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FACIES MODELING AND STRATIGRAPHY OF THE UPPER NANUSHUK FORMATION AT SLOPE MOUNTAIN, ALASKA

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INTRODUCTION

Slope Mountain, Alaska is located in the northern fSlope Mountain, Alaska is located in the northern foothills of the Brooks Range (Fig. 1, Shimer and McCarthy, this volume). The northern foothills of the Brooks Range, also known as the Arctic Foothills, combine with the Arctic Coastal Plain province to form the North Slope (Moore et al, 1994). Slope Mountain represents the northern limb of the east-west trending Marmot Syncline (Fig. 3, Shimer and McCarthy, this volume), a gently folded structure formed from compressive stress in the Cretaceous and Tertiary periods (Bird and Molenaar, 1992; Moore et al, 1994). Much of the Brooks Range foothills and the subsurface stratigraphy of the North Slope represent deposits of the Colville foreland basin, an east-west trending basin formed during collision of the Arctic Alaskan Microplate with island arcs and southern Alaska from the Late Jurassic through the Cenozoic (Bird and Molenaar, 1992). The Brooks Range bounds the basin to the south, while the Barrow Arch – a subsurface structural high – bounds the basin to the north. To the east, the Brooks Range and foreland basin sediments trend northeast and pinch out along the coast of the Beaufort Sea. The Colville Basin also extends to the west to the Chukchi Sea and the remnants of the buried Herald Arch (Bird and Molenaar, 1992).

The stratigraphy of the Colville Basin comprises sediments sourced from erosion of the ancestral Brooks Range and the Herald Arch. These strata are known as the Brookian sequence (Fig. 2, Shimer and McCarthy, this volume; Moore et al, 1994; LePain et al, 2009). The stratigraphic terminology used in this paper follows the Brookian nomenclature developed by Mull et al. (2003). Slope Mountain is composed of the Nanushuk and Torok formations, which together account for nearly 75% of the basin fill (Mull et al., 2003). The Nanushuk and Torok formations are genetically related, coeval marine to non-marine sediments (LePain et al, 2009). The Torok Formation consists of marine shales, mudstones, interbedded siltstones, and minor fine-to-medium grained sandstones. The thickness of the formation varies geographically, ranging from 950-5600 m thick, depending on structural thickening. Fossil records suggest that the Torok Formation was deposited starting in the Aptian and continuing into the Cenomanian (Mull et al, 2003). The Torok underlies and interfingers with the Nanushuk Formation, and is often poorly exposed due to non-resistant qualities, though it is well-exposed on the steep eastern face of Slope Mountain. The Nanushuk Formation is typically divided into the upper and lower Nanushuk. The lower Nanushuk Formation comprises marine sediments, mostly shales, siltstones and very fine grained sandstones, while the upper Nanushuk Formation comprises non-marine to marginal marine sediments such as fine to coarse-grained sandstones, conglomerates, shale, and siltstone (Mull et all, 2003; LePain et al, 2009).

Although the Nanushuk and Torok Formations were originally studied for their value to the petroleum industry, interest in the formations have shifted to include many other areas of study such as paleoecology, paleoclimatology, and tectonics. The primary motivation for this study was to determine how the landscape and its associated depositional environments changed in response to tectonic and climatic variables through description of the sedimentary deposits and classification of ancient environments based on facies interpretations. To do so I conducted a detailed facies analysis. As defined by Middleton (1978), facies are differentiable rock units that can be grouped together based on similar structural, organic, and lithologic qualities (Walker, 2006). Comparisons of modern sedimentary structures such as dunes and ripples to features preserved in sedimentary rocks provide important information about the conditions under which the sediments were deposited (Walker, 2006). Facies associations group together various stacked facies that represent depositional conditions in multiple associated environments. Various depositional environments have facies associations that will often appear only within that environment. Classifying a certain area into various facies associations can offer insight into the environmental evolution of a particular area through time (Walker, 2006).

The analysis presented in this paper is sandstone outcrops from the mid to upper Nanushuk Formation at at Slope Mountain. Previous studies (Johnson and Sokol, 1998; LePain et al., 2009) at Slope Mountain include similar stratigraphic columns and facies analyses, however they do not include data for several outcrops included in this study. The research in this paper has a higher resolution focus than previous studies, and allows for analysis to be completed with greater detail, providing additional insight into the evolution of the Nanushuk Formation throughout the Albian-Cenomanian.

METHODS

Data collection methods in the field focused on lithological descriptions and measurements. Stratigraphic sections were measured using a Jacob's Staff or a tape measure (if applicable). A tape measure and a Brunton compass were used measure morphologic dimensions and orientation of sedimentary structures and beds. The resolution of the stratigraphic sections is based on graph paper with 0.5 cm squares, where each square is equal to 20cm of section. This resolution allowed for the highest detail possible while allowing for an efficient study of multiple outcrops. Field notes and sections were digitized at the University of Alaska Fairbanks and Whitman College using Adobe Illustrator.

Facies were differentiated first by dominant grain size, and further refined by sedimentary structures. Lithologic units that are dominantly sand (>85% sand) were classified as sandstones, and those that are dominantly silt or mud were classified as shales or mudstones. Within sandstone and finer-grained facies, differences in sedimentary structures and morphology are the distinguishing characteristics. An example would be that a sandstone displaying ripple laminations was differentiated from a sandstone displaying planar laminations based on the sedimentary structures rather than grain size. Likewise, differences in scale between similar structures (i.e. large-scale cross-bedding and medium-scale cross-bedding) required further differentiation.

Facies were grouped into facies associations based on their occurrence in outcrop. Drastic changes in energy interpreted from sedimentary structures that define facies determined the boundaries of most facies associations. The related depositional settings of each of the facies within an association were used to extrapolate a depositional environment for that association. The patterns of facies associations in outcrop are critical in determining how the environment changed over time.

RESULTS

Twelve facies (Table 1) were recognized at four outcrops in the Upper Nanushuk Formation at Slope Mountain based on sedimentary structures (Fig. 1), sedimentary textures, and bedform morphologies. Stratigraphic sections were broken down into the facies present at each outcrop, and then facies were grouped into facies associations (Table 2). Type sections of the facies associations appear in Figure 2. Using previous research based on facies analyses of foreland basin deposits (Bhattacharya and Walker, 1991; Johnson and Sokol, 1992, LePain et al, 2009, Olairu et al, 2010), the facies associations were used to interpret depositional environments in the upper Nanushuk Formation. The facies associations provided detailed descriptions of how the paleoenvironment changed over time.

Facies Number	Structure/Rock Type	Description	Interpretation
Facies 1a	Ripple Laminated Sandy Siltstone	Sandy siltstone with millimeter scale ripple laminations. Bed thicknesses range from 5-20cm.	Deposited from suspension under low-flow regime conditions.
Facies 1b	Rippled Silty Shale	Dark grey silty shale, 4 centimeter thick beds with millimeter scale beds.	Deposited from suspension in a low energy environment with minor oscillatory waves
Facies 1c	Planar laminated sandstone	Fine-grained sandstone in sections up to 40cm thick. Centimeter scale planar bedding roughly 3cm thick with millimeter scale laminations.	Deposited as bedload under medium to high flow regime conditions.
Facies 2a	Ripple laminated sandstone	Sandstones containing centimeter scale ripple laminations throughout. Beds range from 5cm to 40+cm thick.	Deposited as bedload under low flow velocities.
Facies 2b	Structureless mudstone	Mudstone that lacks any visible sedimentary structures. Bed is 3cm thick. Lack of structures suggests pervasive bioturbation.	Deposited from suspension under low flow regime conditions and later bioturbated.
Facies 3	Ripple/Planar Laminated interbedded sandstone	Interbedded fine and medium grained sandstones with bed thicknesses ranging from 6-15 centimeters. Medium grained beds containe ripple laminations, while finer grained interbeds display millimeter scale planar laminations.	Deposited over multiple events with varying flow conditions.
Facies 4	Rippled sandstones	Medium grained sandstone about 30 centimeters thick. Pebble lags are visible at the base of some beds	Deposited under unidirectional or bidirectional currents
Facies 5a	Large-scale trough cross bedded sandstone	Sandstones displaying large-scale trough crossbedding. Beds vary from 30cm to amalgamated sections greater than 10m. Measured troughs were 2.8m across and 25cm thick.	Remnants of large three-dimensional bedforms (e.g. dunes) migrating along channel bottom under upper low flow regime conditions.
Facies 5b	Medium-scale trough cross bedded sandstone	Sandstone displaying trough cross bedding ranging from .5-1.6m wide. Occurs in both small scale (30cm or less) outcrops and amalgamated sections up to 10m	Three-dimensional bedforms (e.g. dunes) migrating along channel base under upper low flow regime conditions.
Facies 6	Planar-tabular cross bedded Sandstone	Planar-tabular bedded sandstone with distinct herringbone crossbedding. Foresets dip at 15-25 degrees and alternate West and East dip directions. Foresets range from .5-3.5cm thick. Beds range from 10-30cm thick.	Deposited by two dimensional bedforms migrating in bidirectional current, or as point bar deposits within a channel in upper low flow regimes.
Facies 7	Apparently Structureless Sandstone	Sandstone of varying grain size that lacks visible sedimentary structures. Rippled tops may be present in some beds. Bed thicknesses range from 10cm-1.3m. Rare mud rip-up clasts.	Deposition of high sediment load flows at high energy. Intensity of flow likely varied, but maintained a high rate of deposition.
Facies 8	Conglomerate	Poorly sorted conglomerate made	Deposited as bedload under high flow velocity

Table 1. Table of facies observed at Slope Mountain, along with generalized descriptions and interpretations.

Facies Association	Facies Included	Type Section	Environmental Interpretation
FA 1	5a, 5b, 6	Amalgamated sections of trough cross-bedded sandstones up to 10 meters thick between covered sections of fine grained material. Minor beds of planar-tabular cross bedded sandstone.	Distributary Channel bar. Deposited as point bar accretion or dune forms migrating along channel base (Miall. 1996; LePain et al., 2009)
FA 2	5a, 5b, 6, 7	Meter thick sections of structureless sandstone overlain by several meters of interbedded herringbone cross bedded and trough crossbedded sandstone.	Tidal Channel Deposits. Deposited as duneforms moving along base under bi-directional tidal currents (Dalrymple 1992; LePain et al, 2009)
FA 3	1c, 2a, 2b, 3, 7	5 meter thick sections show interbedded planar and ripple laminated sandstones, often underlain or overlain by structureless sandstone.	Upper Shoreface Deposits. Deposition under various flow conditions, generating planar and ripple laminated sandstone. (Gani and Bhattacharya, 2007; LePain et al, 2009)
FA 4	1b, 2a, 3, 5b, 7	Section beginning with interbedded planar and ripple laminated sandstone, overlain by 5 meters of medium-scale trough cross bedded sandstone.	Distributary mouth bar deposits. Planar and ripple laminated sandstones suggest flow conditions associated with a drop in velocity that might occur at a mouth of a distributary channel (Gani and Bhattacharya, 2007). Trough cross bedding deposited as mouth bar dunes migrating along the base (LePain et al., 2009)
FA 5	5b,7,8	Section begins with beds of structureless sandstone overlain by a channelized conglomerate. Several meters of thin, interbedded trough cross bedded sandstone.	Fluvial channel and channel bar deposits. Structureless sandstone and conglomerate base suggests initial high energy conditions (LePain et al., 2009). Overlying medium-scale trough cross bedding indicate bedforms moving under unidirectional flow (Miall, 1996; LePain et al., 2009). Thin interbeds of trough cross bedded sandstones may suggest constant migration of the channel (LePain et al., 2009)

Table 2. Facies Associations present at Slope Mountain, descriptions and environmental interpretations.

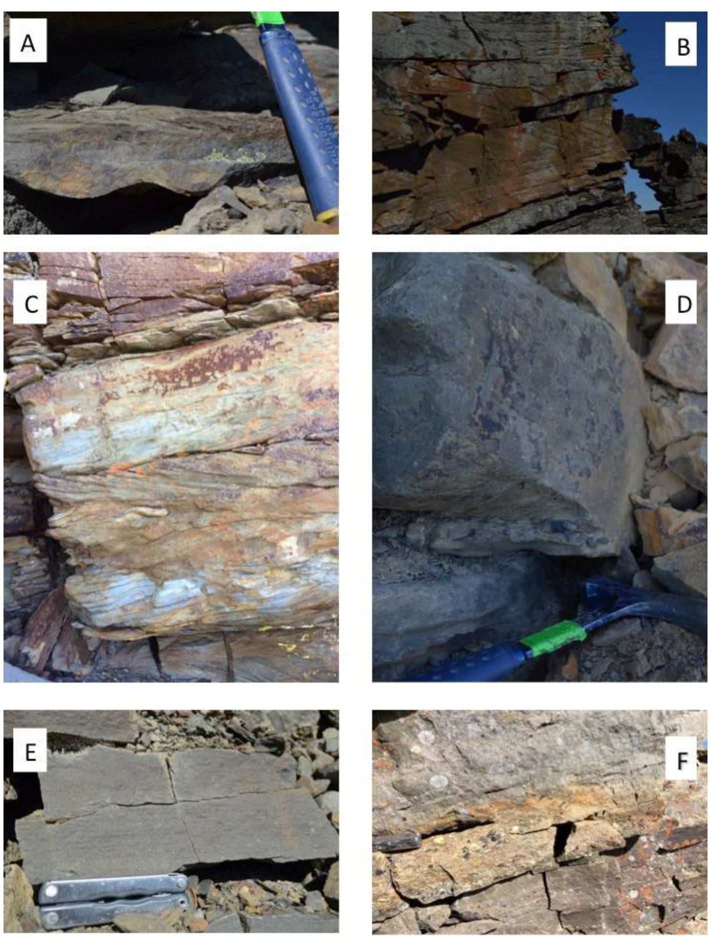

Figure 1. Prominent Facies at Slope Mountain. A) Ripple Laminated sandstone from lower SM5. B) Trough cross-bedded sandstone from the top of SM5. C) Planar-Tabular cross-bedding (Herringbone) from SM3. D) Apparently structureless sandstone from SM5. E) Planar Lamimated sandstone from lower SM5. F) Conglomerate from SM8.

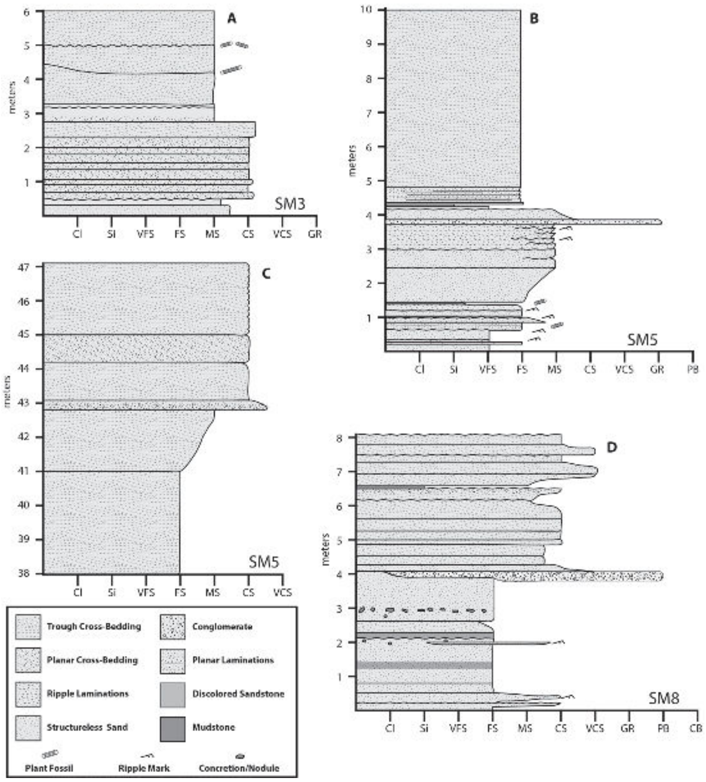

Figure 2: Stratigraphic columns of representative facies associations. A) Type section for Tidal channel/Estuarine (FA2). B) Type section of upper shoreface(FA3: 0-4 m) to distributary mouth bar (FA4: 4-10 m) deposits. C). Type section of distributary channel bar (FA1) deposits. D) Type section of fluvial channel and channel bar deposits (FA5: 4-8 m) above upper shoreface deposits (FA3: 0-4 m).

There were several factors that affected the detail and resolution of the facies analysis given the available time in the field. Certain outcrops at Slope Mountain were inaccessible due to the dangers of weakened overhanging layers or steep slopes. Other outcrops experienced significant frost wedging, generating thick and unstable colluvium that buried intact bedding. Lichen covered surfaces at the outcrops and may have hidden minor sedimentary structures that were present in some rocks.

DISCUSSION

Section SM5 is both the largest of the outcrops in this study, and one that represents the greatest vertical change in facies associations. The bottom 1.5 meters of the section represent fine-grained shoreface deposits (FA3). Facies Association 4 (FA4) separated by a thin transgressive surface that abruptly changes from mudstone to massive structureless sandstone overlies FA3. FA4 is capped by an erosional surface marked by a pebble lag at 3.8 meters from the base. Distributary channel bar deposits (FA1) dominate section SM5 above 4 meters in the section. The overall coarsening upward trend and the continuation of FA1 support the interpretation that SM5 represents a progradational sequence, transitioning from finer grained shoreface to increasingly coarse-grained distrubutary channels, probably in a wave-influenced delta.

Sections SM3 and SM3.1 represent a single facies association, tidal/estuarine deposits (FA2). FA2 is characterized by planar-tabular cross-bedding and trough cross-bedding. Grain size varies little throughout each section, implicating that the energy settings of the environment did not fluctuate drastically. SM3 and 3.1 are interpreted to represent a period of local transgression in which tidally influenced channels developed within an estuarine environment.

SM8 is dominated by a coarse grained sandstones and a thin conglomerate that together represent fluvial channel deposits of FA5. The thickness of beds and coarse sand grains suggest that this environment is a more proximal element of the Nanushuk Formation alluvial-deltaic system, likely that of a fluvial channel that formed above a disconformity. The presence of structureless sandstones at the base of SM8 make interpretation of the underlying environment difficult, but trace fossils of the Skolithos ichnofacies in the structureless sandstones indicate that SM8 represents a transition from a shallow marine setting to a fluvial dominated environment, a likely sign of regression.

The pattern of regression and transgression observed in the Nanushuk Formation at Slope Mountain is supported by regional patterns observed at other outcrops (Houseknecht and Schenk, 2005; LePain et al., 2009), in core and well logs (Shimer et al., 2014), and in seismic cross sections of the Colville Basin (Decker, 2007; Houseknecht et al., 2009). Changes in depositional environment within the marginal-marine to non-marine lithologies suggest that relative sea level varied at least three times in the timeframe encompassed by the stratigraphic sections: (1) A progradational sequence that transitioned from shoreface environments (FA3) to distributary mouth bar (FA4) to distributary channel bar deposits (FA5) in SM5, (2) a partial non-marine transgression and retrogradational succession marked by a transition to a tidal/estuarine environment (FA3) in SM3/3.1, and (3), a progradational regressive succession marked by the deposition of proximal fluvial deposits (FA5) over marine deposits at SM8.

Seismic studies (Decker, 2007; Houseknecht et al., 2009) conclude that the Nanushuk Formation represents topset environments ranging anywhere from nonmarine to shelf deposits. Along with the Torok Formation, the Nanushuk Formation accounts for a vast majority of the sediments within the Colville Basin (Bird and Molenaar, 1992; Moore et al, 1994). The using the facies to track the trajectory of deltaic deposits, the positions of the shoreface/ delta plain environments at the base of SM5 and the fluvial channel environment at SM8 illustrate a pattern of dominantly progradational parasequences (sensu Catuneanu et al., 2009). The progradational parasequences observed at Slope Mountain suggest that the sediment supply was typically far greater than the accommodation available in the foreland basin.

The goal of this project was to construct a detailed facies analysis of the upper Nanushuk Formation in outcrop at Slope Mountain. The results of this paper build upon those of Johnson and Sokol (1998) and LePain et al. (2009) and largely support their findings at Slope Mountain. This study has concluded that a high resolution analysis of the facies present offers detailed insights into the fluctuations in base level and the rate of sedimentation in the Nanushuk Formation at Slope Mountain. I suggest that future work at Slope Mountain attempts to access more stratigraphic intervals, particularly those affected by covered section. Future studies should definitely include outcrops below SM5 and above SM8, as they will cover periods of time not addressed during this project.

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