SEISMIC STRATIGRAPHIC ANALYSIS OF NUIQSUT AREA,
CENTRAL NORTH SLOPE ALASKA, USA

by

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A THESIS

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ABSTRACT

This study focuses on the seismic stratigraphic analysis of the Nanuq South 3D seismic survey acquired over Nuiqsut, Central North Slope, Alaska to interpret the overall strata of the Ellesmerian, Beaufortian, and Brookian mega-sequences. Fourteen stratigraphic horizons were defined based on the seismic reflection patterns, and formation tops from the available well logs, and interpreted using a new semi-automatic horizon picking algorithm. The horizon tracking algorithm only needs interpreters manually picking 15% of the seismic vertical sections to generate horizons over the whole seismic survey. This result confirms that there is a significant decrease in interpretation effort with the automatic horizon picking algorithm.

Four mega-sequences (Franklinian, Ellesmerian, Beaufortian, and Brookian) were identified based on interpreted horizons and well log tops. The thickness maps of mega-sequences were generated to analyze the depositional history and illustrate that four mega-sequences have different thickening directions. The Ellesmerian mega-sequence (Mississippian - Early Cretaceous) shows thickening northwestward with maximum thickness of 1.4 km. The Franklinian basement deepening towards the west caused Ellesmerian mega-sequence thickening in that direction. The Beaufortian (Early to Middle Jurassic and Early Cretaceous) and Brookian (Early Cretaceous to Cenozoic) mega-sequences both show thickening southwestward and the maximum thicknesses are 0.6 km and 2 km, respectively. The different thick patterns are believed related to the Brooks Range orogeny in the south, and the opening of the Canada Basin in the north during Jurassic–Early Cretaceous time. To further identify the potential reservoir,
self-organizing map (SOM) was applied to multiple seismic attributes to analyze the seismic facies of Brookian mega-sequence. The results clearly highlight the west-east orientated incised valleys, moved sand to the basin floor fan delta in the southeast. Sand bodies along the shelf edge, slope, and basin floor could be a potential hydrocarbon production zone.
DEDICATION

This thesis is dedicated to my father, İbrahim BARIN who sees me from a peaceful place.

You will be in my heart and mind for the rest of my life.
### LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>AACM</td>
<td>Arctic Alaska–Chukotka Microcontinent</td>
</tr>
<tr>
<td>ANWR</td>
<td>Arctic National Wildlife Refuge</td>
</tr>
<tr>
<td>GRZ</td>
<td>Gamma Ray Zone</td>
</tr>
<tr>
<td>HST</td>
<td>Highstand System Tract</td>
</tr>
<tr>
<td>LCU</td>
<td>Lower Cretaceous Unconformity</td>
</tr>
<tr>
<td>LST</td>
<td>Lowstand System Tract</td>
</tr>
<tr>
<td>MD</td>
<td>Measured Depth</td>
</tr>
<tr>
<td>ms</td>
<td>Millisecond</td>
</tr>
<tr>
<td>MS</td>
<td>Mega-sequence</td>
</tr>
<tr>
<td>NPRA</td>
<td>The Northern Petroleum Reserve in Alaska</td>
</tr>
<tr>
<td>SOM</td>
<td>Self-Organizing Map</td>
</tr>
<tr>
<td>TST</td>
<td>Transgressive System Tract</td>
</tr>
<tr>
<td>TWT</td>
<td>Two Way Travel</td>
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1. INTRODUCTION

North Slope, Alaska, includes the Colville Foreland Basin, one of the most important hydrocarbons producing basin in the USA (Houseknecht and Bird, 2006). The basin encompasses roughly 240,000 km² (93,000 mi²) and is divided into four tectonostratigraphic mega-sequences that include oil- and gas-prospective strata; from oldest to youngest, Pre-Mississippian Franklinian, Mississippian-Triassic Ellesmerian, Jurassic through Early Cretaceous Beaufortian, and Cretaceous-Tertiary Brookian mega-sequences (Bird, 1987; Houseknecht 2003, Houseknecht, 2019a).

The Colville Foreland Basin has three major petroleum provinces: The Northern Petroleum Reserve (NPRA), Central North Slope Alaska, and 1002 Area of Arctic National Wildlife Refuge (ANWR) (Fig. 1) (Houseknecht and Bird, 2006). These provinces contain important oil-producing fields such as Prudhoe Bay, Kuparuk River, Alpine, Greater Mooses Tooth, Colville River, and Pikka-Horseshoe oil-gas fields. Besides these current hydrocarbons producing fields, recent studies focused on the undiscovered hydrocarbon occurrences in the Central North Slope of Alaska. An assessment by the United States Geological Survey (USGS) in 2020, reported that there are 3.6 billion barrels of oil and 8.9 trillion cubic feet of natural gas conventional reserves in Alaska’s Central North Slope (Houseknecht et al., 2020).
Figure 1. Map of the North Slope, Alaska, with boundaries of the NPRA, Central North Slope, and 1002 Area of the ANWR with tectonostratigraphic provinces. It is modified from a Digital Elevation Model (DEM) image of northern Alaska (Riehle et al., 1997). Physiographic province boundaries are modified from Payne et al. (1951). Red area shows the study area in the Central North Slope Alaska. A-A’ is the cross-section shown in Figure 6. Geologic structures based on Bird (1985) and Grantz and May (1983).

The Nuiqsut area (Fig. 1) is adjacent to the eastern boundary of the Northern Petroleum Reserve in Alaska (NPRA). Previous studies (e.g., Bird 2001, 2018, Houseknecht and Schenk, 2001, and Houseknecht, 2001, 2003) established stratigraphic sequences in the NPRA. The stratigraphy of the Colville Foreland Basin and thickness changes for each-mega-sequence were established by Bird (1984) and Saltus and Bird (2003). Houseknecht (2019a) established a geological framework that describes the sedimentary evolution of the basin.

The Pre-Mississippian Franklinian mega-sequence constitutes the basement rocks of Northern Alaska (Houseknecht and Bird, 2004, Houseknecht, 2019). The overlying Ellesmerian mega-sequence is Mississippian through Triassic in age and was derived from a northerly source in the Arctic Platform (Bird, 2001; Houseknecht, 2019a). In coastal areas, the sediment thickness
changes from 0.5 to 3 km, whereas the thickness range changes from 5 to 6 km in the southern part of the basin (Saltus and Bird, 2003). The Beaufortian mega-sequence overlies the Ellesmerian and is middle Jurassic to Early Cretaceous in age. It was deposited during rifting as the Canada Basin opened (Bird, 2001, Houseknecht, 2003, Houseknecht, 2019). This sequence has a variable thickness from 1.3 km and 0.7 km from south of the Barrow arch to beneath the Brooks Range (Hubbard et al., 1987; Houseknecht and Bird, 2004; Houseknecht, 2019a). The Brookian sequence contains Cretaceous and Tertiary clastic rocks that were derived from the Brooks Range orogeny (Bird and Houseknecht, 2011, Ramon-Duenas, et al., 2018; Houseknecht, 2019a). Helland-Hansen and Hampson (2009) and Houseknecht et al. (2009) stated that Brookian sequence is thinning from Brooks Range into the Canada Basin in general from south to north direction. The Brookian is made up of prograding deposits with the thickness that changes between 0.6 - 2.5 km (Bird and Molenaar, 1992; Houseknecht et al., 2009, 2012; Ramon-Duenas et al., 2018).

The Colville Foreland Basin contains various basinal, submarine-fan, slope, and shelf or delta facies. McMillen (1991) stated that sediment in the basinal facies includes parallel seismic reflections with moderate-amplitude in sandy units and parallel reflections with low-amplitude in shaley intervals. For the submarine fans, McMillen (1991) stated that they have mounded seismic reflection patterns. While slope facies consist of low-amplitude, discontinuous seismic reflections, and isolated continuous seismic reflections in sigmoid and tangential clinoforms, shelf and deltaic facies are characterized by parallel, moderate-amplitude reflections (McMillen, 1991). These facies correspond to different seismic reflection patterns and are mappable to determine lateral lithofacies and depositional changes by using seismic stratigraphic interpretation (Vail, 1987).
The seismic stratigraphy is used to extract stratigraphic information using seismic reflection data to determine relationships. Seismic stratigraphy involves using seismic horizons to divide seismic sequences for the development and assessment of 3D geologic models. A seismic sequence is a set of seismic reflection packages that envelope depositional sequences (Vail, 1987).

In this study, the seismic sequence analysis describes how these genetic depositional intervals are interpreted from seismic data. Seismic horizons are characterized by seismic reflections that represent mappable, isochronous, and sequence boundaries in a depositional environment, which can be presented as three-dimensional surfaces between sequence boundaries (Payton 1977; Wilgus et al., 1988; Tearpock and Bische, 2002; Faraklioti and Petrou, 2004). Considering that it is time-consuming to identify the reflection termination patterns for whole seismic sections, many algorithms are developed to save interpretation time for large 3D seismic volumes. Lou et al. (2020) developed an algorithm that automatically simulates the procedure of manual seismic horizon picking. However, it is very important to verify that the horizon picking algorithms can be used in other data sets to determine their efficiency and accuracy.

This study focuses on the seismic stratigraphic interpretation of the Nanuq South 3D seismic survey acquired over the Nuiqsut area in the Central North Slope Alaska. The seismic survey covers approximately 455 km² (176 mil²) onshore on the north coast of the Central North Slope (Alaska Geologic Materials Center, 2019). The study focuses on understanding the patterns of sediment distribution within the depositional profile and the potential for and distribution of hydrocarbon-bearing strata. In this context, the thickness changes, and depositional systems of each mega-sequence will be established for the Nuiqsut region. In
addition, the efficiency of the horizon picking algorithm developed by Lou et al., (2020) will be evaluated.

This study proposes to bring new insights to the following research questions:

1) How efficient and accurate is an automatic horizon tracking method developed by Lou et al. (2020)?

2) What are the thickness distribution and dominant depositional environments of major seismic stratigraphic sequences in the study area?

3) How does the seismic stratigraphic interpretation in the study area fit into the general geologic history of the North Slope, Alaska?
2. GEOLOGIC OVERVIEW OF THE STUDY AREA

2.1 Tectonic Evolution

The North Slope is located on the Arctic Alaska-Chukotka Microcontinent (AACM), which was a continental fragment (Hubbard et al., 1987). The geological history of North Slope was affected by two major tectonic events; 1) the opening of the Canada Basin in the Arctic Ocean, and 2) the uplift of the Brooks Range (Sweeney, 1985; Mayfield et al., 1983; Coakley and Watts, 1991; Houseknecht, 2019).

During the Jurassic–Early Cretaceous, due to rifting and seafloor spreading of the Canada Basin in the Arctic Ocean, the AACM began to rotate counterclockwise direction from the Canadian margins (~142.5 Ma) (Bird, 1999; Shephard and Seton, 2013; Fig. 2). This counterclockwise rotation of the AACM is the most broadly accepted hypothesis (Tailleur, 1973; Grantz et al., 1998; and Embry, 2000).

Figure 3 shows the tectonic evolution of Circum-Arctic terranes from Early Mississippian time (350 Ma) to the present. During the Brooks Range orogeny (Fig. 3c-3f) that began to form approximately 145 Ma ago during Late Jurassic and Early Cretaceous time (Mull, 1982), the Koyukuk Island Arc and Devonian-to-Jurassic south facing passive margin collided (e.g., Moore et al., 1994). Regional subsidence occurred north of the range forming the Colville Foreland Basin (Bird, 2001).
Figure 2. Topographic map of the circum zone of the Arctic with major structural features. Shaded polygons are approximate regions (modified from Shephard and Seton, 2013). Red rectangular shows the North Slope Alaska.
Figure 3. a) Early Mississippian (ca. 350 Ma), b) Late Triassic–Early Jurassic (ca. 200 Ma), c) Early Cretaceous (Berriasian, ca. 140 Ma), d) Late Cretaceous (Turonian ca. 90 Ma) e) Early Miocene (ca. 20 Ma) and f) present paleotectonics showing initial docking of Circum-Arctic terranes (modified from Blakey, R. (2021)). Red rectangular shows the AACM.
Canada Basin, Beaufort rifted margin with Dinkum Graben, Barrow Arch, Colville Foreland Basin, the frontal fold-thrust belts of the Chukotka (Herald arch) and Brooks Range orogens were formed by these two major tectonic events (Fig. 1). Crustal extension by the counterclockwise rotation of the AACM created a rift system (Grantz and May, 1982), which formed the Barrow arch between the Beaufort rifted margin and Colville Foreland Basin (Houseknecht, 2019). As the plate continued to rotate, the collision with the island belt chain to the south initiated the Brooks Range Orogeny (Bird and Molenaar, 1992). While the Brooks Range continued to uplift, subsidence caused a huge amount of accommodation space to the north, which became the Colville Foreland Basin (Bird and Molenaar, 1992).

2.2 Stratigraphy

Sediment accumulation in the Colville Foreland Basin has evolved from Pre-Mississippian to the present. The basin consists of four major tectonostratigraphic mega-sequences, from oldest to youngest: The Franklinian, the Ellesmerian, the Beaufortian, and the Brookian (Bird, 1987; Houseknecht 2003; Alvey et al., 2008; Helwig et al., 2011) (Fig. 4).

2.2.1 Franklinian Mega-sequence

The Pre-Mississippian Franklinian mega-sequence is the basement of Northern Alaska (Houseknecht and Bird, 2004), and was deposited in the continental margin of Laurentia during terrane accretion. Deposition continued in a foreland basin that was progressively formed during the Ellesmerian orogeny (Trettin et al., 1991; Harrison and Brent, 2005; Embry, 2009; Hadlari et al., 2014, Houseknecht, 2019). It contains various successions (Fig. 4), ranging from metamorphic rocks to local volcanic and intrusive igneous rocks (Bird and Molenaar, 1987; Bird, 1999).
2.2.2 Ellesmerian Mega-sequence

The Mississippian-Triassic age Ellesmerian mega-sequence is divided into two distinct stratigraphic successions (Houseknecht, 2019); Lower Ellesmerian (Mississippian-Permian), and Upper Ellesmerian (Permian-Triassic). The lower Ellesmerian succession is made up of siliciclastic deposits on the bottom and mainly carbonate strata that deposited on a broad platform at the top (Wicks et al., 1991; Moore et al., 1994; Bird, 2001; Sherwood et al., 2002; Dumoulin et al., 2013). This succession contains Endicott Group (siliciclastic) and Lisburne Group (carbonate).

The Upper Ellesmerian contains a wedge of siliciclastic deposits overlying the Lower Ellesmerian strata (Houseknecht, 2019). This succession includes siliciclastic strata of the Sadlerochit Group, mixed carbonate and siliciclastic Shublik Formation, and Sag River Sandstone (Houseknecht, 2019). In the study area, the Ellesmerian mega-sequence shows
variable thickness, ranging from 0.5 to 3 km in the coastal plain (Bird, 1988; Saltus and Bird, 2003).

2.2.3 Beaufortian Mega-sequence

The Jurassic to Early Cretaceous Beaufortian mega-sequence was deposited during a period of rifting (Bird, 2001). The thickness of this mega-sequence ranges from 0.7 to 1.3 km in the study area (Houseknecht, 2001; Houseknecht, 2019). The Kingak Shale consists of marine shale (Hubbard, et al., 1987; Scherr et al., 1991). The Pebble Shale consists of black, organic-rich marine shale which is part of the condensed section that lies unconformably above the Kingak Shale (Moore et al., 1994). These two shale units are separated by a Lower Cretaceous Unconformity (LCU) (Houseknecht, 2003). The LCU is a known migration pathway for regional hydrocarbons and is capped by Cretaceous mudstones that act as a stratigraphic trap (Bird and Molenaar, 1992).

2.2.4 Brookian Mega-sequence

The Brookian mega-sequence contains Cretaceous and Tertiary clastic rocks derived from the Brooks Range orogeny (Bird and Houseknecht, 2011). It is mainly dominated by siliciclastic deposits with shallow marine and terrestrial depositional environments (Houseknecht, 2019). The thickness of the Brookian mega-sequence is between 0.6 and 2.5 km (Bird and Molenaar, 1992; Saltus and Bird, 2003; Houseknecht et al., 2009, 2012; Ramon-Duenas et al., 2018.).

The mega-sequence is divided into three stratigraphic successions: Lower Cretaceous, Upper Cretaceous, and Cenozoic (Houseknecht, 2019). The Lower Cretaceous succession contains GRZ of Hue Shale, Torok Formation, and Nanushuk Formation. The Upper Cretaceous contains the Seabee, Tuluvak, lower part of Canning, Schrader Bluff, and Prince Creek
Formations, while the Cenozoic succession includes the upper part of the Canning Formation and the Sagavanirktok Formation (Houseknecht, 2019). The mega-sequence contains important formations for hydrocarbon exploration like the Hue Shale, Torok, Nanushuk, and Seabee (Bird and Molenaar, 1992; Houseknecht and Bird, 2006).

2.3 Tectonostratigraphic Evolution

The Colville Foreland Basin is bounded by the Brooks Range to the south and the Beaufort Sea to the north, Herald arch and the northward-trending Chukchi platform to the west, and the Alaska-Canada border to the east (Bird and Molenaar, 1992). The generalized cross-section in Figure 5 shows the major structural elements of Central North Slope with related stratigraphy. The location of the profile is shown in Figure 1. The cross-section includes the Brooks Range, the Colville Foreland Basin, the Beaufort rift shoulder, and the Barrow arch with Dinkum Grabens. The orange box represents the approximate location of the study area on the Arctic coastal plain.

The tectonostratigraphic evolution of North Slope is shown in Figure 6. The AACM was part of a passive continental margin during the deposition of the Ellesmerian mega-sequence (Bird and Molenaar, 1992). Beaufortian mega-sequence was deposited during rifting (Miller et al., 2006; Alvey et al., 2008; Bird and Houseknecht, 2011), which created the Barrow Arch that is a hinge line fault zone. This regional structural high caused the Ellesmerian and Beaufortian mega-sequences to uplift and then deposit the south-dipping sediment fill in the study area. On the south, the Brooks Range and the Colville Foreland Basin occurred as a result of the collision of the passive continental margin with arc terrains (Lawver et al., 2002). This event created north dipping sediment fill in the basin.
Figure 5. Generalized vertically-exaggerated N-S regional structural cross-section across the North Slope from the Brooks Range to the northern margin of the Beaufort rift shoulder (modified from Bird and Bader, 1987). The study area located in the northern Colville Foreland Basin. The location of the profile is the blue line in Figure 1.
Figure 6. Schematic diagram demonstrating how stratigraphy affected by rifting process and Brooks Range orogeny (Modified from Gryc, 1985 and Kassarie, 2008).

2.4 Sedimentary Depositional Environments and Facies

In the Ellesmerian mega-sequence, the Endicott Group (lower to middle Mississippian) includes non-marine, marginal-marine, and mainly siliciclastic shallow-marine depositional facies in a regressive-transgressive cycle (Scherr et al., 1991; LePain et al., 1994; Houseknecht, 2019). The Lisburne Group (Mississippian to Early Permian) represents a transgressive cycle with mainly shallow-marine carbonates (Scherr, et al., 1991; Houseknecht, 2019). The
Sadlerochit Group has mainly siliciclastic rock and includes marine, fluvial, floodplain, and alluvial fan sedimentary rocks in a Permian transgressive succession and Triassic regressive-transgressive cycles (Hubbrad, et al., 1987; Scherr et al., 1991; Houseknecht, 2019). The Shublik and Sag River Sandstone Formations represent a transgressive-regressive cycle. The facies change of Shublik and Sag River Sandstone sandy to organic-rich mudstone and limestone, to mudstone (Houseknecht, 2019). The Sag River Sandstone is bioturbated sandstone deposited in the low-energy marine environment (Hubbrad et al., 1987).

The Jurassic to Lower Cretaceous Beaufortian mega-sequence includes marine slope and basin deposits that are dominated by shale (Hubbrad, et al., 1987). These deposits have a southward offlapping depositional succession trend.

The Brookian mega-sequence (Cretaceous to Tertiary) is a syn- and post-tectonic strata related to orogenesis and the home for one of the world’s largest clinothems in a foreland basin setting (Houseknecht, 2019). The seismic facies of the Lower Cretaceous clinothem in the Colville Foreland Basin shows proximal to distal sedimentological variation from west to east (Fig. 7) (Houseknecht, 2019). The GRZ condensed shale is bottomset in the basin. The Torok formation contains foresets deposited in marine-slope and basin facies that contains silty mudstone, and sandstone beds in local turbidite (Houseknecht and Bird, 2009). The Nanushuk Formation is thick fluvial-deltaic shelf succession (topset) and has marine-shelf through non-marine facies with shallow water deposits. This formation contains sandstone and siltstone deposits (Molenaar, 1983).
Figure 7. Conceptional model for Lower Cretaceous clinothem of Brookian Mega-sequence that shows sediment routing system and depositional systems. Heavy blue lines represent lowstand conditions. Abbreviations are: BFF - basin-floor fans, FDW - foredeep wedge, LSM - lowstand shelf margin, LCU - Lower Cretaceous unconformity, PSU - Pebble Shale Unit, GRZ - gamma-ray zone of Hue Shale (modified from Houseknecht et al., 2009b).
3. SEISMIC STRATIGRAPHIC ANALYSIS

Seismic stratigraphic analysis uses the combination of well and seismic data to examine the sequence boundaries (Veeken, 2007). Depositional sequence boundaries need to be determined to define the system tract and provide information on ancient sediment accumulation conditions (Van Wagoner et al., 1988). These boundaries in seismic sections are interpreted by using reflector termination patterns to determine the stratal discontinuities. Figure 8a shows the reflector termination patterns on a schematic sequence model. These termination patterns are truncation, toplap, onlap, downlap, and offlap. Depositional sequences and system tracts might be formed by tectonic subsidence, eustatic sea-level change, sediment supply in a basin, and climate variations (Vail, 1987; Fig. 8b). These changes create stratal discontinuities that separate depositional sequences and system tracts from one another (Vail, 1977; Mitchum, 1977).

Based on reflection termination patterns, seismic reflections can be subdivided into systems tracts: lowstand system tract (LST), transgressive system tract (TST), highstand system tract (HST), and regressive system tract (Van Wagoner et al. 1987; Vail, 1987; Veeken, 2007, Fig. 9).
Figure 8. a) Sequence boundaries defined by reflection termination patterns. b) Seismic reflection, lithofacies, and major variables that effects stratigraphy (modified from Vail, 1987).
3.1 Seismic Facies Units and Seismic Facies Classification

Seismic facies analysis allows mapping the distribution of the defined seismic facies (Mitchum, 1977). Thus, depositional interpretations can be achieved by using seismic data. Seismic facies can be defined and grouped according to their reflection patterns. In this way, these groups can be separated to their seismic reflection patterns that include configuration, amplitude, continuity, frequency, and interval velocity (Mitchum, 1977). Seismic attributes are commonly used in assisting seismic facies analysis. Reflection configuration includes parallel, subparallel, divergent, prograding, and chaotic patterns (Mitchum, 1977). Reflection groups with the same seismic reflection patterns form a seismic facies unit. Table 1 shows the reflection configuration within a sequence and its sub-groups.
Table 1. Geologic interpretation of seismic facies parameters (Mitchum, 1977)

<table>
<thead>
<tr>
<th>Reflection Configuration</th>
<th>Geometric explanation</th>
<th>Depositional energy of the environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Parallel                 | Uniform rates of deposition  
Subparallel                | Generally, deposit on a uniformly subsiding shelf or stable basin plain setting. |
| Divergent                | Lateral variations in the rate of deposition, or progressive tilting. |
| Sigmoid                  | Low sediment supply, Relatively rapid basin subsidence, Rapid rise in sea level to allow deposition and preservation of the topset units, A relatively low-energy sedimentary regime. |
| Oblique                  | Relatively high sediment supply, Slow to no basin subsidence, A stillstand of sea level to allow rapid basin fill and sedimentary bypass or scour of the upper depositional surface, A relatively high-energy sedimentary regime. |
| Combination              | Smaller scale depositional sequences, Discrete lobes of a prograding depositional unit. |
| Shingled                 | Depositional units prograding into shallow water. |
| Hummocky                 | Strata forming small, interfingering clinoform lobes building into shallow water in a prodelta or inter-deltaic position. |
| Chaotic                  | Deposited in a variable, relatively high-energy setting, or as initially continuous strata which have been deformed so as to disrupt continuity. |
4. DATA and METHODS

4.1 Seismic and Well Data

The 3D seismic dataset includes the Nanuq South 3D seismic survey covering approximately 175.7 mi² (≈455 km²) with a bin size of 110 ft x 110 ft and average fold of 35. The 3D seismic survey consists of 716 inline and 728 crossline sections. Figure 1 shows the 3D seismic cube and Horseshoe 1 and Itkillik River Unit 1 wells in the study area and Cronus 1 and Flat Top 1 wells nearby (Fig. 10 and Fig. 11).

Figure 10. The 3D seismic volume with the locations of available wells.
Figure 1. Location of wells. The yellow closed curve shows the basemap of the seismic survey.

4.2 Seismic Character

Four main zones were recognized in the seismic data (Fig. 12): a) permafrost area with chaotic reflection (Zone A, Fig.12a), b) clinoform progradation (Zone B, Fig.12b), c) high-amplitude reflectors beneath the clinoforms (Zone C, Fig.12c), and d) chaotic basement (Zone D, Fig.12d).

Permafrost is defined as sediments that have remained at or below zero degrees C. In the North Slope, the thickness of the permafrost layer usually ranges from 300 m to 600 m, and reaching the maximum thickness beneath the Arctic coastal plain of the Central North Slope (Matson et al., 2013). The permafrost zone has a negative impact on the seismic quality (Zone A, Fig. 13).
Figure 12. A representative crossline seismic section showing seismic character of the study area.
Figure 13. a) Inline, and b) crossline seismic sections for Zone -A showing the permafrost layer. The blue and red lines show the location of the inline and crossline on the seismic basemap.

Zone B represents prodeltaic deposits from Brookian mega-sequence. The seismic section in Figure 14 shows low amplitude seismic reflection intervals that are separated by thinner, high-amplitude continuous reflections.

Zone C contains parallel and semi-parallel reflections with variable amplitude from high to low (Fig. 15). High amplitude reflectors are laterally continuous and are dominantly parallel. Moderate to low amplitude reflectors are semi-continuous. Zone D corresponds to the basement (Fig. 15). The top of the basement shows high amplitude with an angular unconformity.
Figure 14. Seismic section showing clinoform with sigmoidal geometry in Zone B.

Figure 15. The seismic section for Zone -C, and Zone -D showing the parallel and semi-parallel reflections with variable amplitude from high to low, and basement complex, respectively. a) crossline seismic section, b) inline seismic section.
4.3 Methods and Workflow

Vail (1987) indicated that the seismic stratigraphy interpretation procedure consists of seven steps: 1) Seismic sequence analysis, 2) Well-log sequence analysis, 3) Well-to-seismic ties, 4) Seismic facies analysis, 5) Interpretation of depositional environment and lithofacies, 6) Forward seismic modeling and 7) Final interpretation. Steps six and seven are out of the research scope of this thesis. Figure 16 shows the workflow. First, I interpreted the sequence boundaries and seismic horizons with the aid of an auto-picking algorithm. Then, seismic well tie and depth conversion were performed to determine the formations in the seismic section and to generate thickness maps of each mega-sequence, respectively. Finally, seismic facies maps were generated to show the spatial distribution of seismic reflections based on changes in configuration, continuity, and amplitude within the Brookian mega-sequence.

Figure 16. The workflow followed during the study.
4.3.1 Seismic Well Tie

The seismic well-tie was used to correlate the formations observed from well-logs in depth-domain with seismic horizons in the time-domain (Cunningham and Droxler, 2000; Yılmaz, 2001). The seismic well-tie procedure correlates seismic traces at the well location and a synthetic trace computed from well-logs and the seismic wavelet. First, acoustic impedance (AI) is computed by multiplying density log with velocity. Then, reflection coefficient (RC) is calculated using the formula given below.

\[ RC = \frac{AI_{n+1} - AI_n}{AI_{n+1} + AI_n} \]

where \( n \) is the formation index. Next, the synthetic seismogram is generated using:

\[ S = RC \ast W, \]

where \( \ast \) stands for convolution operator, \( W \) is a wavelet defined by interpreter (e.g., Ricker wavelet) or extracted from seismic and well data.

After generating the synthetic seismogram, the well tops and seismic reflections are matched by aligning seismic reflections with the synthetic seismogram. Horseshoe 1 and Itkillik River Unit 1 wells were used for the seismic well-tie. While Horseshoe 1 well was used to determine the Seabee and Nanushuk Top Formation, the Itkillik River Unit 1 well was used to determine the Torok, GRZ of Hues Shale, Pebble Shale, LCU, Kingak Shale, Sag River Sandstone, Shublik Formations, and Basement. Figure 17 shows a seismic well-tie created using the Horseshoe 1 and Itkillik River Unit 1 well data. The Itkillik River Unit 1 well does not have density logs between 1200-1600 ms, 1850-2000 ms and 2200-2600 ms. Density logs within those intervals were calculated from the sonic log using Gardner’s equation (Gardner et al., 1974): \( \rho = 0.23V_p^{0.25} \)
Figure 17. Well logs and synthetic seismogram from the A) Horseshoe 1 well and B) Itkillik Unit River 1 well. The Horseshoe 1 well has A1) density log (red), A2) sonic log (black), and A3) gamma ray (GR) logs (green). The Itkillik River Unit 1 well has B1) original density log (crimson), B2) corrected density log from sonic log using Gardner’s equation (red), B3) sonic log (black), B4) gamma ray logs (green). The synthetic is shown with the calibrated sonic log, density log (blue), acoustic impedance, reflection coefficient, and seismic image of Horseshoe 1 where the well is located.
4.3.2 Horizon Picking

A semi-automatic horizon interpretation method developed by Lou et al. (2020) was used for horizon picking. This algorithm simulates the procedure of manual seismic horizon interpretation. First, manually interpretation is performed on a coarse grid of seismic survey. Then, the algorithm uses the manually picked reference horizon to track the horizons within the 3D dataset. Tracking these numbers of the manual interpreted seismic sections provides an answer for the first research question. The aim is to determine how many manually interpreted seismic sections are needed for the algorithm to function properly. The third step is the auto-picking where the algorithm tracks the sequence boundaries on every inline and crossline. The final step is manually checking the quality of the automatically extracted sequence boundaries. Figure 18 shows an example of an interpreted horizon. With the yellow curve illustrating one manually interpreted horizon on one representative inline section. Figure 18b shows the automatically extracted horizon under the constraints of the manually interpreted horizon(s) shown in Figure 18a. The white zone in Figure 18b is the area where the algorithm failed to extract the horizon. Thus, I manually interpreted the horizons of the white zone shown in Figure 18b. Figure 18c illustrates one representative seismic section with a 2D and 3D interpreted horizon.
Figure 18. Extracted horizon and its grid that derived from automatic horizon picking algorithm.
4.3.3 Time to Depth Conversion and Thickness Map Generation

After the horizon interpretation on seismic sections in the time domain, the time-to-depth conversion was applied to calculate thickness changes in the mega-sequences. The conversion process utilized velocity, depth, and lithology information to generate a velocity model for the time-depth conversion. Well data include sonic logs P-wave (Vp) and S-wave (Vs), gamma-ray, resistivity, bulk density, neutron porosity and sonic logs. In this study, I use a simple velocity model derive from the Vp log,

\[ V = V_0 + k \times (Z - Z_0) \]

where, \( V \) is the velocity (ft/s) at the depth of \( Z \), \( V_0 \) is the velocity at the depth of \( Z_0 \), and \( k \) is the velocity factor (a constant value).

Time surface maps were converted into depth maps via the defined velocity model. Thickness maps of sequences were generated from interpreted horizons to evaluate depositional trends and sub-regional variations in the stratigraphic thickness of each mega-sequences. After the data were depth converted, thickness maps were constructed by subtracting the depth of the bottom surface from the depth of top surface.

4.3.4 Self-Organizing Mapping (SOM)

Seismic facies maps were generated for Brookian mega-sequence to show the spatial distribution of seismic facies based on changes in seismic reflection configuration, continuity, and amplitude. The Self Organizing Mapping (SOM) (Kohonen, 2001) is a pattern recognition technique used for unsupervised seismic facies analysis. SOM analysis captures the information residing in input seismic attributes by reorganizing data samples based on their topological relation (Zhao and Marfurt, 2016). The aim of the SOM is to delineate seismic facies in the depositional system.
Roy (2013) gave a fruit analogy example to explain the working principle of SOM. Figure 19a shows fruit with different properties in terms of aspect ratio (fruit shape), peak frequency (fruit color), and vitamin C content. After SOM cluster analysis, the fruit were arranged into three major groups (Roy, 2013; Fig. 19b). The fruit that were round, red, and high vitamin C content were grouped as Cluster 1; elongated, green, and medium vitamin C fruits were in Cluster 2; round, blue, and high vitamin C content fruit were grouped in Cluster 3.

Seismic attributes are input parameters for SOM analysis such as fruit. SOM organizes the dataset of input seismic attributes where the values are normalized or standardized to the same scale (Roden and Sacrey, 2017).

The most critical step in seismic facies analysis is properly selecting the seismic attributes. The commonly used seismic attributes include amplitude, phase, frequency, and polarity properties of seismic data. These attributes are displayed in different color options, helping to observe the relationships and changes between them (Fig 20). Attribute selection in turn depends on careful pattern recognition by the interpreter (Zhao and Marfurt, 2016). The goal is to get fruitful results from the input by selecting the most appropriate group of attributes for seismic facies analysis (Zhao et al., 2015). Figure 20 illustrates the workflow of seismic facies analysis using SOM. First, a set of seismic attributes are properly selected by the interpreter. Then, the seismic attributes are mappable into a 2D topological space. Next, a 2D color bar is chosen to properly display classified results. Finally, the classified results are interpreted after calibration with seismic reflection patterns and well logs (Zhao et al., 2015).
Figure 19. Analogy of classification of fruits illustrating unsupervised SOM clustering analysis. 
a) The fruits before training were unorganized; b) Clustering of the fruits after training using 
three attributes (color, aspect ratio and Vitamin C content of the individual fruits), (modified 
from Roy et al., 2013).
In this study, 70 choices were tried to get an ideal of multi-attribute visualization. Zhao et al. (2015) state that images that are ideal for multi-attribute visualization may be suboptimal for clustering. Thus, it is important to obtain information matching the seismic data for the analysis to be interpretable.

I used geometric, spectral decomposition and texture attributes as input attributes to run the SOM algorithm. These input attributes are sensitive to strata thickness, lithology, and structural deformation, to illuminate the depositional elements presented in the sequence that were interpreted. It is expected to explain the variation in lithology caused by sedimentation. Table 2 explains the attributes that were used and their purpose. Figure 21 shows the representative input attribute surface used.
Generally, seismic geometric attributes, such as dip, curvature, rotation, and convergence, are used to delineate reflector morphology (Chopra and Marfurt, 2007; Zhao et al., 2015). Spectral attributes, such as peak spectral frequency and peak spectral magnitude, crudely represent the spectral response of the seismic data (Zhao et al., 2015). They can be used to differentiate thick from thin channels and overbank deposits (Zhao et al., 2015). Texture attributes provide information about data distribution that quantifies subtle patterns that are hard to define (Chopra and Marfurt, 2007, Zhao et al., 2015). Figures 22, and 23 show the 3D classified volume and classified resulted on one representative strata slice.

Table 2. Attributes used and their purpose (Zhao, et al., 2015; Zhao and Marfurt, 2018)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Why Using This Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Curvedness</td>
<td>To define structural or stratigraphic deformation,</td>
</tr>
<tr>
<td></td>
<td>• Dome-, ridge-, saddle-, valley-, and bowl-shaped features exhibiting high curvedness</td>
</tr>
<tr>
<td></td>
<td>• Planar features exhibiting zero curvedness.</td>
</tr>
<tr>
<td>2) Shape Index</td>
<td>To highlight incisement, channel flanks, and levees,</td>
</tr>
<tr>
<td></td>
<td>• High; dome shape</td>
</tr>
<tr>
<td></td>
<td>• Low; valley shape</td>
</tr>
<tr>
<td>3) Sobel Filter Similarity</td>
<td>To determine lateral changes in the area, Identifying channels, faults, and other types of breaks in reflectors.</td>
</tr>
<tr>
<td>4) Peak Spectral Frequency</td>
<td>High; Shale filled with negative compaction channel thalwegs</td>
</tr>
<tr>
<td></td>
<td>Low; Sand filled with positive compaction channel thalwegs</td>
</tr>
<tr>
<td>5) Peak Spectral Magnitude</td>
<td>High; Channel flanks, onlap onto incisement and canyon edges, dome shape</td>
</tr>
<tr>
<td></td>
<td>Low; Floodplain with lower amplitude, valley shape</td>
</tr>
<tr>
<td>6) Coherent Energy</td>
<td>The evidence of high-energy</td>
</tr>
<tr>
<td>7) GLCM Homogeneity</td>
<td>Imaging the depositional features (channels, fans, and lobes)</td>
</tr>
<tr>
<td></td>
<td>High; Levee, Gas-charged sands, flood plain</td>
</tr>
<tr>
<td></td>
<td>Low; chaotic area or slumps</td>
</tr>
</tbody>
</table>
Figure 21. The input attribute surface used in workflow. Horizon probes showing a stratal slices in an arbitrary seismic section across the survey for each calculated attributes for SOM. a) coherent energy, b) GLCM homogenety, c) shape index, d) peak spektral frequency, e) peak spektral mag., f) curvedness, and g) sobel filter similarity.
Figure 22. An unsupervised seismic facies 3D cube after the SOM analysis.

Figure 23. Unsupervised seismic facies showing exported a stratal slice in an arbitrary seismic section across the survey.
5. SEISMIC INTERPRETATION

5.1 Determining Seismic Boundaries

5.1.1 Determining Formation Tops

Ten formation horizons have been identified in the seismic data using seismic well-ties. These horizons include the Franklinian Basement, Endicott, Lisburne, Sadlerochit-Shublik, Sag River, Kingak-LCU, Pebble Shale, GRZ, Torok, and Nanushuk. The seismic data that correspond to the Seabee and younger formations (Tuluvak, Schrader Bluff, Prince Creek, and Sagavanirktok) generally show poor data quality in the Brookian mega-sequence, due to the presence of permafrost.

Figure 24 shows the gamma-ray (GR) responses of the Itkillik River Unit 1 well. Each mega-sequence was determined by using the gamma ray log. The interval between the Endicott Group base and the Sag River Sandstone top is defined as Ellesmerian mega-sequence. The Beaufortian mega-sequence is between the Kingak base and the Pebble Shale top. The Brookian mega-sequence encompasses the base of GRZ to present deposits. However, only the Lower Cretaceous part of the Brookian mega-sequence was interpreted on seismic. A selected seismic section in Figure 25 shows the green, pink and blue horizons represent the Brookian, Beaufortian, and Ellesmerian mega-sequences respectively.
**Figure 24.** A stratigraphic column along with the gamma-ray curve (GR) from the Itkillik 1 well (shown in Figure 1). MD is measured depth in the well log; MS corresponds to mega-sequence: Brookian, Beaufortian, and Ellesmerian.
Figure 25. Interpreted horizons during the study. Itkillik Unit River 1 well displayed on a seismic cross section. Each white point along the well trajectory corresponds to a well top pick of a formation. Brown, blue, pink, and green horizons represent Franklinian Basement, Ellesmerian, Beaufortian, and Brookian mega-sequences, respectively.
5.1.2 Determining the Sequence Boundaries, Brookian Mega-sequence

To assist the following seismic facies analysis, four stratigraphic surfaces (T2, T3, T4, T5) were determined in the seismic data using reflector termination patterns. The Brookian mega-sequence represents a prodeltaic seismic sequence. Based on descriptions of geometric reflector patterns given in Figure 8, the types of reflector terminations were recognized in Torok Formation.

Figure 26a shows low amplitude seismic reflection intervals (between 1000-1400 ms) that are separated by thinner, high-amplitude continuous reflections. Figure 26b shows the transitions of topsets to foreshots to bottomsets via onlap and downlap (red arrows) in the prograding clinoform (green lines). Toplap reflectors pinch out basinward. On the landward side, there is a thin zone of gently dipping (~1°) strata to the southeast, whereas the middle part is getting thicker with southeastwards-dipping strata, and foreset slope angle changes between 3° and 4°. The basinward side shows another thin zone that dips gently (~1°) to the southeast.

The progradational cycle in the Brookian mega-sequence is separated by major, regionally flooding events that correspond to relative sea level changes and substantial shifts of the paleoshoreline (Decker, 2007). For this reason, the Brookian mega-sequence was calibrated with available GR logs to show system tracts (Figs. 27 and, 28). Because the Horseshoe 1 well only has well logs between 0-1200 ms in time domain (after seismic-well-tie), the sub-units below the 1200 ms on seismic sections could not be correlated with this well. In addition, in the Itkillik River Unit 1 well, the system tract determination was difficult where the bottomset thins. The abrupt changes of the GR responses were related to unconformities. The prograding zone consists of highstand systems tract (HST), transgressive systems tract (TST), and lowstand
systems tract (LST) (Figs. 27 and 28). After determining the sequence boundaries, all interpreted horizons are shown in Figure 29.

**Figure 26.** a) Uninterpreted selected seismic section showing the clinoform geometry, b) Interpreted horizons (green lines) in the seismic section based on reflection geometry. Yellow lines show the formation boundaries that are tied from available wells.
Figure 27. Systems tracts interpretation from GR log of Horseshoe1 Well. a) Uninterpreted seismic section, b) interpreted systems tracts overlaid on seismic.
Figure 28. Systems tracts interpretation from gamma-ray (GR) log of Itkillik River Unit 1 Well. a) Uninterpreted seismic section, b) interpreted systems tracts overlaid on seismic.
Figure 29. Interpreted horizons by correlating the seismic boundaries, and stratigraphy. Itkillik Unit River 1 well displayed on a seismic cross section. Each white point along the well trajectory corresponds to a well top pick of lithologic formation. Brown, blue, pink, and green horizons represent Franklinian Basement, Ellesmerian, Beaufortian, and Brookian mega-sequences, respectively.
5.2 Seismic Horizon Interpretation

Fourteen horizons were interpreted in the Nanuq South 3D seismic survey. Figure 30 shows the basemap of the seismic survey with the location of three inline and crossline sections. Those six vertical seismic sections are used to illustrate depositional interactions. The sequence boundaries are grouped and colored in terms of mega-sequences. Ellesmerian, Beaufortian, and Brookian boundaries were colored by blue, pink, and green, respectively. Figures 31 to 36 illustrate seismic cross-sections with interpretations.

Figure 30. The locations of the chosen six seismic cross-sections. The red and blue lines represent crosslines and inlines, respectively.
Figure 31. Seismic crossline 10859 showing horizons based on mega-sequences. The orange line is the basement, the blue, pink, and green lines represent Ellesmerian, Beaufortian, and Lower Cretaceous Brookian Mega-sequences, respectively. Faults are shown black lines.
Figure 32. Seismic crossline 10644 showing horizons based on mega-sequences. The orange line is the basement, the blue, pink, and green lines represent Ellesmerian, Beaufortian, and Lower Cretaceous Brookian Mega-sequences, respectively. Faults are shown black lines.
**Figure 33.** Seismic crossline 10429 showing horizons based on mega-sequences. The orange line is the basement, the blue, pink, and green lines represent Ellesmerian, Beaufortian, and Lower Cretaceous Brookian Mega-sequences, respectively. Faults are shown black lines.
Figure 34. Seismic Inline 49029 showing horizons based on mega-sequences. The orange line is the basement, the blue, pink, and green lines represent Ellesmerian, Beaufortian, and Lower Cretaceous Brookian Mega-sequences, respectively.
Figure 35. Seismic Inline 48818 showing horizons based on mega-sequences. The orange line is the basement, the blue, pink, and green lines represent Ellesmerian, Beaufortian, and Lower Cretaceous Brookian Mega-sequences, respectively.
Figure 36. Seismic Inline 48582 showing horizons based on mega-sequences. The orange line is the basement, the blue, pink, and green lines represent Ellesmerian, Beaufortian, and Lower Cretaceous Brookian Mega-sequences, respectively.
To accelerate seismic interpretation, an auto-picking algorithm was used under the constraints of manual horizon interpretation. Table 3 shows the minimum number of interpreted seismic sections that were needed to produce an accurate horizon for each stratigraphic boundary. Figures 37 - 50 show the locations of manually interpreted seismic sections and computed surfaces, respectively. A 3D view of interpreted horizons is shown in Figure 51.

Table 3. Minimum number of manually picked horizons.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Ellesmerian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Endicott Group</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Lisburne Group</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Sadlerochit-Shublik</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Sag River Sandstone</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Beaufortian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kingak- LCU</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pebble Shale</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Brookian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRZ of Hue Shale</td>
<td>4</td>
<td>4</td>
</tr>
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<td>Torok_5 (T5)</td>
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</tr>
<tr>
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</tr>
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<td>Torok_1 (T1)</td>
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<td>7</td>
</tr>
<tr>
<td>Nanushuk Fm.</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>112</td>
<td>109</td>
</tr>
</tbody>
</table>
Figure 37. a) Location of manually interpreted inline and crossline of the basement through seismic. b) Surface grid result of the Basement through seismic. The green arrow shows North.

Figure 38. a) Location of manually interpreted inline and crossline of Endicott Group through seismic. b) Surface grid result of the Endicott Group through seismic. The green arrow shows North.
Figure 39. a) Location of manually interpreted inline and crossline of Lisburne Group through seismic. b) Surface grid result of the Lisburne Group through seismic. The green arrow shows North.

Figure 40. a) Location of manually interpreted inline and crossline of Sadlerochit-Shublik through seismic. b) Surface grid result of the Sadlerochit-Shublik through seismic. The green arrow shows North.
Figure 41. a) Location of manually interpreted inline and crossline of Sag River Ss. through seismic. b) Surface grid result of the Sag River Ss. through seismic. The green arrow shows North.

Figure 42. a) Location of manually interpreted inline and crossline of Kingak - LCU. through seismic. b) Surface grid result of the Kingak-LCU through seismic. The green arrow shows North.
Figure 43. a) Location of manually interpreted inline and crossline of Pebble Shale Unit. through seismic. b) Surface grid result of the Pebble Shale Unit through seismic. The green arrow shows North.

Figure 44. a) Location of manually interpreted inline and crossline of GRZ. through seismic. b) Surface grid result of the GRZ through seismic. The green arrow shows North.
**Figure 45.** a) Location of manually interpreted inline and crossline of Torok (T5) through seismic. b) Surface grid result of the Torok (T5) through seismic. The green arrow shows North.

**Figure 46.** a) Location of manually interpreted inline and crossline of Torok (T4) through seismic. b) Surface grid result of the Torok (T4) through seismic. The green arrow shows North.
Figure 47. a) Location of manually interpreted inline and crossline of Torok (T3) through seismic. b) Surface grid result of the Torok (T3) through seismic. The green arrow shows North.

Figure 48. a) Location of manually interpreted inline and crossline of Torok (T2) through seismic. b) Surface grid result of the Torok (T2) through seismic. The green arrow shows North.
Figure 49. a) Location of manually interpreted inline and crossline of Torok (T1) through seismic. b) Surface grid result of the Torok (T1) through seismic. The green arrow shows North.

Figure 50. a) Location of manually interpreted inline and crossline of Nanushuk through seismic. b) Surface grid result of the Nanushuk through seismic. The green arrow shows North.
Figure 51. 3D presentation of interpreted horizons. The green arrow shows North.

5.3 Mega-sequence Interpretation

5.3.1 Ellesmerian Mega-sequence Interpretation

The Ellesmerian is composed of the basement, Endicott Group, Lisburne Group, Sadlerochit-Shublik, and Sag River Sandstone. The lower sequence boundary is defined as the basement that is an identifiable unconformity (Fig. 52). The Ellesmerian mega-sequence pinches out by onlap onto the Franklinian basement (Fig. 53). During Triassic to Mississippian time, the Endicott, Lisburne, Shublik, and Sag River sub-sequences were deposited on top of the basement.
Figure 52. An arbitrary seismic section across the survey showing the Ellesmerian mega-sequence and its top of sub-sequences boundaries. The black lines are identified as major faults. The green arrow shows North.

Figure 53. 3D presentation of interpreted horizons in the Ellesmerian mega-sequence. The green arrow shows North.

Figures 54 – 58 show a chair display of seismic data and time-structure maps of the basement, top of Endicott Group, top of Lisburne Group, top of Shublik-Sadlerochit, and top of Sag River Sandstone.
Figure 54. Time structure map of the Basement horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.

Figure 55. Time structure map of the Endicott Group horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.
Figure 56. Time structure map of the Lisburne Group horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.

Figure 57. Time structure map of the Shublik-Sadlerochit Group horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.
5.3.2 Beaufortian Mega-sequence Interpretation

The Beaufortian mega-sequence is bounded by the Pebble horizon at the top and, Kingak horizon at the base (Fig. 59 and Fig. 60). The top of Kingak group is the LCU boundary with a distinct truncation of reflections. Time-structure maps with seismic sections are in Figures 61 and, 62.

Figure 58. Time structure map of the Sag River horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.

Figure 59. An arbitrary seismic section across the survey showing the Beaufortian mega-sequence and its sub-sequences. The green arrow shows North.
**Figure 60.** 3D presentation of interpreted horizons in the Beaufortian mega-sequence. Gray surface represents bottom of Kingak which corresponds to the top of Sag River Sandstone in Ellesmerian mega-sequence. The green arrow shows North.

**Figure 61.** Time structure map of the LCU-Kingak horizon with arbitrary lines. The red lines are identified as major faults. The color bar shows the time values in seconds. Blue line represent the top of Sag River Sandstone in Ellesmerian mega-sequence. The green arrow shows North.
Figure 62. Time structure map of the Pebble Shale horizon with arbitrary lines. The red lines are identified as major faults. The color bar shows the time values in seconds. Blue line represent the top of Sag River Sandstone in Ellesmerian mega-sequence. The green arrow shows North.

5.3.3 Brookian Mega-sequence Interpretation

The members of the Lower Cretaceous Brookian mega-sequence include Nanushuk Formation, Torok Formation, and GRZ of Hue Shale (Fig. 63). Seven sequence boundaries are distinguished: Nanushuk, Torok1 (T1), Torok2 (T2), Torok3 (T3), Torok4 (T4), Torok5 (T5), GRZ of Hue Shale. The T1-T5 boundaries were determined in the Torok Formation based on clinoform geometry (Fig. 64). Time-structure maps for each sub-sequence are shown in Figure 65 – 71.
Figure 63. An arbitrary seismic section across the survey showing the Brookian mega-sequence and its sub-sequences. The green arrow shows North.

Figure 64. 3D presentation of interpreted horizons in the Brookian mega-sequence. The green arrow shows North.
Figure 65. Time structure map of the GRZ of Hue Shale horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.

Figure 66. Time structure map of the T5 horizon with identified incised valleys. The red lines are identified as major faults. The green arrow shows North.
Figure 67. Time structure map of the T4 horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.

Figure 68. Time structure map of the T3 horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.
Figure 69. Time structure map of the T2 horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.

Figure 70. Time structure map of the T1 horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.
Figure 71. Time structure map of the Nanushuk horizon with arbitrary lines. The red lines are identified as major faults. The green arrow shows North.
6. THICKNESS MAP OF MEGA-SEQUENCES

Thickness maps for each mega-sequence were used to analyze seismic stratigraphic features and depositional systems. The stratigraphic intervals and depth converted surface grids were used to generate thickness maps for each mega-sequence.

6.1 Ellesmerian Mega-sequence Thickness Distribution

The Ellesmerian mega-sequence contains the Sag River Sandstone to Franklinian basement. The thickness decreases gradually from ~1450 m in the west to 685 m in the east (Fig. 72). This mega-sequence exhibits maximum thickness to the northwestern part.

The 3D conceptional depositional model for the Ellesmerian mega-sequence is shown in Figure 73. The Ellesmerian mega-sequence formed as continental shelf deposits on a passive margin started before counter-clockwise rotation of Canada Basin. Sediments were derived from the Arctic platform deposited east to west direction.
**Figure 72.** Thickness map (based on depth converted 3D seismic) showing the thickness variations from Basement to Sag River Sandstone for Ellesmerian mega-sequence. The green arrow shows North.

**Figure 73.** 3D conceptional depositional model of Ellesmerian mega-sequence showing Sag River Sandstone, Sadlerochit-Shublik, Lisburne Group and, Endicott Group. The green arrow shows North.
6.2 Beaufortian Mega-sequence Thickness Distribution

The Beaufortian mega-sequence is between the Pebble Shale and the top of Sag River Sandstone. The thickness reaches its maximum in the south (approximately 624 m), and minimum value in the north (approximately 441 m) (Fig. 74).

Figure 74. Thickness map (based on depth converted 3D seismic) showing the thickness variations from Sag River Sandstone to Pebble Shale Unit for the Beaufortian mega-sequence. The green arrow shows North.

The 3D conceptional depositional model of the Beaufortian mega-sequence and its sub-sequences is shown in Figure 75. This mega-sequence, which was occurred during the rift opening of the Canada Basin, accumulates from the north to the south due to the counterclockwise rotation of AACM.
Figure 75. 3D conceptional depositional model of Beaufortian mega-sequence showing the Sagriver Sandstone and Kingak Shale. The green arrow shows North.

6.3 Brookian Mega-sequence Thickness Distribution

Two thickness maps were constructed for the Brookian mega-sequence, one shows the Lower Cretaceous Nanushuk Fm. to Pebble Shale interval (Fig. 76); and one from Pebble Shale to the present surface (Fig 77). Determination of the original, maximum depositional thickness is difficult because of the presence of permafrost and poor seismic resolution in the shallow part of the seismic data. Figure 76 shows that sediment thickness of the Lower Cretaceous succession is thinning gradually towards the northeastern part of the study area from 1.2 to 0.7 km. The second thickness map (Fig. 77) also shows that sediment thickness decreases towards the northeastern and changes from 2 km to 1.7 km during the Lower Cretaceous–present time.
Figure 76. Thickness map (based on depth converted 3D seismic) showing the thickness variations from Pebble Shale to Nanushuk Fm. for Lower Cretaceous Brookian mega-sequence. The green arrow shows North.

Figure 77. Thickness map (based on depth converted 3D seismic) showing the thickness variations from Pebble Shale Unit to present. The green arrow shows North.
The Brookian sequence was deposited as part of the major delta system. The 3D conceptional depositional model shows the sub-sequences in Brookian mega-sequence (Fig. 78). Houseknecht (2009) determined that the source of sediments in the Nanushuk and Torok formations were the Brooks Range orogenic highs in the south and the Chukotka highlands that originated at the onset of subsidence of Hanna Trough (Late Devonian time) in the southwest (Fig 7). In the distal zone of the basin, the eastward tilting of the basin caused the basin depocenter to migrate through time to the east, subparallel to the Brooks Range (Bird and Molenaar, 1992) (Fig. 7). My interpretation shows that the patterns of the depositional sequences show a west to east progradational geometry. This sequences gradually thickens southward.

Figure 78. 3D conceptual depositional model of the Brookian mega-sequence, showing the Nanushuk, Torok, and GRZ formations. The permafrost zone is shown in blue. The green arrow shows North.
7. SEISMIC FACIES DISTRIBUTION IN PROGRADING ZONE

The Brookian mega-sequence presents fundamental depositional cycles (Decker, 2007). The seismic data contains the Nanushuk -Torok depositional cycle, one of the important depositional cycles in the Brookian mega-sequence. This depositional cycle includes shelf edges, slope, channels, and basin-floor fans (BFF), with significant seismic reflection patterns. These types of components indicate the most likely location of reservoirs. For that reason, I applied the SOM analysis on the Brookian mega-sequence to determine the potential reservoir area.

Figure 79 shows the facies map of the top of the Nanuhuk Formation which is expressed as topset reflections of thick fluvial-deltaic-shelf succession (Bhattacharya and Verma, 2020). With mainly contains sandstone, siltstone, mudstone (LePain et al., 2009). The dashed black curve outline the purple zone and, seismic reflection patterns with wavy to hummocky, semi-continuous and moderate amplitude. The dashed white lines outline the lateral continuity of strata with parallel bedding, moderate to high seismic amplitude correspond to yellow area. These facies are generally interpreted as deposited in shallow marine environments.
The seismic facies represented by the purple color are heavily affected by the above permafrost zone (Fig. 80). To illustrate the distribution of possible reservoirs (yellow color), I extract the geobodies (Fig. 80) from the SOM volume by setting the non-reservoir to be transparent. To obtain the reservoir geobodies, I calibrate the SOM volume with the well logs of the Horseshoe1 well. The clusters that correspond to non-reservoir lithologies are set to be transparent in the geobodies extracting.

Figure 81 represents the facies map of the T2 boundary of the Torok Formation that contains channel deposits, prograding shelf edges, canyons, slumps, slide blocks, and basin-floor fans that mainly composed of shale, silty mudstone, and sandstone (Bhattacharya, 2020). This facies represents shallow-marine to slope depositional environments. The dashed white close curve represents a reddish and purple area. The red color represents the area of the lateral continuity of strata with parallel bedding and high to moderate amplitude anomalies, whereas the purple zones are partly chaotic. The dashed black closed curve outlines the area of the wavy, semi-continuous strata with low to moderate amplitude. Figure 82 shows the extracting geobodies from the unsupervised classified volume for horizon T2. The yellow to orange color variations were highlighted by setting other colors transparent to show a basin floor fan (BFF) and their feeder channels. This BFF is marked with a white dashed line.
Figure 79. Seismic facies map from SOM clustering analysis considering 7 input seismic attribute dataset. The green interpretation represents the top of Nanushuk horizon a) The seismic section showing AA' on the facies map. b) The seismic section showing BB' on the facies map. The green arrow shows North.
Figure 80. a) Extracting geobodies from the unsupervised classified volume for Nanushuk horizon. b) The certain seismic facies highlighted with modifying the transparency. The yellow facies from the horizon Nanushuk showing mostly the topset in depositional seismic facies in the area. The blue facies has mainly affected by the permafrost zone. The green arrow shows North.
Figure 81. Seismic facies map from SOM clustering analysis considering 7 input seismic attribute dataset. The green interpretation represents the T2 horizon. a) The seismic section showing AA’ on the facies map. b) The seismic section showing BB’ on the facies map. The green arrow shows North.
Figure 8.2. a) Extracting geobodies from the unsupervised classified volume for T2 horizon. b) The certain seismic facies highlighted with modifying the transparency. The yellow facies from the T2 horizon showing mostly the basin floor fan (BFF) in depositional seismic facies in the area. Red arrows showing the direction of sediment transport. The green arrow shows North.
Figure 83 shows the seismic facies on the T5 boundary of the Torok Formation. The dashed white curve shows red and purple zones. Red color corresponds to the area of the lateral continuity of strata with parallel bedding and high to moderate amplitude anomalies, whereas purple color corresponds to zones that have partly chaotic reflections. The dashed closed black curve outlines zones that have the wavy, semi-continuous strata with low to moderate amplitude. Figure 84 shows the extracted geobodies from the SOM volume for horizon T5. Many SW-NE trending incised valleys were identified in horizon T5. Incised valleys known to contain good potential for petroleum reservoirs (Vail, 1987). The yellow variations were highlighted by setting other colors to be transparent and shows incised valleys that are a source for sediment influx from south-southwest to northeast. In addition, red arrows illustrate the main body of the channels. According to the Itkillik River Unit 1 well gamma-ray response, this yellow corresponds to sandstone lithology.

Figure 85 shows the seismic facies map of the GRZ boundary of the Torok Formation. This horizon corresponds to the bottomset of Torok’s clinoform. GRZ is a highly condensed bed that includes organic-rich shale. Figure 86 shows the extracted geobodies from the SOM volume for horizon GRZ in 3D. Orange color represents the lateral continuity of strata with parallel bedding and high to moderate amplitude anomalies. Considering the Itkillik River Unit 1 well gamma-ray response, the orange corresponds to condensed shale. The GRZ is distributed over the whole area.
Figure 83. Seismic facies map from SOM clustering analysis considering 7 input seismic attribute dataset. The green interpretation represents the T5 horizon. a) The seismic section showing AA’ on the facies map. b) The seismic section showing BB’ on the facies map. Red lines show the base of valleys in the seismic section. The green arrow shows North.
Figure 84. Extracting geobodies from the unsupervised classified volume for T5 horizon. The certain seismic facies highlighted with modifying the transparency. The yellow facies from the horizon T5 showing mostly the basin floor fan (BFF) with incised valleys in depositional seismic facies. The green arrow shows North.
Figure 85. Seismic facies map from SOM clustering analysis considering 7 input seismic attribute dataset. The green interpretation represents the GRZ horizon. a) The seismic section showing AA’ on the facies map. b) The seismic section showing BB’ on the facies map. The green arrow shows North.
Figure 86. a) Extracting geobodies from the unsupervised classified volume for GRZ horizon. b) The certain seismic facies highlighted with modifying the transparency. The orange facies from the GRZ horizon showing mostly the condensed shale zone in depositional seismic facies in the area. The green arrow shows North.
8. DISCUSSION

8.1 Efficiency and Accuracy of the Automatic Horizon Tracking

Fourteen major seismic horizons were interpreted to analyze the depositional system. To accelerate the horizon interpretation procedure, I used an algorithm developed by Lou et al., (2020) to track sequence bounding surfaces automatically. The algorithm tracks the horizon over the whole seismic survey under the constraints of the manually interpreted horizon on the coarse grid. The area where the algorithm failed to extract the horizon needs more manual interpretation (Fig. 18b). The minimum number of interpreted seismic sections was tested for each horizon (Table 2).

Figure 87 summarizes the number of manually interpreted inline (blue), crossline (red), and their total sections (gray) needed for each horizon in the automatic horizon extraction. The seismic survey consists of 716 inline and 728 crossline sections. In this area, only 112 inline and 109 crossline sections were interpreted manually. Considering the number of manually interpreted seismic sections, interpretation effort shows a significant decrease. Figure 87 demonstrates that only a few (8-15) manually interpreted seismic sections are needed for the automatic horizon tracking if the seismic reflections of horizon have parallel-semi parallel and high to moderate continuous reflection. However, the automatic horizon tracking algorithm needs more (17-29) manually interpreted seismic sections across the clinoforms.
Figure 87. The graphic showing manual picking results for each horizon.

In my application, the average time of picking one horizon in an inline/cross section is around 1 minute for parallel to semi-parallel seismic reflection (nine horizons) as in Zone C. However, the average time of picking one horizon (T1, T2, T3, T4, and T5) that crosses the clinoforms for horizons is around 2 minutes. If the interpretation grid is 10 by 10 that means I need to interpret 72 (716/10=72) x 73 (728/10=73) seismic sections as shown in Table 4. As a result, I need approximate seventy days to pick the 14 horizons without any rest. For comparison, the horizon picking algorithm only needs 112 inline and 109 crossline sections to generate fourteen horizons over the whole seismic survey. Table 5 summarizes the manual interpretation time that is needed to constraint the semi-automatic horizon picking. In my application, 47 inline and 52 crossline sections were interpreted manually for parallel to semi-parallel seismic reflections (nine horizons), and 65 inline and 57 crossline sections for horizons T1, T2, T3, T4, and T5 (five horizons) in Zone B, respectively.
With the help of horizon picking algorithm, for the manual interpretation time decreased to approximately seven days. In addition, data conversion and preparing the seismic data for the algorithm took three days (for 2.60 GHz, 16 processors). Totally ten days were needed to interpret the whole survey. Based on calculated manual interpretation time, the automatic horizon picking developed by Lou et al., 2020 is more efficient than manual horizon picking. However, it must be considered that manual interpretation time may vary according to the experience of the interpreter, and seismic data quality.

Table 4. Average of manual picking time for the whole survey

<table>
<thead>
<tr>
<th>Horizon Name</th>
<th>Horizon Number</th>
<th>Average Manually Interpretation Time for a horizon in an inline/cross section</th>
<th>Average Manually Picking Time (for every ten inlines and ten crosslines) (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanushuk, GRZ, Pebble Shale, Kingak, Sag River, Sadlerochit-Shublik, Lisburne, Endicott, Basement</td>
<td>9</td>
<td>1 minute</td>
<td>72<em>73</em>9*1= 47304 minutes</td>
</tr>
<tr>
<td>T1, T2, T3, T4, T5</td>
<td>5</td>
<td>2 minutes</td>
<td>72<em>73</em>5*2=52560 minutes</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14</strong></td>
<td></td>
<td><strong>99864 minutes (~70 days)</strong></td>
</tr>
</tbody>
</table>

Table 5. Manual picking time of interpreted inline and crossline during the study.

<table>
<thead>
<tr>
<th>Horizon Name</th>
<th>Average Manually Interpretation Time for a horizon in an inline/cross section</th>
<th>Manually Picking Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanushuk, GRZ, Pebble Shale, Kingak, Sag River, Sadlerochit-Shublik, Lisburne, Endicott, Basement</td>
<td>1 minute</td>
<td>47<em>52</em>1=2444 minutes</td>
</tr>
<tr>
<td>T1, T2, T3, T4, T5</td>
<td>2 minutes</td>
<td>65<em>57</em>2=7410 minutes</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>9854 minutes (~7 days)</strong></td>
</tr>
</tbody>
</table>
The algorithm developed by Lou et al., 2020 uses loop-tie criteria to simulate manual horizon picking. Figure 88 shows the loop-tie checking procedure of picking a horizon over a seismic survey. A closed track of the seismic lines along which correlation are made is called a loop. Loop-tying begins at a starting point on selected seismic section and proceeds by trace to trace correlation along that line till its intersection with another section (Heron, 2011). Based on this loop tie criteria, tracked horizons follow the local seismic reflection events, thus the accuracy of seismic interpretation increases (Zhang, B., et al.,2020).

**Figure 88.** The loop-tie checking procedure on a seismic survey (modified from Herron, et al., 2011).

To evaluate the accuracy of the algorithm, the merged horizon patches were used (Fig. 88b). Considering that the algorithm picks the trough or peak of seismic waveforms that is the same with manual horizon picking, thus the loop-tie met tracked horizon patches by the algorithm will be exact the same with manual horizon picking. Then the produced horizon patches are regarded as accurate interpretation. In this application, I define the accuracy as the area of produced horizon patches (the area with lines in Figures 89a, 90a, and 91a) over the area
with no horizon tracking. Figures 89, 90, and 91 show the tracked horizon across representative a fault zone (basement), a clinoform geometry (horizon T2), and a parallel reflection zone, respectively.

Figure 89a illustrates the tracked merged basement horizon that includes a local fault (the dash red line in Figure 89b). Area with color zone corresponds to loop-tie met horizon patches that is regarded as accurate picking, while white zones on the basemap indicates the algorithm fails to produce horizons that meet the loop-tie criteria, which is regarded as inaccurate picking. Figure 90a illustrates the merged GRZ horizon. The lateral continuity of seismic reflections is contaminated by the shallow permafrost zone (Fig. 90c). As a result, the algorithm fails to pick horizons for the low-quality seismic reflections. Figure 91a illustrates the merged horizon that across the clinoform. White zones in Figure 91a shows the area where the algorithm cannot produce accurate horizon picking due to the poor seismic data quality (Fig. 91c).

**Figure 89.** a) The merged horizon patch window of the basement, b) Seismic section for the basement. The red dashed line shows the fault, the yellow curve illustrating one manually interpreted horizon.
Figure 90. a) The merged horizon patch window of the GRZ, b) Seismic section for the GRZ. The yellow curve illustrating one manually interpreted horizon, c) Seismic section of the GRZ corresponds to the white zone in the horizon patch window.
Figure 91. a) The merged horizon patch window of the horizon T2, b) Seismic section for the horizon T2. The yellow curve illustrating one manually interpreted horizon, c) Seismic section of the horizon T2 corresponds to the white zone in the horizon patch window.
Accuracy of each horizon is shown in Table 6. The accuracy of picked horizon that corresponds to the seismic with parallel and sub-parallel reflections can reach up to 90% and 85%, respectively. The horizons, which pass through the clinoforms (T1, T2, T3, T4, and T5), have a variation accuracy changing between 72%-83%. The Nanushuk Formation has the lowest accuracy (decreases to 70%) due to the low seismic quality that is caused by the shallow permafrost.

Table 6. Accuracy of each horizon.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Tracked Merge</th>
<th>Accuracy</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement</td>
<td><img src="image1.png" alt="Basement" /></td>
<td>0.89</td>
<td>89%</td>
</tr>
<tr>
<td>Endicott Gr.</td>
<td><img src="image2.png" alt="Endicott" /></td>
<td>0.80</td>
<td>80%</td>
</tr>
<tr>
<td>Lisburne Gr.</td>
<td><img src="image3.png" alt="Lisburne" /></td>
<td>0.84</td>
<td>84%</td>
</tr>
<tr>
<td></td>
<td>Percentage</td>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>Sadlerochit-Shublik</td>
<td>0.77</td>
<td>77%</td>
<td></td>
</tr>
<tr>
<td>Sag River Sandstone</td>
<td>0.78</td>
<td>78%</td>
<td></td>
</tr>
<tr>
<td>Kingak- LCU</td>
<td>0.88</td>
<td>88%</td>
<td></td>
</tr>
<tr>
<td>Pebble Shale</td>
<td>0.82</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>GRZ of Hue Shale</td>
<td>Torok_5</td>
<td>Torok_4</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.85 85%</td>
<td>0.83 83%</td>
</tr>
</tbody>
</table>
8.2 Thickness Variations for Mega-sequences

The Ellesmerian mega-sequence, which is a continental shelf deposit on a passive margin, shows an east-west oriented thickness change. This mega-sequence has the largest thickness in the northwest (1.4 km), and thins towards to the northeast (0.6 km). The top of the basement deepening towards the west-southwest was caused this mega-sequence is thickening in this direction. The thickness values have a very good agreement with results specified by Saltus and Bird, (2003) for coastal sections that change from 0.5 to 3 km from northeast to northwest in their study.
The thickness maps of the Beaufortian, and Brookian illustrates that the thickening orientation is from the northeast to the southwest. Thickness increases to the southwest. This same thickening direction may be caused by synchronous tectonic events of the opening of the Canada Basin and Brooks Range orogeny.

The Beaufortian mega-sequence is about 0.4 km thick in northeast but gets thicker towards southwest (~0.6 km). Elsewhere in the Colville Foreland Basin, the thickness of the Beaufortian mega-sequence ranged from 1.3-0.7 km (Hubbard et al., 1990; Houseknecht and Bird, 2004; Houseknecht, 2019a). Thus, the Beaufortian mega-sequence is thinner in the study area than other parts of the Colville Foreland Basin.

The Brookian mega-sequence shows the southwest thickening direction, and thickness increases from ~1.7 in the northeast to ~2 km in the southwest. This thickness is similar to previous studies (Bird and Molenaar, 1992; Houseknecht et al., 2009, 2012; Ramon-Duenas et al., 2018) that state it is between 0.6-2.5 km thick.

8.3 Regional Deposition History

The Mississippian through Triassic Ellesmerian sequence contains the Endicott Group, Lisburne Group, Sadlerocthit - Shublik, and Sag River Sandstone. The Ellesmerian Mega-sequence rests unconformably on top of the pre-Mississippian Franklinian basement, which dips to the southwest by ~3°. The sedimentary strata all dip south - southwestward in all the regional reflectors. The basement and top of Endicott Group show southwest dipping sediment dispersal. However, the direction of sediment dispersal changed from southwest to south between the Lisburne Group and Sag-River Sandstone.

The Jurassic through Lower Cretaceous Beaufortian mega-sequence was deposited on top of the Ellesmerian mega-sequence, and includes the Kingak Formation and Pebble Shale Unit.
The Lower Cretaceous Brookian mega-sequence was deposited as part of a major delta system and comprises the Nanushuk topsets, Torok foresets and GRZ bottomsets. While regional sediment dispersal was northeast to southwest above the GRZ, the sediment dispersal direction changes to northwest to southeast beneath the GRZ. This reversal in polarity of sediment dispersal represents the tectonic transition from the underlying Beaufortian mega-sequence to the overlying Brookian mega-sequence (Hubbard and others, 1987; Bird and Molenaar, 1992; Houseknecht and Schenk, 2001). The Torok formation is characterized by shelf, slope, and basinal facies in its depositional system. This formation shows generally west to east-dipping clinoforms. The depocenter of each deltaic succession moved to the east during their depositional stage due to sea-level changes and sediment sources from the west.

The seismic reflections in the Brookian mega-sequence shows a progradational geometry. Sand in the Nanushuk Formation is transport from the shelf (topset) to the basin-floor (bottomset). In addition, even though Torok Formation has a higher proportion of shale than the Nanushuk Formation, there are thick sandstone packages present in this formation (Bhattacharya and Verma, 2020). The sandstone packages in the Brookian mega-sequence could be a potential reservoir. This mega-sequence shows eastward progradation deposits and downlap onto the Pebble Shale Unit. Basin floor fans in the Torok Formation were defined in the southeastern part (Fig. 82). They show distal zone fan-delta geometry with crevasse splays and channel deposits. The incised valleys feed the basin floor fans in the distal zone accumulation.
9. CONCLUSIONS

Seismic stratigraphic interpretations were conducted to understand the stratigraphic evolution of the Ellesmerian, Beaufortian, and Brookian mega-sequences in the Nanuq South 3D seismic survey. Fourteen key horizons, from Mississippian to Cretaceous time, were tracked automatically by the algorithm developed by Lou et al., (2020). The seismic survey consists of 1444 seismic lines. In the study area, 221 seismic lines were interpreted manually. 15% of the seismic lines were interpreted manually and this interpretation is spread out in the whole survey with the auto-tracking algorithm. The application demonstrates that the algorithm can provide a significant decrease in time effort for the horizon interpretation. Calculated manual interpretation time shows that the automatic horizon picking (approximately seven days) developed by Lou et al., 2020 is more efficient than manual horizon picking (approximately 70 days). It has been observed that the algorithm follows the local reflectors with different seismic reflection patterns. The accuracy can reach up to 90% for parallel and semi-parallel seismic reflections. The accuracy of horizons varies between 72% and 83% for seismic reflections that across the clinoforms. However, the algorithm still can produce horizon with the accuracy of 70% even if the seismic waveform has low quality.

Based on seismic interpretation, the Ellesmerian mega-sequence, which was derived from a sediment source in the north, shows a northeast to southwestward thickening and reaches ~1.4 km. The Beaufortian mega-sequence includes syn-rift deposits that were sourced from the north.
The maximum thickness reaches ~0.6 km to the south. The Brookian mega-sequence, which includes a bottomset (GRZ), foreset (Torok), and topset (Nanushuk) architecture with the clinoform geometry, shows thickening in the southern and southwestern parts and reaches ~2 km.

The Nanushuk and Torok formations contain clastic deposits in the Colville Foreland Basin. These formations have the potential for hydrocarbon production because they were deltas. SOM analysis indicates that the Torok Formation contains a basin floor fan in the southeast. Incised valleys transported the sand to this basin floor fan delta from west to east. The presence of sand bodies along the shelf edge, slope, and basin floor could be a potential hydrocarbon production zone.
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