~1 km north of the Chandler River); 4. Big Bend of the Chandler River; 5. Arc Mountain; 6. Marmot syncline (Slope Mountain); 7. Rooftop Ridge; and 8. Arc Mountain. Geology from Mull (unpublished).

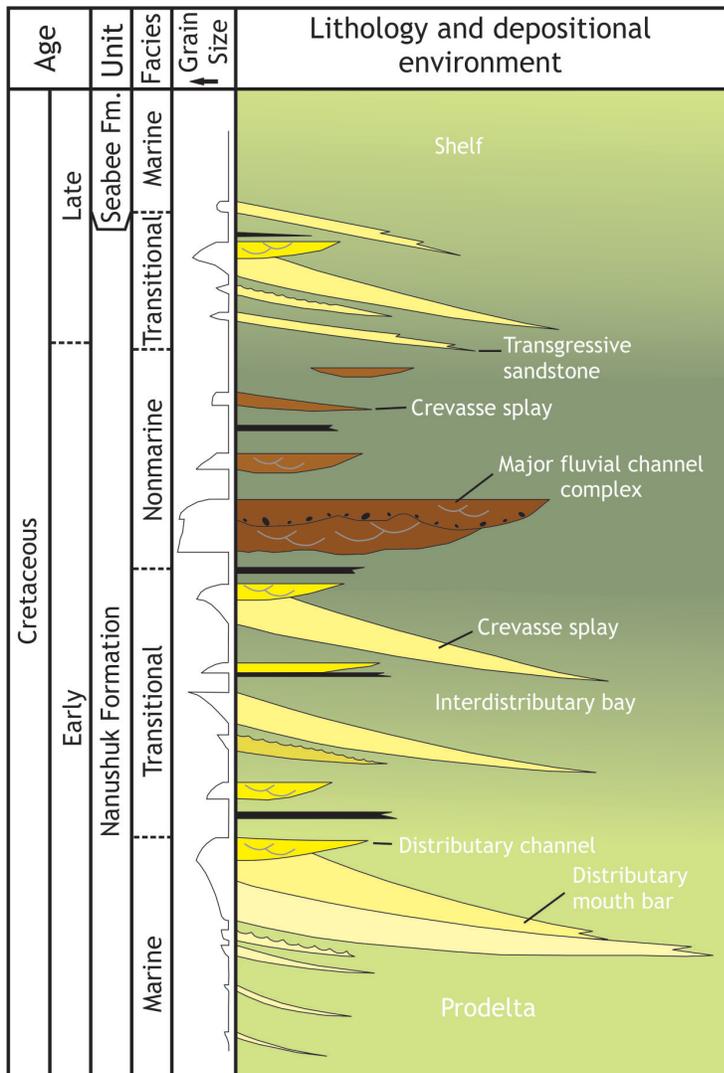


Figure 4. Generalized stratigraphy of the Nanushuk Formation in the south-central North Slope, showing major facies recognized by Huffman and others (1985). No scale is intended. This column illustrates the overall regressive–transgressive organization of the Nanushuk along the northern part of outcrop belt. Toward the south side of the outcrop belt, the Holocene (and older) erosion surface progressively truncates the Nanushuk. Throughout much of the southern part of the outcrop belt, erosion along this surface has stripped away all vestiges of the upper transgressive part of the Nanushuk and cut down into nonmarine strata. Modified from Huffman and others (1985).

north to east–northeast (seaward) to outer-shelf, slope, basal shale, and minor sandstone of the upper Torok Formation (figs. 2B and 3; Molenaar, 1985, 1988; Mull, 1985; Mull and others, 2003). This lower unit grades upsection to a dominantly nonmarine upper unit that consists of mudstones, coal, sandstone, and conglomerate (Chandler Formation of former usage). Nonmarine facies of the upper unit grade seaward to marine facies of the Nanushuk (Molenaar, 1985, 1988; Mull, 1985). Collectively, both units form a thick, regressive package that was interrupted many times by marine transgressions resulting from delta lobe shifting and abandonment.

Throughout the southern part of the study area and the western North Slope the Nanushuk Formation is bounded above by an erosion surface that separates nonmarine strata below from a varying thickness of Pleistocene sediments (fig. 2A). In the northern part of the outcrop belt in the central North Slope and in the subsurface of the eastern NPRA, a succession of intertonguing fluvial sandstone, paludal mudstone and

coal, and shallow-marine sandstone and silty shale of Cenomanian age comprises the uppermost beds of the Nanushuk and overlies dominantly nonmarine strata (fig. 4; Brosgé and Whittington, 1966; Detterman and others, 1963; Molenaar, 1985). An important distinguishing characteristic of this succession is the common presence of thin, altered volcanic ash beds. This intertonguing succession, included in the Niakogon Tongue (Chandler Formation) and Ninuluk Formation of former usage, is up to 350 m thick and records a change from overall regression to regional transgression (Detterman and others, 1963). At outcrop locations where the Nanushuk–Seabee contact is exposed, the lowermost Seabee commonly consists of a basal transgressive lag of fine- to medium-grained sandstone a few centimeters to decimeters thick that either grades upsection to thin-bedded, fine- to very-fine-grained sandstone a few meters thick that is, in turn, abruptly overlain by bentonitic clay shale, or the basal lag is abruptly overlain by bentonitic clay shale with no intervening finer-grained sandstone.

Outcrop studies by Ahlbrandt and others (1979) resulted in recognition of two major delta systems in the Nanushuk: A western delta, referred to as the Corwin delta, and an eastern delta, referred to as the Umiat delta (fig. 5). Neither the Corwin nor Umiat delta is an individual delta, but they represent areally extensive, thick deltaic depocenters, or complexes, each consisting of many individual deltas. Fisher and others (1969) classified the eastern delta as high-constructional

(river-dominated). Ahlbrandt and others (1979) and Huffman and others (1988) regarded both delta complexes as consisting of river-dominated, high-constructional deltas, but recognized that the Umiat delta complex displayed evidence of greater wave reworking. Huffman and others (1985, 1988) subsequently divided the eastern depocenter into the Kurupa–Umiat delta [complex] and the Grandstand–Marmot delta [complex].

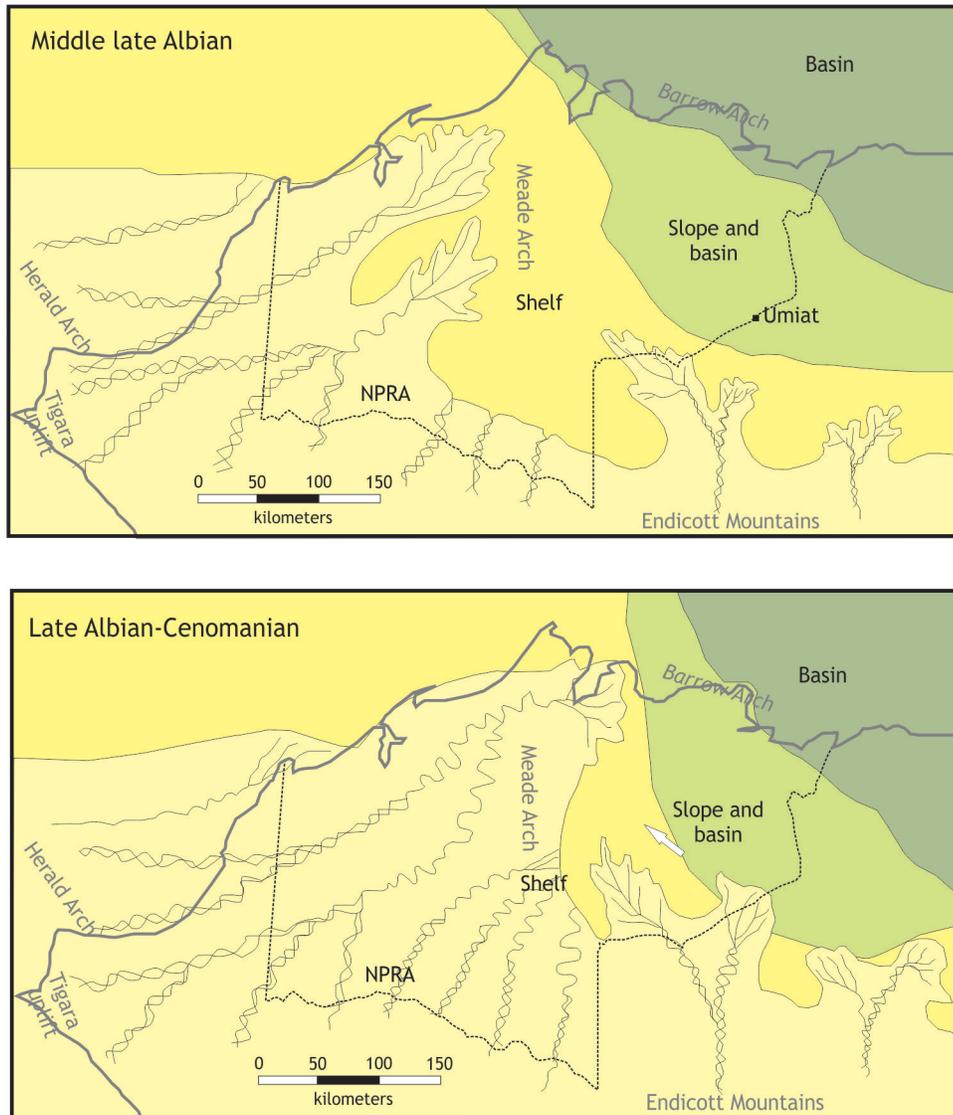


Figure 5. Paleogeographic reconstruction for the central and western Colville basin during middle to late Albian time and late Albian to Cenomanian time. Diagrams show schematic representation of Nanushuk deltas. Deltas west of the Meade arch exhibit greater river dominance and have been referred to as the Corwin delta; deltas east of the Meade arch were thought to exhibit greater wave modification and were originally referred to by Huffman and others (1985) as the Umiat delta. The Umiat delta was subsequently subdivided into the Kurupa–Umiat and Grandstand–Marmot deltas. The Corwin, Kurupa–Umiat, and Grandstand–Marmot deltas, as defined by these workers, are actually delta complexes made up of many delta lobes at any given time during their history. Modified from Huffman and others (1985).

Outcrop and subsurface data indicate that the Corwin delta complex is characterized by high mud and low sand contents (Huffman and others, 1988; Molenaar, 1988). This suggests that the western delta complex was characterized by high-constructional delta lobes (terminology of Fisher and others, 1969) that prograded east–north-eastward obliquely down the axis of the foreland basin (fig. 5; Ahlbrandt and others, 1979; Huffman and others, 1988). Available biostratigraphic data indicate the Corwin delta complex is of early Albian to late Albian age along the Chukchi Sea coast and becomes younger to the east (Ahlbrandt and others, 1979; Huffman and others, 1985, p. 71, references therein). Because of the mud-rich nature of the Corwin delta complex and the fact that it fills most of the western and central Colville basin, where it dominated depositional patterns, Molenaar (1985) concluded that the Corwin complex was derived from a source area that encompassed a large drainage basin that extended west or southwest to the area of the present-day Chukchi Sea and possibly beyond. The Barrow arch is thought to have exerted a silling effect on the foreland basin during deposition of the Corwin delta complex and to have influenced its progradation direction (Molenaar, 1988).

The Kurupa–Umiat and Grandstand–Marmot delta complexes display significant differences from the Corwin complex. The eastern delta complexes include thick prodelta mudstones overlain by thick, sandy, shallow-marine deposits, indicating lower mud and higher sand contents in these delta systems (Molenaar, 1988). Available biostratigraphic data indicate the Kurupa–Umiat and Grandstand–Marmot delta complexes are middle Albian to late Cenomanian, thus establishing that the eastern Nanushuk deltas are slightly younger overall than the Corwin delta complex in the west (Huffman and others, 1985, 1988). The sand-rich character of the eastern delta complexes suggested to Ahlbrandt and others (1985, 1988) and to Molenaar (1985, 1988) that sediment was derived from smaller drainage basins with headwater regions in the ancestral Brooks Range to the south (fig. 5). These drainage basins supplied quartzose detritus to multiple smaller rivers. A greater proportion of the total sediment load carried by these rivers was sand, resulting in sand-rich delta lobes that prograded northward at high angles to the east–west axis of the foreland basin. The sand-rich nature of the eastern deltas is consistent with Molenaar’s (1985) observation that basinward facies changes were more abrupt in the eastern Nanushuk deltas.

As noted earlier, the silling effect of the Barrow arch had largely been removed by the time deposition of the eastern delta complexes commenced (Molenaar, 1985). This was accomplished through the filling of the western part of the foreland basin by the western delta complex and by subsidence of the arch itself. Infill of the western

part of the basin resulted in filling of deep residual accommodation in the central part of the foreland basin (foredeep wedge of Houseknecht and Schenk, 2001). The presence of the foredeep wedge, combined with high sediment supply, allowed the eastern southern-sourced deltas to prograde basinward at a high angle to the basin axis. These southern-sourced deltas and associated shore-zone depositional systems are the subject of this paper.

Paleontologic samples collected during the course of our study confirm earlier age assignments made by the U.S. Geological Survey. Our data indicate a middle to late Albian age for the Nanushuk Formation (both lower and upper units of Mull and others, 2003) in the southern part of the outcrop belt, south of the latitude of Rooftop Ridge (fig. 3), and that interfingering nonmarine and marine strata at the top of the Nanushuk in the northwestern part of our study area range into the late Cenomanian (tables B1 and B2; fig. 4). Our data suggest that Cenomanian-age marine strata in the uppermost Nanushuk Formation extend at least as far south as the latitude of Rooftop Ridge (table B1, sample 99DL64-203 at Rooftop Ridge). Our data also suggest that the upper 200 m of marginal-marine, alluvial floodbasin, and coarse-grained fluvial strata in the Nanushuk at the west end of Arc Mountain anticline, where the structure is breached by the Kanayut River, may be as young as early to middle Cenomanian age (table B1, samples 01DL31-423.3 and 01DL31-472.8).

## FACIES

Deltas are complex depositional systems that grade landward to coeval fluvial systems and seaward to shelf and slope systems, in addition to grading along depositional strike to associated nondeltaic or interdeltic coastal systems (fig. 6). Consequently, detailed analyses of deltaic successions typically include a large number of genetically related facies that reflect differences in the physical, biological, and chemical conditions that shaped the various environments at the time of deposition. In this section we describe 20 facies recognized in marine, marginal-marine, and nonmarine strata of the Nanushuk Formation in the eastern third of its outcrop belt, and present process-response and generalized environmental interpretations for each (table 1). We have combined similar facies to reduce the number to a manageable quantity. Muddy facies are presented first, followed by sandstone and conglomeratic facies. Marine facies described herein represent narrow bands in an environmental continuum and many of the marine facies described (particularly facies 1, 2, 8, 9a, 9b, and 10) grade from one to another over very short distances up and down the depositional profile. Facies relations and detailed environmental interpretations are discussed in the following section on facies associations.

Our focus in this paper is on marine and marginal-marine strata. Our treatment of nonmarine deposits is superficial. We refer interested readers to Finzel (2004) for a detailed discussion of nonmarine facies in the central part of the study area.

Before proceeding, some terms used in the following sections need to be defined to avoid confusion. Fairweather wave base in modern settings corresponds to a bathymetric zone (Plint, 1996, p. 177) that fluctuates with seasonal changes in wave climate. While this may hold true in modern settings, it is difficult to apply to ancient successions. We follow Plint (1996) by defining fairweather wave base as the depth above which mud is not preserved. Fairweather wave base is defined as the base of the shoreface following Walker and Plint (1992). The terms shoreface and delta-front are used in the section addressing facies associations. The delta-front region of wave-influenced and wave-dominated deltas have many features in common with nondeltaic shorefaces and, in the geologic record, some wave-influenced delta-front successions may be difficult to distinguish from shoreface successions. We use the term shoreface

where a direct link to a distributary channel cannot be demonstrated in outcrop and the term delta-front where a link can be demonstrated.

### Facies 1—Laminated Clay Shale

Facies 1 is rarely seen in outcrop due to its non-resistant nature, so its abundance relative to other Nanushuk facies is difficult to assess. We infer that facies 1 is not a common component of the Nanushuk Formation. Facies 1 is light to medium gray clay shale and commonly includes faintly visible millimeter-scale horizontal laminations. Where seen near the top of the Nanushuk, the facies includes scattered millimeter- to centimeter-thick lamina of white–yellow to pale yellow altered volcanic ash beds. Microfossil samples collected from this facies commonly contain marine foraminifera. Preserved fine-scale lamination indicates little or no bioturbation (III–2).

### Interpretation

The laminated clay shale facies is interpreted to represent deposition from suspension in low-energy

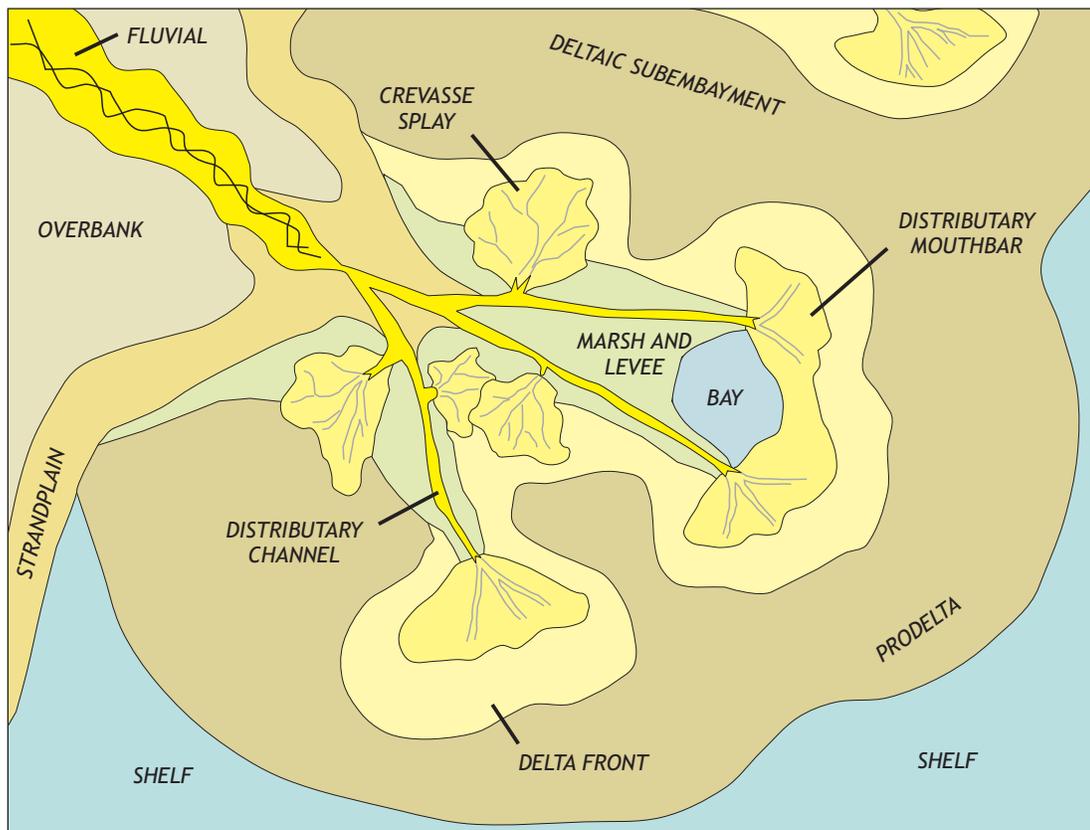


Figure 6. Simplified diagram showing the range of facies and facies complexity typically encountered in deltaic depositional systems. The delta shown in this cartoon is modeled after a river-dominated system. This figure was inspired by Fisher and others (1969) and modified from Huffman and others (1985). Most depositional environments shown are recognized in the Nanushuk in the area addressed in this contribution.

Table 1. Summary of facies recognized in the Nanushuk Formation in outcrop, east-central North Slope, Alaska.

Facies	Characteristics	Abundance	Process Interpretation
1 - Laminated clay shale	Laminated clay shale with millimeter-scale laminae.	Unknown, probably minor	Suspension settling in oxygen deficient setting.
2 - Silty shale	Dark gray, bioturbated silty shale, weathers in short pencil-shaped fragments.	Common	Suspension settling in oxygenated setting.
3a - Silty shale and ripple cross-laminated sandstone	Silty shale with thinly interbedded very fine-grained sandstone beds; sandstones graded with current ripple cross-laminated top; sandstones sparsely bioturbated to moderately bioturbated (II2-4).	Common?	Suspension settling interrupted by dilute turbidity currents transporting and depositing very fine-grained sandstone below storm wave-base.
3b - Ripple cross-laminated sandstone with minor silty shale	Ripple cross-laminated sandstone with thin interbeds of silty shale and argillaceous siltstone; basal part of sandstones graded with mudstone rip-up clasts; sandstones sparsely bioturbated to moderately bioturbated (II2-4).	Common	Deposition from turbulent flows.
4 - Carbonaceous mudstone and coal -	Carbonaceous silty clay shale, siltstone, mudstone, argillaceous sandy siltstone, and coal.	Common	Poorly drained swamp and mire sediments accumulating distal to active sources of coarser-grained sediment.
5 - Blocky sideritic mudstone	Nodular-bedded pale gray to orange-gray mudstone and very fine-grained sandstone; plant fragments, root traces, and cradle knolls common; brownish gray mudstone and muddy siltstone in poorly defined beds with weakly developed blocky texture and waxy clay coatings.	Common	Deposition in poorly drained, reducing environment; brownish mudstone and muddy siltstone with clay-coated beds record pedogenesis under variable drainage conditions.
6 - Platy argillaceous mudstone with plant fragments	Brown laminated or platy mudstone, silty mudstone/siltstone, and sandstone with locally preserved asymmetric and symmetric ripple cross-lamination and bedforms; abundant plant fragments and organic debris; bedding poorly defined; flat-topped asymmetric ripples locally prominent in sandstones; sandstones typically < than 50% of facies, but locally the dominant lithology in beds 4 cm to 20 cm thick. Disarticulated Corbiculid bivalves abundant locally; sandstones unbioturbated to moderately bioturbated (II1-4). Where sandstone comprises significant proportion of facies likely represents interbedded facies 6 and 11.	Common	Deposition in low-energy setting from dilute suspensions; interrupted by higher-energy unidirectional and oscillatory flows transporting sand-sized material. Sand subsequently reworked by short period waves.
7 - Bioturbated silty shale, siltstone and sandstone	Bioturbated silty shale, siltstone, and interbedded very fine- to fine-grained sandstone in coarsening- and thickening-upward successions; sandstone bed thickness from centimeters to multidecimeters; HCS, wavy lamination, and plane-parallel lamination common in sandstone; sandstone beds are bioturbated (II2-4) with degree of bioturbation increasing near bed tops (II3-6), beds completely burrow-mottled locally (II5-6), <i>Cruziana</i> ichnofacies.	Abundant	Silty shale and siltstone deposition below fairweather wave-base in marine setting punctuated by storm-generated flows depositing sandstone with HCS.
8 - <i>Skolithos</i> - and <i>Thalassinoides</i> -bearing sandstone and mudstone	Coarse-grained salt and pepper colored sandstone with abundant <i>Skolithos</i> and mudstone/muddy sandstone with abundant <i>Thalassinoides</i> cut by <i>Skolithos</i> (II4-6).	Minor	<i>Thalassinoides</i> -bearing mudstone and muddy sandstone interpreted as example of <i>Glossifungites ichnofacies</i> ; <i>Skolithos</i> -bearing sandstone deposited as transgressive lag above firmground.
9a - Bioturbated hummocky cross-stratified sandstone	HCS sandstone with prominent bioturbated tops (II3-6) and discontinuous mudstone interbeds to drapes; bioturbation commonly extends significant distance downward into sandstone, but decreases in intensity (II2-4).	Abundant	Deposition from storm-generated oscillatory flows below fairweather wave base.
9b - Amalgamated hummocky cross-stratified sandstone	Amalgamated HCS sandstone lacking prominent bioturbated tops (II1-3) and discontinuous mudstone drapes; mudstone occurs only as rip-up clasts.	Abundant	Deposition from storm-generated oscillatory flows above fairweather wave-base.
10 - Swaley cross-stratified sandstone	SCS sandstone with discontinuous granule- and pebble-lags.	Common	Deposition from storm-generated oscillatory flows above fairweather wave-base, in shallower water than facies 9b.
11 - Small-scale trough cross-bedded sandstone	Very fine- to fine-grained sandstone with small-scale trough cross-bedding in sets a few centimeters to approximately 20 cm thick; interbedded ripple cross-lamination common and locally dominant; plant fragments range from rare to abundant.	Abundant	Deposited from migrating small three-dimensional bedforms under unidirectional flows; some examples of facies could record deposition from oscillatory flows with distinct time-velocity asymmetry. Ripple cross-lamination records small migrating two-dimensional ripple bedform under unidirectional currents that developed in very fine- to fine-grained sand; ripple bedforms were locally transformed to symmetric wave ripples by shoaling, short period waves.
12 - Medium- to large-scale cross-bedded sandstone	Medium- to coarse-grained sandstone with medium- to large-scale trough cross-bedding in sets a few decimeters to 1 m thick.	Common	Deposited from migrating large three-dimensional bedforms under unidirectional flows; some examples of facies could record deposition from oscillatory flows with distinct time-velocity asymmetry.
13 - Apparently structureless sandstone	Very fine- to fine-grained sandstone devoid of sedimentary structures.	Minor	Rapid deposition from sediment-laden flows associated with discrete events.
14 - Plane-parallel laminated sandstone	Fine- to medium-grained sandstone with plane-parallel lamination, common parting lineation, and commonly associated with <i>Macaronichnus</i> , <i>Skolithos</i> and, locally, <i>Rossetia</i> .	Common	Deposition under upper flow-regime, plane-bed conditions in marine setting.
15 - Medium- to large-scale planar cross-bedded sandstone	Medium- to coarse-grained sandstone with medium- to large-scale planar cross-bedding in sets 15 cm to 2 m thick; herringbone cross-bedding prominent locally.	Common	Deposited from migrating large two-dimensional bedforms under unidirectional flows; herringbone cross-bedding suggests reverse current flow directions.
16 - Sigmoidally cross-bedded sandstone	Fine- to medium-grained sandstone with sigmoid-shaped cross-bedding in sets 10 cm to 0.5 m thick; sigmoid cross-beds grade laterally and vertically to plane-bedded sandstone. Sigmoid geometry of foresets and associated plane-bedded sandstone create foreset-topset couplets. Common mudstone drapes with abundant well-preserved plant fragments. Facies grades laterally to facies 12.	Common in southern part of outcrop belt	Deposition from migrating medium to large two-dimensional bedforms that migrated from shallow to deeper water
17 - Argillaceous siltstone and sandstone	Orange-brown to gray siltstone and fine-grained sandstone with dispersed clayey material and small plant fragments throughout beds; wavy, discontinuous beds in bedsets up to 45 cm thick; common root-like structures oblique to bedding; both lithologies display blocky fracture pattern and "bumpy" appearance	Common	Pedogenic modification of silty and sandy substrates under variable drainage conditions. Processes responsible for transport and deposition of sediment have been masked by subsequent pedogenesis.
18 - Granule and pebble conglomerate	Clast-supported granule- and pebble-conglomerate in crudely lenticular beds up to 2 m thick and as lags up to 15 cm thick. Imbricate clast fabrics developed locally.	Common in south; rare in north	Thicker beds are associated with sandy facies containing abundant detrital plant material interpreted as product of bedload transport under turbulent flows and deposition as channel lags and longitudinal barforms. Thin lenticular occurrences associated with marine facies deposited as lags above storm-generated scour surfaces.

settings, below storm wave-base and beyond the influence of coastal rivers. The presence of marine foraminifera and overall stratigraphic context demonstrate deposition in a marine shelf setting. Preserved laminations and undisturbed ash laminae indicate the absence, or near absence, of a burrowing infauna. This is attributed to low oxygen conditions near the sediment-water interface and/or immediately below that interface.

### **Facies 2—Silty Shale**

Facies 2 is medium to dark gray silty shale and argillaceous siltstone, and is common in outcrop. This facies typically weathers to elongate, short, pencil-shaped pieces; fresh surfaces in core typically have a structureless to mottled appearance. Physical sedimentary structures are typically not preserved in this facies (5–6).

#### **Interpretation**

The silty shale facies is interpreted to record deposition from suspension in low-energy settings below storm wavebase. The silt content records deposition closer to the shoreline and reflects relative proximity to active delta lobes. The absence of physical sedimentary structures and the mottled appearance in core indicate complete destruction of original stratification by burrowing organisms in a well-oxygenated setting.

### **Facies 3a—Silty Shale and Ripple Cross-laminated Sandstone**

Facies 3a has only been recognized at a few locations in outcrop, so its abundance is unknown. Facies 3a is silty shale and argillaceous siltstone with minor, but locally prominent, thin beds of greenish gray and brown weathering siltstone and sandstone (figs. 7A and B). Silty shale is typically medium to dark gray and appears structureless to slightly mottled. Sub-millimeter- to millimeter-scale laminae defined by subtle changes in color are present locally. Siltstone and sandstone interbeds range from a few millimeters to ~15 cm thick, consist of silt and very-fine- to fine-grained sand, and have sharp bounding surfaces. Siltstone and sandstone laminae are typically discontinuous at outcrop scale, whereas thicker sandstone beds display greater continuity (few meters to tens of meters). Most siltstone and sandstone beds include plane-parallel to slightly wavy lamination locally overlain by current-ripple cross-lamination. The basal few millimeters to centimeters of some sandstone beds include a normally graded layer that passes into plane-parallel laminated or ripple cross-laminated sandstone. Convolute bedding is prominent locally. Typically siltstone and sandstone beds are unbioturbated to sparsely bioturbated (II1–2), but locally include highly bioturbated beds (II4–6). Trace fossils, where present, typically consist of *Planolites* preserved in semi-relief on the underside of sandstone beds.

#### **Interpretation**

Facies 3a is interpreted to record deposition from suspension in low-energy settings below storm wave-base. The sequence of sedimentary structures observed in siltstone and sandstone interbeds resemble  $T_{a-c}$  and  $T_{bc}$  Bouma sequences and are similar to facies D turbidites of Mutti and Ricci Lucchi (1978). The coarser lithologies in facies 3a are interpreted as the depositional products of shelf turbidity currents (Walker, 1984) that deposited their sediment loads below storm wave-base. Turbidity currents probably originated at distributary mouths as hyperpycnal flows (Mulder and Syvitski, 1995). The facies includes characteristics in common with facies 7 and probably grades laterally and vertically to facies 7.

### **Facies 3b—Ripple Cross-laminated Sandstone with Minor Silty Shale**

Facies 3b is common in outcrop. Facies 3b differs from facies 3a in that very-fine- to fine-grained sandstone is the dominant lithology. Silty shale and argillaceous siltstone are minor components that occur as thin interbeds and as discontinuous drapes on sandstone. Sandstone bed thickness ranges from a few centimeters to 50 cm. Sandstone beds commonly include mudstone ripup clasts near the base and a basal graded part that is overlain, in ascending order, by parallel laminated sandstone,  $\pm$  current-ripple cross-laminated sandstone, and  $\pm$  asymmetric ripple bedforms.

#### **Interpretation**

The sequence of sedimentary structures observed in sandstone of facies 3b resemble  $T_{a-c}$  and  $T_{bc}$  Bouma sequences. Sandstones of this facies are interpreted as the depositional products of shelf turbidity currents (Walker, 1984) that deposited their sediment loads below storm wave-base. Facies 3b is interpreted as a proximal version of facies 3a and, similarly, we infer that turbidity currents originated at distributary mouths as hyperpycnal flows (Mulder and Syvitski, 1995).

### **Facies 4—Carbonaceous Mudstone and Coal**

Facies 4 is common in outcrop and comprises dark brown to black, carbonaceous, silty clay shale, siltstone, mudstone, argillaceous sandy siltstone, and coal (fig. 7C). Bedding in mudstone ranges from papery fissile, to thinly lenticular, to massive with a distinctive blocky parting character. Current-ripple cross-lamination and small plant rootlets are common in the thinly lenticular siltstones. Rootlets are also common in the blocky parting mudstone. Detrital fragments of leaves, twigs, and finely divided organic material are abundant throughout the facies, as are thin coal laminae (<1 cm thick). Some thinner coals have a high percentage of clastic material, whereas the thicker coals (up to 2 m) have less clastic material, but locally contain iron



Figure 7. Outcrop photographs showing typical outcrop expression of selected Nanushuk facies. Photographs are tied to the measured sections included in Appendix A. **A.** Interbedded sandstone and silty shale of facies 3a. Normal size grading is present in some beds, as is hummocky cross-stratification (HCS). Facies 3a shares characteristics in common with distal examples of facies 7. Photograph shows 8–12 m interval in the Big Bend of the Chandler River section. **B.** Thin beds of very-fine- to fine-grained sandstone of facies 3a. Normal size grading and ripple cross-lamination are common. Interbedded platy weathering material is argillaceous siltstone; small-scale HCS is present, but not abundant. Photograph shows 8 m interval in Marmot syncline (Slope Mountain) section. **C.** Coal in facies 4 (474 m above the base of the Kanayut River measured section). **D.** Nodular sideritic mudstone of facies 5 (465 m above the base of the Kanayut River measured section). **E.** Typical exposure of platy argillaceous mudstone and sandstone of facies 6. Sandstone in front of geologist is rooted (412–420 m above the base of the Arc Mountain section).

oxides. Thicker coals are blocky parting and consist of alternating bright and dull bands a few millimeters thick. Sparsely rooted underclays are present beneath some coal beds.

### **Interpretation**

Current-ripple cross-lamination in thinly lenticular siltstone of facies 4 indicates deposition from weak unidirectional currents under lower flow-regime conditions. Dark colored, papery mudstones with high organic content are similar to organic soils or histosols recognized by Leckie and others (1989) and McCarthy and others (1999). Coal is indicative of a wet or waterlogged environment of low clastic input where the accumulation rate of organic matter is equal to the rate of subsidence. The generally low clastic content of thick coals suggests that peat-accumulating environments were isolated from floodplain sedimentation for long periods of time. The close association of siltstone with abundant detrital plant debris and thin laminae of coal, papery mudstone, and thicker coal indicate that mires, possibly raised mires where the thicker coals accumulated, were flanked by submerged areas that received clastic input and by slightly elevated, but poorly drained, areas subjected to minor pedogenic modification. Collectively, these features suggest deposition in swamp or alluvial floodbasin environments.

### **Facies 5—Blocky Sideritic Mudstone**

Facies 5 is common in outcrop. Facies 5 is typically pale gray to orange-gray silty mudstone to very-fine-grained sandstone containing centimeter- and millimeter-scale carbonaceous roots, plant debris, structureless centimeter- to decimeter-scale siderite nodules, and tabular siderite concretions (fig. 7D). Bedding is massive to nodular. Root traces and cradle knolls are common. Well-preserved bedding is absent owing to development of siderite nodules. Many siderite nodules contain root traces and plant fragments.

A variant of facies 5 is recognized that is blocky weathering and consists of medium to dark gray or brownish-gray mudstone and muddy siltstone with few, fine orange and reddish-brown mottles. Bedding is poorly defined and contains millimeter- to centimeter-scale root traces and local siderite nodules. Sphaerosiderite is present locally, most commonly in association with root traces. Waxy clay coatings are occasionally observed along ped surfaces.

### **Interpretation**

The pale gray to gray coloring, combined with siderite nodules and plant debris, are indicative of a reducing, organic-rich environment (Retallack, 2001; McCarthy and others, 1999). Organic matter accumulates under anaerobic conditions that prevent decomposition. The

weak structure, mottling, and presence of large roots are indicative of pedogenesis in a poorly-drained or hydromorphic environment. The hydromorphic conditions are probably related to the presence of a locally high water table in an alluvial floodplain environment.

The variant of facies 5, with its blocky texture, root traces, and oxidized siderite is indicative of pedogenic processes above the water table. For example, shrinking and swelling of fine-grained particles in response to wetting and drying of soils results in development of blocky structures (Retallack, 2001). The presence of waxy ped coatings indicates some weak illuviation of clay has occurred. This process requires the soil to wet sufficiently so that colloidal clay is physically washed down through the soil in suspension, but the soil must also dry out enough so that the clays are retained on ped surfaces (McCarthy and others, 1998). The presence of orange mottles, however, suggests iron migration under variable to poorly-drained conditions, and the presence of sphaerosiderite and gray-brown colors indicate conditions that prevented decomposition of organic matter (McCarthy and others, 1999). These features are best explained by pedogenic development in an area where water table fluctuations were a frequent occurrence. Variable drainage conditions and the weak development of peds are consistent with alternating redox conditions in partially-drained soil (Besley and Fielding, 1989), and are common in floodplain settings (Kraus, 1999).

### **Facies 6—Platy Argillaceous Mudstone with Plant Fragments**

Facies 6 is poorly exposed, but is inferred to be common in outcrop. This facies consists of gray- to brown-laminated or platy mudstone, silty mudstone or muddy siltstone, and interbedded sandstone (fig. 7E). Plant fragments and organic debris are common. Mudstone of facies 6 includes color banding locally that consists of alternating black, brown, and orange layers. Bedding is typically poorly defined but, where visible, ranges in thickness from a few centimeters to a few decimeters.

Some exposures include lenticular and tabular beds of very-fine- to fine-grained sandstone a few centimeters to 15 cm thick. Sandstones have sharp, erosive(?) lower contacts and display either sharp (most common) or gradational upper contacts. Current- and wave-ripple cross-lamination is common, and small asymmetric and symmetric ripple bedforms are prominent on some bed surfaces (figs. 7F–G). Asymmetric ripple bedforms with flat tops cover sandstone bed surfaces locally. Abundant mica and finely divided plant fragments (resembling coffee grounds) litter some sandstone bed surfaces. Ball and pillow structures are present locally in sandstone beds, where they founded in a muddy substrate. Millimeter- to centimeter-scale siderite nodules are

common locally, but overall are a minor component of this facies. Trace fossils are not common and are limited to small vertical burrows in sandstone resembling *Skolithos* (II1–2). Round burrows up to 4 cm diameter, oriented perpendicular to bedding, are visible on some sandstone bed surfaces (fig. 7G). Small bivalves (most are disarticulated *Corbiculids*?) are locally abundant (fig. 7H). Pelecypods show evidence of at least minor transport after death. Plant roots have been recognized locally in the upper part of sandstone beds.

### **Interpretation**

Laminated or platy siltstone and mudstone suggest deposition in a low-energy environment, whereas sandstone beds indicate the low-energy setting was occasionally interrupted by higher energy flows capable of transporting sand-sized material. Siltstone may record deposition under waning flow conditions following higher energy events.

The dark color of the mudstone is from the presence of abundant terrestrial organic matter. Current-ripple cross-lamination and asymmetric ripple bedforms in some sandstone beds record sand transport by unidirectional flows (Harms, 1969, 1979; Harms, and others 1982). The presence of wave-ripple cross-lamination and symmetrical wave ripples on some sandstone bed surfaces indicates reworking by short-period waves in a standing body of water. Flat-topped asymmetric ripple bedforms were initially formed by unidirectional or combined flows and subsequently had their crestal regions planed off by shoaling waves (Allen, 1984; McKee, 1957), probably during the low water part of the tidal cycle in very shallow water. The association of this facies with paleosols (facies 17) and coals (facies 4) suggests deposition in delta plain and alluvial floodbasin settings that included areas that were perennially flooded and areas that were elevated slightly above the water table, at least seasonally (Smith and Smith, 1980). The presence locally of trace fossils and *Corbiculid*(?) bivalves suggests some marine influence (brackish water?).

### **Facies 7—Bioturbated Silty Shale, Siltstone, and Sandstone**

Facies 7 is abundant in outcrop and is dominantly bioturbated silty shale and siltstone, with minor sandstone (fig. 7I–O). Thicker successions of facies 7 typically coarsen gradually upward from silty shale and siltstone with thin sandstone interbeds less than 50 cm thick, to interbedded sandstone and siltstone (no shale), each in beds up to 100 cm thick. Silty shale is dark gray and weathers to small, flattened, irregular-shaped pieces, making physical and biogenic structures difficult to observe in outcrop. Siltstone is medium to dark gray and, where bedding is visible, it is wavy, discontinuous and

nonparallel with scattered disrupted shale partings, and pervasively bioturbated (II3–5).

Sandstone interbeds range from very fine grained to fine grained and have sharp contacts with bounding finer-grained lithologies (fig. 7I–L); gradational upper contacts have been observed (mixing due to burrowing activity of macroinvertebrates), but are not as common. The following vertical sequence, in ascending order, is commonly observed in sandstone beds of this facies: Sharp basal contact with silty shale or siltstone, ± *Planolites* traces and linear groove casts preserved in semirelief, ± mudstone rip-up clast lag, ± massive sandstone, plane-parallel to wavy lamination and/or hummocky cross-stratification (HCS), ± wave-ripple cross-lamination, ± symmetric to slightly asymmetric wave-ripple bedforms (fig. 7M). Plane-parallel lamination and HCS represent the only sedimentary structures in many beds, and these structures were observed to grade laterally from one to the other over relatively short distances (2–3 m). Most sandstone beds are laterally continuous in outcrop, but at one exposure (fig. 3, location 1), HCS sandstone fills a large gutter cast encased in silty shale that is 1 m deep and extends 4 m along outcrop strike (fig. 7L). This gutter cast resembles the shallow, rounded variety shown in Myrow (1992, his fig. 7). Gutter casts have been recognized locally, but are not a common feature in the Nanushuk in this area. The upper few millimeters to several centimeters of most sandstone beds are typically bioturbated (II2–3) and a diverse suite of traces belonging to a mixed *Cruziana*–*Skolithos* association are recognized that commonly include *Diplocraterion*, *Paleophycos*, *Planolites*, *Skolithos*, *Rhizocorallium* (fig. 7N), and *Schaubcylindrichnus*. Less common trace fossils include *Arenicolites*, *Gastrochaenolites*, *Rosselia*, *Terebellina*, and *Thalassinoides*. Some sandstone beds are thoroughly bioturbated and display a burrow-mottled appearance (II5–6; fig. 7O). Body fossils are relatively rare and include echinoid spines, pelecypod molds, and ammonites; body fossils are found mostly in sandstones. Facies 7 is typically gradationally overlain by facies 9a, but locally can grade laterally and vertically to facies 3a and 3b.

### **Interpretation**

Pervasively bioturbated silty shale and siltstone are thought to record slow background sedimentation under fairweather conditions. The sequence of sedimentary structures observed in sandstone beds are interpreted as the product of waning storm-generated flows between storm and fairweather wave-base (Dott and Bourgeois, 1982; Duke and others, 1991; Kreisa, 1981; Walker and others, 1983). Gutter casts recognized in this facies suggest the early history of some storm flows involved combined flows with strong unidirectional components

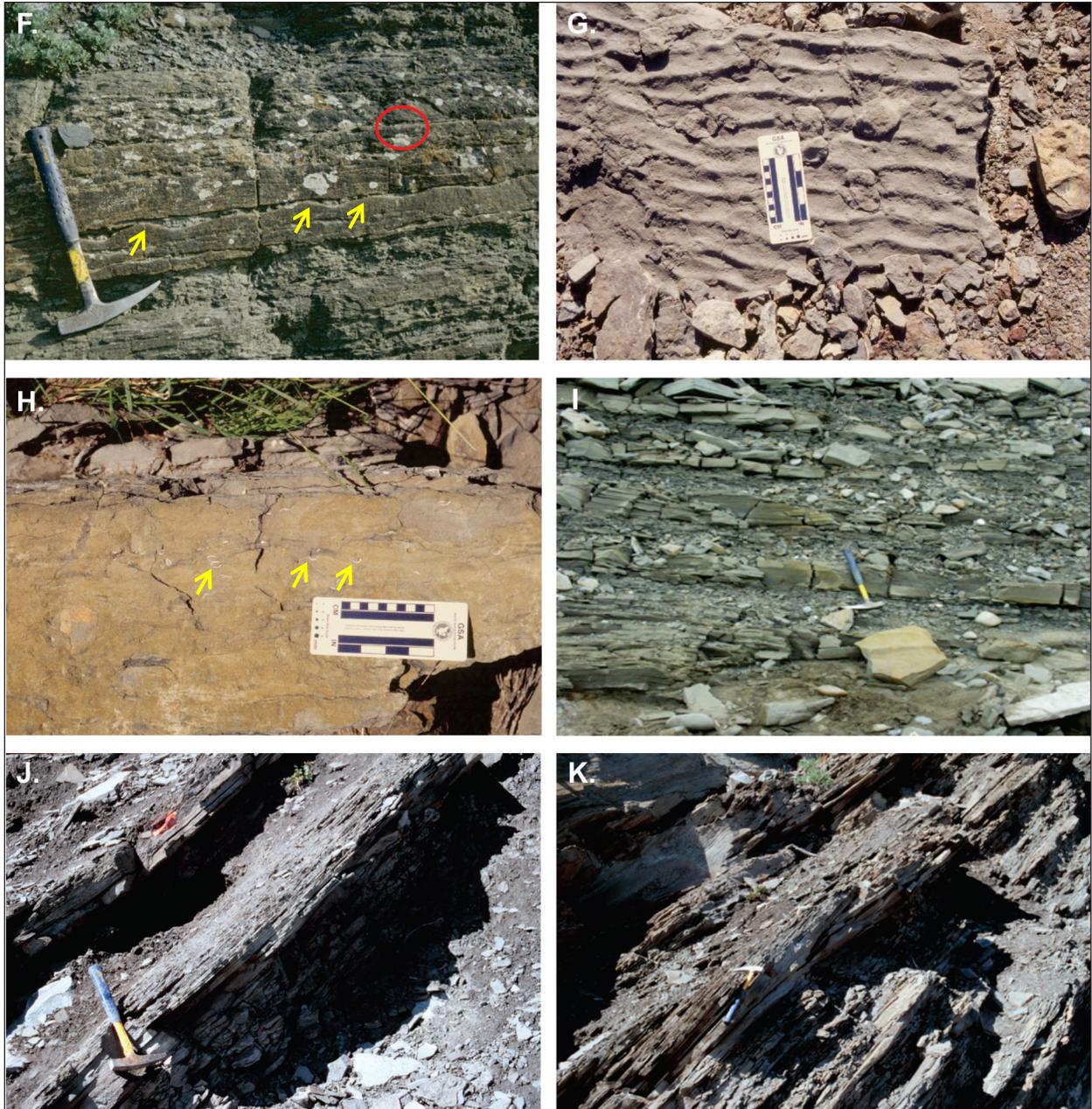


Figure 7 (cont.). **F.** Amalgamated sandstone beds in facies 6. Symmetric to slightly asymmetric ripple bedforms (just beyond tip of arrow heads) record deposition from oscillatory flows associated with short-period shoaling waves (photograph taken at 435 m in the Arc Mountain section). **G.** Small-scale symmetric wave ripples on sandstone bed surface in facies 6. Large circular structures on bed surface are probably infilled bivalve burrows (453 m above the base of the Arc Mountain measured section). **H.** Disarticulated corbiculid(?) valves (beyond arrow tips) in sandstone bed of facies 6 (432 m above the base of the Arc Mountain measured section). **I.** Interbedded siltstone and very-fine-grained sandstone in facies 7. Sandstones include plane-parallel lamination, wavy lamination, and hummocky cross-stratification (1 m above the base of the Colville incision section). **J and K.** Hummocky cross-stratified sandstone separated by burrow-mottled siltstone (I14–5) in facies 7. J and K show sandstone beds 295 m and 297 m, respectively, above the base of the Rooftop Ridge exposure.

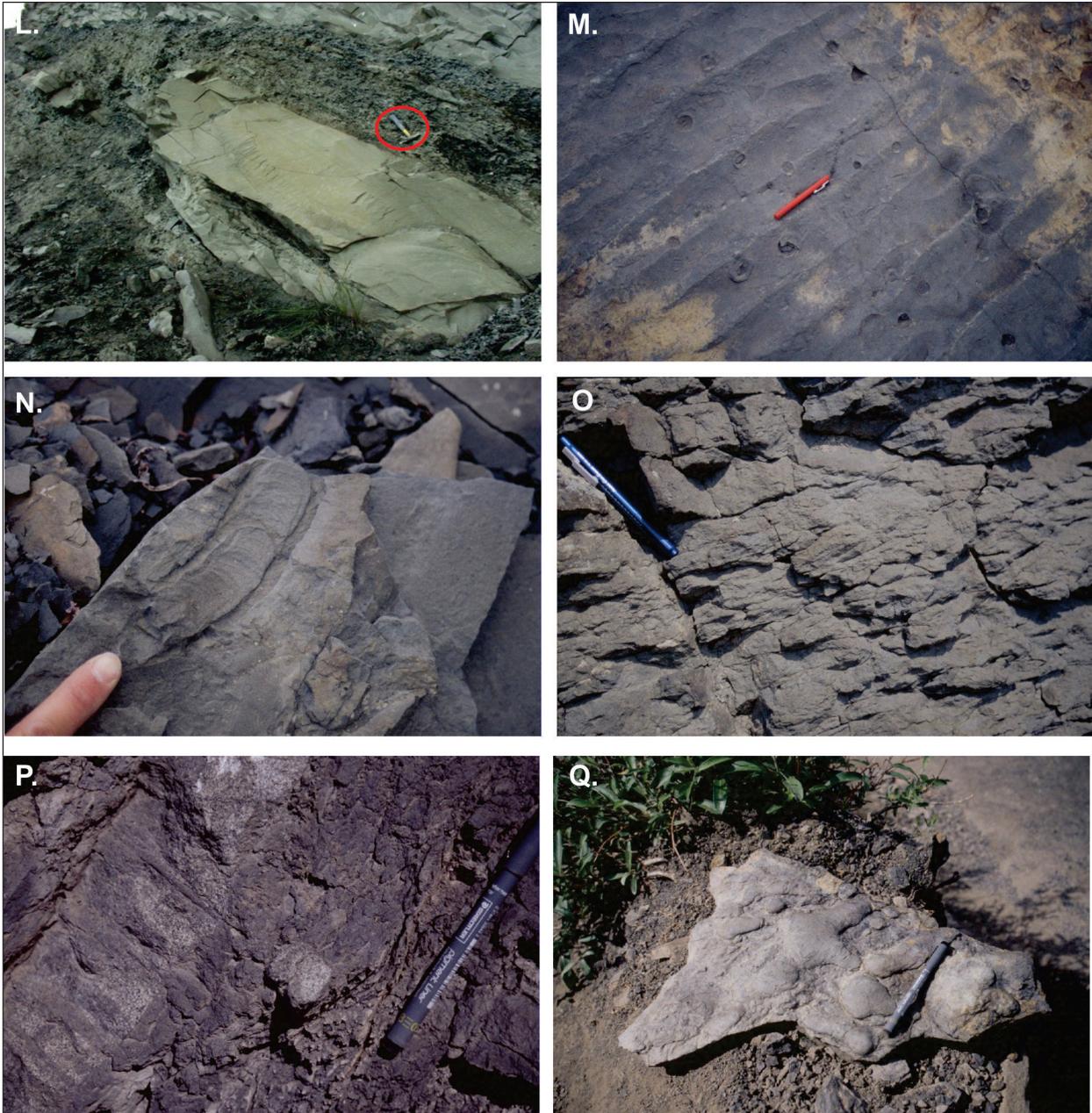


Figure 7 (cont.). **L.** Large gutter cast in silty shale filled with hummocky cross-stratified sandstone in facies 7 (91 m above the base of the Ninuluk Bluff measured section). **M.** Wave-ripple bedforms on the surface of a hummocky cross-stratified sandstone bed in facies 7. The circular structures visible on the bed surface are burrows attributed to infaunal bivalves (165 m in the Rooftop Ridge measured section). **N.** *Rhizocorallium* trace in burrow-mottled sandstone of facies 7 (209 m above the base of the Rooftop Ridge measured section). **O.** Burrow-mottled sandstone of facies 7. **P.** Salt and pepper colored medium- to coarse-grained sandstone of facies 8 with abundant large *Skolithos* burrows (30.2 m above the base of the Kanayut River measured section). **Q.** *Thalassinoides* burrows in sandy mudstone; burrows are filled with sandstone. Assigned to facies 8 (30.0 m above the base of the Kanayut River measured section).

that scoured the muddy substrate, carving out gutter-like troughs oriented parallel to flow (Myrow, 1992). Troughs were subsequently filled (during the same event) with sand deposited from oscillation-dominant flows capable of generating HCS. Wavy lamination is similar to quasi-planar lamination described by Arnott (1993) in Lower Cretaceous strata of central Montana, which he interpreted as the product of combined flows. The presence of a diverse trace fossil assemblage and scattered body fossils indicates deposition in well-oxygenated, open marine settings.

### **Facies 8—*Skolithos*- and *Thalassinoides*-bearing Sandstone and Mudstone**

Facies 8 has been recognized at only two locations, both in the same exposure along the Kanayut River. Facies 8 consists of fine- to coarse-grained sandstone and muddy sandstone/mudstone in beds up to 30 cm thick that are packed with *Skolithos* (fig. 7P) and *Thalassinoides* (fig. 7Q) burrows. The first example of facies 8 includes a bed of black and white (salt and pepper), medium- to coarse-grained, muddy sandstone that overlies a bed of gray sandy mudstone (figs. 7P and 13, measured section at right). The salt and pepper sandstone includes abundant *Skolithos* burrows (II4–5) filled with muddy sandstone. Many *Skolithos* burrows extend through the black and white sandstone bed into an underlying sandy mudstone that is packed with *Thalassinoides* burrows (II4–5; fig. 7Q). *Thalassinoides* burrows are filled with salt-and-pepper-colored sandstone from the overlying bed. The black and white sandstone bed consists dominantly of light gray and white quartz and white, gray, and black chert, and resembles the appearance of salt and pepper. The second example differs from the first in that the overlying *Skolithos*-bearing sandstone bed is separated from the underlying *Thalassinoides*-bearing bed by ~50 cm of silty shale (fig. 13, measured section at left). The contact between the *Thalassinoides*-bearing bed and the overlying lithologies in both occurrences is sharp and appears erosional in the first example.

#### **Interpretation**

We interpret the *Thalassinoides*-bearing lithology in both occurrences as examples of the *Glossifungites* ichnofacies (MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1995). The *Thalassinoides*-bearing beds record a pause in sedimentation between the time the host sediment was deposited and the time *Thalassinoides* burrows were constructed. The overlying coarse-grained sandstones represent transgressive lags deposited above wave-cut erosion surfaces (ravinement surfaces). In the first example (fig. 13, column at right) erosion cut into the *Thalassinoides*-bearing lithology, whereas in the second example (column at left) erosion

was insufficient to remove sediment deposited after formation of the underlying firmground.

### **Facies 9a—Bioturbated Hummocky Cross-stratified (HCS) Sandstone**

Facies 9a is abundant in outcrop. It consists of light to medium gray, very-fine- to fine-grained sandstone in beds 10 cm to >100 cm thick. Plane-parallel laminae, gently undulating laminae a few millimeters to 2 cm in thickness, referred to herein as wavy laminae, and hummocky cross-stratification characterize this facies (figs. 7R and S). Wavelengths in wavy laminae and hummock-to-hummock spacing in hummocky cross-strata range from <1 m to several meters; the amplitude of undulation in wavy laminae ranges from ~1 to 4 cm. Plane-parallel and wavy lamination commonly grade laterally and vertically to hummocky cross-stratification within the same bed. Wavy lamination resembles quasi-planar lamination described by Arnott (1993). Parting lineations are visible on most parting surfaces in all three stratification styles, along with minor to common small, coalified plant fragments (up to 1 cm long). Mudstone rip-up clasts are present at the base of many beds and discontinuous mudstone drapes are present between some beds but thicker shales and siltstones are absent. The upper few centimeters of many sandstone beds are ripple cross-laminated and wave-ripple bedforms are preserved on the tops of many beds (fig. 7T). Ripple bedforms range from slightly asymmetric to symmetric in cross-section. Where visible on bed surfaces, ripple crestlines are continuous and straight to slightly sinuous.

The following vertical sequence, in ascending order, is common in sandstones of facies 9a: Sharp basal contact with the bioturbated part of the underlying sandstone bed, with *Planolites* traces and linear groove casts preserved in semirelief, ± mudstone rip-up clast lag, ± massive sandstone, ± plane-parallel and wavy laminated sandstone, hummocky cross-stratification, ± wave-ripple cross-lamination, ± symmetric to slightly asymmetric wave-ripple bedforms, bioturbated cap.

Bioturbation is limited to the upper few centimeters to 10 cm of sandstone beds and the degree of bioturbation ranges from very slight to moderate (II2–4). A diverse trace fossil assemblage belonging to a mixed *Cruziana-Skolithos* ichnofacies is typically present. Common traces include *Arenicolites*, *Conichnus*, *Diplocraterion*, *Skolithos*, *Paleophycos*, *Planolites*, *Schaubcylindrichnus*, and *Terebellina*. Less common traces include *Rhizocorallium* and *Rosselia*. Body fossils are relatively rare and include echinoid spines, pelecypod casts, and ammonite casts. Shell material is rarely preserved.

Facies 9a is typically present as amalgamated beds in which the degree of amalgamation was insufficient to remove the bioturbated upper parts of individual beds and

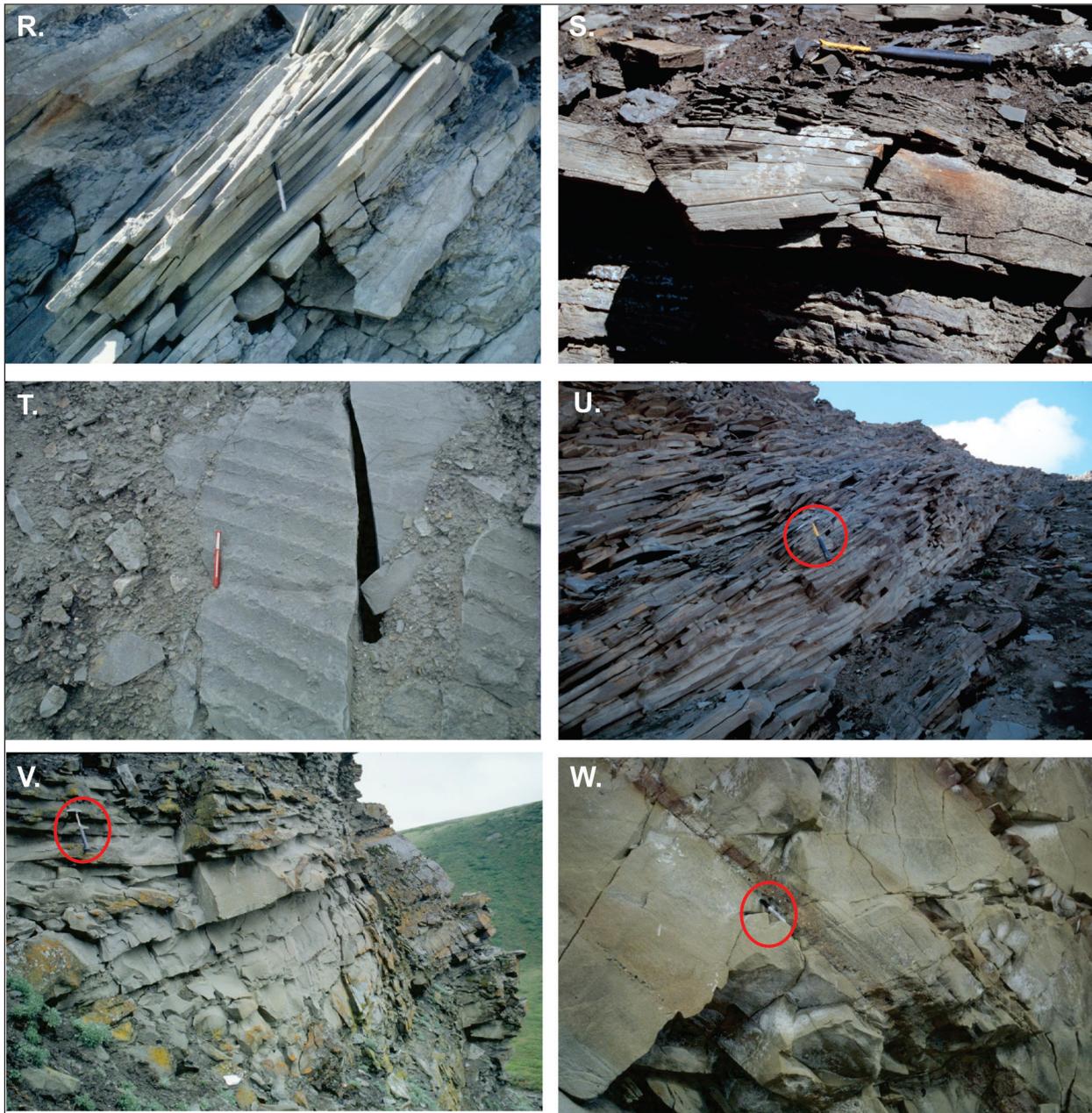


Figure 7 (cont.). **R and S.** Hummocky cross-stratified sandstone with bioturbated bed tops; assigned to facies 9a (295 m and 108 m, respectively, above the base of measured sections at Rooftop Ridge and Arc Mountain). **T.** Surface of hummocky cross-stratified sandstone bed covered with symmetrical wave-ripple bedforms in facies 9a. Small crawling traces are visible on bed surface (photograph taken at 43.8 m above the base of the Rooftop Ridge measured section). **U.** Transition between facies 9a and 10. Note amalgamated swaley cross-stratified sandstone of facies 10 holding up rock hammer (129–135 m above the base of the Rooftop Ridge measured section). **V.** Amalgamated swaley cross-stratified and wavy laminated sandstone of facies 10. Interval includes facies 9b and 10 (33–39 m in the North Tuktu Bluff measured section). **W.** Swaley cross-stratified sandstone with discontinuous pebble lags in facies 10. Lags are 1–2 clasts thick (140 m in the Ninuluk Bluff measured section). Marker (circled) is 13 cm long.

to completely remove mudstone drapes. Facies 9a commonly grades downward to facies 7 and upward to facies 9b and, less commonly, facies 9a is abruptly overlain by swaley cross-stratified sandstone of facies 10 (fig. 7U).

### **Interpretation**

Sandstones in facies 9a resemble storm deposits described by Dott and Bourgeois (1982), Kreisa (1981), and Walker and others (1983). The sequence of sedimentary structures described above is interpreted as the product of waning storm-generated flows (Dott and Bourgeois, 1982; Duke and others, 1991; Kreisa, 1981; Walker and others, 1983). Arnott and Southard (1990) noted the similarity between quasi-planar lamination in the Blackleaf Formation (Bootlegger Member) of central Montana and the bed configuration developed during flow-duct experiments in which a weak unidirectional current was superimposed on a much stronger oscillatory current. Based on these flow-duct experiments and field evidence, Arnott (1993) interpreted quasi-planar-laminated sandstones in the Blackleaf Formation as the product of high-energy combined flows during the waning stages of storm events in lower shoreface and offshore settings. Parting lineations suggest upper flow-regime plane-bed conditions (Allen, 1984; Collinson and Thompson, 1989). Plane-parallel and wavy lamination, and slightly asymmetric wave-ripple bedforms in facies 9a are consistent with deposition from combined flows during the waning stage of storm events. In light of the available evidence for combined flows, the absence of anisotropic HCS (for example, Nottvedt and Kreisa, 1987) is puzzling and may be more apparent than real. Slightly asymmetric ripple bedforms capping many sandstone beds resemble combined flow-generated bedforms described by Harms (1969). If correctly identified, these ripple bedforms indicate that unidirectional flow components persisted well into the waning stage of storm events.

The presence of bioturbated caps on most sandstone beds indicates sufficient time elapsed between successive storm events to allow a burrowing infauna to recolonize the upper part of sand beds and disrupt physical structures. Bioturbated tops on most beds lie immediately below the unbioturbated basal part of the next higher event bed, indicating that the uppermost bioturbated portion of the underlying bed was removed, along with any finer-grained material that may have originally been present, by scour during a subsequent storm event. The trace-fossil assemblage defines a mixed *Cruziana*–*Skolithos* ichnofacies, which is typical of deposition near fairweather wave-base. In many Cretaceous successions *Rosselia* is interpreted as an excellent indicator of lower shoreface settings (MacEachern, 2001; Pemberton and others, 1992). The absence of significant mudstone, other than thin, discontinuous drapes and rip-up clasts,

suggests a moderate degree of amalgamation and is consistent with deposition in the shallower parts of prograding shoreline successions (Walker and others, 1983), near fairweather wave-base.

### **Facies 9b—Amalgamated Hummocky Cross-stratified Sandstone**

Facies 9b is abundant in outcrop. The same suite of sedimentary structures recognized in facies 9a is recognized in facies 9b. The main features distinguishing facies 9b from 9a is that all mud and most, if not all, of the bioturbated upper part of individual sandstone beds have been removed by scour associated with subsequent events.

### **Interpretation**

Wavy lamination and hummocky cross-stratification in facies 9b are interpreted similarly to the same structures in facies 9a. A greater degree of amalgamation is evident in facies 9b, indicated by the absence of bioturbated caps and mudstone drapes. The lack of bioturbation could also mean lower recurrence interval for storms depositing beds in facies 9b, thereby not allowing enough time for a burrowing infauna to become established. These features suggest deposition in shallower water than facies 9a, probably above fairweather wave base (Walker and Plint, 1992).

### **Facies 10—Swaley Cross-stratified Sandstone**

Facies 10 is common in outcrop. It consists of medium to light gray to light tan, very-fine- to fine-grained sandstone in planar to wavy, continuous beds 20 cm to greater than 2 m thick (figs. 7U–W). The dominant sedimentary structures are swaley cross-stratification (SCS) and plane-parallel lamination (figs. 7U and V). HCS is present locally. Planar to gently undulating discontinuous scour surfaces are also common throughout facies 10 and are typically accentuated by a thin lag of granule- to pebble-sized chert, quartz (fig. 7W), and/or sideritized mudstone clasts. Pebble-sized sideritized mudstone clasts are commonly scattered throughout this facies and appear to “float” in sandstone. Bioturbation is usually absent or very sparse and, if present, consists of vertical to sub-vertical sand-filled shafts of *Skolithos* (II2).

### **Interpretation**

Leckie and Walker (1982), who coined the phrase ‘swaley cross-stratification,’ recognized SCS in shallow-marine strata of the Cretaceous Moosebar–lower Gates interval in western Canada, and interpreted the structure as the product of storm waves. SCS sandstones in the Moosebar–Gates strata include a few convex-upward laminae that indicate a genetic connection between HCS and SCS (Leckie and Walker, 1982; Walker

and Flint, 1992). This suggests that hummocks were originally present but were eroded away (decapitated) by storm-related processes. SCS defining facies 10 is similar to that described by Leckie and Walker (1982) and is similarly interpreted. Interbedded plane-parallel laminated sandstone and abundant scour surfaces indicate that upper flow-regime plane-bed conditions were commonly achieved.

### **Facies 11—Small-scale Trough Cross-bedded Sandstone**

Facies 11 is abundant in outcrop, and consists of light gray to tan, fine- to medium-grained trough cross-stratified sandstone in wavy, continuous and discontinuous, nonparallel beds 3–50 cm thick (fig. 7X). Sets of trough cross-strata range from a few centimeters to ~20 cm thick. Small plant fragments are scattered on some bed surfaces and macerated plant debris (“coffee grounds”) line some trough axes. Plane-parallel laminated sandstone with parting lineation is locally interbedded with trough cross-stratified sandstone in this facies.

#### ***Interpretation***

Trough cross-stratification in facies 11 represents the depositional record of small, migrating three-dimensional dunes in a subaqueous setting under lower flow-regime conditions (Harms, 1979; Harms and others, 1982). Small-scale cross-stratification can form in a variety of settings ranging from alluvial to deep marine, and correct interpretation must be made in the context of associated facies. Most trough cross-stratification in facies 11 is interpreted to have formed from unidirectional currents. Some small-scale cross-stratification in facies 11 may have originated from oscillatory or combined-flow currents characterized by distinct time–velocity asymmetry, such as is typical in shoreface settings during fairweather conditions (Clifton and others, 1971). Interbedded plane-parallel laminated sandstone is interpreted to record upper flow-regime plane-bed conditions but, like trough cross-stratification, can form under unidirectional, oscillatory, or combined flows. The presence of parting lineation supports an upper flow-regime interpretation for this structure (Harms, 1969). More specific interpretation can only be made if associated facies are taken into account.

### **Facies 12—Medium- to Large-scale Trough Cross-bedded Sandstone**

Facies 12 is common in outcrop. It consists of light gray, light tan, and salt-and-pepper-colored medium- to very-coarse-grained sandstone characterized by medium- to large-scale festoon trough cross-stratification (fig. 7Y). Sets of trough cross-strata range from 0.2 to 1 m thick. Locally, trough axes are lined with granule- and pebble-sized clasts of chert and quartz and, less

commonly, sideritized mudstone. Mudstone rip-up clasts are present locally, but are not common. Plant fossils, including small coalified plant debris, log impressions up to 80 cm long, and petrified logs up to 50 cm in diameter, are abundant in some successions and absent in others.

#### ***Interpretation***

Trough cross-stratification in facies 12 is the depositional record of medium- to large-scale, migrating, three-dimensional bedforms (dunes) that developed in a subaqueous setting under upper lower flow-regime conditions (Harms, 1979; Harms and others, 1982). Larger-scale trough cross-stratification can form in a variety of settings ranging from alluvial to deep marine and correct interpretation must be made in the context of associated facies. Trough cross-stratification in facies 12 is interpreted as the product of unidirectional currents in channelized flows in nonmarine and marginal-marine settings. Examples of facies 12 with abundant large plant fragments (leaves, twigs, branches, and logs) record deposition from unidirectional flows, probably near the thalweg of fluvial or deltaic distributary channels. Plant fragments were waterlogged and transported as bedload in fluvial channels. Examples of facies 12 lacking abundant and large plant material could record deposition from unidirectional flows in tidal channels or from oscillatory flows in delta-front or shoreface settings (compare to Clifton and others, 1971; McCubbin, 1982). Associated facies are the key to choosing the correct interpretation.

### **Facies 13—Apparently Structureless Sandstone**

Facies 13 is a minor component of the Nanushuk in outcrop. This facies consists of light gray to tan, very-fine- to fine-grained sandstone nearly devoid of internal stratification (fig. 7Z). This facies nearly always occurs in thick sandstone successions in association with one or more of facies 9b, 10, 11, and 12. Bed thickness is difficult to assess due to uniform grain size and composition, and the typical occurrence of this facies in thicker, amalgamated sandstone successions. Very faint horizontal lamination is rarely visible.

#### ***Interpretation***

Facies 13 is difficult to interpret as structures of known affinity have not been recognized. The common association with facies 9b and 10 suggests deposition during discrete events—most likely storms. Faintly visible lamination, although only rarely observed, suggests the possibility that the rest of this facies may not be truly structureless, but that contrasts in grain size and composition are so slight that sedimentary structures are not visible, or are only faintly visible. Bhattacharya and Walker (1991) described structureless



Figure 7 (cont.). **X.** Small-scale trough cross-stratified sandstone of facies 11 (279 m above the base of the Kanayut River measured section). **Y.** Medium- to large-scale trough cross-stratified sandstone in facies 12 (348 m above the base of the Marmot syncline measured section). **Z.** Structureless sandstone of facies 13 (104 m above the base of the Kanayut River measured section). **AA and BB.** Plane-parallel-laminated sandstone of facies 14. Note small *Skolithos* burrows in **BB** (366 m and 347 m, respectively, above the base of the Kanayut River measured section). **CC.** *Macaronichnus segregatus* in facies 14 (248 m above the base of the Marmot syncline measured section).

sandstone from the Cenomanian Dunvegan Formation in northwestern Alberta and suggested possible origins: (1) Rapid deposition with insufficient time for equilibrium structures to develop, (2) destruction of original structure by burrowing organisms, and (3) destruction of original structure by liquefaction and/or dewatering. Given the high sediment supply during deposition of the Nanushuk Formation, the overall deltaic setting for the unit (see discussion below), the lack of bioturbation, and the absence of features suggesting liquefaction and/or dewatering, we favor rapid deposition during storm events without sufficient time to allow formation of equilibrium structures.

#### **Facies 14—Plane-parallel Laminated Sandstone**

Facies 14 is common in outcrop. Facies 14 consists of red–brown–weathering (speckled light gray and white on fresh surfaces) fine- to medium-grained sandstone in thin, planar, parallel, and nonparallel beds from a few centimeters to 20 cm thick (figs. 7AA and BB). Beds of very-coarse-grained sandstone to granule conglomerate are present locally, but rare. Beds are commonly internally laminated (laminae 2–15 mm thick) and, where present, laminae are typically parallel to lamina set boundaries (fig. 7BB). Laminae are present locally that are inclined a few degrees relative to the set-bounding planes forming wedge-shaped bodies. Parting lineation is conspicuous on some parting surfaces. Small-scale trough cross-stratification (similar to facies 11) is present locally. The red–brown and speckled gray and white appearance of many weathered and fresh surfaces, respectively, are due to the trace fossil *Macaronichnus segregatis* (fig. 7CC). *Skolithos* and reworked *Rosselia* bulbs are common and locally abundant. Carbonaceous plant roots are present locally.

#### **Interpretation**

Plane-parallel lamination and parting lineation in sandstones of facies 14 record deposition under upper flow-regime plane bed conditions (Harms, 1979; Harms and others, 1982). Wedge-shaped sets of slightly inclined planar lamination resemble foreshore deposits described by Clifton (1969), Harms and others (1975), Harms (1979), and McCubbin (1982). *Macaronichnus segregatis* is regarded as an excellent indicator of deposition in upper shoreface and lower foreshore settings (Clifton and Thompson, 1978; MacEachern and Pemberton, 1992; MacEachern, 2001). In-situ *Rosselia* indicate normal marine salinity and are also regarded as an indicator of shoreface settings (MacEachern, 2001). Reworked *Rosselia* bulbs suggest nearby source beds where the trace was present in-situ.

#### **Facies 15—Medium- to Large-scale Planar Cross-bedded Sandstone**

Facies 15 is common in outcrop. It consists of medium gray to brown, fine- to medium-grained planar cross-bedded sandstone. Set thicknesses range from 0.15 to 2 m thick. Beds are typically characterized by planar–tangential foresets in single sets or multiple sets (figs. 7DD–FF). Ripple cross-lamination is common near the toe of thicker sets with cross-laminae dip directions opposite that of the larger foresets. Where multiple sets are stacked, successive sets commonly have foresets dipping in opposite directions (herringbone cross-stratification; fig. 7DD, lower center of photograph). Macerated plant material is common on foreset surfaces and near the toe of foresets.

#### **Interpretation**

Medium- to large-scale planar cross-bedding results from the migration of large, two-dimensional bedforms (straight to slightly sinuous crestlines) under upper lower flow-regime conditions (Harms and others, 1975; Collinson and Thompson, 1989). Set thicknesses provide minimum estimates of bedform amplitudes. Planar cross-bedded sandstone can form in a variety of settings, including fluvial, tidal, and shallow-marine environments, and correct interpretation must be made in the context of associated facies. Herringbone cross-stratification suggests deposition in tidally influenced settings (Harms and others, 1975; Harms and others, 1982; Kreisa and Moiola, 1986). The presence of reverse-flow ripple cross-lamination demonstrates that separation eddies were common in the lee of some of the larger bedforms (Allen, 1984).

#### **Facies 16—Sigmoidally Cross-bedded Sandstone**

Facies 16 is common in the southern part of the Nanushuk outcrop belt and consists of light to medium gray, fine- to medium-grained sandstone in beds 0.1–0.5 m thick. Plane-parallel laminae and sigmoid-shaped cross-bedding (fig. 7GG, left of hammer) characterize facies 16, with one structure typically grading laterally into the other. In some exposures, cross-bedded sandstone with sigmoid foresets is overlain by plane-parallel bedded sandstone. Thin, discontinuous mudstone drapes, with abundant small to large plant fragments, are present on some parting surfaces. Sigmoid-shaped cross-beds commonly grade laterally over distances of several meters to trough cross-bedded sandstone of facies 12. Facies 16 resembles facies S<sub>2</sub> of Allen (1983, p. 243).

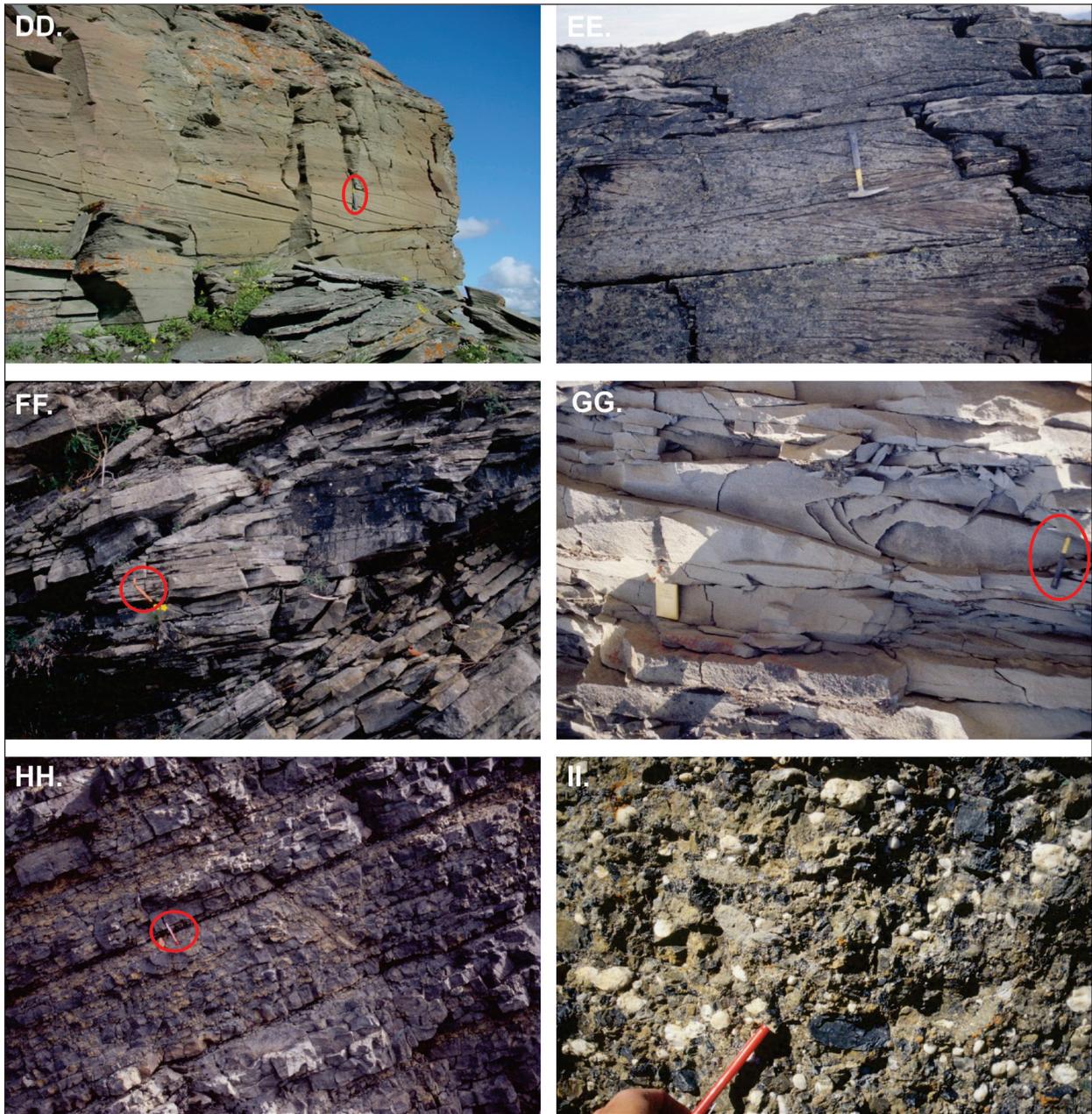


Figure 7 (cont.). **DD, EE, and FF.** Planar-tangential cross-stratification in facies 15 (photographs taken at 217 m, 250 m, and 295 m, respectively, above the base of measured sections at Tuktu Bluff, Marmot syncline, and Kanayut River, respectively). Circled orange surveyor's flag in FF is ~15 cm long. **GG.** Sigmoidally cross-stratified sandstone in facies 16 (493 m above the base of the Arc Mountain measured section). **HH.** Argillaceous sandstone in facies 17 (419–420 m above the base of the Kanayut River measured section). Eraser (circled) is 12.5 cm long. **II.** Clast-supported chert- and quartz-pebble conglomerate in facies 18 (~770 m above the base of the Arc Mountain measured section, above top of section shown in Appendix A).



Figure 7 (cont.). JJ. Tabular and lenticular beds of pebble conglomerate of facies 18. Due to the limited extent of this exposure the geometry of the gently dipping conglomerate beds in the upper left part of the outcrop is unclear. These may represent part of the fill of a shallow channel that cut into the underlying tabular bedded conglomerates. Alternatively, they may represent an accretionary (lateral or downstream) macroform deposited in, or along the margins of, a larger channel (outcrop is above top of Arc Mountain section shown in Appendix A). Outcrop is ~5 m high.

### **Interpretation**

Allen (1983) described sigmoid-shaped foresets (his facies S<sub>2</sub>) in Lower Devonian fluvial deposits of the Lower Old Red Sandstone in Wales, in which the foresets graded upward to plane-bedded sandstone which, together, were arranged in compound sandbars. Allen noted that the examples from the Lower Old Red Sandstone resembled experimental humpback dunes generated under flow conditions near the lower to upper flow-regime transition noted by Saunderson and Lockett (1993), and sand deposits in the Red River attributed by Schwartz (1978, cited in Allen, 1983) to transverse bars. Allen (1983) interpreted the close relation between plane-bedded sandstone and sigmoid-shaped foresets to represent a topset–foreset couplet, such as could be expected to develop as a bedform migrated from shallow water to deeper water over a short distance. Following Allen (1983) we interpret facies 16 as simple compound sandy bar forms that developed along the margins of fluvial channels.

### **Facies 17—Argillaceous Siltstone and Sandstone**

Facies 17 is common in outcrop and consists of orange-brown- to medium-gray-weathering coarse siltstone to fine-grained sandstone (fig. 7HH), with clayey material and small plant detritus scattered throughout. Single beds are wavy and discontinuous over short lateral distances (centimeters to decimeters), but bedsets up to 45 cm thick commonly form well-defined planar features in near-vertical outcrops (fig. 7HH). Sedimentary structures are usually absent, but sandstone locally includes remnants of plane-parallel lamination and current-ripple cross-lamination. Irregular tube-like structures are visible locally and typically oriented oblique to paleo-horizontal. Siltstone and sandstone commonly display a blocky fracture pattern and have a punky, highly weathered appearance.

### **Interpretation**

The blocky fracture pattern and highly weathered appearance of facies 17 resemble paleosols that form

on silty and sandy substrates (Retallack, 2001). Medium gray to orange-brown colors suggest soil formation in both poorly drained and well-drained settings, respectively. These colors are typically not present in the same beds, indicating formation in either well-drained or poorly drained settings. Scattered argillaceous material probably records mixing through pedogenic processes. Locally preserved plane-parallel and current-ripple cross-lamination in sandstone demonstrates traction transport and deposition from unidirectional currents prior to pedogenesis.

### **Facies 18—Granule and Pebble Conglomerate**

Facies 18 is common in the southern part of the Nanushuk outcrop belt and rare in the northern part. Facies 18 consists of gray- to red-brown-weathering clast-supported granule and pebble conglomerate (fig. 7II) in crudely developed tabular and lenticular beds up to a few meters thick (fig. 7JJ). Clasts are dominantly of extrabasinal origin and consist largely of quartz and chert. Mudstone and sideritized mudstone clasts are locally present, but represent a minor percentage of the total clast population. Beds are internally massive and clasts are closely packed. The space between clasts is filled with poorly to moderately sorted medium- to coarse-grained sandstone. Imbricate clast fabrics are recognized locally, but appear poorly developed because of the equant shape of most clasts. Sandstone and pebbly sandstone lenses up to 30 cm thick are locally present; sandstone lenses extend laterally a few meters to ~20 m before pinching out. Sandstone is either crudely bedded or internally massive, and locally includes small- to medium-scale trough cross-stratification similar to facies 11 and 12. Poorly preserved plant fragments are locally present on sandstone bed surfaces. Facies 18 has a broadly lenticular geometry in outcrop; lenses extend along strike for 0.5 km to more than 1.5 km. Channel margins have not been observed. Finzel (2004) provides a more complete description of conglomeratic facies in the Nanushuk Formation along the Kanayut River.

### **Interpretation**

Some occurrences of facies 18 resemble Miall's (1996) facies Gh and are similarly interpreted. Crude horizontally bedded conglomerates can form as channel lag deposits or as longitudinal bar forms in low-sinuosity channels (Miall, 1996; Ramos and Sopena, 1983). Given suitably shaped clasts, weakly developed imbricate clast fabrics indicate transport as bedload in turbulent flows (Harms and others, 1975). During peak flood conditions, flow in channels is commonly competent enough to transport the coarsest clasts (for example, Ramos and Sopena, 1983) and deposition takes place during the waning stage of flood events (Miall, 1996; Rust, 1972). The absence of cross-stratification suggests that gravel was transported during high flow stage as sheets (Collinson and Thompson, 1989; Enyon and Walker, 1974), and thin sheets suggest deposition from shallow flows (Nemec and Steel, 1984). Sandstone lenses were deposited during the waning stage of flood events from bedload and suspension fallout. The massive appearance of sand in some lenses suggests rapid deposition with little subsequent traction transport. Other examples of facies 18 are not associated with fluvial facies and are interpreted as lags deposited above storm-generated scour surfaces in marine and marginal-marine settings.

## **FACIES ASSOCIATIONS**

Facies described in the previous section and summarized in table 1 are arranged in vertical succession forming predictable, recurring associations. We use the term facies association as defined by Walker (1992). Facies associations record the progressive migration (seaward or landward) of each facies belt (depositional environment) through time. Within a facies association, facies stack vertically in the same order as originally arranged along the depositional profile (Walther's Law). Some of the marine facies associations as defined correspond to parasequences of Posamentier and Vail (1988) and Van Wagoner and others (1990). Ten facies associations have been recognized in outcrop and are described in this section. We use the terminology of Fisher and others (1969) and Elliot (1974) for facies associations interpreted as deltaic in origin, and use Walker and Plint (1992) for shoreface and offshore associations. Facies associations are illustrated using segments of measured stratigraphic sections through the Nanushuk Formation exposed in the study area (figs. 9–11). Photographs of selected facies associations are shown in figure 8.

### **Facies Association 1—Offshore**

Facies association 1 (FA1) is not common in outcrop and has only been recognized at the east end of the Nanushuk outcrop belt (figs. 9A and B, below ~63.5 m; figs. 8A and 10A, above 119.1 m; Rooftop Ridge section between 260 and 280 m; and the Big Bend of the

Chandler River section, both included in Appendix A). We infer that FA1 is a common association, particularly in distal settings, but the finer-grained facies that it comprises are nonresistant and easily covered by colluvium and tundra vegetation. Vertical successions through FA1 range from a few meters to 40 m thick and rarely (in outcrop) start with 2–5 m of clay shale (facies 1). Clay shale grades upward over several meters to silty shale (facies 2), which makes up most of the facies association. Silty shale grades upward over several meters to interbedded silty shale and very-fine- to fine-grained ripple cross-laminated sandstone (facies 3a) or interbedded bioturbated silty shale, siltstone, and sandstone (facies 7). FA1 grades upsection to either storm-influenced shoreface (FA2) or delta-front (FA3) associations.

### **Interpretation**

FA1 is interpreted to record deposition below storm wave-base, in offshore to distal offshore transition and distal prodelta settings, where the overall sediment flux was high. Where clay shale of facies 1 is present at the base of facies association 1, an offshore shelf setting removed from sources of coarser detritus (for example, active delta lobes) is inferred, over which silty shale of the distal offshore transition or distal prodelta slope prograded. In most examples of FA1, clay shale is absent and the succession consists of 5–20 m of silty shale (facies 2) that grades upward to interbedded silty shale, siltstone, and current-ripple-laminated sandstone (facies 3a). This gradual coarsening-upward succession indicates deposition in the prodelta region of an actively prograding delta lobe, from which low-density hyperpycnal flows originated. Sandstones near the top of FA1 (facies 3a) are interpreted as the products of hyperpycnal flows generated at river mouths (tributary channel mouths) during major fluvial flood events. Several ancient examples of turbidites interpreted as the product of turbid underflows (hyperpycnal flows) linked to fluvial flood events have been reported in the recent literature (Myrow and others, 2002; Plink-Bjorklund and Steel, 2004; Pattison, 2005). In a survey of 150 rivers worldwide, Mulder and Syvitski (1995) reported that at least nine small to moderate sized "dirty" rivers are capable of generating hyperpycnal underflows at their mouths during one or more periods of the year, and that most other rivers in these size categories are capable of generating hyperpycnal plumes only during floods. The temperate, relatively high latitude setting of the Colville basin during Albian–Cenomanian time (Spicer and Parrish, 1986; Parrish and Spicer, 1988) and the nature of fluvial systems traversing the Nanushuk coastal plain in the eastern part of its outcrop belt (Molenaar, 1985, 1988) would have provided the requisite conditions for the generation of hyperpycnal flows. Facies 7 caps FA1 at locations where sand in the proximal part of offshore

settings was reworked by unusually powerful storm waves that were able to mobilize sand below mean storm wave-base. FA1 is interpreted as the distal expression of the storm-influenced shoreface (FA2) and delta-front (FA3) associations.

### Facies Association 2—Storm-Influenced Shoreface

Facies association 2 (FA2) is the most common of all associations recognized in the marine part of the Nanushuk Formation. It is present throughout the

Nanushuk outcrop belt and southern coastal plain. FA2 consists of sandier-upward successions 10–60 m thick. The vertical succession of facies in FA2 varies according to position along the depositional profile. Incomplete (top-truncated) vertical sections through FA2 are common (figs. 10A and B). In distal settings far down the depositional profile FA2 starts with silty shale (facies 2) and ends with interbedded, bioturbated siltstone and sandstone (facies 7) or bioturbated HCS sandstone (facies 9a; fig. 8A, top of sand body at left side of image marks the top of the distal FA2). In proximal

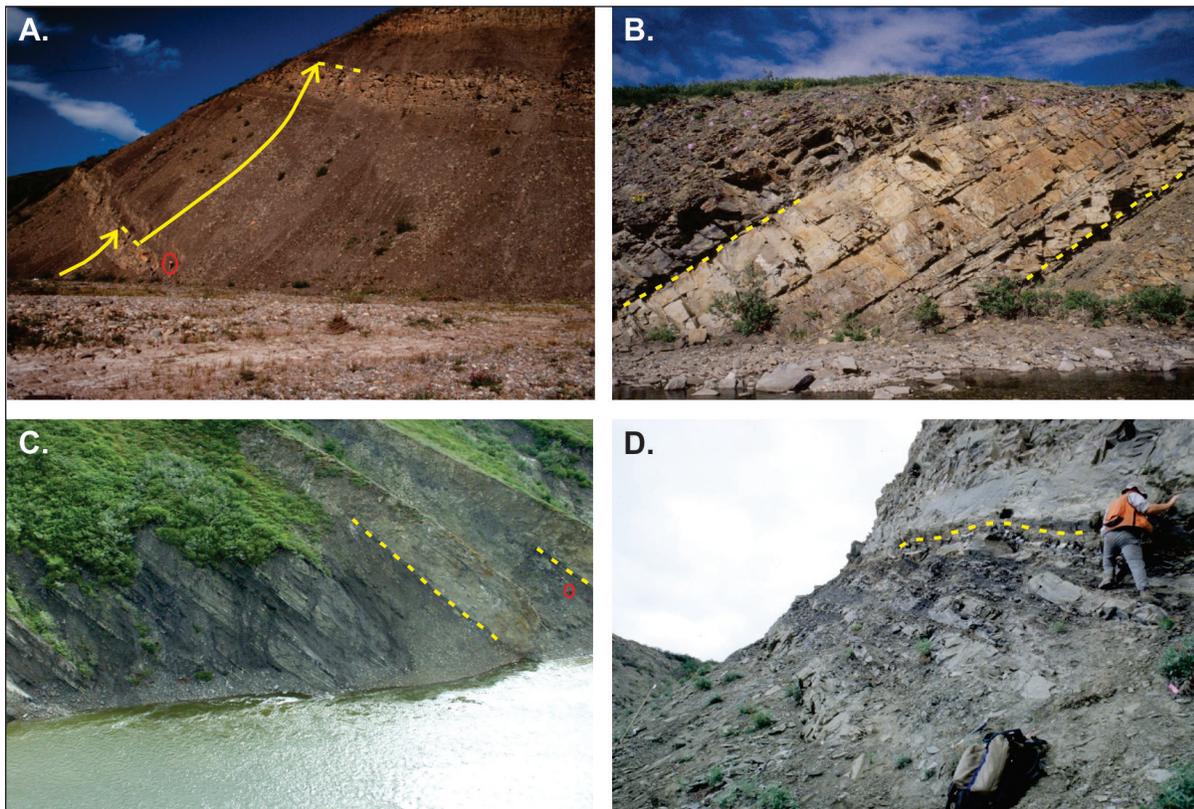


Figure 8. Outcrop photographs showing field expression of facies associations recognized in the Nanushuk Formation. All photographs are tied to the measured sections in Appendix A. **A.** View of two shoreface sandstone bodies (FA2) separated by offshore (FA1) deposits exposed along the south flank of Arc Mountain anticline. The lower sand body is shown in figure 10A and Appendix A. The lower part of a third shoreface sand body is visible in the upper right corner of the image and is shown in figure 10B. The recessive muddy sandstone overlying the lowest sand body is burrow-mottled (I13–4) and represents the reworked upper part of the underlying sand body. Transgressive surface of erosion (ravinement surface) separates the muddy sand above from HCS sandstone below. **B.** Transition between tidal inlet deposits (FA4) and overlying lower shoreface deposits (FA2) along the Kanayut River. This succession is shown in figure 10D and Appendix A. Note prominent color change at the contact between the two facies associations, which is thought to be due to higher detrital(?) clay content in the lower shoreface deposits. Photograph shows the 292–316 m interval in the Kanayut River measured section. **C.** Aerial view of the upper part of the Nanushuk Formation at Ninuluk Bluff. Two prominent buff-colored sandstone bodies near right side of image are interpreted as sharp-based shoreface deposits (FA2) underlain by offshore deposits of FA1. Figure 10C is part of a measured section through these sand bodies. The left two-thirds of the image shows bayfill–estuarine deposits of FA5, FA6, and FA7. Sandstone visible at the left edge of image is the top of the shoreface sand body at 12 m in Appendix A. **D.** Contact between the lower sharp-based shoreface sand body (proximal FA2) and underlying offshore deposits (FA1 to distal FA2) at Ninuluk Bluff (photograph shows the 73–81 m interval in fig. 10C).

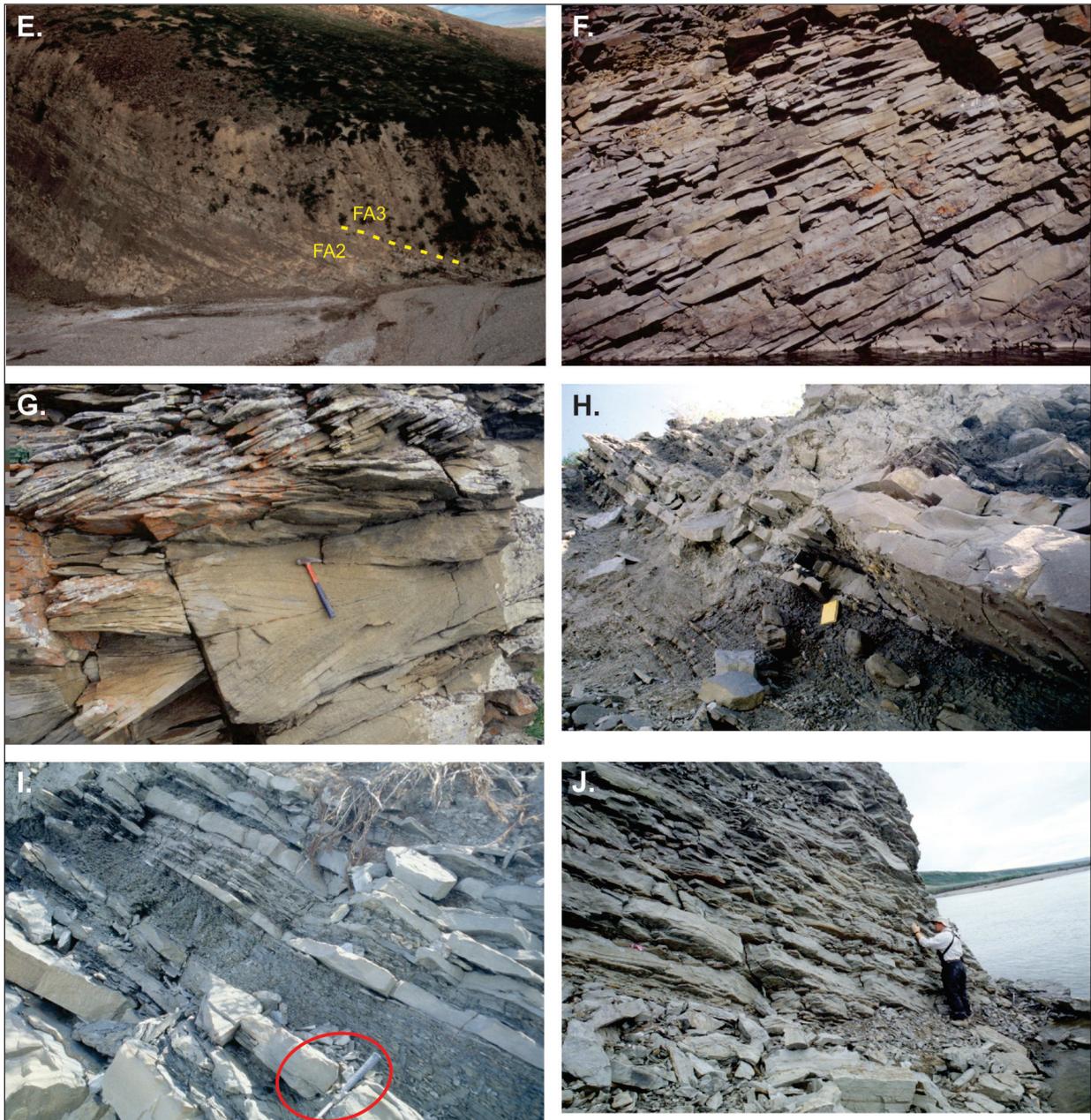


Figure 8 (cont.). **E.** Aerial view of the contact between proximal shoreface deposits (FA2) and distributary mouth-bar and channel-fill deposits (FA3) at Arc Mountain. Photograph shows approximately the 250–360 m interval in the Arc Mountain section, most of which is shown in figure 10B. FA2 shown in this photograph corresponds to the sand body visible at the upper right edge of figure 8A. **F.** Plane-parallel laminated sandstone with abundant reworked *Rosselia* bulbs in FA3. Photograph shows 360 m and 375 m in the Kanayut River measured section, included in figure 11A and Appendix A. **G.** Planar-tabular cross-stratification in FA4. Stacked sets form herringbone pattern and are interpreted to record opposing transport directions associated with tides. Photograph shows beds at 218 m in the Tuktuk Bluff measured section included in Appendix A. **H.** Contact between crevasse channel-fill of FA6 and underlying bayfill–estuarine deposits of FA5. Note foundered sandstone bed below the basal sand of the crevasse channel fill. Photograph shows the 16–22 m interval in the Ninuluk Bluff measured section included in Appendix A. Notebook is 22 cm long. **I.** Upper part of crevasse channel-fill succession shown in H. Photograph taken at ~24 m in the Ninuluk Bluff measured section. **J.** Thick crevasse delta succession in FA7. Alternatively, could represent levee deposits—see text for discussion. This succession is underlain by the bayfill–estuarine association (FA5) and overlain by interpreted marine deposits of the offshore association (FA1). Photograph shows the 60–68 m interval in the Ninuluk Bluff measured section, shown in figure 10C and Appendix A.



Figure 8 (cont.). **K.** Alluvial flood basin and crevasse delta deposits of FA10 and FA7, respectively. Note dipping surfaces in sand body near the lower left corner of the image that extend up-slope and are discordant to the upper contact of the sand body—interpreted as crevasse delta deposits located at the downstream end of a splay channel. Approximately 465–490 m in the Kanayut River measured section. **L.** Slightly asymmetrical and symmetrical ripple bedforms on sandstone bed in FA7. Bed shown is the same bed near geologist’s left hand in J. Photograph taken at approximately 66 m in the Ninuluk Bluff measured section. **M.** Trough cross-stratified sandstone (facies 12) in FA8. Photograph shows the 515–520 m interval in the Arc Mountain measured section shown in Appendix A and the 20–25 m interval in figure 11B. **N.** Sigmoidally cross-bedded sandstone (facies 16) in FA8. Photograph shows beds between 480 and 485 in the Arc Mountain measured section, included in figure 11B and Appendix A. **O.** Log jam in sandstone at the base of a fluvial channel fill (FA8). Photograph taken at ~490 m in the Arc Mountain measured section shown in Appendix A and in figure 11B (~3 m in section at far right). **P.** Aerial view showing interbedded conglomeratic fluvial sheet bodies (FA9) and tundra-covered floodbasin deposits (FA10). View toward the south–southeast, showing the north flank of the syncline immediately south of Arc Mountain anticline. Resistant benches comprise the upper 100 m of section as noted on the measured section in Appendix A.

settings (figs. 10D and 11A) very close to the shoreline FA2 commonly starts with amalgamated HCS sandstone (facies 9b) or SCS sandstone (facies 10) and grades upward through a range of facies (facies 11, 12, and 14), and is most commonly truncated by an erosion surface that is overlain by high-energy facies of the next higher facies association (fig. 10B, contact between FA2 and FA3 at 299.3 m). In another example, FA2 rests in sharp contact above a tidal inlet association (FA4, fig. 10D at 305.2 m and fig. 8B) and is, in turn, overlain by distributary mouth-bar/channel-fill deposits (FA3, contact at ~319.3 m, fig. 10D).

A significant variant of FA2 has been recognized in the northern part of the outcrop belt, at Ninuluk Bluff (figs. 3, 8C, and 10C). At this location the upper 57 m of the Nanushuk consists of two sharp-based shoreface packages separated by marine mudstone and sandstone (FA1) and marginal marine mudstone (FA5; fig. 8C, two sand bodies visible near right side of image). The lower shoreface association starts with medium- to

large-scale trough cross-stratified sandstone (facies 12) in sharp contact with interbedded silty shale, siltstone, and HCS sandstone (facies 7, figs. 7L, 8D, and 10C, at 78.7 m), which passes abruptly upward to plane-parallel laminated sandstone (facies 14). Plane-parallel laminated sandstone is abruptly overlain by carbonaceous shale and silty shale (facies 6) and small-scale trough cross-stratified sandstone (facies 11), which are both assigned to the bayfill-estuarine association (FA5). The higher shoreface association (fig. 8C, right side of image; fig. 10C, starting at 118 m) starts with plane-parallel laminated sandstone with abundant pebble-lined scour surfaces (facies 9b) in sharp contact with silty shale and HCS sandstone. Plane-parallel laminated sandstone with numerous pebble-lined scour surfaces grades upward over 7–8 m to SCS sandstone (facies 10). The succession is capped by a few decimeters of finer-grained plane-parallel laminated and wave-ripple laminated sandstone and dark gray to brown mudstone (facies 6). Dark gray to brown mudstone is abruptly overlain by

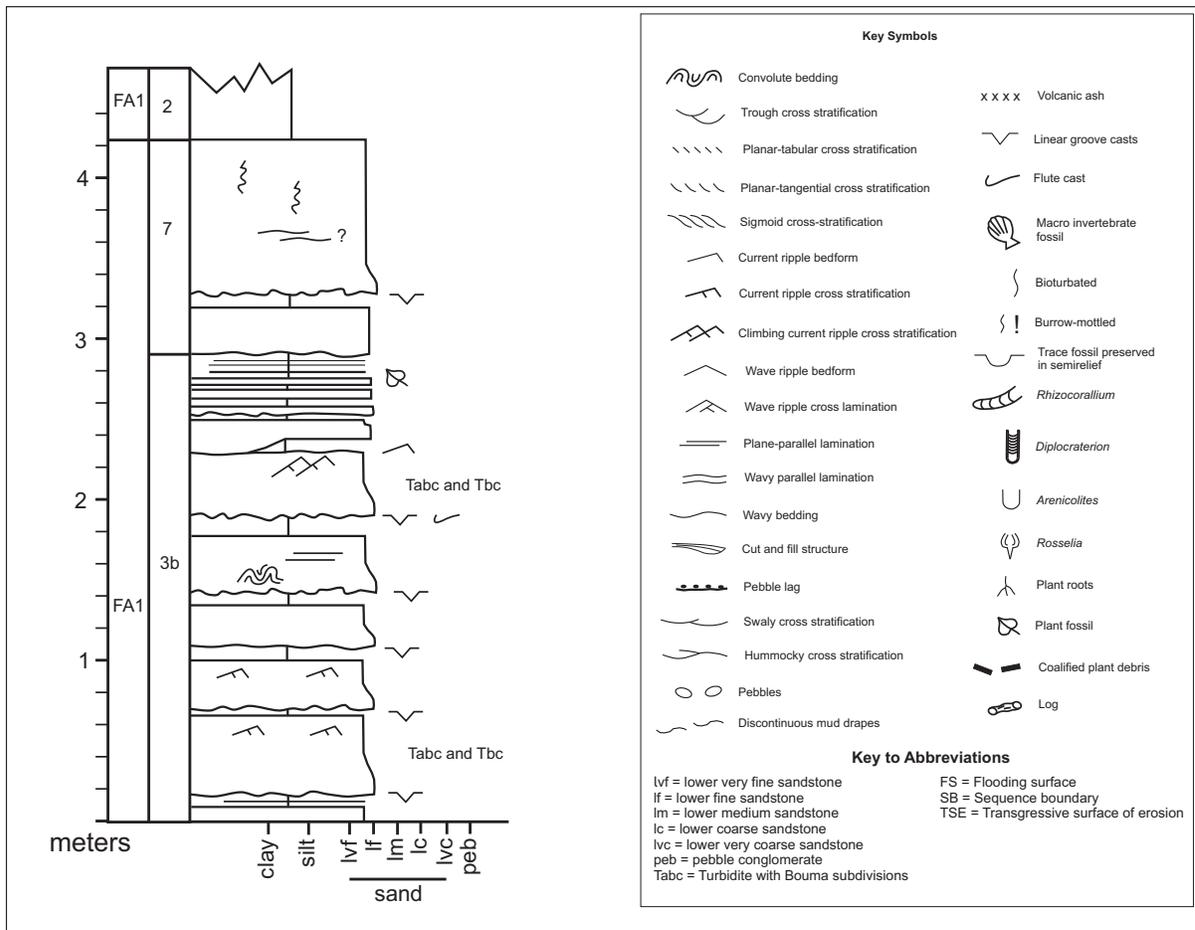
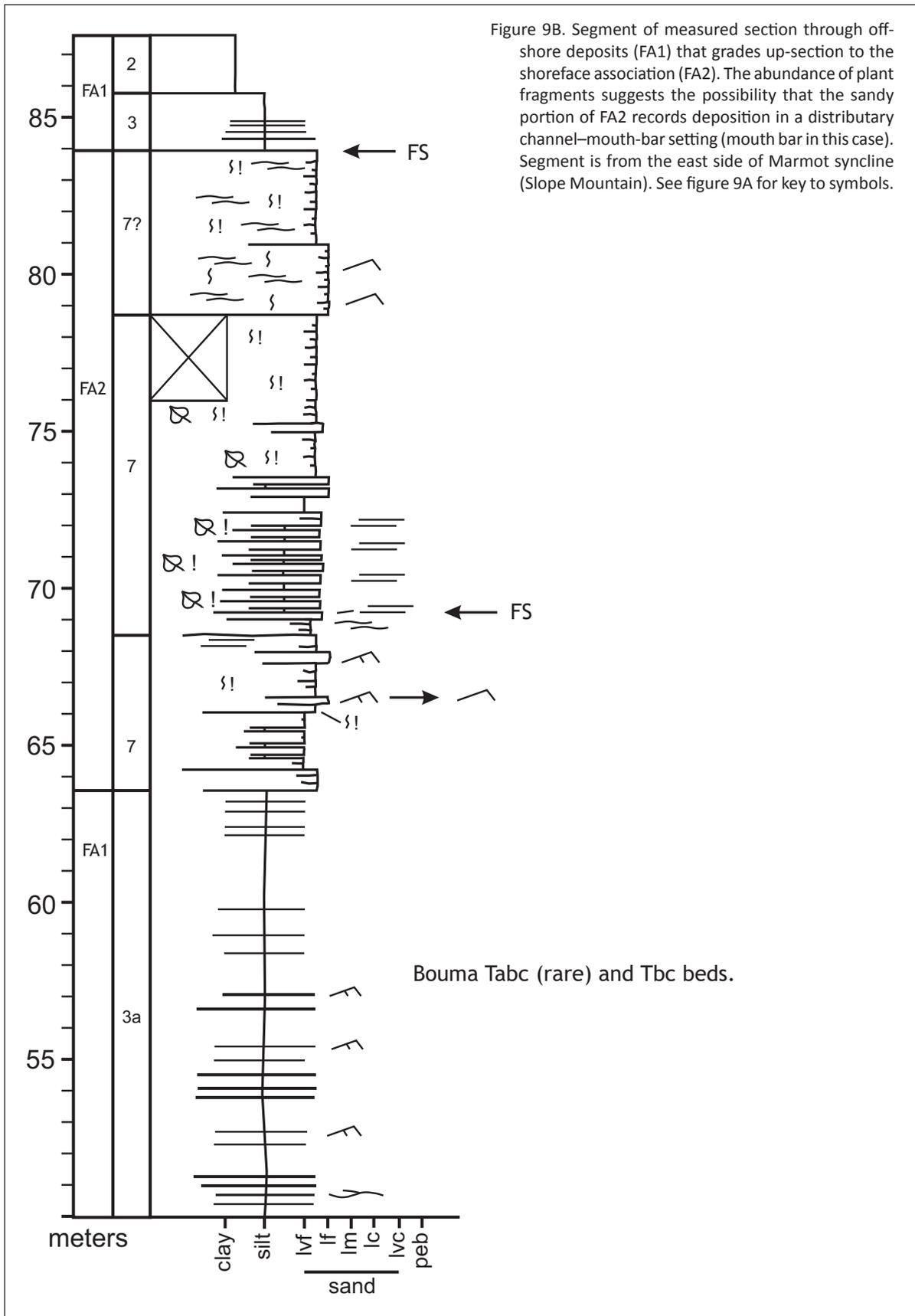


Figure 9A. Segment of measured section through the proximal offshore association (FA1). Sandstone beds are interpreted to be distal hyperpycnites of facies 3b. Segment is from the east side of Marmot syncline (Lupine River) and is near the base of the Nanushuk Formation. Symbols used to show sedimentary structures are shown in the inset box; this key applies to all measured sections used in this report, including Appendix B.



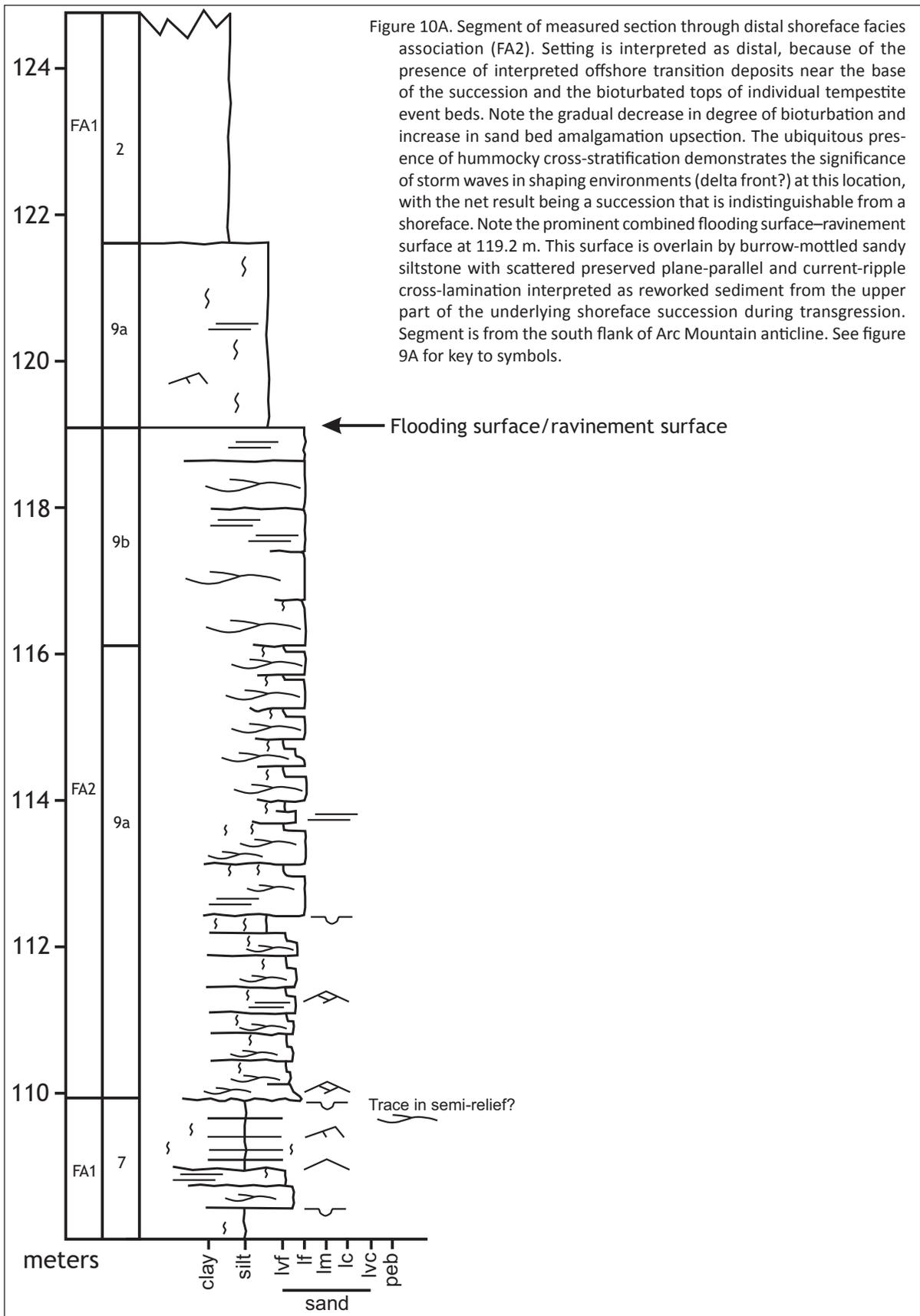


Figure 10A. Segment of measured section through distal shoreface facies association (FA2). Setting is interpreted as distal, because of the presence of interpreted offshore transition deposits near the base of the succession and the bioturbated tops of individual tempestite event beds. Note the gradual decrease in degree of bioturbation and increase in sand bed amalgamation upsection. The ubiquitous presence of hummocky cross-stratification demonstrates the significance of storm waves in shaping environments (delta front?) at this location, with the net result being a succession that is indistinguishable from a shoreface. Note the prominent combined flooding surface–ravinement surface at 119.2 m. This surface is overlain by burrow-mottled sandy siltstone with scattered preserved plane-parallel and current-ripple cross-lamination interpreted as reworked sediment from the upper part of the underlying shoreface succession during transgression. Segment is from the south flank of Arc Mountain anticline. See figure 9A for key to symbols.

← Flooding surface/ravinement surface

Trace in semi-relief?

meters

clay  
silt  
lvf  
lf  
lm  
lc  
lvc  
peb  
sand

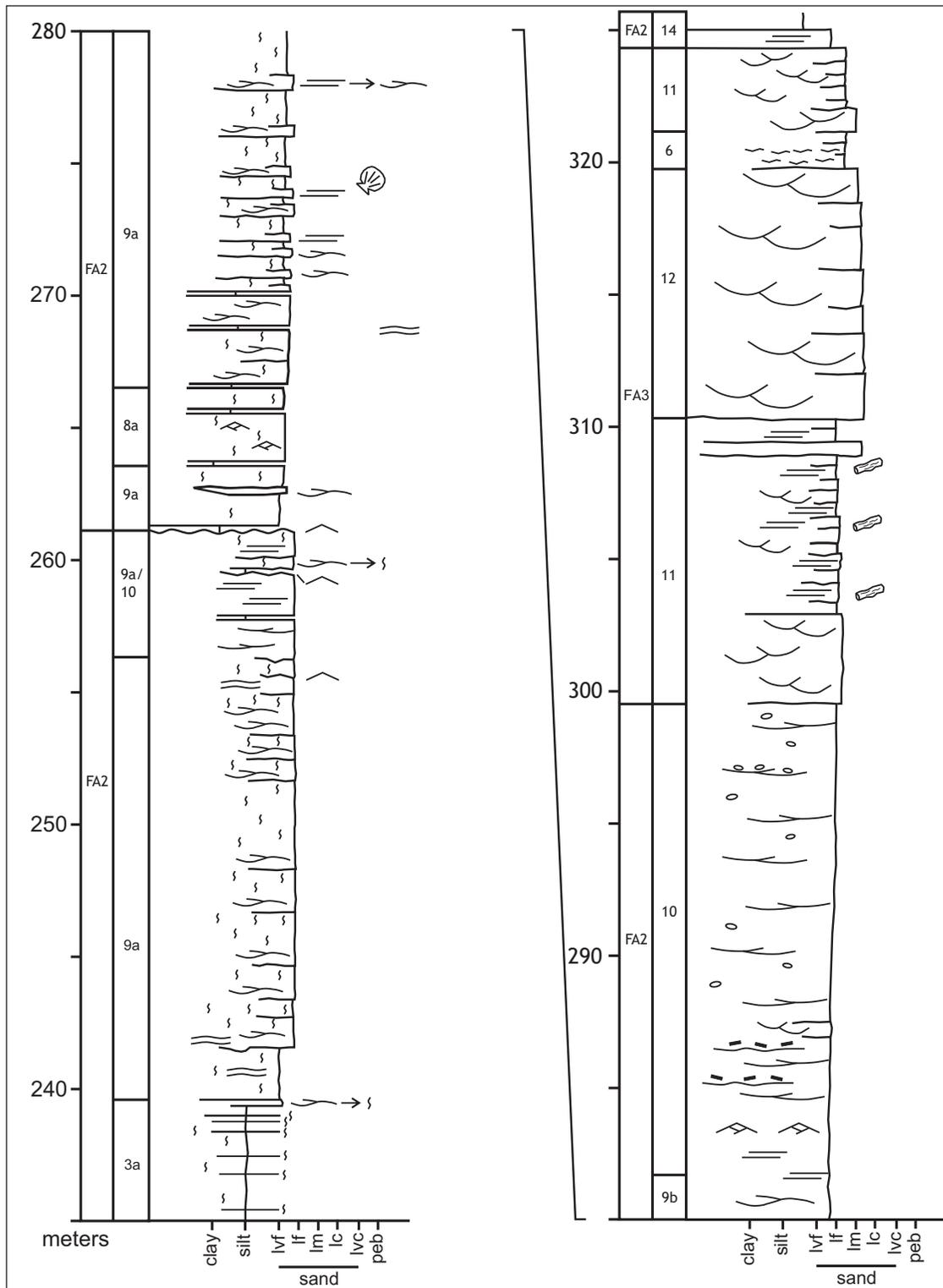
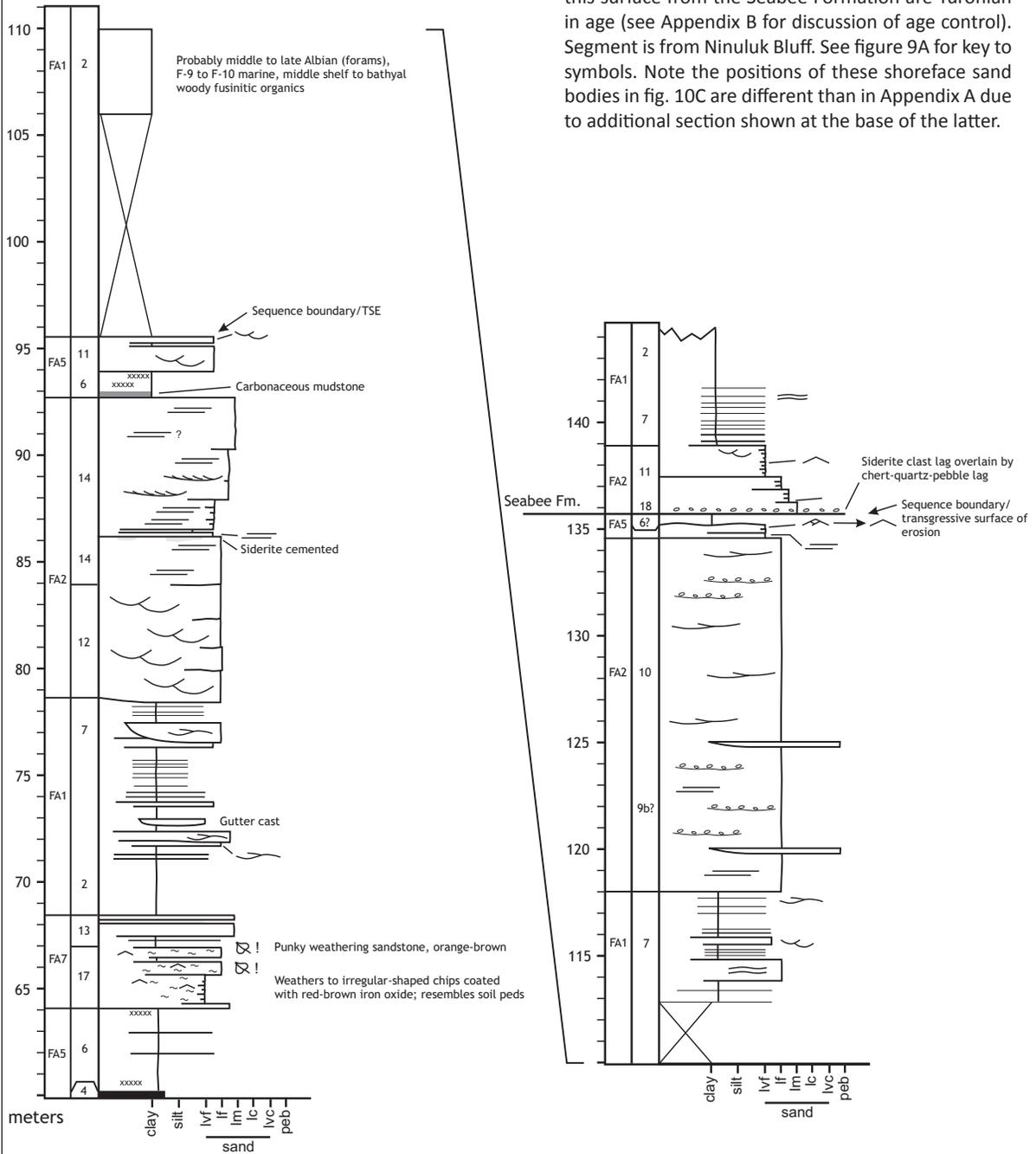


Figure 10B. Segment of measured section through two shoreface facies associations (FA2) and a distributary channel association (FA3). Note the lower shoreface association includes offshore transition strata at its base and coarsens upward through stacked tempestite beds with bioturbated tops, and is capped by sparsely bioturbated, swaley, and plane-parallel laminated sandstone deposited in an upper shoreface setting. The overlying shoreface association starts with a very thin mudstone overlain by storm event beds with bioturbated caps. These event beds are abruptly overlain by amalgamated hummocky and swaley cross-stratified sandstone deposited in a proximal upper shoreface setting. The segment is capped by a distributary mouth bar (299.5–310 m) and distributary channel-fill (310–324.5 m) succession (FA3). Mouth-bar facies and distributary channel deposits are present over a relatively thin stratigraphic horizon along the south side of the Nanushuk outcrop belt. Segment is from the south flank of Arc Mountain anticline. See figure 9A for key to symbols.

Figure 10C. Segment of measured section through the upper part of a bayfill–estuarine succession (FA5) to open marine facies associations (FA1 and FA2). The bayfill–estuarine and crevasse delta associations are overlain by silty shale and thin beds of hummocky cross-stratified bioturbated sandstone (at 68.3 m) interpreted as open marine offshore deposits (FA1). Offshore facies are truncated by trough cross-stratified sandstone (at 78.6 m) interpreted as a proximal shoreface succession. This succession is overlain by a thin wedge of bayfill–estuarine sediment (FA5; back-barrier wedge of Thorne and Swift, 1991). Bayfill–estuarine deposits are buried beneath offshore–prodelta silty shales of FA1 (at 95.6 m), which are truncated by proximal shoreface deposits (at 118 m). This second shoreface succession is capped by a thin wedge of bayfill–estuarine mudstones (FA5, back-barrier wedge), which are truncated by a pronounced erosion surface at 135.8 m. This surface is overlain by a siderite pebble lag that is, in turn, overlain by a chert–quartz–pebble lag. This erosion surface is interpreted as a sequence-bounding unconformity that was modified during a regional transgression. The Nanushuk–Seabee Formation contact is placed at this erosion surface. The macro- and microfauna below this surface are late Cenomanian in age. Macro- and microfossils collected above this surface from the Seabee Formation are Turonian in age (see Appendix B for discussion of age control). Segment is from Ninuluk Bluff. See figure 9A for key to symbols. Note the positions of these shoreface sand bodies in fig. 10C are different than in Appendix A due to additional section shown at the base of the latter.



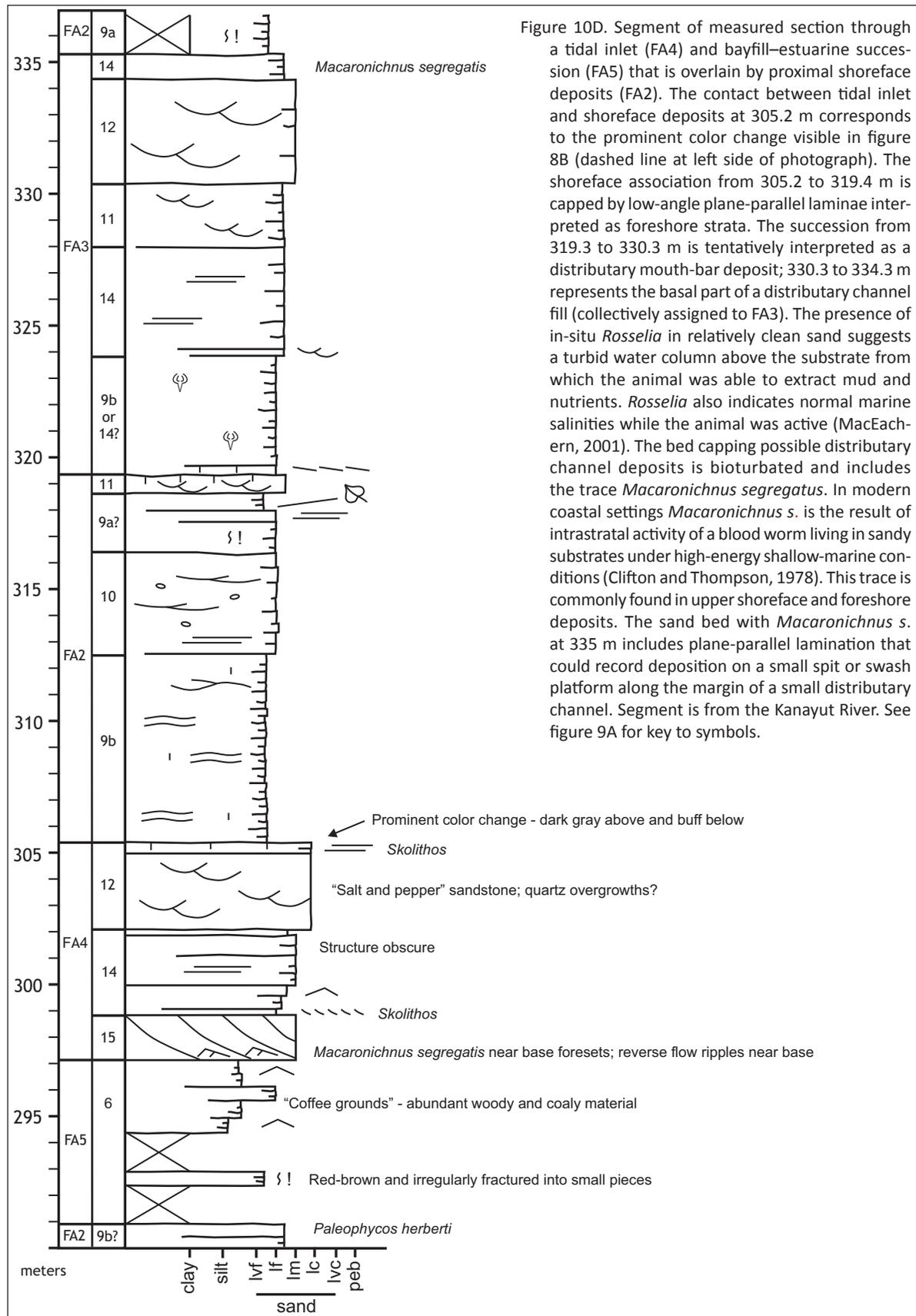


Figure 10D. Segment of measured section through a tidal inlet (FA4) and bayfill-estuarine succession (FA5) that is overlain by proximal shoreface deposits (FA2). The contact between tidal inlet and shoreface deposits at 305.2 m corresponds to the prominent color change visible in figure 8B (dashed line at left side of photograph). The shoreface association from 305.2 to 319.4 m is capped by low-angle plane-parallel laminae interpreted as foreshore strata. The succession from 319.3 to 330.3 m is tentatively interpreted as a distributary mouth-bar deposit; 330.3 to 334.3 m represents the basal part of a distributary channel fill (collectively assigned to FA3). The presence of in-situ *Rosselia* in relatively clean sand suggests a turbid water column above the substrate from which the animal was able to extract mud and nutrients. *Rosselia* also indicates normal marine salinities while the animal was active (MacEachern, 2001). The bed capping possible distributary channel deposits is bioturbated and includes the trace *Macaronichnus segregatus*. In modern coastal settings *Macaronichnus s.* is the result of intrastratal activity of a blood worm living in sandy substrates under high-energy shallow-marine conditions (Clifton and Thompson, 1978). This trace is commonly found in upper shoreface and foreshore deposits. The sand bed with *Macaronichnus s.* at 335 m includes plane-parallel lamination that could record deposition on a small spit or swash platform along the margin of a small distributary channel. Segment is from the Kanayut River. See figure 9A for key to symbols.

a granule to pebble conglomerate 5–10 cm thick with pebble-sized siderite, chert, and white vein quartz clasts. The contact between mudstone and conglomerate at 135.8 m (fig. 10C) corresponds with our placement of the Nanushuk–Seabee Formation contact.

### Interpretation

FA2 resembles modern shoreface deposits (Clifton and others, 1971) and ancient shoreface successions described by Bhattacharya and Walker (1991), Clifton (1981), McCubbin (1982), and Walker and Plint (1992). Bioturbated silty shales deposited below storm wave-base in offshore settings (FA1) grade upsection to pervasively bioturbated silty shale with numerous siltstone and HCS sandstone interbeds. Sand in these interbeds was eroded from proximal shoreface locations and transported seaward by storm-generated flows. Interbedded finer-grained lithologies (silty shale and siltstone) thin gradually upsection to become discontinuous drapes between amalgamated HCS sandstone beds in the distal lower shoreface. HCS sandstones continue to amalgamate upsection as reflected by the gradual disappearance of mudstone drapes and the bioturbated upper part of HCS sandstone beds in more proximal lower shoreface settings. These, in turn, grade upward to SCS sandstone in the middle to upper shoreface. Abundant scour surfaces lined with siderite, quartz, and chert pebbles attest to the energetic conditions shaping this environment. SCS sandstones grade upward to plane-parallel laminated sandstone deposited in foreshore settings. Locally, foreshore deposits are pervasively bioturbated with *Macaronichnus*. Variations in FA2 noted above record deposition in different positions on the shoreface profile. Examples of FA2 capped by bioturbated sandstones of facies 7 record deposition in distal shoreface settings, well down the shoreface depositional profile, whereas examples of FA2 that consist of amalgamated HCS and SCS sandstones, with little or no fine-grained deeper water facies, record deposition very close to the shoreline in proximal shoreface settings. FA2 is commonly truncated by a prominent flooding surface that is locally overlain by a few decimeters to meters of muddy sandstone that records transgressive reworking of the shoreface as it was drowned (fig. 8A).

The ubiquitous presence of storm-generated features such as HCS, SCS, and abundant pebble-lined scours, indicates that storms were significant in shaping the Nanushuk coastline and shelf. The fact that in many examples of this association, structures attributable to fairweather deposition are absent or present only as minor components indicates that storms were frequent and consistently able to remove most of the record of fairweather deposition.

The variant of FA2 recognized at Ninuluk Bluff and described above resembles sharp-based shoreface

successions described by Plint (1988) and Pattison (1995) from Cretaceous strata in Alberta and Utah, respectively, and is similarly interpreted as the record of a prograding storm-influenced shoreface deposited during forced regression. The lower shoreface (fig. 10C, 78.7–92.7 m) is abruptly overlain by silty shale (facies 6) and small-scale trough cross-stratified sandstone (facies 11) interpreted as a thin wedge of back-barrier sediment that we include in the bayfill–estuarine association (FA5). The contact between FA5 and colluvium at 95.6 m (fig. 10C) is interpreted as a compound surface—a sequence-bounding unconformity that was subsequently modified during transgression (ravinement). Trough cross-stratified sandstone (facies 11) immediately below the colluvium is interpreted as a washover fan deposit consisting of sand derived from the top of the shoreface succession and transported landward into a back-barrier setting by powerful storm waves. The higher shoreface (118–134.6 m) is also abruptly overlain by a thin wedge of fine-grained sediment interpreted as remnant bayfill–estuarine deposits (FA5). The abrupt contact between FA5 and FA2 at 135.8 m (fig. 10C, Nanushuk–Seabee contact) is interpreted as another compound surface—a sequence-bounding unconformity that was subsequently modified during transgression (ravinement). The conglomerate immediately above FA5 is a transgressive lag.

### Facies Association 3—Distributary Channel Mouth Bar

Facies association 3 (FA3) is common over a relatively narrow stratigraphic thickness straddling the transition from open marine to alluvial environments in the Nanushuk outcrop belt. It has been recognized in core as far north as Umiat (Fox and others, 1979). Vertical sections through FA3 are 10–25 m thick and start with a scour surface that truncates shoreface deposits (figs. 8E and 10B, surface at 299.5 m; fig. 10D, 319.3 m). This scour surface may be overlain by a variety of interbedded facies, including small- and large-scale trough cross-stratified sandstone (facies 11 and 12) with abundant internal scour surfaces and ripple cross-laminated sandstone (facies 3b), and interbedded small-scale trough cross-stratified sandstone and plane-parallel laminated sandstone (facies 11 and 14; fig. 10D, 319.3 m and above). These internal scour surfaces are commonly mantled with small and large coalified plant fragments or discontinuous lags of sideritized mudstone clasts. In the example shown in figure 10B, small-scale trough cross-stratified and plane-parallel laminated sandstone are truncated beneath a prominent scour surface at 310.2 m and overlain by nearly 10 m of medium- to large-scale trough cross-stratified sandstone (facies 12). In some occurrences, interbedded argillaceous sandstone with abundant finely divided coalified plant material (facies 6) and small-scale trough cross-stratified sand-

stone (facies 11) comprise the upper 4–6 m of the facies association (fig. 10B; 319.9–324.2 m).

### **Interpretation**

FA3 is interpreted as distributary mouth-bar and distributary channel-fill deposits in delta-front settings. Medium- to large-scale trough cross-stratified sandstone was deposited from medium- to large-scale three-dimensional bedforms that migrated seaward along the bottom of distributary channels under lower flow-regime conditions. Sandstones (facies 3b, 6, 11, and 14) underlying and interstratified with larger-scale trough cross-stratified sandstone record deposition from unidirectional flows as distributary mouth bars. Scour surfaces recognized within mouth-bar deposits are attributed to variations in flow velocity related to fluvial flood events. The prominent scour surface recognized at the base of many distributary channel fills is also attributed to fluvial flood events and, in most cases, is attributable to an avulsion event that resulted in establishment of a new channel course. Some occurrences of ripple cross-laminated sandstone (facies 3b or 6) may record deposition in abandoned distributary channels. Similar channel-fill successions have been described from the Dunvegan Formation in northwestern Alberta by Bhattacharya and Walker (1991) and the San Miguel Formation in Texas by Weise (1980).

### **Facies Association 4—Tidal Inlet**

Facies association 4 (FA4) is common over a relatively narrow stratigraphic thickness straddling the transition from open marine to alluvial environments in the Nanushuk outcrop belt. FA4 consists of interbedded planar cross-stratified sandstone (facies 15, figs. 8B and 8G), trough cross-stratified sandstone (facies 11 and 12), and plane-parallel laminated sandstone (facies 14). This association has only been recognized near the south side of the Nanushuk outcrop belt, along the Chandler River near Tuktu Bluff, along the Kanayut River, and at Marmot syncline, in stratigraphic positions high in the marine Nanushuk, where it forms a cap to FA2 (alone or with FA5).

The occurrence along the Kanayut River provides one of the best examples in the study area of FA4 (fig. 3; fig. 10D from 297.1 to 305.3 m). At this location, more than 14 m of interbedded carbonaceous muddy sandstone (facies 6), plane-parallel laminated sandstone (facies 14), large-scale trough cross-stratified sandstone (facies 12), and medium- to large-scale planar tabular and planar–tangential cross-stratified fine- to coarse-grained sandstone (facies 15) cap a thick shoreface succession (291–305 m). The lower 6 m consists of dark brown sandy mudstone with abundant finely divided plant fragments of the bayfill–estuarine association (FA5; facies 6; fig. 8B, right side of photograph below

yellow dashed line). Mudstone is overlain by large-scale planar–tangential cross-stratified sandstone with *Macaronichnus* burrows near the base of foresets (facies 15; fig. 8B, immediately above yellow line at right side of photograph), that is succeeded by plane-parallel laminated sandstone (facies 14) which, in turn, is overlain by medium-scale trough cross-stratified sandstone (facies 12) and a thin cap of plane-parallel laminated sandstone (facies 14). A prominent flooding surface marks the contact with the overlying shoreface succession (fig. 8B, prominent color change on left side of photograph marked by dashed yellow line; fig. 10D, 305.3 m). Other examples of FA4 include herringbone cross-bedding in sandstone (fig. 8G).

### **Interpretation**

FA4 is interpreted as a tidal inlet deposit based on the conspicuous presence of medium- to large-scale planar cross-stratification, including herringbone cross-stratification (facies 15), the local presence of mud drapes on foresets, and common trace fossils. In FA4 planar cross-stratified sandstone records migration of medium- to large-scale two-dimensional bedforms under the influence of tidal currents (Dalrymple, 1992; Kreisa and Muiola, 1986). Reverse-flow ripples recognized in facies 15 are not unique to tide-influenced settings, but indicate counter-currents associated with separation eddies in the lee of large bedforms, or sand transport by weaker currents associated with the other half of the tidal cycle. The presence of *Macaronichnus* in this facies indicates normal marine salinity in the tidal inlet. Muddy drapes and herringbone cross-stratification record slack water conditions and reversing currents, respectively. Medium- to large-scale trough cross-stratified sandstone (facies 12) is locally interbedded with planar cross-stratified sandstone (facies 15), suggesting slightly higher flow velocities were achieved locally, possibly along the thalweg of tidal inlet channels. Associated facies indicate complex interfingering of tidal inlet and adjacent coeval environments, including barrier spit/washover fan (facies 11 and 14) and interdistributary bay deposits (FA5, see below).

### **Facies Association 5—Bayfill–Estuarine**

Facies association 5 (FA5) is common over a narrow stratigraphic thickness straddling the transition from open marine to alluvial environments in the Nanushuk outcrop belt. Vertical sections through this association range from a few meters to more than 65 m thick and display considerable variability (figs. 10C and D and 11A and C). The main constituent of FA5 is platy argillaceous mudstone and scattered thin beds of sandstone, abundant terrestrial plant material (facies 6; fig. 8B, right side of photograph; fig. 8H), and carbonaceous mudstone and coal (facies 4). Bioturbation is difficult to



channels (compare to Elliot, 1974). Scattered thin sandstone beds (facies 6) are interpreted as crevasse splay deposits that resulted when flow in distributary channels overtopped their levees and transported sand into adjacent interdistributary bays as part of sheet flows (Elliot, 1974; Fisk, 1947). Small-scale, symmetrical, wave-ripple bedforms indicate reworking of sand by short period waves in a protected setting, probably in very shallow water. Closely associated coal suggests that swamps or

marshes were present along the margins of bays and estuaries (Galloway and Hobday, 1996; McCabe, 1984). FA5 typically encases other associated marginal-marine facies associations (FA6 and FA7) described below.

**Facies Association 6—Crevasse Channel**

Facies association 6 (FA6) is relatively common in marginal-marine and nonmarine strata of the Nanushuk in outcrop. FA6 consists of fining-upward successions

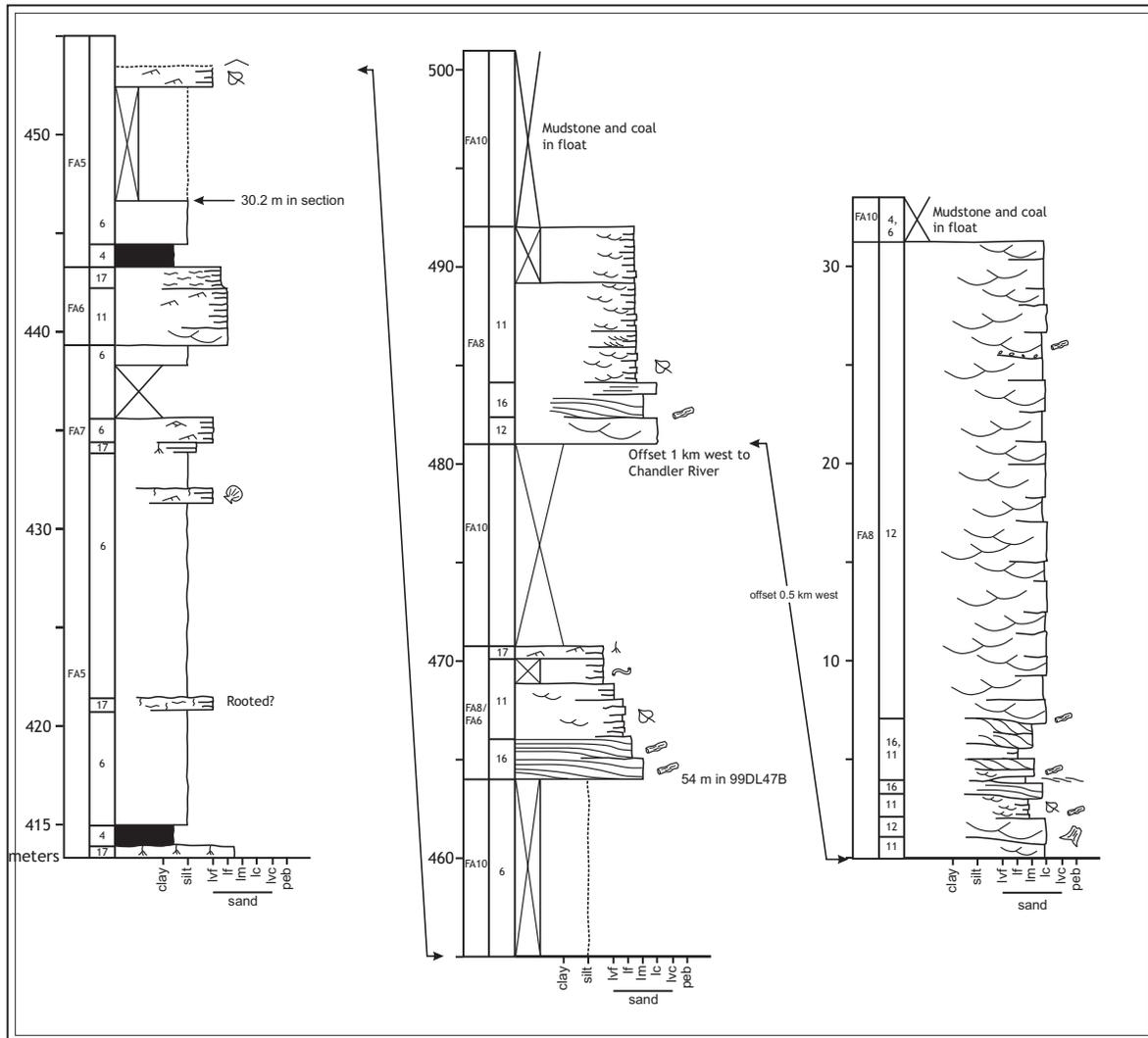
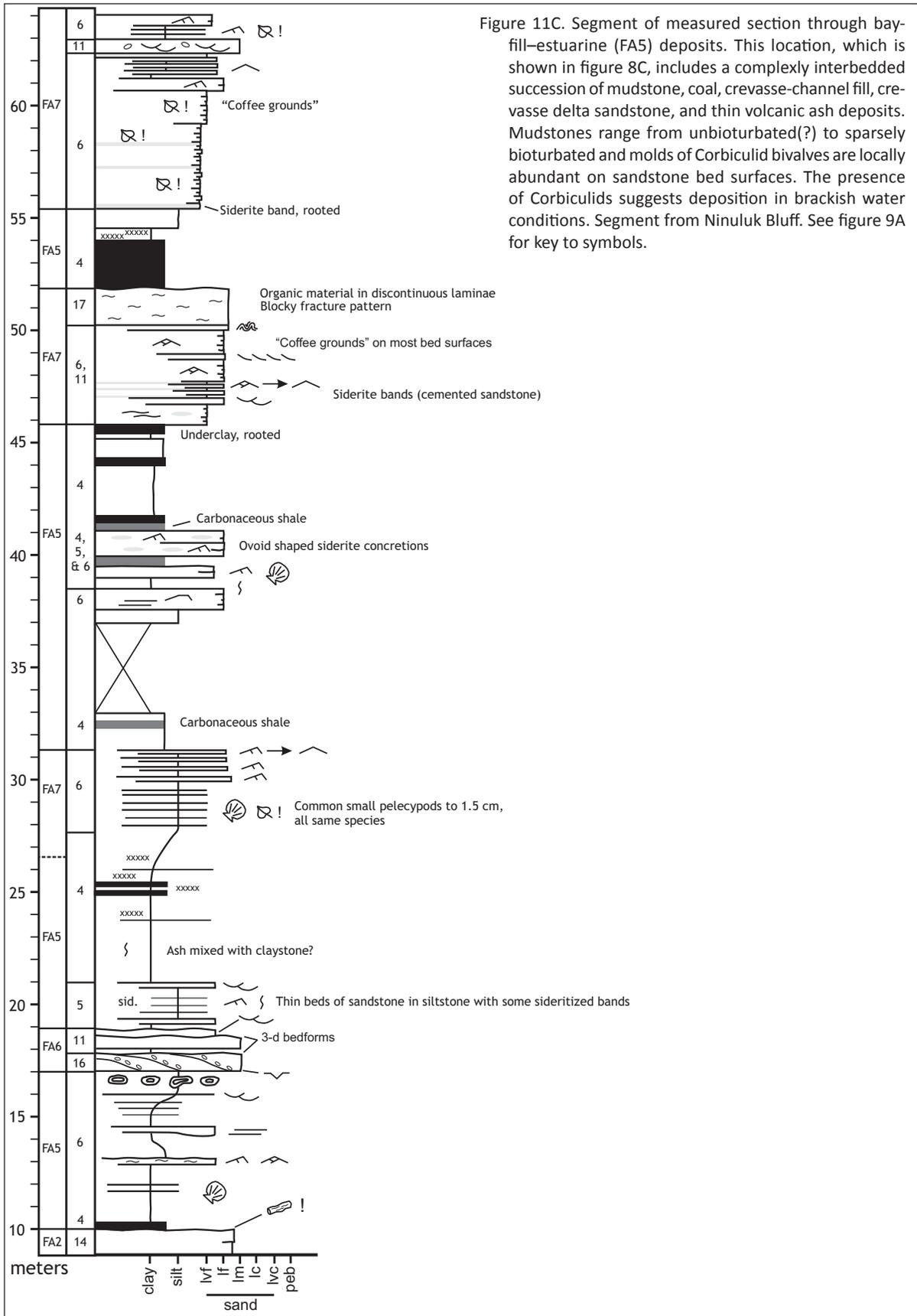


Figure 11B. Segment of measured section through bayfill–estuarine (FA5) succession, fluvial sandy sheet (FA8), and alluvial floodbasin deposits (FA10). Bayfill–estuarine and alluvial floodbasin succession commonly include a similar suite of facies and facies associations (carbonaceous mudstones, crevasse channels and crevasse deltas, coals, etc.) and can be difficult to differentiate in the stratigraphic record when outcrop quality is poor. The bayfill–estuarine deposits in this example are identified based on the presence of abundant *Corbiculid* bivalves at ~432 m and less abundant *Corbiculids* at 435 m. These monospecific accumulations suggest deposition in a brackish water setting. The transition upsection from bayfill–estuarine to alluvial floodbasin deposits is poorly exposed and is arbitrarily placed at the top of the splay sand at ~453 m. The thicker sand bodies above this level are interpreted as sandy fluvial sheet deposits (FA8) and/or crevasse channel fills (464–471 m). Segment from the south flank of Arc Mountain anticline. See figure 9A for key to symbols and Appendix for the complete measured section. Note the Arc Mountain measured section in Appendix A is a composite section of several shorter segments, so the height above the base is off slightly relative to figure 11B.



that range from 3 to 7 m thick (figs. 8H and I, and 11B and C). Vertical sections start with a sharp erosional lower contact with underlying platy mudstone or carbonaceous mudstone (facies 6 or 4, respectively, of facies FA5) overlain by either medium- to large-scale planar-tangential cross-stratified sandstone (facies 15) or small-scale trough cross-stratified sandstone (facies 11; fig. 8H). Planar and trough cross-stratified sandstones are locally overlain by interbedded siltstone and current-ripple cross-laminated fine-grained sandstone (facies 6) of FA5.

### ***Interpretation***

The fining-upward nature of FA6 resembles crevasse channel deposits described by Elliot (1974) and recognized in Cenomanian lower delta plain successions of the Dunvegan Formation by Bhattacharya and Walker (1991). The erosional lower contact and commonly associated ball and pillow structures (fig. 8H) indicate the abrupt introduction of relatively coarse-grained material into a low-energy setting and rapid deposition from discrete events. Medium- to large-scale planar cross-stratified sandstone at the base of FA6 locally suggests channelized unidirectional flows in which sizable two-dimensional bedforms (facies 15) migrated downcurrent. These bedforms were succeeded by small- to medium-scale three-dimensional bedforms (facies 11) as flow in the crevasse channel gradually waned. The vertical sequence of sedimentary structures recognized in FA6 is consistent with deposition from waning flows in crevasse channels that formed during flood events when flow in distributary channels or fluvial channels breached their levees, diverting a portion of the flow into adjacent interdistributary bay or alluvial floodbasin settings (Bridge, 1984; Elliot, 1974). The crevasse channel association is interpreted to grade downdip to the crevasse delta association.

### **Facies Association 7—Crevasse Delta**

Facies association 7 (FA7) is relatively common in marginal-marine and nonmarine strata of the Nanushuk in outcrop. Figures 11A and B show several examples of FA7 encased in mudstones of the bayfill-estuarine (FA5; fig. 8J) and alluvial floodbasin (FA10; fig. 8K) associations. FA7 consists of coarsening- and thickening-upward successions that range from 4 to 8 m thick (figs. 8J and K) and grade upward from platy mudstone (facies 6) and carbonaceous mudstone and coal (facies 4; fig. 8K), to thinly interbedded ripple cross-laminated sandstone and siltstone (facies 6; fig. 8J). The thickness of sandstone beds increases upsection while siltstone beds decrease in thickness and abundance. Near the top of some successions sandstones tend to amalgamate. Ripple bedforms preserved on bed surfaces in the thinly interbedded sandstones and siltstones are

strongly asymmetric, although some bedforms have distinctive flat tops. Where amalgamated sandstones are present, ripple bedforms are typically symmetric or slightly asymmetric in cross-section (fig. 8L) and have continuous and straight crestlines. Some examples of FA7 are capped by blocky weathering, orange-brown argillaceous sandstone with abundant clay and finely divided terrestrial organic material mixed throughout the sandstone (facies 17). Sideritized siltstone beds interbedded with sandstones are common (fig. 8L) and sandstones often include siderite nodules.

### ***Interpretation***

The coarsening- and thickening-upward trend so characteristic of FA7, combined with its occurrence in mudstones and carbonaceous mudstones (facies 6, 4, and 17) of the bayfill-estuarine (FA5) and alluvial floodbasin (FA10) associations, suggest deposition as either channel levees or crevasse deltas (Elliot, 1974). We favor the crevasse delta interpretation as channel levee deposits should include abundant features indicative of subaerial exposure, such as plant roots and paleosol development (Elliot, 1974). Strongly asymmetrical bedforms and associated ripple cross-lamination in the lower part of this association indicates deposition from unidirectional flows. The upward progression from current-ripple bedforms to wave-ripple bedforms suggests gradual shoaling to within wave base (maximum depth of a few meters is inferred for a protected bayfill or alluvial floodbasin setting). Crevasse deltas require the presence of crevasse channels that supply sediment to the growing crevasse delta lobe (for example, Coleman and others, 1964). If correctly interpreted, this association should grade up depositional dip to crevasse channel-fill deposits of FA6.

### **Facies Association 8—Sandy Fluvial Sheet**

Facies association 8 (FA8) is common in outcrop, where it comprises an important part of the nonmarine Nanushuk record (fig. 11B). FA8 forms fining-upward sandstone successions up to 35 m thick that typically begin with interbedded medium- to large-scale trough cross-stratified sandstone (facies 12; fig. 8M) and horizontally bedded and sigmoidally cross-bedded sandstone (facies 16; fig. 8N). These facies commonly account for most of the facies association's thickness but are capped, at least locally, by a few meters of small-scale trough cross-stratified sandstone (facies 11). Abundant small to large plant fragments litter irregular-shaped parting surfaces in channel-fill successions (fig. 8O). On the south limb of Arc Mountain anticline, medium- to large-scale trough cross-stratified sandstone (facies 12; fig. 8M) grades laterally over 200–300 m to interbedded horizontally and sigmoidally bedded sandstone (facies 16; fig. 11B; fig. 8N) and small-scale trough cross-stratified sandstone (facies 11). The latter facies grades upward

to current-ripple cross-laminated sandstone (facies 17, unidirectional flow only and lacking bivalves). FA8 has a sheetlike geometry and is encased within poorly exposed mudstones of the alluvial floodbasin association (FA10).

#### **Interpretation**

FA8 is interpreted as the fill of bedload-dominated fluvial channels (Collinson, 1996; Galloway and Hobday, 1996). Medium- to large-scale trough cross-stratified sandstone (facies 12) represents deposition from moderate- to large-scale three-dimensional bedforms (Harms and others, 1975; Miall, 1996) that migrated downcurrent near the thalwegs of channels. Interbedded trough cross-stratified and horizontally bedded sandstone near the base of channel-fill successions may have resulted from river stage fluctuations due to seasonal variations in flow or from shorter-term flood events. Lateral gradation from medium- to large-scale trough cross-stratification (facies 12) to small-scale trough cross-stratification (facies 11) records the gradation from larger three-dimensional bedforms near channel axes to smaller-scale bedforms that formed near channel margins, possibly associated with laterally accreting or downstream accreting macroforms (for example, Miall, 1996, element LA or DA, respectively). Small-scale trough cross-bedded sandstone and ripple cross-laminated sandstone (facies 11 and 6, respectively) that cap some channel-fill successions are interpreted to record channel abandonment.

#### **Facies Association 9—Conglomeratic Fluvial Sheet**

Facies association 9 (FA9) is common in the southern part of the Nanushuk outcrop belt where it consists largely of facies 18, with minor interbeds of small-scale trough cross-stratified sandstone (facies 11) and horizontally-bedded sandstone (facies 16). These minor interbeds comprise lenticular accumulations of sandstone that extend along local strike for a few meters to a few tens of meters before pinching out in conglomerate (facies 18). FA9 forms sheets in poorly exposed alluvial floodbasin successions (FA10, see below) (fig. 8P).

#### **Interpretation**

FA9 is interpreted as longitudinal bar deposits laid down in mixed-load, low-sinuosity rivers (Miall, 1977, 1985, 1996; Rust, 1978). Longitudinal bars grew during episodes of high water and sediment flux through vertical and downstream accretion (Miall, 1985). Minor lenses of sandstone were deposited during the waning stages of high-discharge events (Miall, 1977). FA9 resembles the gravelly bars and bedforms architectural element of Miall (1996, p. 139).

#### **Facies Association 10—Alluvial Floodbasin**

Facies association 10 (FA10) is very common in outcrop, but is largely concealed by tundra vegetation (figs. 8P, 11B). It is only exposed in river cuts, holes dug by ground squirrels and grizzly bears, or where sandstone is a significant local component of the succession. As a result, component facies and their stacking patterns are poorly known. Available exposure suggests FA10 consists largely of carbonaceous mudstone and coal (facies 4) and blocky sideritic mudstone (facies 5). Sharp-based fining-upward successions of FA6 and upward-thickening successions of FA7 are encased in FA10 locally.

#### **Interpretation**

FA10 records deposition in alluvial floodbasin settings and resembles modern floodbasin successions documented by Fisk (1947) and Smith and others (1989). The common presence, where exposed, of carbonaceous mudstone and coal (facies 4) and blocky sideritic mudstone (facies 5), suggests that large areas landward of the delta plain were poorly drained and probably occupied by swamps and lakes. The local presence of FA6 and FA7 in FA10 identifies locations relatively close to active fluvial channels.

### **FACIES ASSOCIATION STACKING PATTERNS**

Most shallow marine facies associations recognized in the Nanushuk Formation comprise coarsening- and/or thickening-upward successions a few meters to >50 m thick that record deposition in progressively shallower water upsection. These successions consist of one or more facies associations and are bounded by flooding surfaces across which there is facies evidence for an abrupt increase in water depth (that is, an abrupt landward shift in facies belts). These coarsening- and/or thickening-upward successions record relatively short-lived episodes of coastline progradation and correspond to parasequences as defined by Van Wagoner and others (1990).

Most Nanushuk successions are characterized by aggradational and progradational facies association (parasequence) stacking patterns. We infer the existence of retrogradational stacking patterns in exposures of uppermost Nanushuk strata (Cenomanian) near its northern outcrop limit along the Colville River, where nonmarine strata are overlain by an intertonguing marine–nonmarine succession (Detterman and others, 1963). This part of the Nanushuk comprises intertonguing nonmarine and marine strata of Niakogon Tongue and Ninuluk Formation, respectively, of former usage and represents an overall transgressive succession punctuated many times by smaller-scale progradational successions. In

this section we first describe stacking patterns along the southern part of the Nanushuk outcrop belt and then shift to describe stacking patterns along the northern part of the belt.

## SOUTHERN OUTCROP BELT

### TUKTU BLUFF

The Nanushuk is at least 1,800 m thick in the vicinity of Tuktu Bluff, including at least 600 m of marine and transitional strata exposed along the bluff and discontinuously along the Chandler River immediately to the north (fig. 12A<sup>4</sup>, location 3). Marine and transitional strata grade upsection toward the north to a thick, nonmarine succession that is discontinuously exposed down the dip slope that forms the north side of Tuktu Bluff and continues up the south flank of an east–west-trending syncline (fig. 3; Huffman and others, 1981). Figure 12A shows a 375-m-thick succession of marine to marginal-marine strata in the lower Nanushuk (Tuktu Formation of former usage) to which 870 m of nonmarine strata have been appended from the measured section of Huffman and others (1981).

At least six stacked shoreface facies associations (FA2) are exposed at Tuktu Bluff (fig. 12A, column 3, 0–307 m), and at least two additional shoreface associations are exposed along the west side of the Chandler River, ~0.5 km north of the bluff (fig. 12A, column 3, 307–375 m). The lower 150 m of the Tuktu succession consists of three stacked shoreface associations, each of which is capped by sparsely bioturbated to nonbioturbated hummocky cross-stratified sandstone interpreted as lower shoreface deposits. The absence of more proximal facies in each higher association suggests an aggradational stacking pattern. Each shoreface association is terminated by a marine flooding surface.

Shoreface associations in the upper 157 m of the Tuktu exposure (150–307 m) and those exposed along the west side of the Chandler River to the north (307–375 m) display a prominent progradational stacking pattern, as demonstrated by progressively shallower water facies capping successive shoreface associations, including interpreted foreshore and tidal inlet deposits (fig. 12A, 300 and 362–372 m, respectively), and successively thinner parasequences. The stratigraphically highest shoreface association is truncated by a prominent scour surface (362 m) overlain by a tidal inlet facies association (FA4).

The thickness of marine and marginal-marine strata upsection from the 375 m level is unclear. Huffman and others (1981) identified tidal facies at ~666 m and herringbone cross-stratification at ~755 m (fig. 12A). They showed coarse sandstone and conglomerate discontinuously exposed for another several hundred meters. Due to northward bed dips, these coarse-grained facies are a

kilometer or more north of Tuktu Bluff. Stacking patterns are unclear in this part of the Nanushuk due to discontinuous exposure. We suggest that the progradational stacking pattern continues upsection to the top of the preserved Nanushuk in this area. We infer fine-grained alluvial floodplain facies underlie covered intervals, as at Arc Mountain and Marmot Syncline (discussed below), and that outcropping coarse-grained facies represent channel belts whose stratigraphic positions are the result of base-level falls (unconformity-bounded). It should be noted that the fluvial conglomerates north of Tuktu Bluff grade northward over a very short distance to much finer-grained lithologies inferred to be marine.

### KANAYUT RIVER

The Nanushuk in the vicinity of the Kanayut River and location 5 is at least 1,000 m thick (Huffman and others, 1981), of which ~620 m is exposed on the north side of Arc Mountain anticline (figs. 3 and 12A). The base of the Nanushuk at this location is concealed by tundra; the amount of Nanushuk concealed is unknown, but is thought to be no more than a few hundred meters of muddy offshore shelf to lower shoreface deposits.

At least nine shoreface facies associations (FA2) are recognized in the marine part of the Nanushuk at location 5 (fig. 12A). Facies associations in the lower 185 m of the Kanayut River exposure stack to form an aggradational to weakly progradational pattern. The interval from 185 to 386 m displays a clear progradational stacking pattern. This progradational motif continues upsection through bayfill–estuarine facies associations (FA6 from 386 to 425 m), alluvial floodbasin associations (FA11 from 425 to at least 500 m), and fluvial sheet associations (FA10 from 535 m to the Holocene erosion surface at 620 m).

Two firm-ground surfaces have been recognized in marine strata at the Kanayut River location, one near 30 m and another at 186.8 m (figs. 12A and 13). Trace fossils of the *Glossifungites* ichnofacies have been recognized at both stratigraphic levels, including abundant *Thalassinoides* and *Skolithos*. These surfaces correspond to erosional discontinuities and represent nontrivial breaks in sedimentation (omission surfaces) (Pemberton and MacEachern, 1995).

### ARC MOUNTAIN

The Nanushuk in the vicinity of Arc Mountain anticline (fig. 3) is at least 800 m thick (Huffman and others, 1981), of which ~680 m are shown in figure 12A (location 6). At least 100–150 m of additional Nanushuk strata are discontinuously exposed between the top of our measured section and the axis of the next syncline to the south. This combined succession represents a complete section through the preserved Nanushuk Formation, from its lower gradational contact with the Torok For-

<sup>4</sup>Figure 12 is in pocket, inside back cover.

mation near the axis of Arc Mountain anticline to the Holocene erosion surface near the axis of the syncline.

Facies associations stack to form a complex succession in the vicinity of Arc Mountain (fig. 12A, location 6). The basal 335 m of exposed marine strata form an aggradational (0–190 m) to progradational (190–335 m) succession of largely offshore (FA1) and shoreface facies (FA2) associations. The highest interpreted shoreface package in the latter succession is overlain by sandstones from 310 to 335 m interpreted as delta-front distributary mouth-bar deposits (FA3). Distributary mouth-bar sandstones are separated from overlying mudstones, interpreted as offshore deposits, by a marine flooding surface (335 m). Alternatively, these mudstones may represent deposition in a back-barrier

bay setting landward of a shoreface-distributary mouth-bar complex. The sandstone package from 340 to 360 m is poorly known due to difficult access, but is interpreted as another delta-front distributary mouth-bar sand body (FA3) and thus part of the progradational package that starts at 190 m.

Discontinuous exposure upsection to the south obscures stacking patterns, but the progradational motif is thought to continue to the top of the preserved Nanushuk. Trough cross-stratified sandstone from 360 to 372 m is interpreted as the fill of a distributary channel (FA3). Discontinuously exposed sandstones from 379 to 402 m are interpreted as a single prograding shoreface (FA2) succession capped by foreshore deposits. Poorly exposed mudstone, coal, and fine-grained sandstone with

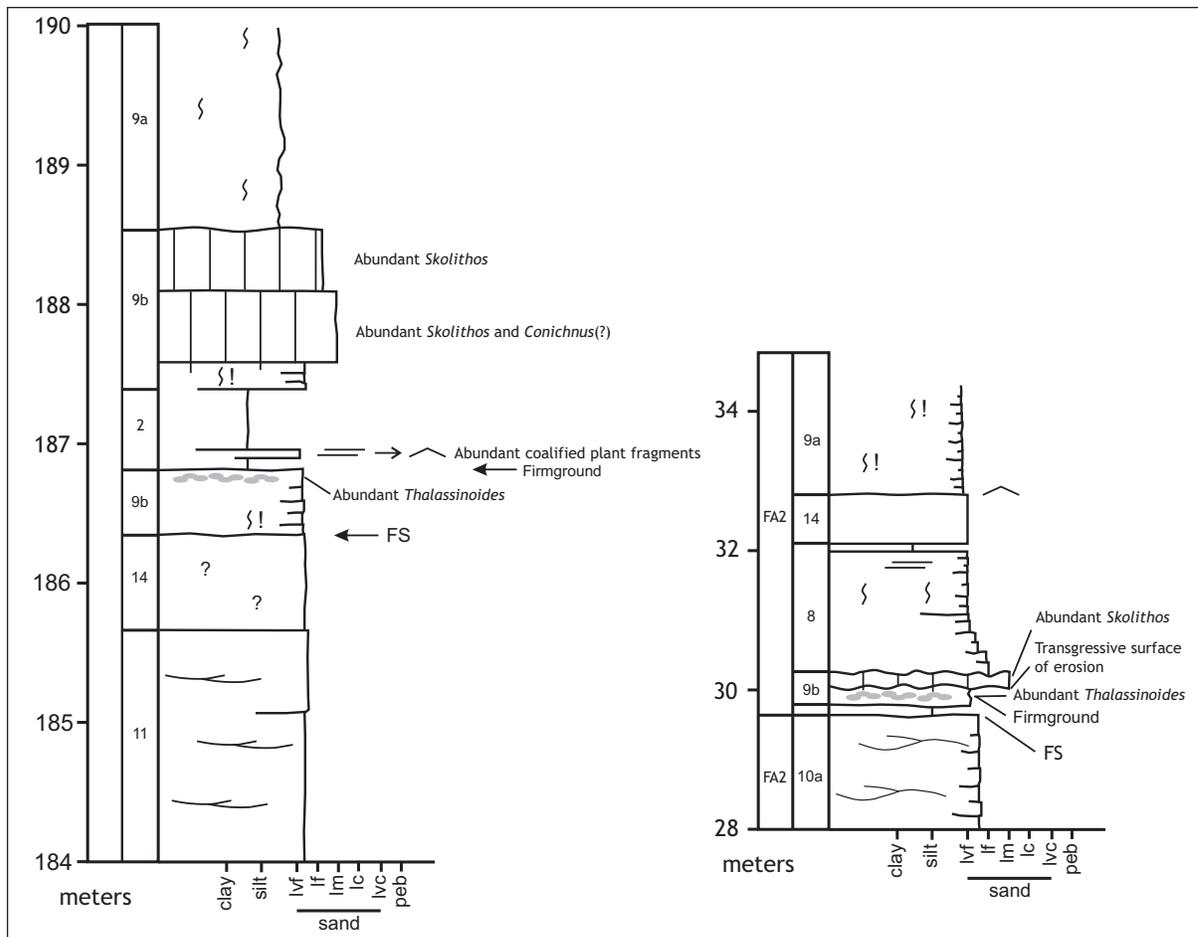


Figure 13. Measured sections through firmgrounds developed in transgressive deposits above shoreface successions. The salt-and-pepper-colored sandstone packed with *Skolithos* burrows and shown in figure 7P is the bed from 30.0 to 30.15 m in the measured section at right. *Thalassinoides* shown in figure 7Q is from the bed immediately below this *Skolithos*-burrowed sandstone (column at right). *Thalassinoides* burrows are interpreted to belong to the *Glossifungites* ichnofacies. Many *Skolithos* burrows extend through the sand into the underlying *Thalassinoides*-bearing mudstone. This sandstone is interpreted as a transgressive lag deposited above a ravinement surface (transgressive surface of erosion). The section at left includes *Thalassinoides* at 186.8 m interpreted as a firmground. This occurrence lacks the transgressive lag immediately above the firmground. Both examples are from the Kanayut River.

Corbiculid bivalves between 402 and 485 m are interpreted to be bayfill deposits (FA5). The bayfill succession is truncated by a 50-m-thick sandy fluvial channel complex (FA8). This channel complex is overlain at 535 m by a poorly exposed succession of alternating alluvial floodbasin deposits (FA10) and fluvial deposits of pebbly sandstone and pebble conglomerate (FA9) that comprise the remaining thickness of Nanushuk strata in this area.

Between the south flank of Arc Mountain anticline and the axis of the syncline immediately to the south, sheetlike sandy and conglomeratic fluvial deposits of FA8 and FA9, respectively, form resistant ledges encased in tundra-covered mudstones of FA10 (fig. 8P). When viewed from the air, these ledges form broad lenses that extend along structural strike (probably close to depositional strike) from 1.0 to ~4.0 km and represent fluvial channel belts. Each successive ledge is slightly coarser grained than the next ledge downsection, creating a coarsening-upward succession. A similar outcrop pattern is present immediately west of the Kanayut River, where resistant ledges of nonmarine strata define an eastward-plunging syncline. Correlation of nonmarine ledges between these two locations is not possible because of a 6-km-wide tundra-covered area immediately west of the Nanushuk River.

#### MARMOT SYNCLINE (SLOPE MOUNTAIN)

The Nanushuk in the vicinity of Marmot syncline is more than 1,000 m thick (Huffman and others, 1981) (figs. 3 and 12A, location 8), and is gently folded into a “thumbprint” syncline that Huffman and others (1981) referred to as Marmot syncline. An additional 15–20 m of outer shelf to upper slope facies (Torok Formation) are discontinuously exposed stratigraphically below our measured section. Keller and others (1961) and Huffman and others (1981) identified marine strata near the axis of the syncline. Keller and others (1961) correlated these beds with the Cenomanian Ninuluk Formation (former usage).

The lower 300–400 m of Nanushuk strata are relatively well exposed along the east side of Marmot syncline (fig. 12A, location 8). The lower 117 m of Nanushuk strata in this exposure consist of stacked offshore to shoreface facies associations (FA1 and FA2, respectively) that define an aggradational to progradational stacking pattern. Each succession includes a thick mudstone (silty shale) at its base that grades upsection to interbedded silty shale, siltstone, and fine-grained sandstone and, finally, to bioturbated thin- to medium-bedded wavy laminated and hummocky cross-stratified sandstone. This succession records deposition in offshore to lower shoreface settings. The shoreface association (FA2) from 117 to 187 m (fig. 12A) includes an anomalously thick sand-rich portion that displays little facies differentiation through nearly 40

m of section, until the upper 5–10 m, where sparsely bioturbated to nonbioturbated swaley cross-stratified sandstone caps the interval. This succession represents either a thick aggradational–progradational delta-front association, or a strongly progradational succession of thinner amalgamated shoreface facies associations.

The shoreface succession from 117 to 187 m is truncated by an irregular erosion surface with up to 10 m of local relief (fig. 12A). This surface is difficult to recognize on the ground, but is conspicuous when viewed from the air (fig. 14). Where intersected by our measured section, the surface is overlain by a thin pebble conglomerate (Facies 18) and trough cross-stratified sandstone (Facies 11), interpreted to comprise a thin fluvial succession (FA8 or FA9) at the base of an incised valley. The fluvial association is overlain by 7–10 m of poorly exposed, sparsely bioturbated siltstone interpreted as an estuarine deposit (FA5), which forms the base of the valley fill along strike from our measured section.

The valley-fill deposits are succeeded upsection (figs. 12A and 14, 205–348 m) by a progradational succession of shoreface, delta-front, bayfill-estuarine, and distributary channel facies associations. The remaining 600+ m of section is a rubbly, discontinuously exposed succession of alluvial deposits, including fluvial channel-fill and overbank facies, and a thin cap of marine facies (Huffman and others, 1981; Myers and others, unpublished field data). Assuming the upper 80 m of section have been correctly identified as marine to marginal marine, we interpret this part of the exposure as a retrogradational succession of lower delta plain and delta-front facies associations, and extend this stacking pattern downsection to approximately the 780–800 m level (fig. 12A, location 8). Although we do not have age control for this part of the Nanushuk, based on facies and stratigraphic position we follow Keller and others (1961) and infer a Cenomanian age for these marine beds.

#### NORTHERN OUTCROP BELT ROOFTOP RIDGE

The Nanushuk in the vicinity of Rooftop Ridge anticline is more than 500 m thick (figs. 3 and 12B, location 7). At the east end of this structure, along the west bank of the Nanushuk River, the Nanushuk is in fault contact with the underlying Torok Formation and overlain disconformably(?) by Turonian-age bentonitic clay shales of the Seabee Formation, and is 520 m thick. The thrust fault separating the Nanushuk from the Torok is north vergent and is interpreted as a minor structure with limited displacement (Gil Mull, oral commun.). Thus the 520 m thickness is interpreted as being close to the depositional thickness of the Nanushuk near this location. This estimate is considerably (>200 m) less than thickness estimates for the formation near the southern edge of the outcrop belt.

The Nanushuk at Rooftop Ridge is organized into two prominent successions (fig. 12B, location 7). The lower succession is ~238 m thick and consists of at least ten smaller-scale sandier-upward successions (parasequences) ranging in thickness from 15 to 50 m. These smaller-scale successions are organized in four to five progradational successions equivalent to parasequence sets of Van Wagoner and others (1990), each consisting of two or more of the smaller-scale sandier-upward successions. The lower 238-m-thick succession displays an aggradational to weakly progradational stacking pattern.

The upper succession is ~281 m thick, consists of at least nine sandier-upward successions ranging in thickness from 5 to 65 m, and displays an organization similar in gross appearance to the lower succession, but is different in detail. The basal 35–40 m displays a retrogradational stacking pattern of tidal inlet or bayfill–estuarine associations (FA4 or FA5 from 238 to 248 m), muddy shoreface associations (FA2 as estuary mouth barriers from 248 to 258? m), and a relatively thick interpreted marine mudstone deposit (258 to ~278 m). The stacking pattern changes from retrogradational to

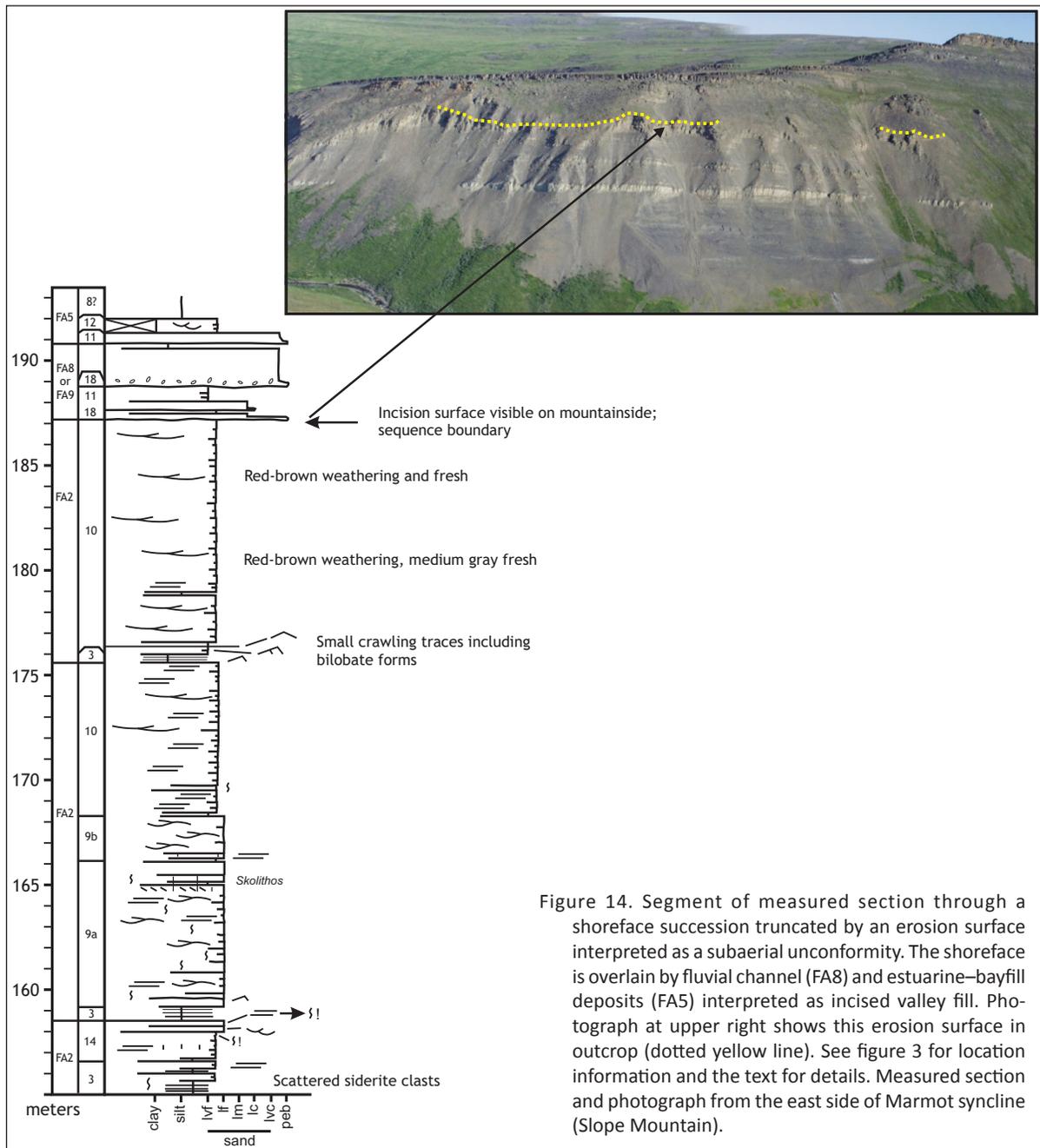


Figure 14. Segment of measured section through a shoreface succession truncated by an erosion surface interpreted as a subaerial unconformity. The shoreface is overlain by fluvial channel (FA8) and estuarine–bayfill deposits (FA5) interpreted as incised valley fill. Photograph at upper right shows this erosion surface in outcrop (dotted yellow line). See figure 3 for location information and the text for details. Measured section and photograph from the east side of Marmot syncline (Slope Mountain).

aggradational at ~278–280 m and gradually becomes distinctly progradational in the upper 80 m of the upper succession (above 440 m), which consists of amalgamated sand-rich shoreface parasequences.

Thin mudstone beds ~60 m below the Nanushuk–Seabee contact yielded foraminifera of probable Cenomanian to Turonian age (table B1, sample 99DL64-203 collected between 457 and 460 m; fig. 12B). A Turonian age for the Nanushuk is ruled out on regional considerations, but a Cenomanian age is plausible. Assuming the upper 60–65 m of the Nanushuk at this location is Cenomanian, and given its progradational organization, we conclude that the upper part of the Nanushuk Formation in this part of the basin either predates the prominent relative sea level rise documented for Cenomanian Nanushuk strata farther north and at Marmot syncline to the east–southeast, or sediment supply was consistently high enough to drive progradation at this location in spite of evidence for rising relative sea level throughout much of the central Colville basin.

#### NINULUK BLUFF

Approximately 320 m of uppermost Nanushuk and basal Seabee strata are discontinuously exposed at Ninuluk Bluff (Huffman and others, 1981) (fig. 3). Our measured section includes the uppermost 147 m of marginal-marine and marine strata of the Nanushuk Formation (undifferentiated Ninuluk Formation and Niakogon Tongue of former usage) and the basal 70 m of offshore and offshore transition strata of the Seabee Formation (fig. 12B, location 1).

Regional relations suggest a larger-scale (at least a few hundred meters thick) retrogradational stacking pattern for Cenomanian-age beds in the upper part of the Nanushuk Formation. Superimposed on this larger-scale pattern is at least one smaller-scale progradational succession of stacked shoreface (FA2), bayfill (FA5), crevasse channel (FA6), and splay (FA7) facies associations that culminates somewhere between 58 m and 80 m in figure 12B. Above that interval a retrogradational stack of offshore (FA1) and offshore transition (distal FA2) associations are truncated at 90 m by a sharp-based shoreface association (proximal FA2). The uppermost 58 m of Nanushuk strata at Ninuluk Bluff (from 90 to 148 m) consists of two stacked shoreface associations (FA2) interpreted as sharp-based shoreface successions (in the sense of Plint, 1988) separated by a 22-m-thick succession of the offshore facies association (FA1). Facies recognized in the lower of the two shoreface associations indicate deposition in an upper shoreface to foreshore setting, whereas facies in the higher of the two indicate deposition in a lower to upper shoreface setting. Samples collected for micropaleontologic analysis from offshore strata below the first sharp-based shoreface package (table B1, samples 00DL16–60 to 78.4 m) and

between the two shoreface packages (sample 00DL16–135.3 m, which corresponds approximately to 123 m in the Ninuluk Bluff section in fig. 12B) yielded species of foraminifera characteristic of marine environments (inner neritic), whereas samples collected from the bayfill succession below (table B1, samples 00DL16–1.0 and 30.6) were barren of foraminifera. These results, combined with associated facies, suggest that the mud-rock successions immediately below each sharp-based shoreface package accumulated in open-marine settings (not brackish-water settings) subject to powerful storms (as evidenced by the large gutter cast at ~90 m, fig. 7L), and that the higher shoreface package was deposited in slightly deeper water. These observations are consistent with the larger-scale retrogradational stacking pattern recognized in the upper Nanushuk in this part of the basin. The retrogradational pattern continues through the basal 40–50 m of the overlying Seabee Formation, above which the stacking pattern changes to progradational.

#### COLVILLE INCISION

Approximately 90 m of Nanushuk strata are discontinuously exposed below the Seabee Formation at the Colville incision location (figs. 3 and 12B, location 2). The exposure extends nearly continuously for ~1.0 km along the north bank of the Colville River. Our measured sections include 65 m of Nanushuk strata in the east-central part of the exposure and 28 m at the east end. Figure 12B shows our tentative correlation of the two sections. The contact with the Seabee Formation is not exposed, but its location is somewhere between the uppermost rubblecrop of sandstone and colluvium of light-colored bentonitic clay shale with prominent “popcorn” weathering characteristics visible near the west end of the exposure.

We have no data demonstrating the age of the Nanushuk at the Colville incision. Its stratigraphic position a short distance below bentonitic shales of the Seabee Formation suggests a Cenomanian age, probably comparable to the succession exposed at Ninuluk Bluff and near the base of Umiat Mountain (Houseknecht and Schenk, 2005).

As stated in the discussion of stacking patterns at Ninuluk Bluff, regional relations suggest a larger-scale (at least a few hundred meters thick) retrogradational pattern for Cenomanian strata in the upper part of the Nanushuk Formation. We recognize smaller-scale progradational successions, like the Nanushuk at Ninuluk Bluff, that are superimposed on the larger-scale retrogradational pattern. The east end of the exposure is described first, followed by the central part, which is ~0.5 km west of the east end (fig. 12B, location 2).

The lower 6 m, consisting of thinly interbedded silty shale and hummocky cross-stratified sandstone, represent the distal part of a shoreface association

(offshore transition strata forming the base of FA2). This association is truncated by a prominent erosion surface and overlain by medium- to large-scale trough cross-stratified sandstone with abundant chert- and quartz-pebble-lined internal scour surfaces interpreted as a multi-scoured fluvial channel-fill succession (FA9) that extends to the top of the exposure (fig. 12B).

Approximately 0.5 km west of the east end, shoreface sandstones, offshore mudstones, and fluvial channel-fill sandstones make up the uppermost 66 m of exposed Nanushuk strata below bentonitic clay shales of the Seabee Formation. These facies associations make up a prominent bluff on the north side of the Colville River that extends along the river for more than 500 m. The base of the exposure (from river level to 4 m above river level) includes amalgamated beds of hummocky cross-stratified sandstone. Individual beds are recognized by laterally continuous scour surfaces (at outcrop scale) overlain by discontinuous pebble lags one to two clasts thick of sideritized mudstone and scattered broken and abraded bivalve shell fragments. Amalgamated beds near river level represent lower to middle shoreface deposits (FA2). These sandstones are overlain by poorly exposed siltstone and silty shale (4–22 m) interpreted as an offshore deposit (FA1). The offshore succession is truncated by a prominent erosion surface at 22 m and overlain by ripple cross-laminated sandstone and medium- to large-scale trough cross-stratified sandstone of the sandy fluvial sheet association (FA8). This channel-fill succession is abruptly overlain at 41 m by interbedded siltstone and hummocky cross-stratified sandstone interpreted as offshore transition deposits (distal shoreface association, FA2). Offshore transition strata are truncated once more by a prominent erosion surface at 62 m and overlain by swaley cross-stratified sandstone (facies 10) which, in turn, is truncated erosively by trough cross-stratified sandstone of the sandy fluvial sheet association (FA8). Fluvial facies are overlain by offshore transition (distal FA2) to offshore (FA1) associations that form a retro-gradational succession that continues upward into the Seabee Formation. We place the Nanushuk–Seabee contact at the top of the highest resistant sandstone several meters above the second fluvial channel-fill association.

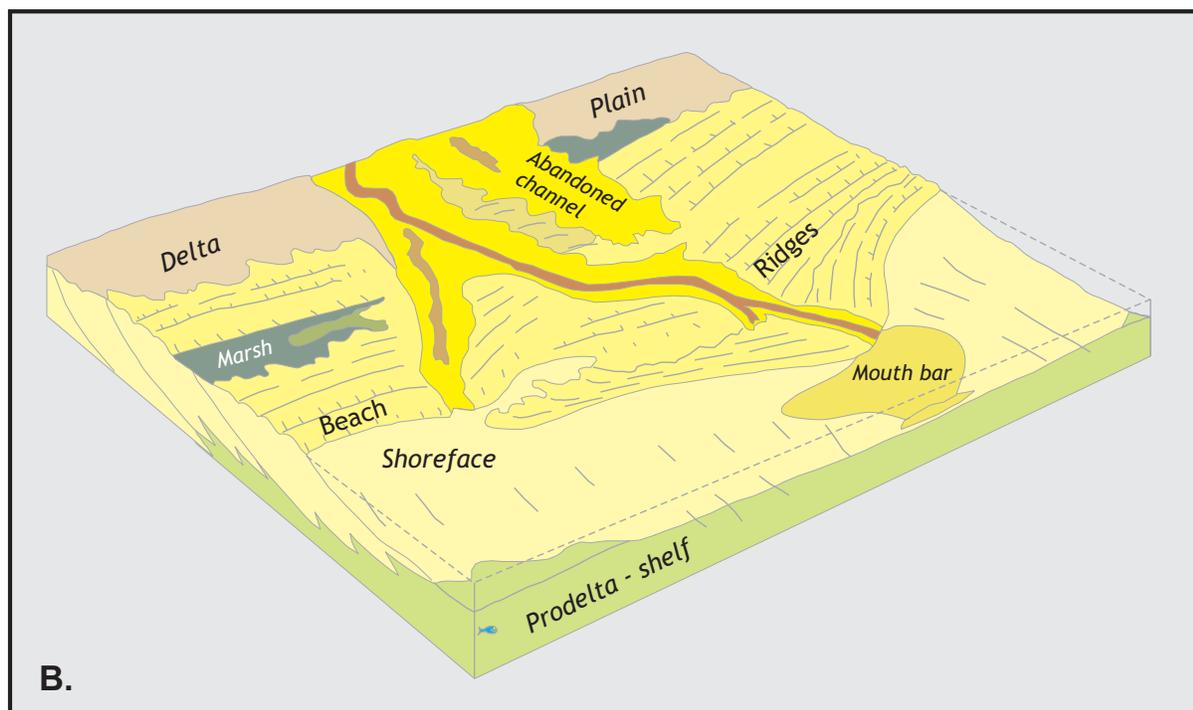
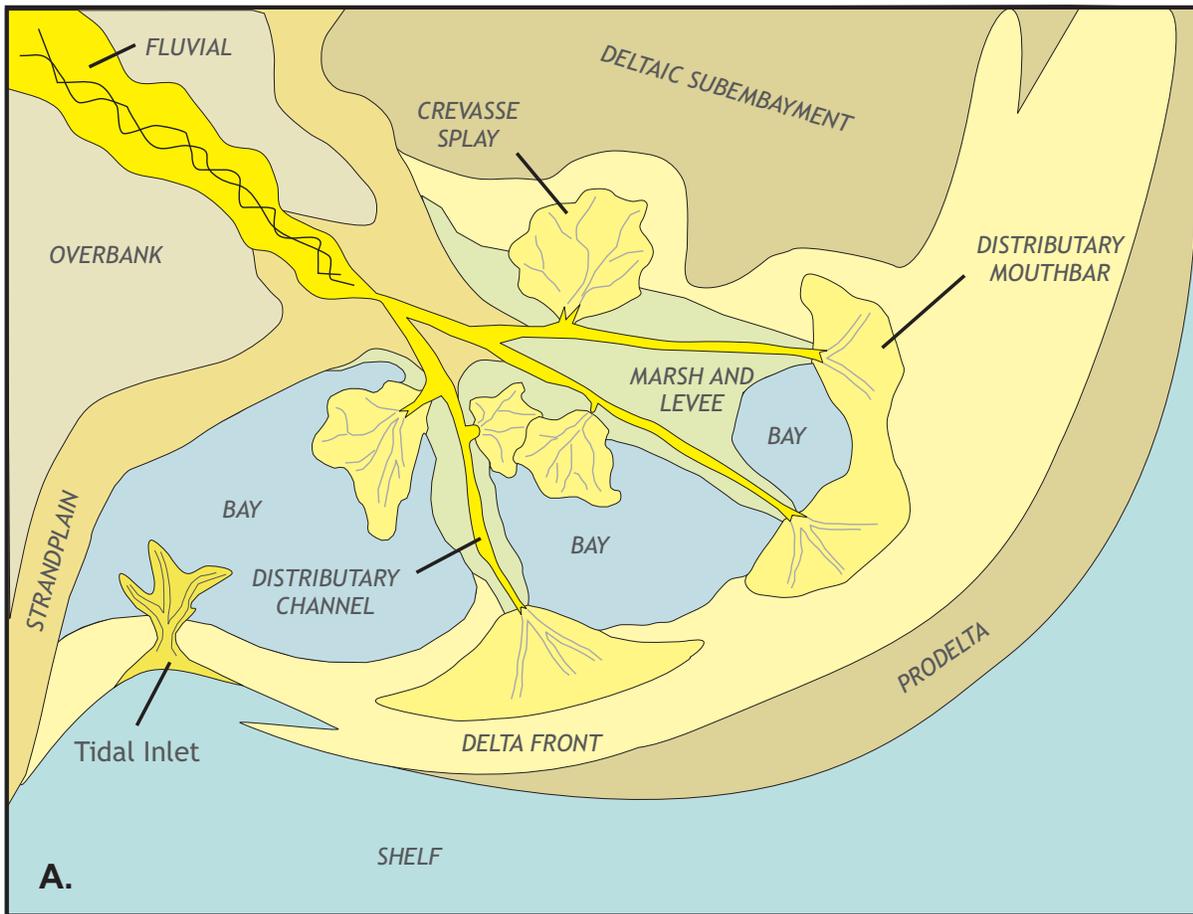
## DEPOSITIONAL SYSTEMS

Fisher and others (1969, p. 69–70) were first to interpret the Nanushuk as the product of a deltaic depositional system. They noted similarities between the Nanushuk and high-constructive (river-dominated) delta systems recognized in Tertiary and Cretaceous strata of the gulf coast and western interior basin, respectively. Ahlbrandt and others (1979) and Huffman and others (1985; 1988) examined the Nanushuk across the east–west extent of its outcrop belt and provided the first detailed facies-based interpretation of the unit. They documented the mud-rich

nature of the Nanushuk in the western foothills (west of 157th meridian, fig. 5)—their Corwin delta complex—by showing that net sand rarely exceeds 25 percent (only near the Chukchi Sea coast), that delta-front sand bodies are thin (<10 m) and do not stack to form multiple sandier-upward successions, and that nonmarine channel and crevasse-splay sandstones are present as isolated sand bodies (presumably encased in marginal-marine and nonmarine mudstones). These characteristics led to the conclusion that the Corwin delta complex was made up of muddy elongate, river-dominated delta lobes fed by muddy, meandering rivers (Huffman and others, 1985; 1988; Molenaar, 1985). In contrast, the Umiat and Marmot delta complexes in the central North Slope are coarser grained and include thick delta-front sand sheets that stack to form much thicker delta-front successions (Huffman and others, 1985; 1988). These characteristics were interpreted to indicate that the eastern deltas were wave-modified lobate deltas (Huffman and others, 1985) and wave-dominated deltas (Huffman and others, 1988).

Our data suggest that Nanushuk deltas in the eastern foothills region ranged from wave-modified to wave-dominated (fig. 15) and the suite of sedimentary structures recognized indicates that storm waves were a significant agent in shaping the middle Albian to late Cenomanian shorezone across the south-central North Slope. Throughout the eastern third of the Nanushuk outcrop belt, mudstones of the offshore–prodelta facies association (FA1) grade upsection to sandstones with abundant storm-generated sedimentary structures. In distal settings offshore–prodelta deposits grade upsection to interbedded mudstone and very-fine- to fine-grained bioturbated hummocky cross-stratified sandstone. In more proximal settings the offshore–prodelta association is thin to absent and interbedded mudstone and hummocky cross-stratified sandstone grade upsection to amalgamated hummocky and swaley cross-stratified sandstone. In the most proximal settings, the interbedded mudstone–sandstone facies is absent and sandstones of the storm-dominated shoreface association amalgamate to form thick, composite sand bodies (amalgamated parasequences) with cryptic erosion surfaces separating successive shoreface associations.

The key observation in our study is the ubiquitous presence of storm-generated sedimentary structures (wavy lamination, HCS, SCS, and pebble lags and associated scour surfaces, and abundant symmetrical wave-ripple bedforms capping tempestite beds) throughout much of the thickness of Nanushuk shorezone deposits. The abundance and stratigraphic distribution of storm-generated sedimentary structures throughout the lower and upper marine parts of the Nanushuk attest to the frequency with which storms influenced the middle Albian to late Cenomanian shoreline.



In addition to abundant storm-generated sedimentary structures, Nanushuk storm-dominated shoreface successions display other important related characteristics. The sandy upper part of most shoreface associations tend to be thick (>15–20 m); this is attributed to high sediment supply from distributary channels and efficient reworking of coarse sediment along high-energy shorefaces flanking distributary channel mouths. The sandy upper beds of most shoreface associations lack interbedded mudstone, other than thin partings between sandstone beds in more distal settings. This was due to constant agitation by shoaling waves, which were effective at winnowing most fine-grained material. Distributary channel and associated mouth-bar deposits are present locally, but represent a relatively minor component of Nanushuk deltaic successions in this region. Where distributary channel and/or mouth-bar deposits have been recognized they are invariably very close to, or at the top of, the marine successions and are typically overlain

by transitional marine–nonmarine facies. These characteristics are consistent with deposition in deltas that were significantly modified by waves (Bhattacharya and Walker, 1991; Bhattacharya, 2006). Ryer and Anderson (2002) documented similar shoreface stacking patterns in the Ferron Sandstone in Utah. They showed that wave-dominated and wave-modified deltaic successions in the Ferron lack mudstone in proximal settings and that mudstone interbeds are common throughout Ferron river-dominated deltas.

Tidal currents affected the Nanushuk coastline but were not a dominant control on depositional patterns and products. Herringbone cross-stratification, sigmoidal cross-stratification, and large-scale planar cross-stratification (all included in facies 15 and 16) occur in vertical successions underlain by prominent scour surfaces that collectively suggest deposition in tidal inlets (FA4) that cut down into underlying facies associations. The tidal inlet facies association has been recognized at three locations (Kanayut River, 272–306 m; Tuktu Bluff, 217.7–220 m and 365–375 m; North Tuktu Bluff, 58.7 m to top of section at 67 m) and always near the top of the marine succession in the lower part of the Nanushuk. This association demonstrates that tidal currents affected the Nanushuk shoreline but were not significant in shaping regional depositional patterns; this was probably a result of the open coastline morphology.

In distal settings the offshore–prodelta facies association (FA1) forms the base of parasequences and commonly includes thin beds of very-fine- to fine-grained sandstone with the characteristics of turbidites. These sandstones were deposited by turbidity currents that originated as density underflows (hyperpycnal flows) at the seaward termination of distributary channels. Many of the storms that affected the Nanushuk coastline likely also resulted in significant precipitation in the fluvial hinterland. These events could have generated flood conditions in at least some parts of the catchment area feeding the coastline. Mulder and Syvitski (1995) analyzed average discharge, average sediment concentration, and discharge during flood events for 150 modern rivers around the world and showed convincingly that large rivers are incapable of producing hyperpycnal flows, whereas many small to moderate rivers are capable of generating density underflows with geologically brief recurrence intervals (<10,000 years) and that rivers in this size range classified as moderately dirty to moderately clean are capable of generating this type of flow with very brief recurrence intervals (<1,000 years). Considering the smaller catchment areas thought to be typical of Nanushuk fluvial systems in the eastern foothills, we suggest that hyperpycnal flows were relatively common along certain stretches of the coast, particularly in the vicinity of present-day Marmot syncline, where thin-bedded turbidites are a prominent (not volumetrically abundant) component of the offshore–prodelta association.

Figure 15. Block diagrams summarizing delta style inferred from facies and facies associations recognized in the Nanushuk from the south-central North Slope. **A.** Wave-modified lobate delta similar to the modern Danube, Po, and Rhone deltas. Waves were responsible for reworking distributary mouth-bar sands into a relatively continuous delta-front sand body. Distributary mouth-bar and associated channels are relatively rare features in the delta-front setting in this type of delta. This sand body resembles a shoreface sand in most respects. Diagram modified from Huffman and others (1985). **B.** Wave-dominated cusped delta similar to the modern Grijalva delta. Strong waves are responsible for completely reworking distributary mouth-bar sediments and transporting sand via longshore currents to feed strike-elongate shoreface–beach ridge complexes. Most cusped wave-dominated deltas are fed by a single stable distributary channel. In the rock record for this type of delta, distributary channel fills should make up a relatively minor component of the overall deltaic wedge. Diagram modified from Weise (1980). Marine facies associations recognized in the Nanushuk in the study area include abundant examples of HCS, SCS, and lower energy wave-formed structures (for example, symmetrical and asymmetrical wave-ripple bedforms) throughout a significant stratigraphic thickness to suggest that deltas in this part of the outcrop belt were wave modified to strongly wave modified and probably resembled in plan-view the modern Danube, Po, and Rhone deltas. At any given time during Nanushuk deposition, the coastline was probably characterized by actively prograding delta lobes separated by interdeltaic embayments, or bights, and delta lobes that had been abandoned and were in the process of having their uppermost beds reworked by marine processes to form top-truncated delta lobes. The Nanushuk in the vicinity of Rooftop Ridge includes deposits of wave-dominated deltas similar to fig. 15B.

Bhattacharya and Walker (1991) noted that storm- and wave-dominated deltaic successions typically consist of a series of prograding shoreface and beach-ridge complexes that were fed sand from a nearby river. They added that one vertical succession of this type indicates only a prograding wave- or storm-dominated shoreface and that good three-dimensional control is required to positively identify a succession as a delta. Weise (1980) and Bhattacharya and Walker (1991) worked in areas with limited outcrop control but were able to draw from extensive subsurface datasets in southwestern Texas and northern Alberta, respectively, that included modern wireline logs and core. With their respective datasets they were able to delineate facies and map sandbody geometries in three dimensions, and thereby make robust interpretations of delta type (for example, river-dominated, wave-influenced, and wave-dominated). Bhattacharya and Walker (1991) demonstrated the link between wave-dominated delta-front and shoreface facies associations. Our study relied exclusively on outcrop control and facies to interpret delta type. Available well control is sparse at best. Given the suite of storm-generated sedimentary structures recognized in Nanushuk shorezone successions, it is reasonable to infer that Nanushuk wave-influenced and wave-dominated deltas in the eastern foothills had lobate to cusped plan-form morphologies, respectively. That some stretches of the coastline had more characteristics of strandplains than deltas is consistent with our data from Rooftop Ridge where the Nanushuk consists almost entirely of 500+ m of stacked shoreface successions, with no hint of alluvial material.

Transitional marine–nonmarine deposits in the lower Nanushuk of the eastern foothills are thin (<100 m) and the change upsection from marine to nonmarine facies tends to be one way—toward increasingly nonmarine facies. This contrasts sharply with transitional beds in the Nanushuk farther west along the Colville River north of Ivotuk where interbedded marine, marginal-marine, and nonmarine facies make up successions several hundred meters thick (LePain and others, 2008). This suggests a fundamentally different control, or controls, on Nanushuk deposition in the east. This difference may be related to deposition at different locations in the foreland basin—the study area addressed in this paper corresponds to locations well south of the northern hingeline of the foredeep, where accommodation would have been greater compared to exposures farther west that record deposition closer to the northern hingeline where accommodation would have been less (D. Houseknecht, oral commun.).

The fluvial systems that supplied sediment to the Nanushuk coastline in the east consisted of bedload to mixed-load streams. Our data from Marmot syncline and Arc Mountain show relatively coarse-grained sandstone

and conglomerate bodies 5–15 m thick encased in much thicker, poorly exposed alluvial mudstone successions. Sediments comprising these bodies form sheetlike and lenticular masses of conglomerate, pebbly sandstone, and sandstone, and are interpreted to record deposition in gravelly and sandy low- to moderate-sinuosity braided fluvial channels. At Arc Mountain the fluvial succession coarsens slightly upsection toward the north flank of the east–west-trending syncline immediately south of Arc Mountain anticline, suggesting that an overall progradational motif continued through the preserved thickness of nonmarine strata. These mudstone-encased fluvial sandstone and conglomerate bodies form a very prominent succession in the foothills south of Arc Mountain anticline where, when viewed from the air, they form a succession of partially overlapping, shingle-like bodies (ledges) separated by tundra-covered alluvial mudstone successions (figs. 8P and 12). Along the west end of Arc Mountain anticline, near the Kanayut River, Finzel (2004) interpreted a thick succession of pebble conglomerate and minor sandstone as the product of a braided fluvial system where deposition took place contemporaneous with a growing fold structure (Arc Mountain anticline). Ledges of resistant fluvial strata are also prominent immediately east of the Kanayut River, where they likely form the westerly continuation of the same syncline recognized east of the Nanushuk River, immediately south of Arc Mountain anticline.

The nonmarine succession south of Arc Mountain anticline is at least 400 m thick, and it pinches out between the south and north flanks of the structure, a distance of less than 5 km. This northward transition from relatively thick and coarse-grained nonmarine facies to marine and marginal-marine successions over relatively short distances is a common theme in the Nanushuk in the southern part of the outcrop belt between the Trans-Alaska Pipeline corridor on the east and the Chandler River on the west. A simple hydraulic explanation may help account for this abrupt transition. Orton and Reading (1993) note that many coarse-grained fluvial systems lose their gravelly bedload over very short distances as rivers descend from their alluvial valley to the delta plain. This transition usually corresponds to a decrease in channel gradients and bifurcation of relatively few channels to relatively many channels. This results in an abrupt decrease in flow competence and deposition of the coarser bedload. We suggest that Orton and Reading's observation may help explain the abrupt northward pinchout in nonmarine Nanushuk facies.

The relatively coarse nature of the fluvial sediment bodies is consistent with the sandy nature of the shorezone depositional systems—sand-rich, wave-influenced, and wave-dominated deltas and associated strandplains. Orton and Reading (1993) link the characteristics of the fluvial feeder systems to the characteristics of the coeval

shorezone depositional systems. Their research shows a strong grain size control on the character of coeval shorezone depositional systems.

Molenaar (1985) noted several factors that potentially influenced the character of the eastern Nanushuk deltas, including the presence of quartzose rocks exposed to erosion in the ancestral Brooks Range (Kanayut Conglomerate in the Endicott Mountains allochthon) to the south and the likelihood that Nanushuk fluvial systems in the central foothills had relatively steep gradients that fed much coarser sediment to delta lobes at the coast. Molenaar (1985, 1988) speculated that by the time the eastern deltas began to prograde northward, the western deltas had nearly over-topped the Barrow arch and, possibly through subsidence of the arch, its silling effect had been eliminated, thereby allowing wave energy from the open ocean to the north to buffet the Nanushuk shoreline in the east. The western Nanushuk system (Corwin delta complex) had also filled much of the deep accommodation in the basin to the east. The foredeep wedge of Houseknecht and Schenk (2001) is thought to represent the infill of this deep accommodation. This wedge provided the foundation over which southern-sourced Nanushuk deltas in the study area were able to prograde into a basin with relatively high wave energy.

## **SEQUENCE STRATIGRAPHY OF THE NANUSHUK FORMATION**

### **PREVIOUS SEQUENCE**

#### **STRATIGRAPHIC INTERPRETATIONS**

McMillen (1991) applied sequence stratigraphic concepts to the Torok and Nanushuk in the eastern NPRA, where he recognized several third- and fourth-order seismic-scale unconformity-bounded sequences and associated lowstand and highstand systems tracts. He noted that unconformities involving Nanushuk topsets were only recognizable through overlap seismic geometries, and unconformities internal to the Nanushuk were not resolvable on available two-dimensional seismic data. McMillen identified lowstand fans in the Torok that were sand rich and had no equivalent shelf deposits, implying shelf bypassing and the existence of unconformities in topset strata some distance updip. He also identified highstand fans that were mud rich and could be traced up depositional dip to coeval shelf strata, and that some highstand systems tracts were characterized by both aggradational and progradational geometries, and others by only progradational geometries.

Houseknecht and Schenk (2001) interpreted a regional grid of two-dimensional seismic data covering the NPRA, an area with sparse outcrop and well control, situated north and northwest of the outcrop belt addressed

in this report. They identified broadly defined seismic sequences that formed repetitive motifs. Their seismic sequences consist of four components including a basal regressive package deposited during times of falling relative sea level, a transgressive package deposited during times of rising relative sea level, an aggradational package deposited during times when relative sea level rise was nearly balanced by sediment supply, and a progradational package deposited during times when sediment supply outpaced relative sea level rise. These packages were equated to lowstand, transgressive, and highstand systems tracts (LST, TST, and HST, respectively). The aggradational and progradational packages are interpreted as early and late HST deposits, respectively. Their LST deposits are equivalent to McMillen's (1991) LSTs, and their breakdown of the HST into aggradational and progradational packages is similar to McMillen's aggradational-progradational and progradational division of highstand deposits. The character of systems tracts in the southern NPRA led to the conclusion that the rate of tectonic subsidence (accommodation) was so large that the foredeep may have been an area of nearly continuous sedimentation (zone B of Posamentier and Allen, 1993) and that significant fluvial incision on the shelf may have been unusual (Houseknecht and Schenk, 2001, p. 193). This observation is consistent with our outcrop data (LePain and others, 2004) and is discussed further in the following paragraphs.

Work in the outcrop belt has been limited and much more localized. Schenk and Bird (1993) recognized two unconformities in the Nanushuk at Marmot syncline (fig. 3), including one near the base of dominantly non-marine strata (Killik Tongue of former usage) and one at the top of dominantly nonmarine strata (Killik Tongue-Ninuluk Formation contact of former usage). Myers and others (1995) identified three sequence-bounding unconformities at the same location; using two-dimensional seismic data, they attempted to tie the Marmot syncline exposure to the Forest Lupine #1 well 40 km to the north. They noted a low-angle, ramp-like profile for the southern margin of the Colville basin during Nanushuk deposition in this area. This contrasts sharply with the prominent shelf-slope break recognized in similar-age strata to the west, where seismic data clearly show topset-clinoform-bottomset geometries and shelf-to-basin relief of 4,000–5,000 ft (1,220–1,525 m) (compacted; Houseknecht and Schenk, 2001). Phillips and others (1990) recognized an unconformity in lower(?) Cenomanian strata of the uppermost Nanushuk. More recently, Houseknecht and Schenk (2005) identified an upward-deepening estuarine facies succession capped by an abrupt flooding surface at the top of the Nanushuk at Umiat Mountain that they assigned to the base of the transgressive systems tract. They also identified two candidate sequence boundaries a short distance

downsection in the nearby Umiat No. 11 well that were attributed to incision during the preceding lowstands.

All attempts to erect a sequence stratigraphic framework for the Nanushuk in outcrop, including ours, suffer from a lack of outcrop continuity and poor biostratigraphic control. The result is that direct physical tracing of significant stratal surfaces and stratigraphic packages, such as sequence boundaries, flooding surfaces, and parasequences, is not possible anywhere in the study area. This results in largely unconstrained correlations between widely spaced locations.

## PRESENT STUDY

The limitations outlined above prevent us from attempting detailed correlations between our widely spaced measured sections. In the paragraphs that follow, we present some general observations from our work and discuss in detail the sequence stratigraphy of five outcrop locations (Arc Mountain anticline, Marmot syncline, Rooftop Ridge, Ninuluk Bluff, and the Colville incision; figs. 3 and 12A and B). Simplified measured sections acquired during the course of our work are provided in Appendix A, and include tentative sequence stratigraphic interpretations.

Stacking patterns recognized in marine and marginal-marine strata of the Nanushuk Formation near the south side of its outcrop belt suggest deposition during cycles of very high to high positive accommodation, in which sediment supply was nearly always able to keep pace with, or slightly outpace, accommodation. This observation is consistent with Houseknecht and Schenk's (2001) observation that the rate of tectonic subsidence was so large that the foredeep may have been an area of nearly continuous positive accommodation and sedimentation. As a result, significant stratal surfaces such as sequence-bounding unconformities, transgressive surfaces (other than parasequence boundaries), and maximum flooding surfaces are difficult to recognize. With a few notable exceptions outlined below, our data suggest that sedimentation was nearly continuous throughout deposition of the lower marine and marginal-marine portion of the Nanushuk in the southern part of its outcrop belt.

The only known unequivocal example of an erosional subaerial unconformity (negative accommodation) is near the eastern edge of the Nanushuk outcrop belt at Marmot syncline (Slope Mountain), where a prominent irregular erosion surface can be traced along the east face of the mountain (figs. 3, 12A, and 14). This surface (187.2 m, fig. 14), which probably corresponds to Schenk and Bird's (1993) sequence boundary 5, truncates upper shoreface strata and is overlain by a thin succession of pebble conglomerate, sandstone, and siltstone interpreted as fluvial and estuarine deposits. Estuarine deposits are overlain by a poorly exposed sandy package of uncertain

affinity that may represent a lower-energy shoreface succession deposited in the protective confines of an estuary. This surface is characterized by complex relief over short lateral distances, suggesting the exposure is near the knickpoints for associated paleodrainages.

Two questionable examples of negative accommodation have been recognized along the Kanayut River (figs. 3 and 13). Two firmground surfaces (with associated *Glossifungites* ichnofacies) may each represent a period of negative accommodation that resulted in submarine erosion and exhumation (on the sea floor) of a compacted and dewatered muddy substrate (fig. 13). Firmground surfaces such as these can be associated with unconformities, but can form in other ways and all they represent with certainty are pauses in sedimentation (Pemberton and MacEachern, 1995). We tentatively interpret as compound surfaces sequence-bounding unconformities that were subsequently modified during transgression. We recognize that, given the limited exposure, it is not possible to prove this interpretation.

It is unclear whether the accommodation-dominated regime continued during deposition of the 300–600 m nonmarine cap typical of the Nanushuk in the southern part of the outcrop belt. Prominent east–west-trending ledges of nonmarine sandstone, pebbly sandstone, and pebble conglomerate form conspicuous features between the south limb of Arc Mountain anticline and the axial region of Arc Mountain syncline to the south (fig. 8P). Each resistant ledge is separated by a tundra-covered, mudstone-dominated, recessive interval interpreted as alluvial floodbasin deposits (see description of stacking patterns at Arc Mountain and discussion of depositional systems above). The resistant ledges extend along depositional strike 1.0 to ~4.0 km and form broadly lenticular lithosomes interpreted as originating in braided fluvial settings. These fluvial lenses could be the products of autocyclic processes operating within the nonmarine system. Alternatively, each lens could be bounded at its base by a subaerial unconformity recording a downward shift in fluvial base level and corresponding seaward shift in facies belts. If this interpretation is correct, these unconformities record times of negative accommodation. Analysis of nonmarine Nanushuk strata immediately east of the Kanayut River (fig. 3) suggests the possibility of deposition along the flank of a growing fold structure and the formation of local unconformities (Finzel, 2004). Brosgé and Whittington (1966, p. 524–526) alluded to syndepositional folding during deposition of the Niakogon Tongue and Ninuluk Formation (both of former usage) a short distance north of the confluence of the Ikpikpuk River and Maybe Creek.

Given available data, we tentatively interpret these fluvial lenses as unconformity bounded, and assign them to the early TST and HST, when rising base levels would

have created nonmarine accommodation. High sediment supply would have ensured that this space was quickly filled as relative sea-level rise gradually slowed and stopped. If our interpretation is correct and each lens is bounded at its base by an unconformity, the accommodation-dominated regime characteristic of the lower marine and marginal-marine Nanushuk strata during middle Albian to early late Albian time evolved to a regime characterized by pulses of positive accommodation separated by times of negative accommodation during late Albian time. Falling relative sea level (negative accommodation) resulted in exposure of the coastal plain (including the delta plain) and inner shelf to erosion and sediment bypass. We recognize that this interpretation requires a causative link between relative sea level fall or rise and the destruction or creation of alluvial accommodation in nonmarine Nanushuk strata. These locations were most likely relatively close to the coeval shorelines (few tens of kilometers at most) and modest changes in relative sea level likely would have exerted some control on fluvial equilibrium profiles (Posamentier and Allen, 1999, p. 14 and 15).

The Rooftop Ridge location includes the most complete Nanushuk succession exposed in the study area and, as a result, is viewed herein as a sequence stratigraphic reference section for the Nanushuk in the study area. Although the Nanushuk at this location is in fault contact with the underlying Torok Formation, only a minor amount of section is likely concealed (C.G. Mull, oral commun.) (fig. 3). The Nanushuk is overlain by Turonian-age clay shale of the Seabee Formation at the southwestern end of the exposure (fig. 3) and the contact is interpreted as disconformable. As outlined above, the Rooftop Ridge exposure is organized in two thick, sandier-upward successions (figs. 3 and 12B, location 7). Each succession is interpreted as a second-order sequence and each includes higher order (third-order) sequences. The lowest part of the lower second-order sequence (0 to 38 m) consists of a progradational parasequence stack that is in fault contact with the underlying Torok Formation. This progradational stack is interpreted as the late HST deposits of a basal third-order sequence in the Nanushuk—a sequence whose base is located in outer-shelf mudstones of the lowermost Nanushuk or upper Torok Formation. The overlying 200 m that makes up the rest of the lower second-order sequence is interpreted to consist of two third-order sequences. The lower third-order sequence includes a basal aggradational–progradational stack succeeded by a thinner progradational stack. The contact between these two third-order sequences is interpreted as conformable (158 m). The second third-order sequence caps the lower succession (lower second-order sequence) and includes a basal retrogradational parasequence stack (TST) that

is overlain by an aggradational–progradational stack at ~177 m (maximum flooding surface and base of HST). A sequence-bounding unconformity is tentatively identified at the base of interpreted estuarine deposits at ~238 m.

The upper second-order sequence at Rooftop Ridge consists of at least two third-order sequences. The surface at 238 m forms the base of a retrogradational package situated at the base of the lower third-order sequence. The retrogradational package culminates in a maximum flooding surface at ~275 m for both the second- and third-order sequences, and is assigned to the transgressive systems tract (TST). The maximum flooding surface is succeeded by an aggradational parasequence to weakly progradational parasequence stack (275–350 m). The aggradational and progradational successions comprise early and late parts of the HST, respectively. Swaley cross-stratified sandstone in sharp contact with underlying offshore-shelf mudstones at 350 m is tentatively assigned to the falling stage systems tract (FSST). Slightly deeper water facies immediately above are assigned to the TST, and lowstand deposits appear absent. The remaining Nanushuk strata at Rooftop Ridge include latest Albian to late Cenomanian deposits of a third-order HST. The upper progradational succession is truncated by an erosion surface at ~519 m, which, in turn, is overlain by a transgressive lag ~1 m thick. This erosion surface marks the contact between late Cenomanian strata of the Nanushuk and Turonian deposits of the Seabee Formation, and is interpreted as an unconformity that was subsequently modified during the Seabee transgression (transgressive surface of erosion). It should be noted that available age control (microfossil and macrofossil based) does not require a hiatus at this boundary (see discussion in Appendix B), and our interpreted unconformity is based solely on facies association stacking patterns.

Late Cenomanian-age Nanushuk strata exposed along the north side of the outcrop belt display stacking patterns that suggest deposition in an accommodation-limited regime. At Ninuluk Bluff and the Colville incision (figs. 3 and 12B) stacking patterns reflect an overall regional transgression interrupted by minor(?) relative sea level falls (creating negative accommodation). At least two sequences (third-order?) and part of a third are recognizable in the Nanushuk at these locations. At Ninuluk Bluff two sharp-based shoreface associations recognized in the upper 60 m of the Nanushuk are interpreted to record deposition during forced regressions (LePain and Kirkham, 2002; figs. 10C and 12B, location 1) and correspond to the FSST of Hunt and Tucker (1992). If correctly identified, these sharp-based shoreface successions each correspond to a subaerial unconformity in the updip direction. We place

an unconformity at the top of each shoreface package following the reasoning of Hunt and Tucker (1992). Both unconformities were modified during the ensuing transgressions and also represent transgressive surfaces of erosion.

Based on angular discordance between beds in the uppermost Nanushuk and lower Seabee Formations in the Chandler River region, Detterman and others (1963, p. 261 and 268) interpreted the formation contact as an angular unconformity. We agree with their interpretation that this contact is unconformable, but suggest the angular discordance visible at Ninuluk Bluff (their fig. 43) could be the result of flexural slip on the south limb of the Little Twist anticline. We should point out our placement of the Nanushuk–Seabee contact in this exposure is different than Detterman and others' placement. Based on facies association stacking patterns, we place the contact (unconformity) at the base of the slightly darker colored interbedded sandstone–shale package immediately to the left of the dashed line in their figure 43—the dashed line marks their placement of the contact.

At the Colville incision the uppermost 60–70 m of Nanushuk is exposed beneath poorly exposed bentonitic clay shales of the Seabee Formation and includes two incised valley-fill fluvial successions (fig. 12B, location 2). These valley fills represent LST to early TST deposits. The unconformity at the top of the highest FSST at Ninuluk Bluff (Nanushuk–Seabee contact) is tentatively correlated with the unconformity at the base of the highest incised valley-fill fluvial succession at the Colville incision (fig. 12B, location 2, 63 m level in the western column). The valley-fill deposits above this surface, comprising the LST and early TST, are inferred to pinch out between this location and Ninuluk Bluff and above older Nanushuk deposits to the south. Valley-fill deposits are bounded above by a transgressive surface that corresponds to the Nanushuk–Seabee contact. This flooding surface merges with the unconformity at the top of the FSST (and top of Nanushuk) at Ninuluk Bluff and at the top of the Nanushuk at Rooftop Ridge. As previously noted for the Nanushuk–Seabee contact at Rooftop Ridge, available age control does not require a hiatus at this boundary (see discussion in Appendix B), and our interpreted unconformity is based solely on facies criteria.

The uppermost Nanushuk (late Cenomanian) at the two Colville River locations clearly records periods of positive and negative accommodation and contrasts sharply with older (Albian) Nanushuk marine strata to the south, where sequence-bounding unconformities are relatively rare or difficult to recognize because of nearly continuous positive accommodation. Periods of negative accommodation on the scale recognized in outcrop at these two locations (third order?) may be visible on regional seismic lines by toplap relations between slope

and shelf facies and, possibly, by a downward trajectory recognized in shoreface and delta-front facies associations in outer shelf positions. It is important to restate that these examples of negative accommodation are situated in late Cenomanian strata, and correspond to a time when Nanushuk depositional systems were undergoing a slow process of flooding and shutdown due presumably to a combination of relative sea level rise and gradual reduction in sediment supply that affected the eastern half of the Colville basin. This regional transgression was interrupted several times by relative sea level falls to create the stratal pattern recognized in the Cenomanian part of the Nanushuk Formation.

Poor outcrop continuity and limited biostratigraphic control preclude detailed correlations across the outcrop belt (figs. 12A and B). Adding to this challenge is the fact that deltaic depositional systems are complex and made up of depositional elements that are laterally discontinuous by nature. Individual delta lobes have finite strike and dip extents (figs. 6 and 15). While a delta lobe progrades in one area, laterally adjacent areas likely include abandoned lobes that are experiencing relative sea-level rise and transgression as lobes gradually subside from compaction of an underlying muddy sediment column (for example, Coleman and Gagliano, 1964; Penland and others, 1988). Correlation in this depositional setting at the scale of individual delta lobes would require laterally continuous outcrop and a great deal more subsurface data than are presently available.

## **CONTROLS ON FACIES STACKING PATTERNS AND SEQUENCE DEVELOPMENT**

Tectonics, autocyclicality, eustatic sea-level fluctuations, and climate are mechanisms that likely influenced depositional patterns in the Torok and Nanushuk Formations. Their relative influence is difficult to evaluate and no conclusive links have been found in this study. It seems clear that tectonics controlled formation-scale depositional patterns in the Torok and Nanushuk Formations. Mid-Cretaceous regional uplift and associated denudation resulted in a flood of siliciclastic sediment entering the foreland basin from the orogen to the south (Vogl and others, 2002) and, as such, is a first-order control on deposition of these units. Included in this phase of exhumation is an episode of normal faulting on the south side of the Brooks Range inferred from structural and thermochronologic data (Miller and Hudson, 1991; Blythe and others, 1996). This tectonic event contributed to at least two second-order depositional cycles (lower Torok–Fortress Mountain and upper Torok–Nanushuk).

Other than this well-documented orogen-wide event and associated progressive denudation, tectonic events in the fold and thrust belt, eustatic sea level fluctuations,

climate, and autocyclicality may each have exerted some control on Nanushuk depositional patterns. We suggest load-induced compaction and autocyclicality, including delta lobe switching, were significant factors controlling stratal patterns in the Nanushuk along the south side of its outcrop belt. We further suggest that eustatic sea-level fluctuations influenced stratal patterns in the Nanushuk during Cenomanian time (see Sahagian and Jones, 1993). Much additional work is required to adequately address the relative significance of these mechanisms.

## CONCLUSIONS

We have conducted a detailed facies analysis of marine and associated strata in the Nanushuk Formation throughout the eastern third of its outcrop belt in the south-central North Slope. Twenty facies have been recognized that combine to form ten facies associations: offshore-prodelta (FA1), storm-dominated shoreface (FA2), distributary channel (FA3), tidal inlet (FA4), bayfill-estuarine (FA5), crevasse channel (FA6), crevasse splay (FA7), sandy fluvial sheet (FA8), conglomeratic fluvial sheet (FA9), and alluvial floodbasin (FA10). The ubiquitous presence of hummocky and swaley cross-stratification in marine sandstones of the Nanushuk suggests deposition in storm-wave-modified to storm-wave-dominated settings. Facies in the marine portion of the Nanushuk stack to form conspicuous sandier-upward cycles, or parasequences that are nearly indistinguishable in most physical characteristics from prograding high-energy shoreface successions (Walker and Plint, 1992). These observations, combined with the presence of thick nonmarine fluvial and overbank successions above marine facies associations, suggest that sandier-upward marine successions preserved in the eastern third of the Nanushuk outcrop belt record deposition in storm-wave-modified to storm-wave-dominated deltas and associated settings (for example, shoreface).

Facies stacking patterns in the lower marine part of the Nanushuk along the south side of its outcrop belt suggest deposition in an accommodation-dominated setting (zone B of Posamentier and Allen, 1993). In this area, high sediment supply and continuous positive accommodation resulted in nearly continuous deposition, and erosional sequence boundaries are rare. Stacking patterns in the upper, nonmarine part of the outcrop belt, and of intertonguing marine and nonmarine strata in the upper Nanushuk (Cenomanian) along the northern edge of the outcrop belt, suggest a change upsection to an accommodation-limited setting in which brief periods of negative accommodation resulted in formation of erosional sequence boundaries.

Paradoxically, the accommodation-limited setting during the last episodes of Nanushuk deposition (Cenomanian) corresponds to a period when the sea

was gradually encroaching on the coastal plain and drowning nonmarine Nanushuk dispersal systems in a regional transgression. Recognition of erosional sequence boundaries in this part of the Nanushuk indicates that the regional transgression that gradually terminated deposition was interrupted by minor(?) relative sea-level falls (negative accommodation). During these times at least part of the Nanushuk shelf would have been exposed to subaerial erosion, increasing the probability that sand was transported to the shelf edge and beyond.

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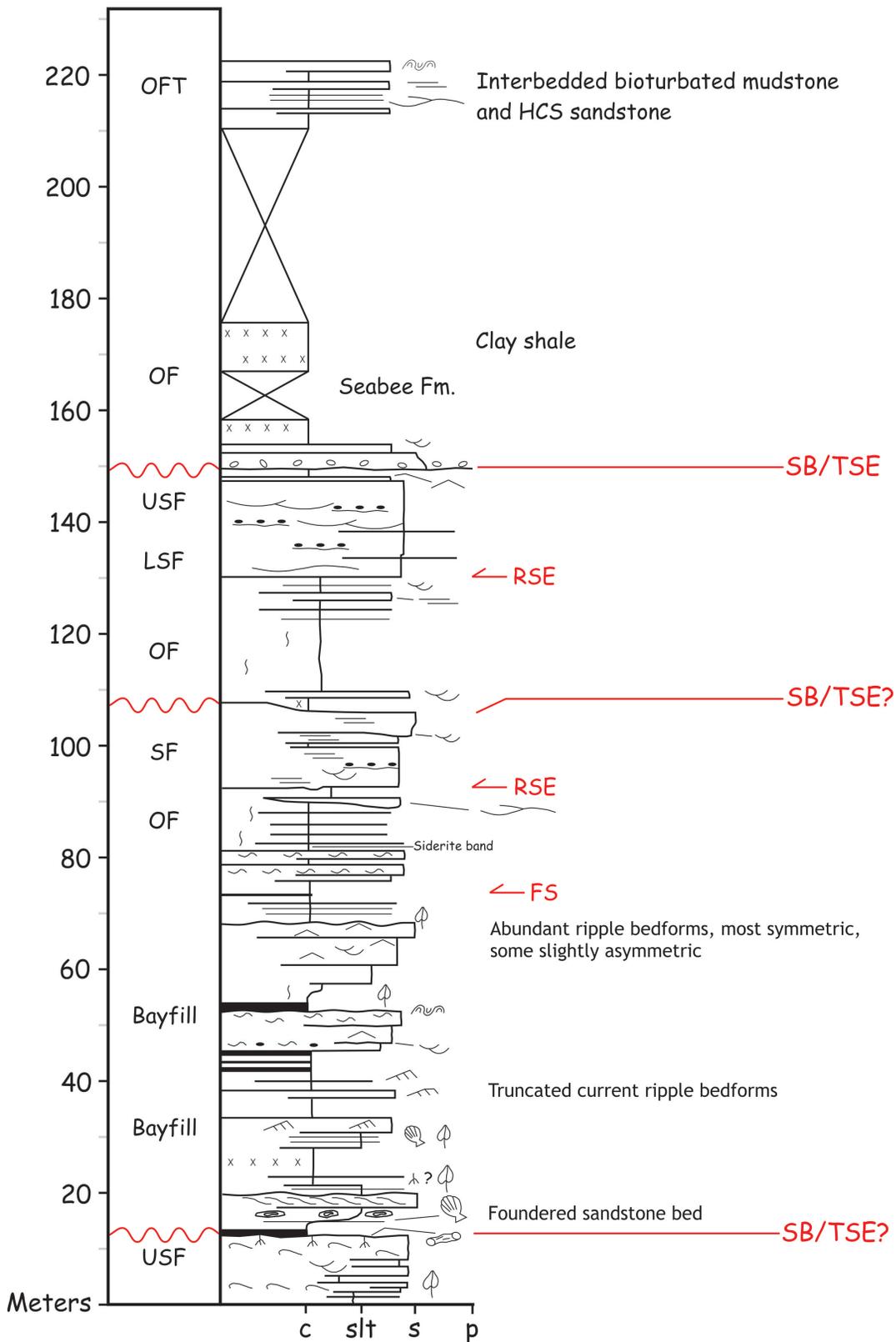
**APPENDIX A**  
**MEASURED STRATIGRAPHIC SECTIONS**

Table A1. Location Information for Measured Sections

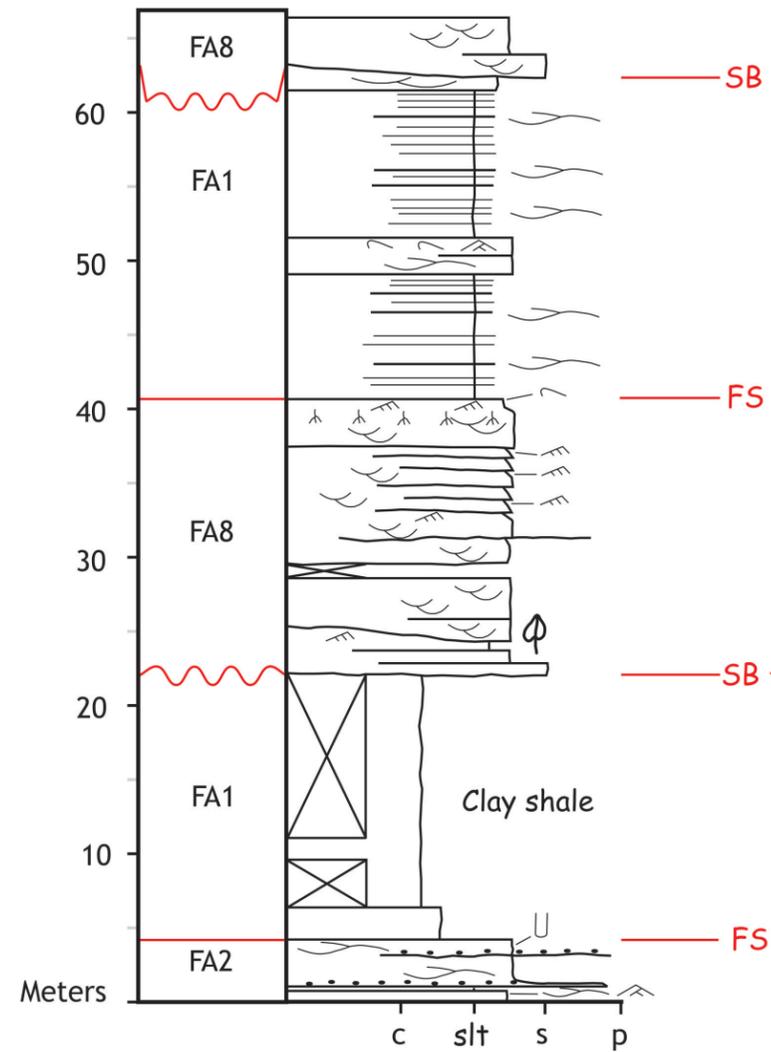
Location Number <sup>a</sup>	Location Name	Latitude <sup>b</sup>	Longitude <sup>b</sup>	Comments
1	Ninuluk Bluff	69.1288	153.2850	Section extends southwest (upstream) from the base, along the south bank of the Colville River. Base of measured section does not correspond to the base of the exposure.
2	Colville Incision West Colville Incision	69.2735 69.2724	152.5765 152.5883	Colville incision is at the east end of long exposure on the north side of the Colville River. West Colville incision is ~0.75 km west of Colville Incision. Both sections extend north from base, up slope.
3	Tuktu Bluff North Tuktu Bluff	68.73105 68.74787	152.28998 152.30415	Coordinates for base of Tuktu Bluff and North Tuktu Bluff sections. Tuktu Bluff section extends north, upslope from base. North Tuktu Bluff section extends west from west side of Chandler River at river level.
4	Big Bend of the Chandler River	69.07747	151.93132	Scrappy exposure on the east side of the river.
5	Kanayut River	68.64613	150.90888	Section extends north from base, along the east side of the Kanayut River.
6	Arc Mountain	68.65174	150.59488	Section extends south from base, along the east side of the Nanushuk River.
7	Rooftop Ridge	68.8450	150.5507	Section extends west (upstream) from the base, along the west (north) side of the Nanushuk River. Base of Nanushuk is in thrust contact with the Torok Formation.
8	Marmot Syncline (Slope Mountain)	68.727	149.02238	Base of section is 15–20 m above the base of the exposure. Section extends upslope toward the north west.

<sup>a</sup>Location numbers in table A1 correspond to location numbers shown on figure 3.<sup>b</sup>Datum – NAD27

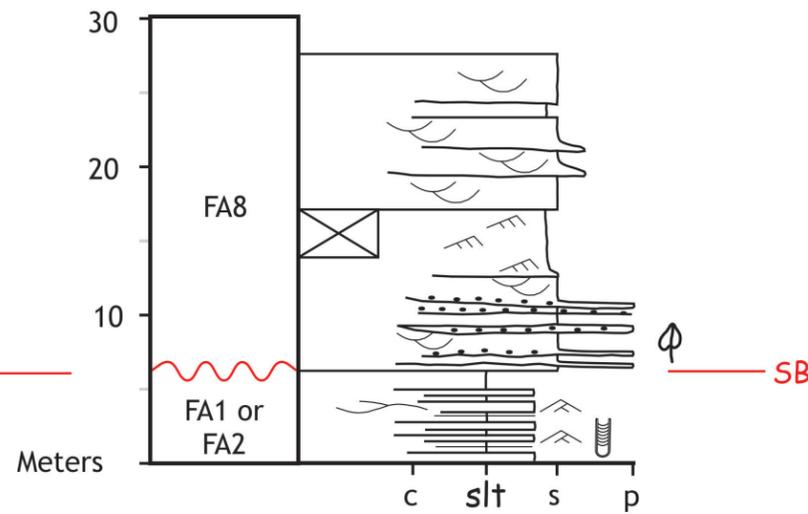
# 1 NINULUK BLUFF



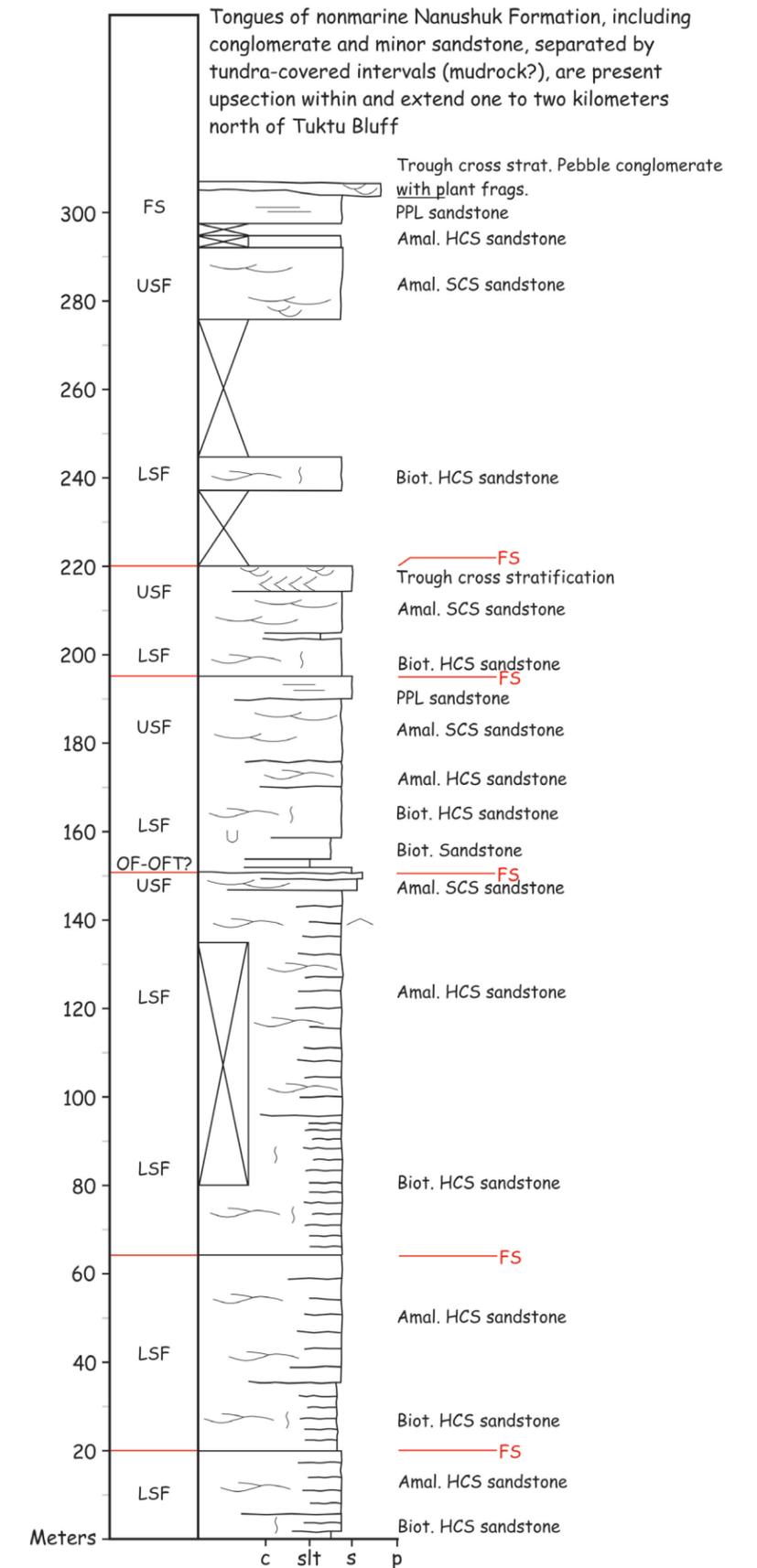
## 2 WEST COLVILLE INCISION



## 2 COLVILLE INCISION

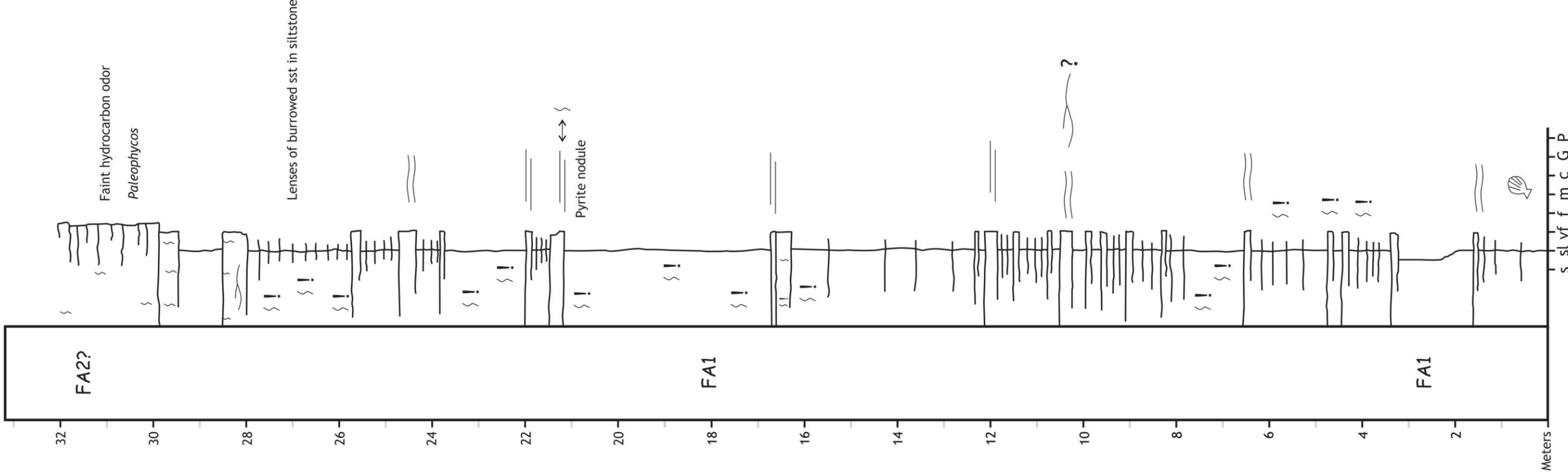
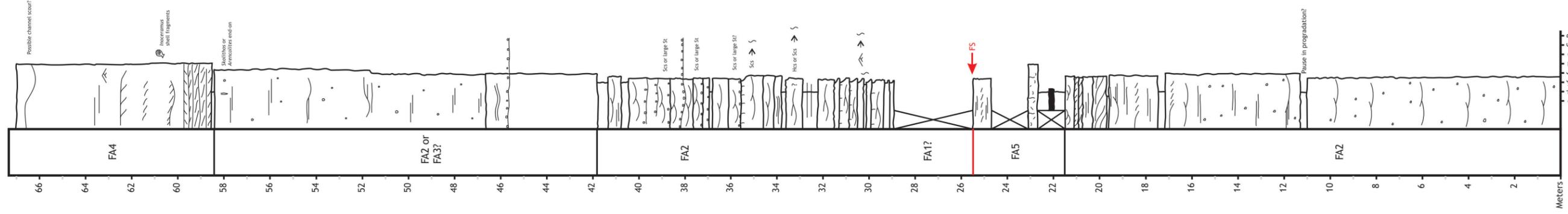


## 3 TUKTU BLUFF



### 3 NORTH TUKTU BLUFF

### 4 BIG BEND OF CHANDLER RIVER



Cover to 76m. Approximately 80 cm of orange-brown weathering, 1m sandstone crops out at 76m and from top of Nanushuk exposure on west side

Structure obscure due to difficult access

Tidal inlet?

Herringbone cross-bedding

Sparsely burrowed

Plane parallel lamination cut by low-relief scours

Plane parallel lamination

Structure obscure; massive sst. possible faint sp and scs/st; some faint quasi

Abundant siderite concretions

SCS sandstone

HCS sandstone

No coal in float

Tidal inlet - approximately 17.6 m to 2 Sigmoidal cross bedding

Beach or split?

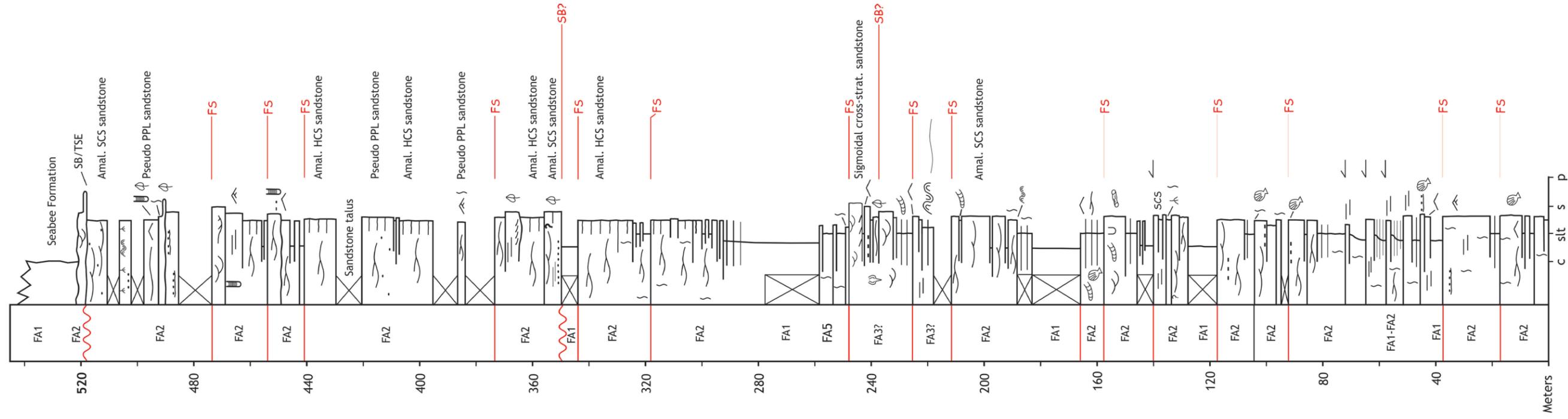
Plane-parallel laminated and SCS sandstone

Green-gray argillaceous siltstone

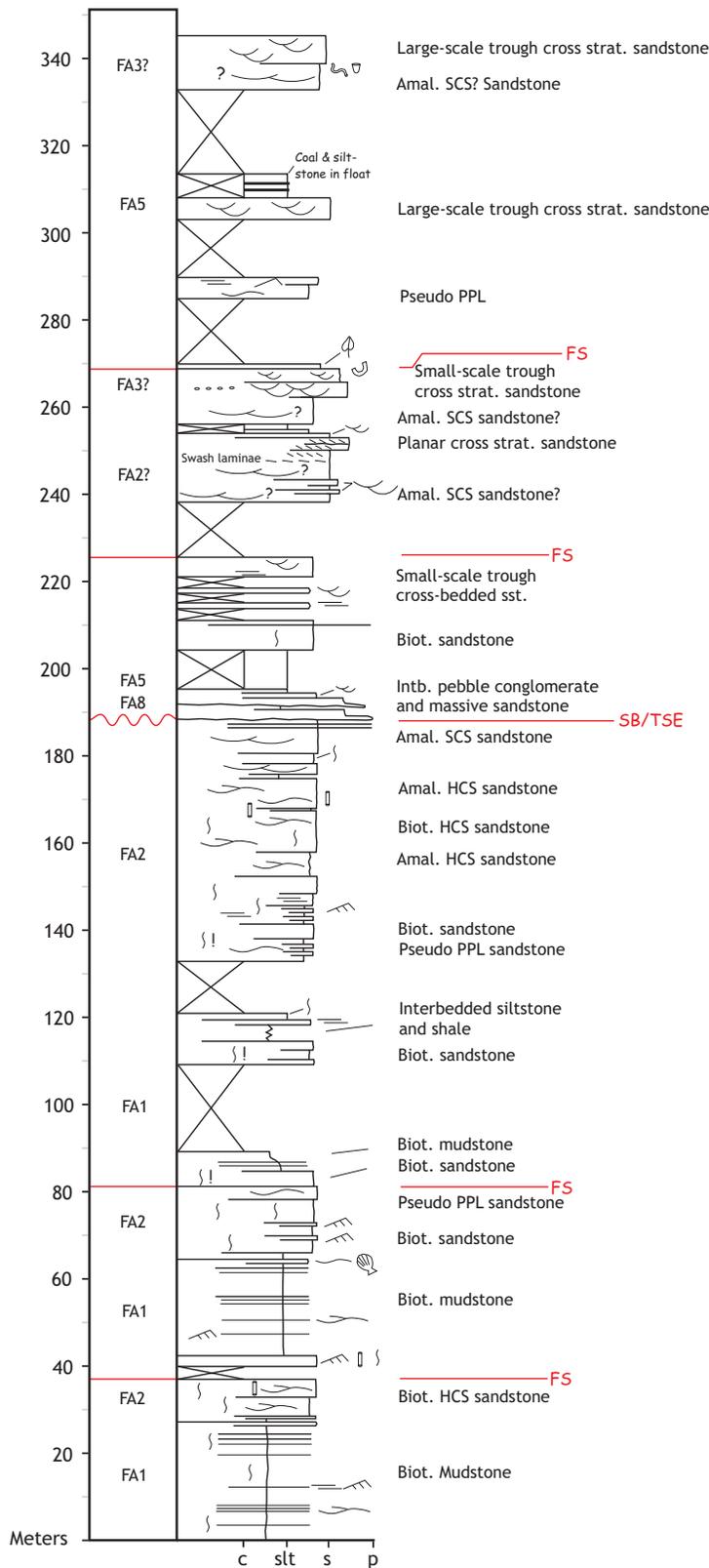
SCS sandstone



# 7 ROOFTOP RIDGE



# 8 Slope Mountain



Laterally continuous ledges of marginal-marine and nonmarine Nanushuk Formation, including conglomerate and minor sandstone separated by tundra-covered intervals (mudrock?), are present upsection toward the west. Highest Nanushuk strata preserved at this location are interpreted as marginal-marine facies above fluvial sandstones near stratigraphic top of Nanushuk Formation.

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## APPENDIX B

### BIOSTRATIGRAPHIC CONTROL

#### TUKTU BLUFF

Imlay and Reeside (1954, p. 242) and Imlay (1961) assigned a basal middle Albian age to marine Nanushuk strata exposed near the base of Tuktu Bluff at the Chandler River (Appendix A), based on the presence of two ammonite species and one Inoceramid species collected by Detterman and others (1963). Overlying nonmarine strata immediately to the north were assigned a middle Albian age by Detterman and others (1963, p. 256) based on stratigraphic position above basal middle Albian marine beds and northward intertonguing relations with marine strata (Grandstand Formation of former usage) that include specimens of *Inoceramus anglicus*. This species of Inoceramid was recovered from the Nanushuk at exposures along the Kanayut River to the east during our study and was assigned a middle to late Albian age by Will Elder (table B2, sample 01DL31-131). This not only suggests that nonmarine strata north of Tuktu Bluff are also of middle to late Albian age, but that the upper part of the marine succession near Tuktu Bluff may be as young as late Albian.

#### KANAYUT RIVER

For the reasons cited in the discussion of the Tuktu Bluff exposure, the lower marine part of the Nanushuk Formation along the Kanayut River is assigned a basal middle Albian to late Albian age (table B2, 01DL31-131). Microfossil data collected during our study confirm this age assignment and indicate the nonmarine succession at the top of the Nanushuk shown in Appendix A is of late Albian age. A single microfossil sample yielded palynomorphs of possible early to middle Cenomanian age (table B1, sample 01DL31-472.8).

#### ARC MOUNTAIN

Several marine invertebrate fossils were collected from marine strata in the lower two-thirds of the Nanushuk at Arc Mountain by Detterman and others (1963). Included in their collections are age-diagnostic ammonites and one Inoceramid. The ammonite, identified by Imlay as *Paragastropolites cf. G. kingi*, was collected between 360 m and 400 m in our measured section (Appendix A), and indicates a basal middle Albian age, while the Inoceramid, identified by Imlay as *Inoceramus anglicus*, indicates a basal middle Albian age (see discussion for Tuktu Bluff above). A specimen of *Paragastropolites flexicostatus* was collected from float. The same species was collected during our study (table B2, sample 00DL24a; collected between 240 and 280 m in the Arc Mountain section shown in Appendix A) and assigned a middle middle Albian age by Will Elder. Based on the information summarized in this section, we infer a basal middle Albian to late age marine strata in the lower two-thirds of the Nanushuk at Arc Mountain. A middle to late Albian age is also inferred for nonmarine strata at Arc Mountain based on correlation with nonmarine strata exposed along strike to the west (Kanayut River).

#### MARMOT SYNCLINE (SLOPE MOUNTAIN)

For the reasons cited in the discussion of the Tuktu Bluff exposures, the lower marine part of the Nanushuk in this area is assigned a basal middle Albian to late Albian age (table B2). Microfossil samples collected during our study indicate a middle to late Albian age for the lower marine part of the Nanushuk at Marmot syncline (table B1). Keller and others (1961) inferred a middle to late Albian age for nonmarine strata at this location and a late Cenomanian age for marine beds exposed near the axis of Marmot syncline.

#### ROOFTOP RIDGE

An ammonite specimen collected during our study 164 m above the base of the Nanushuk (table B2, 00DL22-164.3) indicates a late middle Albian age for the lower Nanushuk at this location. Detterman and others (1963) reported a specimen of the bivalve *Inoceramus anglicus* ~154 m below the top of the Nanushuk (~200 m above the ammonite) to which Imlay assigned a middle Albian age. Our microfossil-based biostratigraphic control is consistent with these age assignments. A single sample of shale collected ~40 m below the Nanushuk–Seabee contact (table B1, 99DL64-203) yielded foraminifera of Cenomanian to Turonian age, suggesting that at least the upper 40 m of the Nanushuk at this location is Cenomanian.

**NINULUK BLUFF**

U.S. Geological Survey Mesozoic location 25157 is ~8 m below the base of our measured section, from which Detterman and others (1963) collected a specimen of *Inoceramus dunveganensis*. Imlay and Reeside (1954, p. 243) infer a late Cenomanian age for this part of the Nanushuk (Ninuluk Formation of former usage) based on the presence of this pelecypod and correlation with the Dunvegan Formation in northern British Columbia. In that formation, *I. dunveganensis* is associated with the ammonite *Dunveganoceras*. All occurrences of *Dunveganoceras* in Canada, Montana, and England are in beds below the lowest ammonite zone of the Turonian. The stratigraphic position of *Dunveganoceras* was considered upper Cenomanian (Imlay and Reeside, 1954, p. 243). Jones and Gryc (1960, p. 152) interpreted *I. dunveganensis* as a late Albian to late Cenomanian species. Our macrofossil and microfossil collections do not allow refinement of this age assignment. Two tephra samples from the Nanushuk at this exposure each included biotite and potassium feldspar grains that were dated at the University of Alaska using the  $^{40}\text{Ar}/^{39}\text{Ar}$  method. Results are somewhat ambiguous, but suggest a depositional age of late Cenomanian, which is consistent with available fossil-based age control.

Table B1. Summary of palynologic and foraminifera samples tied to measured stratigraphic sections of the Nanushuk Formation in the central North Slope, Alaska.

Sample ID	Quadrangle	Location Name	Location	Latitude	Longitude	Formation	Lithology	Sample Type	Contractor	Significant Taxa	Age	Environment	TAI	Comments
99DL47B-12.0*	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Deltoidospora</i> spp., <i>Hymenozonitrites lepidophytus</i> , <i>Osmundacites</i> spp., Dinocysts: <i>Cribreridium edwardsii</i> , <i>Cyclonephelium distinctum</i> , <i>Oligosphaeridium</i> complex, <i>?Wigginsella grandstandica</i>	Probable Albian		2.3	Palynomorphs are corroded.
99DL47D-1.0	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk		Palynomorph	MCI	Barren of palynomorphs	Indeterminate		2.3 to 2.5?	Organic recovery consists of coaly material.
00DL24-22.05*	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Gleichenioides senonicus</i> , Taxodiaceae, <i>Odontochitina operculata</i>	Cretaceous undifferentiated	Marginal? Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material and common herbaceous material.
00DL24-24.63	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> sp., <i>Hymenozonitrites lepidophytus</i> , <i>Palaeoperidium cretaceum</i>	Cretaceous undifferentiated	Marginal? Marine	2.3 to 2.4	Organic recovery consists mainly of woody fusinitic material.
00DL24-24.63	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk	Slightly silty shale	Foraminifera	MCI	<i>Haplophragmoides excavatus</i> , <i>Haplophragmoides gigas</i>	Probable middle to late Albian (F-9 to F-10)	Middle shelf to upper slope		Small coaly particles and pyrite.
00DL24-31	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> sp., <i>Gleichenioides senonicus</i> , <i>Hymenozonitrites lepidophytus</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium anthophorum</i> , <i>Oligosphaeridium</i> complex, <i>Oligosphaeridium cretaceum</i> , <i>?Pseudoceratium interiorensense</i> (poorly preserved)	Possible middle-late Albian (P-M17?)	Marine	2.0 to 2.5	Organic recovery consists mainly of herbaceous material.
00DL24-98.5	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River	68.65	150.5983	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex (thick walled), <i>Palaeoperidium cretaceum</i>	Cretaceous undifferentiated	Marine	2.0 to 2.4	Organic recovery consists mainly of woody fusinitic material.
99DL64-29.7**	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> sp., <i>Deltoidospora</i> spp., <i>Gleichenioides senonicus</i> , <i>Hymenozonitrites lepidophytus</i> , <i>Osmundacites</i> sp., Dinocysts: <i>Cyclonephelium distinctum</i> , <i>Oligosphaeridium</i> complex	Cretaceous undifferentiated		2.3 to 2.5?	Organic recovery consists mainly of woody fusinitic material.
99DL64-106.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk		Palynomorph	PAZ	<i>Cooksonites</i> , <i>Dorocysta litotes</i>	Late Albian		3	
99DL64-106.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk	Micaceous shale	Foraminifera	MCI	<i>Bathysiphon vitta</i> , <i>Haplophragmoides topogorukensis</i>	Probable Albian (F-9 to F-10)			Fish debris and tar in sample.
99DL64-151.4	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites venustus</i> , <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Gleichenioides senonicus</i> , <i>Hymenozonitrites lepidophytus</i> , <i>Lycopodiumsporites</i> spp., <i>Osmundacites</i> sp., <i>Taeniaesporites</i> spp., Taxodiaceae, Dinocysts: <i>Palaeoperidium cretaceum</i>	Probable Early Cretaceous		2.3	Organic recovery consists mainly of woody fusinitic material.
99DL64-165.8	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk		Palynomorph	PAZ	<i>Cicatricosisporites venustus</i>	Early Turonian to Late Hauterivian		3	
99DL64-165.8	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk	Micaceous shale	Foraminifera	MCI	<i>Bathysiphon vitta</i>	Probable Albian (F-9 to F-10)	Inner shelf to upper slope		
99DL64-168	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> cf. <i>C. venustus</i> , <i>Hymenozonitrites lepidophytus</i> , <i>Lycopodiumsporites</i> sp., <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex	Cretaceous undifferentiated	Marine	2.5 to 3.0+	Organic recovery consists mainly of woody fusinitic material.
99DL64-168	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk	Iron-stained silty shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate	Indeterminate		
99DL64-203	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk		Palynomorph	PAZ	<i>Podocarpidites canadensis</i> , <i>Acanthotriletes varispinosus</i>	Early Campanian to Oxfordian		3	Abundant coaly and woody fragments.
99DL64-203	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk	Shale	Foraminifera	MCI	<i>Haplophragmoides bonanzaensis</i> , <i>Haplophragmoides excavatus</i> , <i>Textularia gravenori</i> , <i>Verneuilinoides fischeri</i>	Probable Cenomanian to Turonian (F-5 to F-8)	Middle shelf to upper slope		Pyrite in sample.
99DL64-244.5	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee		Palynomorph	PAZ	<i>Nycticysta lacustra</i>	Middle Albian		3- to 3	Woody fragments in sample.
99DL64-244.5	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee	Sandy siltstone	Foraminifera	MCI	<i>Haplophragmoides</i> spp., <i>Verneuilinoides fischeri</i>	Probable Cenomanian to Turonian (F-5 to F-8)	Middle shelf to upper slope		
99DL64-245.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee		Palynomorph	PAZ	<i>Neoraistrickia robusta</i>	Cenomanian to Barremian		3- to 3	Woody fragments in sample.
99DL64-245.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Deltoidospora</i> sp., <i>Gleichenioides senonicus</i> , <i>Klukisporites foveolatus</i> , <i>Laevigatosporites</i> spp., <i>Lycopodiumsporites</i> spp., <i>Neoraistrickia</i> cf. <i>N. truncata</i> , <i>Osmundacites</i> spp., Taxodiaceae, <i>Trilobosporites apiverrucatus</i> , <i>?Cleistosphaeridium</i> sp., <i>Oligosphaeridium</i> complex (thick-wall)	Aptian-Albian (P-M18 to P-M17)	Marginal marine	2.3	Organic recovery consists mainly of herbaceous and woody fusinitic material.
99DL64-245.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee	Sandy siltstone	Foraminifera	MCI	Barren of foraminifera: <i>Cenosphaera</i> spp.	Undifferentiated			Woody and minor heterogeneous amorphous organic material.
99DL64-268.8	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee		Palynomorph	PAZ	<i>Globorotundata acrita</i> , <i>Azolla</i> spp.	Cenomanian to Berriasian			
99DL64-268.8	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Seabee	Shale	Foraminifera	MCI	<i>Haplophragmoides excavatus</i> , <i>Saccamina lathrami</i> , <i>Trochammina diagonis</i> , <i>Trochammina ribstonensis</i> , <i>Trochammina rutherfordi</i> , <i>Trochammina whittingtoni</i> , <i>Verneuilinoides fischeri</i>	Cenomanian (F-8)	Outer shelf to upper slope		
00DL22-20**	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> cf. <i>C. venustus</i> , <i>Gleichenioides senonicus</i> , <i>Hymenozonitrites lepidophytus</i> , <i>Lycopodiumsporites</i> spp., <i>Osmundacites</i> spp., <i>Cribreridium edwardsii</i> , <i>Cyclonephelium distinctum</i> , <i>Luxadinium propatulum</i> , <i>Oligosphaeridium</i> complex, <i>Oligosphaeridium pulcherrimum</i> , <i>Palaeoperidium cretaceum</i> , <i>Pseudoceratium expollitum</i> , <i>Spiniferites</i> spp.	Middle-late Albian (P-M17)	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL22-159.95	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> sp., <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Gleichenioides senonicus</i> , <i>Hymenozonitrites lepidophytus</i> , Taxodiaceae, <i>Cribreridium edwardsii</i> , <i>Luxadinium propatulum</i> , <i>Oligosphaeridium anthophorum</i> , <i>Oligosphaeridium</i> complex, <i>Oligosphaeridium pulcherrimum</i> , <i>Palaeoperidium cretaceum</i> , <i>Spiniferites</i> spp.	Middle-late Albian	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.

Table B1 (cont.). Summary of palynologic and foraminifera samples tied to measured stratigraphic sections of the Nanushuk Formation in the central North Slope, Alaska.

Sample ID	Quadrangle	Location Name	Location	Latitude	Longitude	Formation	Lithology	Sample Type	Contractor	Significant Taxa	Age	Environment	TAI	Comments
00DL22-191.7	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Camarozonosporites insignis</i> , <i>Cicatricosisporites</i> spp., <i>Deltoidospora</i> spp., <i>Foveosporites</i> sp., <i>Gleicheniidites senonicus</i> , <i>Hymenozonotriletes lepidophytus</i> , <i>Osmundacidites</i> spp., Taxodiaceae, <i>Triobosporites perversulentus</i> , <i>Triobosporites</i> sp., <i>Oligosphaeridium</i> complex, <i>Palaeoperidinium cretaceum</i>	Probable Aptian-Albian	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL22-218.3	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> cf. <i>C. venustus</i> , <i>Densosporites</i> spp., <i>Hymenozonotriletes lepidophytus</i> , <i>Lycopodiumsporites</i> spp., <i>Osmundacidites</i> spp., Taxodiaceae, <i>Cyclonephelium distinctum</i> , <i>Palaeoperidinium cretaceum</i>	Probable Early Cretaceous	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic organics.
00DL22-225.8	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	PAZ	<i>Cleistosphaeridium multispinosum</i> , <i>Cedripites canadensis</i>	Late Albian to early Cenomanian		2+ to 3	Woody fragments in sample.
00DL22-225.8	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Silty shale	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Ammodiscus rotarius</i> , <i>Ditrupea cornu</i> , <i>Haplophragmoides excavatus</i> , <i>Haplophragmoides gigas</i> , <i>Haplophragmoides topogorukensis</i> , <i>Hippocrepina barksdalei</i> , <i>Trochammina mcMurrayensis</i> , <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Middle shelf to upper slope		
00DL22-250	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> cf. <i>C. venustus</i> , <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Gleicheniidites senonicus</i> , <i>Hymenozonotriletes lepidophytus</i> , <i>Cyclonephelium distinctum</i> , <i>Luxadinium propatum</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex, <i>Oligosphaeridium pulcherrimum</i> , <i>Pseudoceratium exolitum</i>	Middle-late Albian (P-M17)	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL22-250.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	PAZ	<i>Cyclonephelium</i> sp., <i>Dorocysta litotes</i>	Late Albian to early Cenomanian		2+ to 3	Woody fragments in sample.
00DL22-250.2	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Silty shale	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Haplophragmoides</i> spp., <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Middle shelf to upper slope		
00DL22-257	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> cf. <i>C. venustus</i> , <i>Densosporites</i> spp., <i>Hymenozonotriletes lepidophytus</i> , Taxodiaceae, <i>Cribooperidinium edwardsii</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex, <i>Oligosphaeridium pulcherrimum</i> , <i>Pseudoceratium retusum</i> , <i>Wigginsella grandstandica</i>	Middle-late Albian (P-M17)	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL22-257	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Iron-stained shale	Foraminifera	MCI	Arenaceous spp.	Indeterminate	Probable marine		
00DL22-291	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk		Palynomorph	PAZ	<i>Cleistosphaeridium multispinosum</i>	Hauterivian to Turonian		2+ to 3	Woody fragments in sample.
00DL22-291	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Siltstone or silty shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate			Samples collected from near base of 99DL64.
00DL16-1.0	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Aequitriradites spinulosus</i> , <i>Deltoidospora</i> spp., <i>Densosporites</i> sp., <i>Lycopodiumsporites</i> spp., <i>Osmundacidites</i> spp., <i>Podocarpidites</i> sp., Taxodiaceae, <i>Triobosporites perversulentus</i> , <i>Triporetetes reticulatus</i> , <i>Cleistosphaeridium</i> sp., <i>Gardodinium deflandrei</i> , <i>Palaeoperidinium cretaceum</i>	Early Cretaceous undifferentiated		2.0 to 2.4	Organic recovery consists mostly of herbaceous and abundant woody fusinitic material.
00DL16-1.0	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk	Micaceous shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate			Abundant small coal particles.
00DL16-30.6	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Deltoidospora</i> spp., <i>Gleicheniidites senonicus</i> , <i>Hymenozonotriletes lepidophytus</i> , Taxodiaceae, <i>Triporetetes reticulatus</i> , <i>Odontochitina operculata</i>	Cretaceous undifferentiated	Marine	2.0 to 2.5	Organic recovery consists mostly of woody fusinitic material.
00DL16-30.6	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk	Micaceous shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate			
00DL16-54.3	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Gleicheniidites senonicus</i> , Taxodiaceae, <i>Oligosphaeridium</i> sp., <i>Palaeoperidinium cretaceum</i>	Probable Aptian-Albian (P-M18 to P-M17)	Marine	2.0 to 2.3	Organic recovery consists mainly of herbaceous material.
00DL16-60 to 78.4	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Aequitriradites spinulosus</i> , <i>Cicatricosisporites</i> spp., <i>Deltoidospora</i> spp., <i>Endosporites</i> sp., <i>Foveosporites</i> sp., <i>Gleicheniidites senonicus</i> , <i>Lycopodiumsporites</i> spp., <i>Osmundacidites</i> spp., <i>Rouseisporites reticulatus</i> , <i>Sestrosporites pseudoalveolatus</i> , Taxodiaceae, <i>Oligosphaeridium</i> complex, ? <i>Palaeoperidinium cretaceum</i>	Probable Middle Cretaceous	Marginal marine	2.5	Organic recovery consists mostly of herbaceous and woody fusinitic material.
00DL16-60 to 78.4	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk	Micaceous shale	Foraminifera	MCI	<i>Haplophragmoides bonanzaensis</i> , <i>Saccamina lathrami</i> , <i>Trochammina ribstonensis</i> , <i>Trochammina rutherfordi</i> , megaspores	Latest Albian to Cenomanian (F-8 to F-9)	Probable marginal marine to inner shelf		Cenomanian based on negative evidence.
00DL16-92.8 to 93.4	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Densosporites</i> sp., <i>Gleicheniidites senonicus</i> , <i>Lycopodiumsporites</i> spp., Taxodiaceae, <i>Cleistosphaeridium</i> sp., <i>Gonyaulacysta</i> sp. G, <i>Oligosphaeridium</i> complex, <i>Palaeoperidinium cretaceum</i>	Probable Aptian-Albian (P-M18 to P-M17)	Marine	2.0 to 2.5	Palynomorphs are poorly preserved. Organic recovery consists mainly of woody fusinitic material.
00DL16-109	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> sp., <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Gleicheniidites senonicus</i> , <i>Osmundacidites</i> spp., <i>Podocarpidites</i> sp., Taxodiaceae, <i>Cleistosphaeridium</i> sp., <i>Cyclonephelium distinctum</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex				Organic recovery consists mostly of woody fusinitic material.
00DL16-109	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk	Micaceous shale	Foraminifera	MCI	<i>Haplophragmoides excavatus</i> , <i>Haplophragmoides gigas</i> , <i>Haplophragmoides kirki</i> , megaspores, ostracods	Probable middle to late Albian (F-9 to F-10)	Middle shelf to upper slope		[Reworked foraminifera from older Nanushuk strata.]
00DL16-135.3	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Convolutispora</i> sp., <i>Densosporites</i> sp., <i>Osmundacidites</i> spp., <i>Taeniaesporites</i> sp., <i>Cyclonephelium distinctum</i> , <i>Gonyaulacysta</i> sp., <i>Oligosphaeridium</i> complex (thick-wall), <i>Sentusidinium rioultii</i> , <i>Sirmiodinium grossi</i>	Probable Early Cretaceous		2.0 to 2.4	Organic recovery consists mostly of woody fusinitic material.
00DL16-135.3	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Nanushuk	Micaceous silty shale	Foraminifera	MCI	<i>Bathysiphon</i> sp., megaspores	Indeterminate	Marine		
02DL26A***	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.1247	153.2879	Seabee		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> sp., <i>Densosporites</i> spp., <i>Foveosporites</i> sp., <i>Gleicheniidites senonicus</i> , <i>Osmundacidites</i> sp., Taxodiaceae, <i>Triobosporites perversulentus</i> , <i>Cyclonephelium distinctum</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex, <i>Oligosphaeridium</i> complex (thick-wall), Tasmanaceae	Possible Aptian-Albian (P-M18?)	Marginal marine	2.3 to 2.5	Organic recovery consists mainly of woody fusinitic material with some herbaceous material. [Composite sample collected over 10 m from 00DL16-139 to 149.]

Table B1. Summary of palynologic and foraminifera samples tied to measured stratigraphic sections of the Nanushuk Formation in the central North Slope, Alaska.

Sample ID	Quadrangle	Location Name	Location	Latitude	Longitude	Formation	Lithology	Sample Type	Contractor	Significant Taxa	Age	Environment	TAI	Comments
02DL26A	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.1247	153.2879	Seabee	Slightly sandy pyritic shale	Foraminifera	MCI	<i>Cenosphaera</i> spp. (pyritized), <i>Haplophragmoides excavatus</i> , <i>Haplophragmoides topagorukensis</i> , <i>Præbulimina nannina</i> , <i>Trochammina mcmurrayensis</i> , <i>Trochammina umiatensis</i> , megaspores	Aptian-Albian (F-10 to F-11)	Outer shelf to slope		Common pyrite and rare gypsum particles. [Composite sample collected over 10 m from 00DL16-139 to 149.]
00DL16-142.5	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Seabee		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites venustus</i> , <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Osmundacidites</i> spp., <i>Podocarpidites</i> sp., Taxodiaceae, <i>Cleistosphaeridium</i> spp., <i>Cyclonephelium distinctum</i> , <i>Hystrichodinium pulchrum</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex, <i>Spiniferites</i> sp., <i>Sverdrupiella usitata</i> , <i>Veryhachium</i> sp.	Probable Early Cretaceous	Marine	2.0 to 2.4	Organic recovery consists mostly of woody fusinitic material.
00DL16-154.95	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Seabee		Palynomorph	MCI	Undifferentiated bisaccates, <i>Deltoidospora</i> spp., <i>Gleichenioidites senonicus</i> , <i>Kraeuselisporites</i> sp., <i>Lycopodiumsporites semimurus</i> , <i>Osmundacidites</i> spp., Taxodiaceae, <i>Cleistosphaeridium</i> spp., <i>Hystrichodinium pulchrum</i> , <i>Odontochitina operculata</i> , <i>sentusidinium rioultii</i> , <i>Spiniferites</i> spp.	Probable Early Cretaceous	Marine	2.3 to 2.5	Organic recovery consists mainly of amorphous and herbaceous material.
00DL16-198	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Seabee		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Foveosporites</i> sp., <i>Gleichenioidites senonicus</i> , <i>Hymenozonitretes lepidophytus</i> , <i>Osmundacidites</i> spp., Taxodiaceae, <i>Cyclonephelium distinctum</i> , <i>Gardodinium deflandrei</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex, <i>Palaeoperidinium cretaceum</i>	Cretaceous undifferentiated	Marine	2.0 to 2.5+	Organic recovery consists mainly of woody fusinitic material.
00DL16-198	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Seabee	Slightly silty micaceous shale	Foraminifera	MCI	<i>Bathysiphon</i> sp., <i>Gaudryina irenensis</i> , <i>Haplophragmoides excavatus</i> , <i>Verneuilinoides fischeri</i>	Probable Turonian to Coniacian (F-6)	Middle shelf to upper slope		
00DL16-204.7	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Seabee		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Gleichenioidites senonicus</i> , <i>Lycopodiumsporites</i> sp., <i>Osmundacidites</i> spp., Taxodiaceae, <i>Cleistosphaeridium</i> sp., <i>Deflandrea</i> sp., <i>Palaeoperidinium cretaceum</i> , <i>Sverdrupiella usitata</i>	Cretaceous undifferentiated	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL16-204.7	Ikpikuk River A-1	Ninuluk Bluff	South bank Colville River, southwest end of Ninuluk Bluff	69.128	153.2887	Seabee	Micaceous siltstone or silty shale	Foraminifera	MCI	<i>Saccammina lathrami</i>	Indeterminate	Marine		
00DL18-0.0****	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Deltoidospora</i> spp., <i>Gleichenioidites senonicus</i> , <i>Osmundacidites</i> sp., <i>Podocarpidites</i> spp., <i>Rogalskaiisporites cicatricosus</i> , <i>Cyclonephelium distinctum</i> , <i>Hystrichosphaeridium stellatum</i> , <i>Oligosphaeridium</i> complex, <i>Pseudoceratium retusum</i> , <i>Sentusidinium rioultii</i>	Aptian-Albian (P-M18 to P-M17)	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL18-0.0	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk	Siltstone	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Bathysiphon</i> sp., <i>Haplophragmoides gigas</i> , <i>Haplophragmoides topagorukensis</i>	Probable middle to later Albian (F-9 to F-10)	Middle shelf to upper slope		
00DL18-30.0	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk		Palynomorph	MCI	Barren of palynomorphs	Indeterminate		2.3 to 2.5	Organic recovery consists mainly of woody fusinitic material.
00DL18-30.0	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk	Gypsiferous sandy shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate	Indeterminate		Gypsum in sample.
00DL18-32	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Gleichenioidites senonicus</i> , <i>Osmundacidites</i> spp.	Indeterminate	No evidence of marine	2.0 to 2.4	Organic recovery consists mainly of woody fusinitic material.
00DL18A-11.0	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> spp., <i>Contignisporites cooksonii</i> , <i>Deltoidospora</i> spp., <i>Gleichenioidites senonicus</i> , <i>Hymenozonitretes lepidophytus</i> , <i>Leptolepidites verrucatus</i> , <i>Lycopodiumsporites</i> spp., <i>Osmundacidites</i> spp., Taxodiaceae, <i>Cribooperidinium edwardsii</i> , <i>Gardodinium deflandrei</i> , <i>Odontochitina operculata</i> , <i>Palaeoperidinium cretaceum</i>	Probable Aptian-Albian (P-M18 to P-M17)	Marine	2.3 to 2.4	Organic recovery consists mainly of woody fusinitic material.
00DL18A-32.6	Chandler Lake C-4	North Tuktu Bluff	West bank Chandler River, ~1.0 km north of Tuktu Bluff	68.7477	152.3041	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Deltoidospora</i> spp., <i>Densosporites</i> spp., <i>Lycopodiumsporites</i> spp., Taxodiaceae, <i>Palaeoperidinium cretaceum</i> , <i>Pseudoceratium retusum</i> , <i>Spiniferites</i> sp.	Possible Aptian-Albian (P-M18? to P-M17?)	Marine	2.0 to 2.5	Organic recovery consists mainly of woody fusinitic material.
01DL23-0	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk		Palynomorph	PAZ	<i>Vesperopsis longicornis</i> , <i>Lanciniadinium</i> spp.	Early to Middle Albian		2+ to 3	
01DL23-0	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk	Micaceous mudstone or shale	Foraminifera	MCI	<i>Bathysiphon</i> , <i>Haplophragmoides bonanzaensis</i> , <i>Haplophragmoides excavatus</i> , <i>Trochammina ribstonensis</i>	Cenomanian to Turonian (F-5 to F-8)	Probable shelf		Spurious results; this part of succession known to be of Albian age.
01DL23-31	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk		Palynomorph	PAZ	<i>Nyctericysta lacustra</i> ?	Middle to ?late Albian		2+ to 3	
01DL23-31	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk	Micaceous mudstone or shale	Foraminifera	MCI	<i>Gaudryina irenensis</i> , <i>Haplophragmoides bonanzaensis</i> , <i>Trochammina ribstonensis</i>	Probable Cenomanian to Turonian (F-5 to F-8)	Probable shelf		Spurious results; this part of succession known to be of Albian age.
01DL23-159.1	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk		Palynomorph	PAZ	<i>Vesperopsis longicornis</i> , <i>Nyctericysta lacustra</i>	Early to Middle Albian		2+ to 3	Rare pollen and dinoflagellates, poor preservation.
01DL23-159.1	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk	Micaceous shale	Foraminifera	MCI	<i>Haplophragmoides bonanzaensis</i>	Probable Turonian to Coniacian (F-5 to F-6)	Probable shelf		Shell fragments. Spurious results; this part of section known to be Albian.
01DL23-188.7	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk		Palynomorph	PAZ	Long-ranging Cretaceous taxa	Cretaceous undifferentiated		2+ to 3	Rare, poorly preserved pollen.
01DL23-188.7	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk	Micaceous siltstone or silty mudstone	Foraminifera	MCI	Barren of foraminifera	Indeterminate			
01DL23-209.4	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk		Palynomorph	PAZ	Long-ranging Cretaceous taxa	Indeterminate		2+ to 3	Abundant pollen, very poor preservation.
01DL23-209.4	Phillip Smith Mountains C-4	Slope Mountain	East side of Slope Mountain and west of Dalton Highway (mile 302)	68.727	149.0224	Nanushuk	Micaceous shale	Foraminifera	MCI	<i>Bathysiphon brosegi</i> , <i>Haplophragmoides rota</i> , <i>Trochammina ribstonensis</i>	Probable Turonian to Coniacian	Probable shelf		
01DL31-8.45	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Vesperopsis longicornis</i> , <i>Nyctericysta lacustra</i>	Early Albian to middle Albian		2+	Abundant pollen and dinoflagellates.
01DL31-8.45	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Sandy siltstone	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Ammodiscus rotarius</i> , <i>Ditrupea cornu</i> , <i>Haplophragmoides</i> cf. <i>kirki</i> , <i>Haplophragmoides gigas</i> , <i>Haplophragmoides topagorukensis</i> , megaspores	Middle to late Albian (F-9)	Inner to middle shelf		
01DL31-29.6	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Nyctericysta lacustra</i> ?	Middle to late Albian		2+	Abundant pollen and dinoflagellates.

Table B1 (cont.). Summary of palynologic and foraminifera samples tied to measured stratigraphic sections of the Nanushuk Formation in the central North Slope, Alaska.

Sample ID	Quadrangle	Location Name	Location	Latitude	Longitude	Formation	Lithology	Sample Type	Contractor	Significant Taxa	Age	Environment	TAI	Comments
01DL31-29.6	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Silty mudstone or siltstone	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Arenaceus</i> spp., <i>Haplofragmoides excavatus</i> , <i>Haplofragmoides topagorukensis</i> , <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Shelf		
01DL31-31.9	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Nyctericyta lacustra</i>	Middle to late Albian		2+	Abundant poorly preserved pollen; common freshwater(?) dinoflagellates.
01DL31-31.9	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Slightly silty mudstone or shale	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Ammobaculites wenonahae</i> , <i>Ammodiscus rotularius</i> , <i>Bathysiphon</i> sp. (coarse), <i>Gaudryina canadensis</i> , <i>Haplofragmoides</i> cf. <i>kirki</i> , <i>Haplofragmoides excavatus</i> , <i>Haplofragmoides gigas</i> , <i>Haplofragmoides topagorukensis</i> , <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Shelf		
01DL31-89.7	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Vesperopsis longicornis</i> , <i>Nyctericyta lacustra</i>	Early Albian to middle Albian		2+	Abundant poorly preserved pollen; common freshwater(?) dinoflagellates.
01DL31-89.7	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Siltstone	Foraminifera	MCI	<i>Haplofragmoides topagorukensis</i>	Probable middle to late Albian (F-9)	Probable marginal marine to inner shelf		
01DL31-135.1	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Vesperopsis longicornis</i>	Late Barremian to early Albian		2+	Abundant poorly preserved pollen; rare freshwater(?) dinoflagellates.
01DL31-135.1	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Slightly silty micaceous shale	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Ammobaculites wenonahae</i> , <i>Ammodiscus rotularius</i> , <i>Arenaceus</i> spp., <i>Gaudryina canadensis</i> , <i>Haplofragmoides</i> cf. <i>kirki</i> , <i>Haplofragmoides excavatus</i> , <i>Haplofragmoides topagorukensis</i> , <i>Psamminopelta bowsheri</i> , <i>Psamminopelta subcircularis</i> , <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Middle to outer shelf		
01DL31-150	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Aurtulinasporites deltaformis</i>	Berriasian to late Albian		2	Common poorly preserved pollen.
01DL31-150	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Slightly silty shale	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Ammobaculites wenonahae</i> , <i>Gaudryina canadensis</i> , <i>Haplofragmoides</i> cf. <i>kirki</i> , <i>Haplofragmoides excavatus</i> , <i>Haplofragmoides topagorukensis</i> , <i>Psamminopelta bowsheri</i> , <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Middle to outer shelf		
01DL31-191	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Odontochitina singhii</i> , <i>Triporopollenites</i> spp.?	Late Albian to early Cenomanian		2 to 2+	Common poorly preserved pollen, rare dinoflagellates.
01DL31-191	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Slightly silty shale	Foraminifera	MCI	<i>Ammobaculites fragmentarius</i> , <i>Ammobaculites wenonahae</i> , <i>Bathysiphon vitta</i> , <i>Gaudryina canadensis</i> , <i>Haplofragmoides</i> cf. <i>kirki</i> , <i>Haplofragmoides excavatus</i> , <i>Haplofragmoides gigas</i> , <i>Haplofragmoides topagorukensis</i> , <i>Verneuilinoides borealis</i>	Middle to late Albian (F-9 to F-10)	Middle to outer shelf		
01DL31-240.6	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Wallodinium krutzschii</i> , <i>Dorocysta litotes</i>	Late Albian		2 to 2+	Common poorly preserved pollen, rare dinoflagellates.
01DL31-240.6	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate			
01DL31-289.6	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Nyctericyta lacustra</i> , <i>Palaeohystrichophora infusorioides</i>	Middle to late Albian		2 to 2+	Common poorly preserved pollen, abundant well preserved dinoflagellates.
01DL31-289.6	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Slightly silty shale	Foraminifera	MCI	<i>Gaudryina canadensis</i> , <i>Gaudryina irenensis</i> , <i>Haplofragmoides excavatus</i> , <i>Verneuilinoides borealis</i> , <i>Verneuilinoides fischeri</i>	Late Albian to Cenomanian (F-8 to F-10)	Shelf		
01DL31-407	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Nyctericyta lacustra</i> , <i>Palaeohystrichophora infusorioides</i>	Middle to late Albian			Common poorly preserved pollen, abundant well preserved dinoflagellates.
01DL31-407	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Shale	Foraminifera	MCI	<i>Gaudryina canadensis</i> , <i>Gaudryina irenensis</i> , <i>Haplofragmoides excavatus</i> , <i>Trochammina ribstonensis</i> , <i>Verneuilinoides borealis</i> , <i>Verneuilinoides fischeri</i>	Late Albian to Cenomanian (F-8 to F-10)	Shelf		
01DL31-421.5	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Cicatricosisporites hughesii</i> , <i>Microreticulatisporites uniformis</i>	Aptian to late Turonian		2	Abundant well preserved pollen, very rare poorly preserved dinoflagellates.
01DL31-421.5	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Coaly mudstone or shale	Foraminifera	MCI	Barren of foraminifera				Small coal particles.
01DL31-423.3	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Diconodinium arcticum</i> , <i>Palaeohystrichophora infusorioides</i>	Middle Albian to Maastrichtian		2	Rare poorly preserved pollen, abundant poorly preserved dinoflagellates.
01DL31-423.3	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Paper shale	Foraminifera	MCI	Barren of foraminifera; <i>Cenosphaera</i> spp. (pyritized)	Possible Cenomanian to Turonian (F-7? to F-8?)			
01DL31-442.4	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Cerebropollenites mesozoicus</i> , <i>Cicatricosisporites venustus</i>	Late Hauterivian to early Cenomanian		2	Abundant well preserved pollen.
01DL31-442.4	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Mudstone or shale	Foraminifera	MCI	Barren of foraminifera; megaspores	Indeterminate			Small coal particles.
01DL31-472.8	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk		Palynomorph	PAZ	<i>Cerebropollenites mesozoicus</i> , <i>Cicatricosisporites</i> sp.	Early to middle Cenomanian		2	Abundant well preserved pollen. <i>Cicatricosisporites</i> sp. Singh 1983 has few citations - base age may range older.
01DL31-472.8	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Coal, mudstone, or shale	Foraminifera	MCI	Barren of foraminifera	Indeterminate			Small coal particles.
02DL30B-4.2 to 8.2	Umiat B-5	Colville incision	North bank Colville River	69.2724	152.5883	Nanushuk		Palynomorph	MCI	Undifferentiated bisaccates, <i>Cicatricosisporites</i> cf. <i>C. hallei</i> , <i>Cicatricosisporites</i> cf. <i>C. venustus</i> , <i>Deitoidospora</i> spp., <i>Densosporites</i> sp., <i>Gleicheniidites senonicus</i> , <i>Podocarpidites</i> sp., <i>Sestrosporites pseudoalveolatus</i> , <i>Cyclonephelium distinctum</i> , <i>Odontochitina operculata</i> , <i>Oligosphaeridium</i> complex, <i>Spiniferites</i> sp.	Possible Aptian-Albian (P-M18?)	Marginal marine	2.3 to 2.5+	Organic recovery consists mainly of woody fusinitic material and minor herbaceous material.
02DL30B-4.2 to 8.2	Umiat B-5	Colville incision	North bank Colville River	69.2724	152.5883	Nanushuk	Mudstone or shale	Foraminifera	MCI	<i>Arenaceus</i> sp., megaspores	Indeterminate	Possible marine		

**Notes:**

Contractor initials: MCI = Micropaleo Consultants, Inc., Hideyo Haga and Michael B. Mickey; PAZ = Pierre A. Zippi. All samples are tied to measured stratigraphic sections. Sample numbers include the year collected, collector's initials, measured section number, hyphen, and the position of the sample above the base of the section in meters.

\*The Arc Mountain section is a composite section from several shorter measured sections (99DL47A through 99DL47E). Section 99DL47B starts at the base of sand immediately below the coal bed at 412 m on the composite section. Section 99DL47D starts at 663 m on the composite section shown in Appendix A. The base of section 00DL24 corresponds to the base of the third prominent sand body visible on the south flank of Arc Mountain anticline, along the east bank of the Nanushuk River, which is approximately 237 m in the composite section.

\*\*The Rooftop Ridge section was measured over the course of two field seasons. The southern half of the exposure was measured during the 1999 field season and all samples collected from this part of the exposure are numbered 99DL64- followed by the position in meters above the base of that segment of the exposure. The base of 99DL64 corresponds to 287 m in the composite section shown in Appendix A.

\*\*\*02DL26A is a composite sample collected from the basal 10 m of the Seabee Formation at Ninuluk Bluff. The Ninuluk section is shown in Appendix A.

\*\*\*\*The latitude and longitude provided from measured section 00DL18 corresponds to our spike camp location, which was midway between two prominent exposures on the west side of the Chandler River, north of Tuku Bluff. 00DL18 is in the section north of our camp location. The section shown in Appendix A is the southern exposure, labeled 00DL18A. The correlative stratigraphic position in 00DL18A is a few meters below the base of the measured section.

Table B2. Summary of macrofossils specimens collected from the Nanushuk Formation as part of this study.

Sample ID	Quadrangle	Location Name	Location	Latitude	Longitude	Formation	Fossil Type	Significant Taxa	Age	Environment	Comments
00DL24a	Chandler Lake C-1	Arc Mountain	East bank Nanushuk River			Nanushuk	Ammonite	<i>Paragastropolites</i> cf. <i>P. flexicostatus</i> Imlay	Middle middle Albian	Normal marine	Found in float.
01DL29-C	Chandler Lake C-1	East Arc Mountain	West bank, west fork May Creek	68.6492	150.2563	Nanushuk	Gastropod	<i>Gyrodes</i> ex. gr. <i>americanus</i> Wade	Albian		Similar to <i>Gyrodes onoensis</i> Popoenie; Saul and Susuki found in Albian strata of the Pacific slope.
01DL29-D	Chandler Lake C-1	East Arc Mountain	West bank, west fork May Creek	68.6492	150.2563	Nanushuk		<i>Flaventia kukpowrukvensis</i> Imlay	Albian	Nearshore	
99DL64-76	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk	Bivalve	Bivalve	Indeterminate		
99DL64-77	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Nanushuk	Bivalve	<i>Tancredia</i> sp. cf. <i>T. kurupana</i>	Albian	Nearshore	May range both up and down the stratigraphic section.
99DL64-244.5	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8433	150.5617	Seabee	Bivalve	<i>Inoceramus</i> sp. aff. <i>I. cuvieri</i> Sowerby	Middle Turonian	Normal marine	
00DL22-92	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Bivalve	<i>Panopea? elongatissima</i> (McLearn)	Indeterminate	Deep infaunal bivalve in nearshore setting	Characteristic of Albian rocks, but comparable bivalves are also known to extend from the Neocomian through Late Cretaceous on the North Slope.
00DL22-160	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Ammonite	<i>Paragastropolites</i> cf. <i>G. kingi</i> McLearn	Middle Albian	Normal marine	Partial specimen.
00DL22-163.6	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Bivalve	Venerid bivalve	Albian		This is a really big clam? It is possible that it is a really big specimen of <i>Arctica</i> sp., which is common in Albian age rocks of northern Alaska. It is more elongate than typical of other specimens of that genus, but this difference could result from its large size, and possibly some deformation.
00DL22-164.3	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Ammonite	<i>Paragastropolites</i> cf. <i>spiekeri</i> (McLearn)	Late middle Albian	Normal marine	
00DL22-230	Chandler Lake D-1	Rooftop Ridge	West bank Nanushuk River	68.8455	150.5513	Nanushuk	Bivalve	<i>Entolium utukokense</i> Imlay	Albian	Nearshore marine	Epifaunal bivalve adapted to live in areas that were at times turbulent.
00DL16-1.8	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River	69.128	153.2887	Nanushuk	Bivalve	<i>Corbicula</i> sp.?	Indeterminate	Brackish water?	Assignment of bivalve is problematic. The subtle radial ornament appears like that on some <i>Buchia</i> or <i>Aucellina</i> , however the overall shape was not consistent with these, nor is the late Albian age for the unit in which they are thought to occur. The shape of the bivalve and gregarious nature of these clams is consistent with that of a corbiculid, although the radial ornamentation is not typical.
00DL16-19	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River	69.128	153.2887	Nanushuk	Bivalve	Corbiculid	Not age-specific	Brackish water	
00DL16-29.4	Ikpikpuk River A-1	Ninuluk Bluff	South bank Colville River	69.128	153.2887	Nanushuk	Bivalve	<i>Corbicula</i> sp.?	Indeterminate	Brackish water?	Assignment of bivalve is problematic. The subtle radial ornament appears like that on some <i>Buchia</i> or <i>Aucellina</i> , however the overall shape was not consistent with these, nor is the late Albian age for the unit in which they are thought to occur. The shape of the bivalve and gregarious nature of these clams is consistent with that of a corbiculid, although the radial ornamentation is not typical.

Table B2 (cont.). Summary of macrofossils specimens collected from the Nanushuk Formation as part of this study.

Sample ID	Quadrangle	Location Name	Location	Latitude	Longitude	Formation	Fossil Type	Significant Taxa	Age	Environment	Comments
00DL17-0.0	Umiat A-4	Big Bend, Chandler River	East bank Chandler River	69.0812	151.9377	Nanushuk	Bivalve	<i>Nuculana</i> sp.	Indeterminate		This bivalve inhabits muddy sediments in many environments and has no age significance.
00DL23a	Chandler Lake C-2	Kanayut River	East bank Kanayut River			Nanushuk	Bivalve	<i>Entolium</i> cf. <i>utukokense</i> Imlay, <i>Ditrupea cornu</i> Imlay	Albian		A fairly typical Albian fauna. Not aware of <i>Entolium utukokense</i> or <i>Ditrupea cornu</i> extending above the Albian. Found in float.
01DL31-131	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Bivalve	<i>Inoceramus anglicus</i> ? Woods	Middle to late Albian	Normal marine	This inoceramid has the concentric ornament style to be species identified, but it also appears to have a radial ornament that makes it look like some Santonian or Campanian to Maastrichtian inoceramids. It is possible that the radials are a result of compaction and crushing of the shell parallel to the plane of the commissure.
01DL31-253	Chandler Lake C-2	Kanayut River	East bank Kanayut River	68.6461	150.9089	Nanushuk	Bivalve	<i>Modiolus</i> sp.	Not age-specific	Nearshore to shoreline	
01DL32-165	Chandler Lake	Kanayut River				Nanushuk	Bivalve, annelid	<i>Nucula</i> sp.?, <i>Flaventia kukpowrukwensis</i> Imlay, <i>Ditrupea cornu</i> (annelid)	Albian	Fairly typical nearshore Albian fauna.	Not aware of <i>Ditrupea cornu</i> extending above Albian.

All samples are tied to measured stratigraphic sections. Sample numbers include the year collected, collector's initials, measured section number, hyphen, and the position of the sample in meters above the base of the section.

All macrofossil identifications and comments on paleoecology were taken from sample identification reports submitted to DGGs by Dr. Will Elder.