An integrated chemostratigraphic and biostratigraphic
framework and benthic foraminifera morphogroup response
to paleoenvironmental conditions of the Upper Cretaceous
Kanguk Formation, Canadian Arctic Archipelago

by

Marissa Davies

A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Master of Science

in

Earth Sciences

Carleton University

Ottawa, Ontario

© 2016, Marissa Davies

Abstract

The Kanguk Formation, a unit of dominantly shales and siltstones deposited within the Sverdrup Basin, records the Late Cretaceous history of the Sverdrup Basin, Canadian Arctic Archipelago. This project aimed to refine foraminiferal biostratigraphy and to understand the benthic foraminiferal response to spatial and temporal changes in paleoenvironmental conditions of the Late Cretaceous Polar Sea by integrating chemostratigraphic, lithologic, geochemical, and faunal records at two study localities on Ellesmere Island, Nunavut, Canada. Two biostratigraphic zones with refined ages from chemostratigraphic correlations, the Turonian to late Santonian *Evolutinella boundaryensis* Zone and the late Santonian to Campanian *Verneuilioides bearpawensis* – *Glaphyrammina spirocompressa* Zone, are proposed and correlate to assemblages across the Arctic region. Comparison of the boundary interval between the Hassel and Kanguk formations across the basin shows that the uppermost Cenomanian OAE 2 interval is only preserved in more distal sections. Major and trace element geochemistry are largely influenced by sediment source proximity and diagenetic processes, and changes relate to the two informal members of the formation. Global transgressive-regressive cycles of the Late Cretaceous are recognized in the Kanguk Formation and correspond to benthic foraminifera morphogroup assemblage and diversity changes. During transgressive intervals, infaunal species are a dominant portion of the assemblage, with increasing dysoxia due to increased primary production and therefore organic matter flux to the seafloor. Continued oxygen depletion, increased organic matter flux promoting high foraminiferal populations, and expansion of the oxygen minimum zone in

highstand intervals caused *Trochammina*-dominated assemblages with small test size or the complete loss of taxa to occur. Regressive intervals bring back oxygenated conditions to the benthos and assemblages become more diverse. The highstand intervals with elevated organic matter flux are within the Coniacian to Santonian, an interval where OAE 3 is recognized within the Western Interior Sea and Atlantic Ocean. This indicates that the Sverdrup Basin may have also contributed to the continued CO₂ drawdown and cooling during the Late Cretaceous. This research contributes to the understanding of the dynamics of the Late Cretaceous Polar Sea within the Sverdrup Basin region and provides a refined stratigraphic framework for the Kanguk Formation.

Acknowledgements

First and foremost, I would like to thank my supervisor, Dr. Claudia Schröder-Adams for giving me the opportunity to work on this project integrating geochemical and microfossil data to study Late Cretaceous Arctic paleoclimate and whose knowledge, time, and passion for the subject throughout its duration were extremely helpful.

Secondly, I would like to thank Dr. Jens Herrle, for allowing me to spend a month in his research lab at the University of Frankfurt, Germany to learn carbon isotope and total organic carbon preparation methods and whose time and help with the interpretations of the chemostratigraphy greatly improved this thesis. B. Schminke is also thanked for help learning processing techniques and for the measurement of the TOC and $\delta^{13}\text{C}$ values.

This work would not have been possible without C. Schröder-Adams, A. Quesnel, and J. Herrle, who collected the samples for the Slidre Fiord locality, and P. Hülse, who collected and donated the Sawtooth Range locality samples. The committee members, Dr. Steve Cumbaa and Dr. Bill Arnott are also thanked for their input and time reviewing this thesis. I would also like to thank all the support staff in the department and my fellow graduate students, for making my time in the department an enjoyable experience. Last but certainly not least, I would like to thank my friends, family, and Carter Grondahl, whose support and understanding throughout the project kept me motivated.

This research was funded by a Natural Sciences and Engineering Research Council (NSERC) Collaborative Research and Development Grant to C. Schröder-Adams with GSC (GEM Program) and ConocoPhillips as partners. Polar Continental Shelf (PCSP) also provided generous support for field logistics to C. Schröder-Adams.

Financial support to Herrle was provided by the German Research Foundation (DFG) (HE 3521/6). Funding also came from an NSERC Canada Graduate Scholarship, Ontario Graduate Scholarship, and a Cushman Foundation William V. Sliter Research Award awarded to M. Davies.

Table of Contents

Abstract.....	i
Acknowledgements	iii
Table of Contents	v
List of Figures.....	viii
List of Tables	xiii
List of Appendices.....	xv
Chapter 1: Introduction	1
1.1: Cretaceous Climate and Oceans	1
1.2: Oceanic Anoxic Events in the Late Cretaceous.....	2
1.3: Benthic Foraminifera and Their Paleoenvironmental Significance	4
1.4: Research Objectives and Significance.....	6
Chapter 2: Study Region and Geologic Setting	8
2.1: Sverdrup Basin	8
2.2: Kanguk Formation.....	12
2.2.1: Previous Stratigraphic and Chronostratigraphic Work.....	12
2.2.2: Previous Biostratigraphic Work and Paleoenvironmental Interpretations	15
Chapter 3: Methods and Materials	18
Chapter 4: Results	25

4.1: Lithostratigraphy	25
4.1.1: Sawtooth Range.....	25
4.1.2: Slidre Fiord.....	28
4.1.3: Section Comparison.....	31
4.2: Chemostratigraphy and Total Organic Carbon (TOC).....	32
4.3: Whole Rock Geochemistry.....	36
4.4: Foraminiferal Abundance and Biostratigraphy	40
4.4.1: Sawtooth Range.....	40
4.4.2: Slidre Fiord	54
4.5: Foraminiferal Morphogroups and Diversity.....	57
4.5.1: Foraminiferal Morphogroups Descriptions for the Kanguk Formation at Sawtooth Range	60
4.5.2: Variation of Morphogroups and Diversity within the Kanguk Formation at Sawtooth Range	62
Chapter 5: Discussion	68
5.1: Taphonomy.....	68
5.2: Criteria for Stage Boundary Placement within the Kanguk Formation.....	70
5.3: Comparison of Kanguk Formation Foraminiferal Assemblages of the Sverdrup Basin	78

5.4: Regional Biostratigraphic Correlations between the Arctic Region and North America.....	83
5.5: Temporal and Spatial Changes within the Kanguk Formation Across the Sverdrup Basin	87
5.6: Paleoenvironmental Conditions and Foraminiferal Response to Paleoredox Conditions of the Kanguk Formation	90
Chapter 6: Conclusions	100
6.1: Summary.....	100
6.2: Future Research	104
Appendices.....	105
References.....	128

List of Figures

Figure 1: Geologic map of the Canadian Arctic Archipelago. Blue lines indicate the outline of the Sverdrup Basin, after Embry and Beauchamp (2008). Arrows indicate dominant sediment source direction (Embry 1991; Embry and Beauchamp, 2008).

Geologic unit data from the Geologic Survey of Canada (Wheeler *et al.*, 1996). AH: Axel Heiberg Island, BA: Banks Island, BF: Baffin Island, EL: Ellesmere Island, ER: Ellef Ringnes Island, DE: Devon Island, GR: Greenland, ME: Melville Island PP: Prince Patrick Island 10

Figure 2: Upper Cretaceous lithostratigraphic units for the Sverdrup Basin (A) and Arctic region (B). Units are formations unless indicated otherwise. **A:** Cross section of the Sverdrup Basin, after Embry (1991) and Embry and Beauchamp (2008) trending southwest to northeast, with the geographic regions labelled for each interval. BA: Banks Island, ME: Melville Island, LO: Lougheed Island, ER: Ellef Ringnes Island, AH: Axel Heiberg Island, EL: Ellesmere Island. **B:** Equivalent strata in other regions of the Arctic to the Sverdrup Basin. Mb.: Member..... 13

Figure 3: Locality map for the Arctic region, showing the sites for this study and previous studies mentioned in text. Outlined region in A is shown in B. Sverdrup Basin outline after Embry and Beauchamp (2008). 1: Slidre Fiord (this study), 2: Sawtooth Range (this study), 3: Wall (1983); 4: Lenniger *et al.* (2014), 5: Schröder-Adams *et al.* (2014), Herrle *et al.* (2015), Davis *et al.* (2016), 6: Pugh *et al.* (2014), 7: Chin *et al.* (2008), 8: Thomson *et al.* (2011), 9: McNeil (1997b), 10: Tappan (1962), 11: Setoyama

<i>et al.</i> (2011a). AH: Axel Heiberg Island, DE: Devon Island, ER: Ellef Ringnes Island, GR: Greenland.	19
Figure 4: Stratigraphic section of the Kanguk Formation at the Sawtooth Range locality. For facies descriptions see Table 1.	27
Figure 5: Stratigraphic section of the Kanguk Formation at the Slidre Fiord locality. Photo numbers refer to images found in Figure 6. For facies descriptions see Table 1 ...	29
Figure 6: Images of the Kanguk Formation at the Slidre Fiord locality, courtesy of C. Schröder-Adams. A: Sharp contact at the Hassel- Kanguk formation boundary. B: Black paper shales at the base of the Kanguk Formation. C: Abundant bentonites in the lower member. D: Boundary between the grey siltstones and shales of the lower member and the rusty brown siltstones, shales and mudstones of the upper member. E. Sharp boundary between the Kanguk and Expedition formations. F: Bed of <i>Sphenoceras</i> <i>patootensis</i> shells.	30
Figure 7: Carbon isotope stratigraphy ($\delta^{13}\text{C}_{\text{org}}$) and total organic carbon (TOC) content for the Slidre Fiord and Sawtooth Range localities. Intervals interpreted to be correlative between the $\delta^{13}\text{C}_{\text{org}}$ values of both localities are labelled A-E. For lithological descriptions see Figures 4 and 5 and Table 1.	33
Figure 8: Total organic carbon (A), carbon isotope stratigraphy (B), major element concentrations (C-F) and excess trace element concentrations (G-I) for the Kanguk Formation at Slidre Fiord. Trace element excess is based on average continental crust of McLennan (2001). Dashed line indicates boundary between subzones of GEOC-2. For lithological description refer to Figure 5 and Table 1.....	37

Figure 9: Element vs. Al plots for the Slidre Fiord locality for Fe (A), Σ S (B), Ca (C), V (D), Zn (E), and Mo (F). Grey line represents linear fit to data. R^2 and Spearman's rank correlation coefficient are recorded on plot.	39
Figure 10: Foraminifera biostratigraphy and relative abundance in the Kanguk Formation at the Sawtooth Range, showing the long ranging, <i>Evolutinella boundaryensis</i> Zone, and <i>Verneuilioides bearpawensis</i> - <i>Glaphyrammina spirocompressa</i> Zone taxa. For lithological description see Figure 4.	41
Figure 11: Foraminifera biostratigraphy and relative abundance in the Kanguk Formation at the Sawtooth Range, showing the <i>Evolutinella boundaryensis</i> Zone and <i>Verneuilioides bearpawensis</i> - <i>Glaphyrammina spirocompressa</i> Zone taxa, concentrations, and other fossil taxa. For lithological description see Figure 4.....	42
Figure 12: Plate 1: Foraminifera from the Upper Cretaceous Kanguk Formation at Sawtooth Range, Ellesmere Island, Nunavut, Canada. Photos taken at 40 X magnification.	43
Figure 13: Plate 2: Foraminifera of the Upper Cretaceous Kanguk Formation at Sawtooth Range (1-3) and Slidre Fiord (4-19), Ellesmere Island, Nunavut, Canada. Photos taken at 40 X magnification.	487
Figure 14: Foraminifera biostratigraphy in the Kanguk Formation at the Slidre Fiord locality. For lithological description see Figure 5 and Table 1.....	55
Figure 15: Foraminiferal morphogroups and diversity indices for the Kanguk Formation at the Sawtooth Range locality. For lithologic description refer to Figure 4 and Table 1.	63

Figure 16: Age assignments and transgressive-regressive framework for the Kanguk Formation at Sawtooth Range (A) with reference to the composite carbon isotope curve of Jarvis <i>et al.</i> (2006) and major transgressive-regressive cycles of Gradstein <i>et al.</i> (2012) (B) CTBE: Cenomanian-Turonian Boundary Event, SP: Occurrence of <i>Sphenoceras patootensis</i> , E: early, M: middle, L: late or lower, U: upper.	73
Figure 17: Age assignments and transgressive-regressive framework for the Kanguk Formation at Slidre Fiord (A) with reference to the composite carbon isotope curve of Jarvis <i>et al.</i> (2006) and major transgressive-regressive cycles of Gradstein <i>et al.</i> (2012) (B). CTBE: Cenomanian-Turonian Boundary Event, SP: Occurrence of <i>Sphenoceras patootensis</i> , E: early, M: middle, L: late or lower, U: upper	74
Figure 18: Foraminiferal biostratigraphy comparison chart of proposed foraminiferal zonation for the Kanguk Formation.	79
Figure 19: Regional correlations of foraminiferal biostratigraphic zones for the Polar and Western Interior Seas covering the Cenomanian to Maastrichtian interval.	85
Figure 20: Comparison of lithologic, biostratigraphic, and chemostratigraphic changes across the Sverdrup Basin with study localities from Ellef Ringnes (Pugh <i>et al.</i> , 2014; Davis <i>et al.</i> , 2016), Axel Heiberg (Lenniger <i>et al.</i> , 2014; Schröder-Adams <i>et al.</i> , 2014; Herrle <i>et al.</i> , 2015; Davis <i>et al.</i> , 2016) and Ellesmere islands (this study). Ages are from Davis <i>et al.</i> (2016) for the Hoodoo Dome and Glacier Fiord localities. L: lower, M: middle, U: upper.....	88
Figure 21: Summary of morphogroup response in relation to changes in transgressive - regressive cycles of Gradstein <i>et al.</i> (2012). Epifaunal % includes all epifaunal to shallow	

infaunal taxa (Morphogroups A, B, D, E) and infaunal % is represented by Morphogroup C. OMZ: oxygen minimum zone, TOC; total organic carbon content, OAE 2: Oceanic Anoxic Event 2. See Tables 2 and 3 for morphogroup descriptions. 92

Figure 22: Schematic of the major changes in the morphogroup assemblages in relation to transgressive-regressive cycles, after Leckie and Olson (2003) and Nagy *et al.* (2009). During a regression (A), the shelf has an even and relatively diverse assemblage with oxygenated conditions. During a transgressive phase (B) the erosion of the coastline brings in nutrients, which enhances primary production and increases organic matter flux. Dysoxic conditions form and infaunal species become more dominant with the expansion of the oxygen minimum zone (OMZ). During highstand (C) the oxygen minimum zone continues to expand, and may cause either anoxic conditions at the benthos and loss of benthic fauna or dysoxic low diversity assemblages dominated by trochamminids, both of which were recorded in the Kanguk Formation..... 93

List of Tables

Table 1: Facies descriptions of the Kanguk Formation lithology at Slidre Fiord and Sawtooth Range localities. Microfossil changes are from the Sawtooth Range locality only, due to poor preservation at the Slidre Fiord locality. SF: Slidre Fiord, SR: Sawtooth Range. Foraminifera abundance defined in table as: absent: 0 foraminifera/sample, present: 1 – 50 foraminifera /sample, common: 50 – 200 foraminifera/sample, and abundant > 200 foraminifera/sample.	26
Table 2. Foraminiferal morphogroup categories A to C for the Upper Cretaceous Kanguk Formation at Sawtooth Range. Foraminifera genera were assigned to each morphogroup based on Murray <i>et al.</i> (2011), Nagy <i>et al.</i> (2009), Setoyama <i>et al.</i> (2011b) and van den Akker <i>et al.</i> (2000). Life mode, feeding strategy, and environments based on Murray <i>et al.</i> (2011), Setoyama <i>et al.</i> , (2011b), Cetean <i>et al.</i> (2011), and Nagy <i>et al.</i> , (2009, 2010).....	58
Table 3. Foraminiferal morphogroup categories D to F for the Upper Cretaceous Kanguk Formation at Sawtooth Range. Foraminifera genera were assigned to each morphogroup based on Murray <i>et al.</i> (2011), Nagy <i>et al.</i> (2009), Setoyama <i>et al.</i> (2011b) and van den Akker <i>et al.</i> (2000). Life mode, feeding strategy, and environments based on Murray <i>et al.</i> (2011), Setoyama <i>et al.</i> , (2011b), Cetean <i>et al.</i> (2011), and Nagy <i>et al.</i> , (2009, 2010). U: umbilical view, S: spiral view.....	59
Table 4: Biostratigraphic datum levels and stage boundaries used to recalibrate the Jarvis <i>et al.</i> (2006) with the revised ages of Gradstein <i>et al.</i> (2012). Bold datum levels were	

used in calculation of sedimentation rate, after model of Jarvis *et al.* (2006). *:

Interpolated from age model used in Jarvis *et al.* (2006).....71

List of Appendices

Appendix A: Taxonomic List of Foraminifera for the Upper Cretaceous Kanguk

Formation.....105

Appendix B: Data Sheets119

Table B-1: Foraminiferal counts for Sawtooth Range, Ellesmere Island.....119

Table B-2: Foraminiferal counts for Slidre Fiord, Ellesmere Island.....121

Table B-3: Concentrations of selected major and trace elements from Slidre
Fiord, Ellesmere Island.....123

Table B-4: Carbon isotope ($\delta^{13}\text{C}_{\text{org}}$) and TOC data for the Slidre Fiord
locality.....124

Table B-5: Carbon isotope ($\delta^{13}\text{C}_{\text{org}}$) and TOC data for the Sawtooth Range
locality.....126

Chapter 1: Introduction

1.1: Cretaceous Climate and Oceans

The Cretaceous Period, characterized by a greenhouse climate with warmer temperatures, higher sea levels, and more frequent volcanism than today, serves as a potential analogue for a future warmer climate (Keller, 2008; Hay, 2011). Volcanic activity, due to high sea floor spreading rates and the formation of large igneous provinces (LIPs), caused atmospheric CO₂ levels to reach an estimated 600 to 2400 ppm by the mid Cretaceous (Jones and Jenkyns, 2001; Bice *et al.*, 2006; Coffin *et al.*, 2006). High atmospheric CO₂ concentrations and elevated volcanism resulted in peak sea surface temperatures as high as 35°C at the equator in the late Cenomanian (Norris *et al.*, 2002). Temperatures were also more equitable, with a smaller equator-to-pole temperature gradient causing slower wind systems and sluggish ocean currents (Hay, 2008; Hay and Floegel, 2012). High sea level, caused by tectonic-driven eustasy and generally ice-free poles, led to shallow water seas occupying parts of the continents and created extensive continental shelves, impacting ocean circulation and marine species distribution (Leckie *et al.*, 2002; Miller *et al.*, 2005; Schröder-Adams, 2014). Major tectonic changes, such as the opening of the southern Atlantic, also occurred in the Cretaceous, influencing ocean circulation and chemistry as well as global temperature (Friedrich *et al.*, 2012; Granot and Dymant, 2015).

In the Arctic region, the Cretaceous Polar Sea was more restricted than the Arctic Ocean today and was periodically connected to tropical regions through the Western

Interior Seaway of North America (Hay and Floegel, 2012; Schröder-Adams, 2014). Furthermore, the Arctic was influenced by a temperate climate but still experienced seasonal light limitation as today, which has no modern analogue (Falcon-Lang *et al.*, 2004; Chin *et al.*, 2008; Hay and Floegel, 2012). The greenhouse climate of the Cretaceous would have had the most pronounced effect on the polar regions, with sea surface temperatures projected to have reached more than 20°C at their peak during the Cenomanian -Turonian interval and limited ice sheets would have been present (Huber *et al.*, 2002; Bice *et al.*, 2003; Jenkyns *et al.*, 2004). Due to the remoteness of the High Arctic and lack of core from the Arctic Ocean that sampled Cretaceous strata, only few studies have been performed to understand the response of biota to paleoenvironmental changes in the Cretaceous Polar Sea to date (e.g. Hills and Strong, 2007; Chin *et al.*, 2008; Schröder-Adams *et al.*, 2014). The Kanguk Formation, a Cenomanian to Campanian-aged unit deposited in the Sverdrup Basin of the Canadian Arctic Archipelago (Embry and Beauchamp, 2008), offers a unique opportunity to study Late Cretaceous climate in the Arctic region and is the focus of this study.

1.2: Oceanic Anoxic Events in the Late Cretaceous

Warmer and more stagnant waters in Cretaceous oceans made them more prone to periodic extensive low oxygen conditions, called Oceanic Anoxic Events (OAEs) (Schlanger and Jenkyns, 1976). These events are recognized by regional to global deposition of organic-rich black shales and represent significant perturbations of the global carbon cycle (e.g. Emeis and Weissert, 2009; Waple, 2009). The expansion of the oxygen minimum zone caused by enhanced primary productivity, enhanced

upwelling, increased nutrient supply through continental runoff, and elevated ocean stratification are used to explain the occurrence of these events throughout the Cretaceous (Erbacher *et al.*, 2001; Herrle *et al.*, 2003; Takashima *et al.*, 2006; Poulton *et al.*, 2015).

At least eight OAEs are recognized within the Cretaceous Period, two of which occurred during the Late Cretaceous. The most extensive OAE was the latest Cenomanian to early Turonian OAE 2 (Schlanger *et al.*, 1987; Jarvis *et al.*, 2011). OAE 2 corresponds to the highest temperatures and sea levels of the Cretaceous and is a complex event, with an enhanced hydrological cycle contributing nutrients to the oceans, increasing stratification, and promoting primary productivity (Davies *et al.*, 2009; van Helmond *et al.*, 2013). These events in turn contributed to rapid carbon burial and CO₂ drawdown, triggering cooling temperatures within the OAE 2 interval (Forster *et al.*, 2007; Davies *et al.*, 2009; Barclay *et al.*, 2010; Jarvis *et al.*, 2011; van Helmond *et al.*, 2013). This event is also signified by a large (> 2‰) positive isotopic excursion, with the burial of significant amounts of isotopically light organic carbon (Arthur *et al.*, 1988).

The last oceanic anoxic event of the Cretaceous, OAE 3, occurred during the Coniacian to Santonian and differs from OAE 2 in that it is not a global event and occurs over a large time interval (Locklair *et al.*, 2011). OAE 3 is restricted to mainly the equatorial Atlantic and surrounding regions, such as the Western Interior Seaway (Wagreich, 2009; Tessin *et al.*, 2015). The event also has a much reduced positive isotopic excursion (0.5 – 1 ‰) and is related to different-aged strata within the Coniacian to Santonian interval, making regional to global correlations difficult (Wagreich, 2009). Outside of the equatorial Atlantic region, such as in the Pacific and Tethys oceans, the

deposition of Cretaceous Oceanic Red Beds (CORBs) are associated with decreasing temperatures and more oxic deep waters in the Coniacian to Santonian (Locklair *et al.*, 2011; Wang *et al.*, 2011). The restricted nature of the Atlantic during this interval was likely the cause of continued organic carbon burial and would have contributed to CO₂ drawdown and the decrease in temperature in the Turonian to Maastrichtian (Wagreich, 2009; Locklair *et al.*, 2011).

Within the Arctic region, OAE 2 has recently been recognized within late Cenomanian intervals of the Sverdrup Basin on Axel Heiberg (Lenniger *et al.*, 2014; Schröder Adams *et al.*, 2014; Herrle *et al.*, 2015; Davis *et al.*, 2016) and Ellef Ringnes islands (Pugh *et al.*, 2014), but limited research has been done within the Coniacian – Santonian “OAE 3” interval in the Cretaceous Polar Sea to date (Pugh *et al.*, 2014). This study aims to investigate the carbon isotope record of the Upper Cretaceous Kanguk Formation, and to compare to previous work in order to understand the temporal and spatial variability of benthic oxygen conditions and the faunal response to oceanic anoxic events in the Arctic region.

1.3: Benthic Foraminifera and Their Paleoenvironmental Significance

Benthic foraminifera are marine unicellular protists that form a test, which is readily preserved in the fossil record (Murray, 2006). They are commonly used to interpret paleoceanographic conditions of the benthos, as they are sensitive to changes in salinity, temperature, oxygen, and nutrient levels (e.g. Loubere and Fariduddin, 2002; Friedrich, 2010). Foraminiferal morphogroups, which are groupings based on the chamber arrangement and shape of the test, are commonly used to interpret

environmental conditions in both fossil and modern assemblages, as the life modes and environments associated with these groups have been generally conserved through time (e.g. Nagy, 1992; Tyszkla, 1994; van den Akker *et al.*, 2000; Nagy *et al.* 2009; Murray *et al.*, 2011). Foraminiferal species richness can also indicate environment, as assemblages tend to be more diverse in stable, oxygenated environments further from the shoreline (Murray *et al.*, 2011). Stressed environments, such as those caused by high organic matter flux and limited oxygen recharge or variable salinity, promote the dominance of taxa adapted to live in those conditions and results in low species richness (e.g. Nagy *et al.*, 2010; Reolid *et al.*, 2014). Because benthic foraminifera are abundant in the fossil record, they are used in biostratigraphic and sequence stratigraphic studies (Leckie and Olson, 2003; Murray, 2006). Benthic foraminifera can have long species ranges, however, making their use in zone refinement difficult in some cases (e.g. Schröder-Adams, 2014).

In the Arctic region, Upper Cretaceous foraminifera biostratigraphic frameworks have been established in Alaska (Tappan, 1962) and Canada (Wall 1983; McNeil, 1997b; Thomson *et al.*, 2011; Schröder-Adams *et al.*, 2014), but limited studies that aim to understand the paleo-redox conditions of the Late Cretaceous Polar Sea have been done to date. Recent work on Axel Heiberg Island by Schröder-Adams *et al.* (2014) in the Canadian Arctic Archipelago has interpreted the Cretaceous paleoenvironmental conditions and refined the biostratigraphy of the latest Cenomanian to Santonian portion of the Kanguk Formation in the Sverdrup Basin. More work is needed, however, to understand the changes in foraminiferal assemblages throughout the entire formation, as

well as understanding the faunal response to changes in paleoenvironmental and paleoclimatic conditions spatially. An improved understanding of the foraminiferal assemblage changes in the Arctic both temporally and spatially will advance our knowledge about the Arctic region's response to changes in the polar ocean-climate system and potentially allow for the recognition of global events, such as oceanic anoxic events, during the Late Cretaceous interval.

1.4: Research Objectives and Significance

In order to understand the paleoenvironmental conditions in the Late Cretaceous Polar Sea, two sections from the Upper Cretaceous Kanguk Formation of the Sverdrup Basin in the Canadian Arctic Archipelago were investigated. Foraminiferal assemblage data were combined with chemostratigraphy ($\delta^{13}\text{C}$), sedimentology, total organic carbon (TOC) content, and selected redox-sensitive element concentrations at each site to understand both spatial and temporal environmental changes of the Late Cretaceous and their influence on benthic faunal assemblages. Comparison to previous studies allowed for a better understanding of the basin-wide response to changing paleoenvironmental conditions. Furthermore, refining the foraminiferal biostratigraphy for the Kanguk Formation allows for more detailed correlations to the rest of the Arctic region, as well as the Western Interior Sea. An improved foraminiferal framework calibrated with carbon isotope stratigraphy will provide a basis for future microfossil zonations based on diatoms and radiolarians that will utilize the same sample sets. Continued refinement of Arctic stratigraphy and paleoenvironmental interpretation of the Late Cretaceous portion

of the Sverdrup Basin also has implications for future petroleum exploration, as multidisciplinary studies make for robust paleoenvironmental interpretations (Embry, 2011). Finally, a better understanding how the Arctic responded to a greenhouse climate in the past may help predict the Arctic's response to warming in the future.

Overall, this thesis aims to answer the following questions:

1. How did paleoenvironmental conditions in the Late Cretaceous Polar Sea change both temporally and spatially? Can significant global events that characterize the Cretaceous be detected in the Polar Sea?
2. How did benthic foraminifera respond to these changing paleoenvironmental conditions?
3. How did the occurrence of oceanic anoxic events influence the benthic foraminiferal assemblages in the Polar Sea? Is there any spatial variability in the expression of these events?
4. How can the benthic foraminiferal biostratigraphy of the Canadian Arctic be refined?

Chapter 2: Study Region and Geologic Setting

2.1: Sverdrup Basin

The Sverdrup Basin, located in the Queen Elizabeth Islands of Arctic Canada, is a pericratonic basin that formed in the Early Carboniferous with rifting of the Siluro-Devonian Ellesmerian Orogeny (Balkwill, 1978; Stephenson *et al.*, 1987; Embry, 1991; Embry and Beauchamp, 2008). It contains up to 13 km of Carboniferous to Eocene-aged deposits and its axis trends from northern Ellesmere Island in the northeast to Melville Island in the southwest (Figure 1) (Balkwill, 1978; Embry, 1991; Embry and Beauchamp, 2008). Sediments were delivered to the basin dominantly from the south and east, where erosion of the proximal Ellesmerian Orogeny strata and the distal Precambrian continental craton of Greenland and Canada occurred (Embry, 1991). A minor source from the northwest, a landmass called Crockerland, contributed to the basin from the Triassic to mid-Jurassic (Embry, 2009). With the development of the proto-Amerasian Basin adjacent to the Sverdrup Basin in the Late Jurassic, however, Crockerland was fragmented and a rift shoulder, called the Sverdrup Rim, developed between the two basins (Embry, 1991; Embry and Beauchamp, 2008). The Sverdrup Rim continued to be a minor source of sediment in the northwest when it was exposed periodically in the Mesozoic (Embry, 1991).

In the early stages of the Sverdrup Basin, from the Carboniferous to the Permian, slow thermal subsidence occurred and deposits were dominated by marine carbonates and evaporites in the axial parts of the basin (Davies and Nassichuk, 1991). At the start of the Triassic, the shelves of the Sverdrup Basin were flooded due to a major transgression and

deltas were established, shifting the basin to a siliciclastic-dominated regime (Balkwill, 1978; Embry, 1991). Sediments slowly filled the basin and by the end of the Early Jurassic the central portion of the basin was filled and the shelf-slope-basin topography was replaced with a broad shelf (Balkwill, 1978; Embry, 1991; Embry and Beauchamp, 2008). Reduced siliciclastic influx and slow subsidence characterized the rest of the Jurassic (Embry, 1991). Sediment loading of the Carboniferous evaporite deposits with the infilling of the central basin caused various salt structures to form (Balkwill, 1978; Embry, 1991). Subsequent episodes of halokinesis occurred during rapid sedimentation rates resulting from delta progradation into the basin (Stephenson *et al.*, 1992).

At the beginning of the Cretaceous, renewed extension and rapid subsidence in the Sverdrup Basin occurred in association with the main rifting phase in the adjacent Amerasian Basin (Embry, 1991). Deposition of fluvial sediments of the Isachsen Formation coincided with increased sediment supply (Embry and Beauchamp, 2008). A large transgression in the late Aptian caused the shorelines to move onto the craton and the offshore mud and silt of the Christopher Formation were deposited (Embry and Beauchamp, 2008; Herrle *et al.*, 2015). Deltas prograded into the basin again in the Albian, forming the Hassel Formation (Embry and Beauchamp, 2008). The shales of the Bastion Ridge Formation were deposited in a restricted rift basin in the late Albian to Cenomanian and the deltaic and shoreface sand of the Hassel Formation continued to be deposited in more marginal settings (Embry, 1991; MacRae, 1992; Schröder-Adams *et al.*, 2014). Deposits of the Strand Fiord volcanics of latest Albian to Cenomanian-age

Figure 1: Geologic map of the Canadian Arctic Archipelago. Blue lines indicate the outline of the Sverdrup Basin, after Embry and Beauchamp (2008). Arrows indicate dominant sediment source direction (Embry 1991; Embry and Beauchamp, 2008). Geologic unit data from the Geologic Survey of Canada (Wheeler *et al.*, 1996). AH: Axel Heiberg Island, BA: Banks Island, BF: Baffin Island, EL: Ellesmere Island, ER: Ellef Ringnes Island, DE: Devon Island, GR: Greenland, ME: Melville Island PP: Prince Patrick Island.

cap the Hassel Formation and can be found in contact or capping the Bastion Ridge Formation depending on location within the basin (MacRae, 1992; Embry and Beauchamp, 2008; Schröder-Adams *et al.*, 2014).

The Late Cretaceous saw renewed slow thermal subsidence as seafloor spreading in the Amerasian Basin began, marked by a regional unconformity at the Albian-Cenomanian boundary (Embry and Dixon, 1990; Embry, 1991) placed on Ellef Ringnes Island between the two informal members of the Hassel Formation (Galloway *et al.*, 2012) and on Axel Heiberg Island at the base of the Bastion Ridge Formation (Schröder-Adams *et al.*, 2014). A major transgression occurred near the Cenomanian-Turonian boundary, causing the shorelines to extend well beyond the basin margins and the Kanguk Formation, consisting of dominantly organic-rich shales and siltstones, was deposited (Embry and Beauchamp, 2008). Increased sedimentation rates in the latest Cretaceous led to the progradation of sand-dominated deltas into the basin once more, forming the Expedition Formation (Embry and Beauchamp, 2008). Seafloor spreading in the Amerasian Basin continued to the end of the Cretaceous (Embry and Dixon, 1990; Embry and Beauchamp, 2008). Peak uplift of the Eurekan Orogeny in the late Eocene ended the depositional history of the basin and the late Paleozoic and Mesozoic strata were folded and faulted, especially in the northeastern region (Embry, 1991; Embry and Beauchamp, 2008).

The Cretaceous Period was also characterized by periods of volcanism in the Arctic, which were associated with the rifting and seafloor spreading that occurred in the Amerasian Basin, as well as a mantle plume north of the basin (Maher, 2001; Estrada and

Henjes-Kunst, 2013; Davis *et al.*, 2016). The various phases of the mantle plume are named the High Arctic Large Igneous Province (HALIP) (Trettin and Parrish, 1987; Embry and Osadetz, 1988; Maher, 2001; Døssing *et al.*, 2013; Jowitt *et al.*, 2013). The Strand Fiord Formation, which consists of mainly subaerial basalts and is one of the younger phases of the HALIP, extruded into the basin during the Cenomanian and can be mapped on northwestern Axel Heiberg Island (Embry and Osadetz, 1988). It typically overlies the Hassel Formation, but intertongues with the Bastion Ridge Formation in central Axel Heiberg Island (Trettin and Parrish, 1987). In northeastern Ellesmere Island the Hansen Point Volcanics, also mainly subaerial basalts, were deposited on top of Upper Cretaceous strata (Figure 2) (Embry, 1991; Embry and Osadetz, 1988; Estrada and Henjes-Kunst, 2013).

2.2: Kanguk Formation

2.2.1: Previous Stratigraphic and Chronostratigraphic Work

The Late Cretaceous, the focus of this study, is mainly represented by the Kanguk Formation in the Sverdrup Basin. The Kanguk Formation unconformably to conformably overlies the Hassel Formation, a large deltaic to shoreface system that prograded into the basin prior to the major transgression near the Cenomanian-Turonian boundary (Figure 2) (Embry, 1991). This transgression brought offshore marine conditions with low sediment supply to the Arctic shelf (Embry, 1991). On Axel Heiberg Island, the Kanguk Formation overlies the marginal to non-marine deposits of the Bastion Ridge Formation (Figure 2) (Embry, 1991; MacRae, 1992; Schröder-Adams *et al.*, 2014). In central and

Figure 2: Upper Cretaceous lithostratigraphic units for the Sverdrup Basin (A) and Arctic region (B). Units are formations unless indicated otherwise. **A:** Cross section of the Sverdrup Basin, after Embry (1991) and Embry and Beauchamp (2008) trending southwest to northeast, with the geographic regions labelled for each interval. BA: Banks Island, ME: Melville Island, LO: Loughheed Island, ER: Ellef Ringnes Island, AH: Axel Heiberg Island, EL: Ellesmere Island. **B:** Equivalent strata in other regions of the Arctic to the Sverdrup Basin. Mb.: Member.

northwestern Axel Heiberg Island, the Kanguk overlies the Strand Fiord Volcanics, which erupted co-eval with the Bastion Ridge Formation (Figure 2) (Ricketts *et al.*, 1985; Embry, 1991, Embry and Beauchamp, 2008). Upper Cretaceous strata outside the Sverdrup Basin on Banks and Devon islands are also included within the Kanguk Formation (Miall, 1979; Embry, 1991).

The lowermost part of the Kanguk Formation consists of black, offshore deposits of organic-rich paper shales associated with the Oceanic Anoxic Event (OAE) 2 and abundant bentonite beds (Embry, 1991; Lenniger *et al.*, 2014; Schröder-Adams *et al.*, 2014; Herrle *et al.*, 2015; Davis *et al.*, 2016). Sedimentation rates were generally low during this time (Balkwill, 1978; Davis *et al.*, 2016). Recent work by Davis *et al.* (2016) at Glacier Fiord confirmed OAE 2 in the Arctic with an age of $> 93.03 \pm 0.21$ Ma just above the positive isotopic excursion of Herrle *et al.* (2015) as well as determining another eight ages for bentonites at Glacier Fiord and Hoodoo Dome localities.

The Kanguk Formation becomes lighter in colour and siltier up section, with the sedimentation rates increasing in the Santonian (Balkwill, 1978; Embry, 1991). Campanian deltas prograded into the basin from the south and west, and the Kanguk Formation is capped unconformably by the deltaic sands of the Expedition Formation (Figure 2) (Embry, 1991; Embry and Beauchamp, 2008). The Kanguk Formation is comprised of two informal members, the black to grey siltstones and shales in the lower part of the formation, and the dark brown to grey shales with abundant concretions in the upper part (Fricker, 1963; Balkwill and Hopkins, 1976; Evenchick and Embry, 2012). Equivalent formations to the Kanguk in the Arctic region include the Seebee and

Schrader Bluff formations in northern Alaska and the Boundary Creek and Smoking Hills formations in the Beaufort- Mackenzie Basin (Figure 2).

2.2.2: Previous Biostratigraphic Work and Paleoenvironmental Interpretations

Limited foraminiferal biostratigraphic work has been done on the Kanguk Formation to date. Wall (1983) established the first foraminiferal biostratigraphy for the eastern Sverdrup Basin, and split the formation into two biozones, the *Dorothia smokyensis* Zone of Turonian to early Campanian age, and the *Verneulinoides bearpawensis* Zone of the early to late Campanian. Recent work by Schröder-Adams *et al.* (2014) has since refined this biostratigraphy at Glacier Fiord proposing three zones, the *Trochammina rutherfordi* Zone of latest Cenomanian to Turonian age, mainly spanning the OAE 2 interval, the *Dorothia smokyensis-Evolutinella boundaryensis* Zone of Turonian to late Santonian age, and the *Glaphyrammina spirocompressa* Zone of late Santonian to early Campanian age. The upper 140 m of the section was covered at Glacier Fiord, not allowing for upper Campanian foraminiferal zones to be established at that locality. Other time correlative sections in the North American Arctic served as a base for Late Cretaceous foraminiferal biostratigraphic zonations, namely Tappan (1962) in the Arctic Slope of Alaska, Thomson *et al.* (2011) in the Peel Plateau region of the Northwest Territories, McNeil (1997b) in the Beaufort Mackenzie Basin region of the Yukon and Northwest Territories, and Setoyama *et al.* (2011a) at Lomonosov Ridge.

Other microfossil assemblages have also been used to characterize the Kanguk Formation. Pugh *et al.* (2014) established the first tentative radiolarian biostratigraphy of Cenomanian to Santonian age at Hoodoo Dome, Ellef Ringnes Island and determined that

the assemblage changes reflected transgressive events and the expansion of oxygen minimum zones. Núñez-Betelu *et al.* (1994) established relative abundances of marine and terrestrial palynomorphs of the Kanguk Formation at multiple sites across Axel Heiberg and Ellesmere islands and determined that the Kanguk Formation transitions from marine dominated in the lower portion to terrestrial dominated in the upper portion, reflecting the start of progradation of the Expedition Formation clastic sediments into the Sverdrup Basin. Hills and Strong (2007) utilized dinoflagellate assemblage changes through the Kanguk Formation at Remus Creek, Ellesmere Island and Glacier Fiord, Axel Heiberg Island to establish paleoenvironments. Diatom assemblages of the Kanguk Formation on Devon, Ellef Ringnes, Eglinton, and Axel Heiberg islands and the Smoking Hills and Mason River formations at Horton River have delivered an Arctic zonation (e.g. Tapia and Harwood, 2002; Witkowski *et al.*, 2011). A combination of diatoms and other fossil groups in Chin *et al.* (2008) were used on Devon Island to interpret the Arctic marine ecosystem of Santonian to Campanian aged deposits. Utilizing diatoms, dinoflagellates, pollen, marine vertebrate and invertebrate fossils, and coprolites, they determined that the ecosystem would have been an ice-free and productive system with high terrestrial organic matter input from the then forested landscape.

Macrofossils reported in the Arctic region are summarized by Jeletzky (1970). Within the Kanguk Formation, the inoceramid *Sphenoceras patootensis* (de Loriol), a boreal marker species for late Santonian to early Campanian age, occurs within the upper member on both Axel Heiberg and Ellef Ringnes islands (Jeletzky, 1970; Olsen and Pedersen, 1991; Pugh *et al.*, 2014; Schröder-Adams *et al.*, 2014). A bentonite age of

83.80 ± 0.21 Ma just below the first occurrence of *S. patootensis* at Glacier Fiord by Davis *et al.* (2016) confirmed the utility of this marker for the late Santonian – early Campanian. Other macrofossils identified within the Kanguk Formation at Glacier Fiord are two ammonite species, *Scaphites nigricollensis* (Cobban) and *Scaphites corvensis* (Cobban) of late Turonian age (Schröder-Adams *et al.*, 2014). Hills *et al.* (1994) identified the late Coniacian species *Scaphites depressus* also at Glacier Fiord higher up in the section.

Chapter 3: Methods and Materials

The localities of this study, Slidre Fiord (79.86796° N 85.33763°W; 25m elevation) and Sawtooth Range (79.594583° N 83.563302° W; 221 m elevation) are situated on the Fosheim Peninsula of Ellesmere Island, Nunavut, Canada (Figure 3). Both localities have the entire Kanguk Formation exposed with only ~ 15 % covered at Sawtooth Range and ~ 3 % at Slidre Fiord. The Sawtooth Range locality lies southeast of Slidre Fiord and represents the more marginal position of the two sections within the Sverdrup Basin (Figure 3). At the Sawtooth Range locality, the section is ~190 m thick and 140 samples at a 1 to 4-meter interval were collected for foraminiferal, carbon isotope, and total organic carbon (TOC) analyses by CASP in 2013. At the Slidre Fiord locality, the section is ~285 m thick and was sampled at a 4 to 10-meter interval for a total of 82 samples for foraminiferal and geochemical analysis. For carbon isotope and TOC analysis, the sample interval was every 0.5 to 10 m for a total of 132 samples. Samples for Slidre Fiord were collected by C. Schröder-Adams, A. Quesnel, and J. Herrle in 2014. Samples were taken from freshly exposed faces to avoid effects of weathering.

For TOC and organic carbon isotopic ($\delta^{13}\text{C}_{\text{org}}$) analyses, a 5 g subsample was pulverized and 1 g of powder was treated with 10% HCl at ~ 70°C for 24 hours. Sample preparation was performed by M. Davies for the Slidre Fiord locality and by B. Schminke for the Sawtooth Range locality. TOC and $\delta^{13}\text{C}_{\text{org}}$ of both Slidre Fiord and Sawtooth Range localities were analyzed at the Institute for Geosciences of Goethe-University Frankfurt, Germany by B. Schminke. TOC values were determined on 0.1 g subsample using a LECO RC-412 carbon elemental analyzer. Samples had a reproducibility within

Figure 3: Locality map for the Arctic region, showing the sites for this study and previous studies mentioned in text. Outlined region in A is shown in B. Sverdrup Basin outline after Embry and Beauchamp (2008). 1: Slidre Fiord (this study), 2: Sawtooth Range (this study), 3: Wall (1983); 4: Lenniger *et al.* (2014), 5: Schröder-Adams *et al.* (2014), Herrle *et al.* (2015), Davis *et al.* (2016), 6: Pugh *et al.* (2014), 7: Chin *et al.* (2008), 8: Thomson *et al.* (2011), 9: McNeil (1997b), 10: Tappan (1962), 11: Setoyama *et al.* (2011a). AH: Axel Heiberg Island, DE: Devon Island, ER: Ellef Ringnes Island, GR: Greenland.

± 0.01 ‰. Sample $\delta^{13}\text{C}_{\text{org}}$ values were determined using a Thermo Scientific Flash Elemental Analyzer 1112 connected to a continuous flow inlet system of a Thermo Scientific MAT 253 gas source mass spectrometer. Sample values are recorded in reference to the Vienna Pee Dee Belemnite standard (‰ VPDB) and both replicates and standards were within ± 0.2 ‰. The composite $\delta^{13}\text{C}_{\text{carb}}$ reference curve of Jarvis *et al.* (2006) was recalibrated to ages from Gradstein *et al.* (2012) using the method of Herrle *et al.* (2015) and used to identify major isotopic excursions in the Sawtooth Range and Slidre Fiord localities.

For whole rock geochemistry of the Slidre Fiord locality, 42 samples of 20 to 40 g were sent to ACME Labs Vancouver where they were pulverized to ≥ 85 % passing through a 75 μm sieve. A total of 15 g of sample went through 1:1:1 Aqua Regia digest (concentrated HCl, concentrated HNO_3 , deionized H_2O). Elemental concentrations were determined with inductively coupled plasma (ICP) mass spectrometry (MS) and emission spectrometry (ES) methods on 0.5 g of sample. Standard (STD DS10, STD OXC129) and average replicate relative standard deviations were all within $\pm 7\%$ for the elements utilized in this study (Ca, Fe, S, Al, V, Mo, Zn). For element values below the detection limit, which was only 1% of the values, concentrations were set at half the detection limit for plotting purposes (see Appendix B for sample values). For the redox sensitive elements Mo, V, and Zn, elemental concentrations are reported as trace metal excess ($\text{TM}_{\text{excess}}$) values relative to average upper continental crust values (McLennan, 2001) using the following equation:

$$TM_{\text{excess}} = TM_{\text{sample}} - Al_{\text{sample}} \left(\frac{TM}{Al} \right)_{\text{crustal}} \quad (1)$$

Where TM_{sample} is the trace metal concentration in the sample, Al_{sample} is the Al concentration of the sample and $\left(\frac{TM}{Al} \right)_{\text{crustal}}$ is the ratio of the trace metal concentration and Al from the upper crustal values in McLennan (2001). Major and trace element concentrations were compared to Al utilizing element vs. Al plots. Linear trends were fit to each plot and R^2 values were calculated in OriginPro 2016 v. b9.3.226. Due to the non-normality of each of the elemental datasets (Shapiro-Wilk Test; $p < 0.05$ for all elements), Spearman's rank correlation coefficients were calculated, also in OriginPro 2016 v. b9.3.226. The uppermost sample, which lies within the Expedition sandstones at 288 m, was left from these plots, due to multiple elemental concentrations below the detection limit (Appendix B). Carbon isotopic, TOC, foraminiferal and geochemical data associated with this thesis are found in Appendix B.

For foraminiferal analysis, 140 samples were processed for the Sawtooth Range locality at Global GeoLabs, Medicine Hat, Alberta, and 82 samples were processed for the Slidre Fiord locality by M. Davies. Each sample set was processed using the same technique modified from Then and Dougherty (1983). A total of 150 g of sample was crushed, sieved to $< 2\text{mm}$, and treated with $\sim 3\%$ hot H_2O_2 and $\sim 1\%$ detergent/water solution with sample sieving to $> 63 \mu\text{m}$ between steps. A total of 22 of the processed samples from the Sawtooth Range locality and 20 of the processed samples from the Slidre Fiord locality were selected for detailed foraminiferal analysis, having a resolution of every 4 - 10 m and 8 - 21 m respectively. For the Sawtooth Range locality, residues of

~ 1 - 50 g were picked entirely or were split by only picking a fraction of each tray to reach > 250 foraminifera. Total foraminifera picked from samples ranged from 0 to 750 specimens. For the Slidre Fiord locality, residues of ~ 10 -120 g were sieved into four size fractions (> 710 μm , 710 – 250 μm , 250 – 125 μm , and < 125 μm). In each fraction, five trays were investigated and if no foraminifera were found, it was considered barren. If foraminifera were found in the size fraction, the entire fraction was picked.

For both study localities, foraminiferal identification was done to the lowest taxonomic level possible referencing mainly Tappan (1962), North and Caldwell (1970,1975), Wall (1983), McNeil and Caldwell (1981), McNeil (1997b), and Setoyama *et al.* (2011a). Preservation of some foraminifera only allowed up to a generic classification, and others were placed in an unknown category. A detailed list of synonymy and key references for each taxon can be found in Appendix A and raw counts found in Appendix B. Picking of residues was performed at 8 – 16x magnification and identification was performed at 25 - 32x magnification on an Olympus SZX9 dissecting microscope. Photographs were taken with a Canon Rebel T3i at 40x magnification.

Percentages were calculated minus the unknown foraminifera for each taxonomic group. The tubular taxon *Bathysiphon* was included in the percentage calculation despite their tendency to break and be overrepresented in counts (e.g., Setoyama *et al.*, 2011b), due to very low abundances. Concentrations are reported as the number of foraminifera / 150 g of sample at Sawtooth Range, and was multiplied by what portion of the sample was picked if appropriate. In order to limit the effects of rare taxa and allow for better comparison between samples than with just species abundance, diversity indices were

calculated in PAST version 3.12 for the Sawtooth Range locality (Hammer *et al.*, 2001; Murray, 2006). The diversity indices used were the Shannon Index (H):

$$H = - \sum_i \left(\frac{n_i}{N} \right) \ln \left(\frac{n_i}{N} \right) \quad (2)$$

where n_i is the number of individuals in species i and N is the total number of individuals, equability (E):

$$E = \frac{H}{H_{max}} \quad (3)$$

$$H_{max} = \ln(S) \quad (4)$$

where H is the Shannon index and H_{max} is the maximum value for the Shannon Index, or the natural logarithm of the number of species, Simpson dominance (D) and diversity (SD) indices:

$$D = \sum_i \left(\frac{n_i}{n} \right)^2 \quad (5)$$

$$SD = 1 - D \quad (6)$$

where n_i is the number of individuals in species i and N is the total number of individuals, and the Berger Parker Dominance Index (BP):

$$BP = \frac{n_d}{N} \quad (7)$$

where n_d is the number of individuals in the most dominant species and N is the total number of individuals. The diversity indices were calculated at both the species and

generic levels of taxonomic classification. Confidence intervals of 95% were calculated for each of the diversity indices using a bootstrap method with 9999 computations.

For the Sawtooth Range locality, morphogroups were defined based on the chamber arrangement, number of chambers, and supposed life mode (infaunal or epifaunal) (van den Akker *et al.*, 2000; Nagy *et al.*, 2009; Murray *et al.*, 2011). Each genus identified in the section was assigned a morphogroup and the sum of the relative abundances for each group was calculated. Calcareous taxa were not included in the analysis, as they are rare ($< 0.5\%$), are likely influenced by taphonomic processes in this study, and morphologies and supposed life modes are defined differently than for agglutinated taxa (Murray *et al.*, 2011).

Chapter 4: Results

4.1: Lithostratigraphy

The Kanguk Formation at Slidre Fiord and Sawtooth Range localities are characterized by two informal members, as previously described on Ellef Ringnes (Balkwill, 1974; Balkwill and Hopkins, 1976; Evenchick and Embry, 2012; Pugh *et al.*, 2014) and Axel Heiberg (Fricker *et al.*, 1963) islands. The lower member is characterized by grey to black shales and siltstones to fine sandstones, whereas the upper member is dominantly rusty brown shales to siltstones with uncommon interbeds of grey to black shales and concretions. A total of six facies were observed within the Kanguk Formation between the two sections, which are split into subfacies based on colour and grain size differences (Table 1).

4.1.1: Sawtooth Range

A total thickness of 194 m was measured at the Sawtooth Range locality, 147.5 m of which is assigned to the Kanguk Formation. At the base of the section, which occurs at 0.5 m, a sharp contact between the Hassel and the Kanguk formations is observed (Figure 4). The lithology is initially dark grey shales of Facies 2A at the base. The lower member at this locality is characterized by very dark to dark grey shales (Facies 2A and 2B respectively), with silty intervals occurring from 8 to 28.5 m and 57 to 65.5 m. The lower silty interval is characterized by a light grey siltstone of Facies 3B, and the upper silty interval a light brown siltstone of Facies 3C. The upper interval of the lower member is characterized by a dark grey paper shale (Facies 1C) from 70 – 73 m. Abundant

Table 1: Facies descriptions of the Kanguk Formation lithology at Slidre Fiord and Sawtooth Range localities. Microfossil changes are from the Sawtooth Range locality only, due to poor preservation at the Slidre Fiord locality. SF: Slidre Fiord, SR: Sawtooth Range. Foraminifera abundance defined in table as: absent: 0 foraminifera/sample, present: 1 – 50 foraminifera /sample, common: 50 – 200 foraminifera/sample, and abundant > 200 foraminifera/sample.

<i>Facies</i>	<i>Sub-Facies</i>	<i>Lithology Colour and Characteristics</i>	<i>Section Where Present</i>	<i>TOC</i>	<i>Microfossils (Sawtooth Range)</i>	<i>Paleoenvironment</i>
<i>1 – Paper shale</i>	A	Black	SF	High in dark grey-black	Foraminifera abundant; Algal cysts present in interval at the base of section	Lower offshore; limited oxygen conditions (lack of bioturbation)
	B	Grey	SF	(~ 4 - 10%); lower in grey (~0.5 to 1%)	Foraminifera present to abundant; Radiolarians rare to common with good preservation	Lower offshore; variable oxygen conditions
	C	Dark grey	SR	Variable, 1 to 6 %		
	A	Very dark grey	SF/SR			
<i>2 – Grey to black shale (soft to platy)</i>	B	Dark grey	SF/SR			
	C	Grey with sulphur bands	SF			
	D	Black	SF			
	A	Interbedded with shales	SF	Generally low, (< 3%), with some moderate levels (3 – 5%)	Foraminifera absent to abundant; Radiolarians absent to common	Mid -upper offshore, increased silt content more proximal to shoreline (increased sedimentation rate)
<i>3- Siltstone to fine Sandstone (massive)</i>	B	Light grey	SF/SR			
	C	Light brown	SR			
	A	Light grey	SF			
<i>4 – Grey silty shale</i>	B	Grey	SF			
	A	Rusty brown	SF	Generally between 2 to 4%	Foraminifera absent to common; Radiolarians largely absent	Middle to lower offshore; variable oxygen conditions
	B	With dark grey shale intervals	SR			
<i>5 – Brown shale and mudstone</i>	A	Rusty brown	SF			
	B	With dark grey shale intervals	SR			
<i>6 – Brown silty shale and mudstone</i>	-	Rusty brown	SF	Generally between 3 to 4 %	-	Mid -upper offshore, increased silt content more proximal to shoreline (increased sedimentation rate)

bentonites also characterize the lower member, and are brown, yellow, or green in colour (Figure 4).

The base of the upper member of the Sawtooth Range section is recognized by the first appearance of rusty-brown shales and mudstones at 84 m (Figure 4). The upper member of the Sawtooth Range locality is not uniformly rusty brown, but alternates between rusty- brown shale and mudstone (Facies 5B) and very dark to dark grey shales (Facies 2A-B). The rusty intervals are also associated with abundant concretionized beds and individual concretions (Figure 4; Table 1). Bentonites also occur in the upper member, but are not as abundant (Figure 4). The contact between the Kanguk and Expedition formations is within a covered portion of the section. Above the covered portion are planar-stratified sandstone and siltstone assigned to the Expedition Formation (Figure 4).

4.1.2: Slidre Fiord

At Slidre Fiord the base of the Kanguk Formation, at 0 m, forms a sharp contact with the underlying Hassel Formation sandstone (Figures 5 and 6A). The Hassel Formation is overlain by black paper shale of Facies 1A (Figure 6B). The remaining section of the lower member consists of black to grey shales that are soft to platy in appearance (Facies 2A-B) with intervals of silty shale to fine sandstone (Facies 3A-B, 4A-B) at 23 to 63 m and 80 to 84 m. Grey paper shale (Facies 1B) is found between 63 to 85 m, surrounding the second silty interval. The basal 50 m of the section is dominated by sulphur-rich intervals, and from 96.5 to 112 m sulphur-rich bands are interspersed within the grey shale (Facies 2C). Abundant bentonite beds are also seen within the lower

Figure 5: Stratigraphic section of the Kanguk Formation at the Slidre Fiord locality. Photo numbers refer to images found in Figure 6. For facies descriptions see Table 1.

Slidre Fiord

Figure 6: Images of the Kanguk Formation at the Slidre Fiord locality, courtesy of C. Schröder-Adams. **A:** Sharp contact at the Hassel- Kanguk formation boundary. **B:** Black paper shales at the base of the Kanguk Formation. **C:** Abundant bentonites in the lower member. **D:** Boundary between the grey siltstones and shales of the lower member and the rusty brown siltstones, shales and mudstones of the upper member. **E:** Sharp boundary between the Kanguk and Expedition formations. **F:** Bed of *Sphenoceras patootensis* shells.

member of the Slidre Fiord section and vary in colour from green-yellow to brown (Figures 5 and 6C).

At 112 m the lithology changes to the rusty brown shale and mudstone (Facies 5A) of the upper member and concretion beds and individual concretions, some red in colour are found throughout the interval (Figures 5 and 6D). The rusty brown shale and mudstone is the dominant lithology of the upper member in the Slidre Fiord locality, with very dark to black shales (Facies 2A-B) only observed between 135 to 140 m and 247.5 m to the top of the section at 287.5 m. Sulphur-rich intervals occur again above 180 m. Two siltier portions are observed in the upper member at 140 to 141.5 m and 222.5 m to 232 m (Facies 6; Figure 5). Bentonites also occur throughout the upper member but are not as abundant as in the lower member (Figure 5). At the top of the section there is a sharp contact with the Expedition Formation sandstones, where the base of the sandstone appears altered to a rusty colour (Facies 2D; Figure 6E).

4.1.3: Section Comparison

The Sawtooth Range and Slidre Fiord sections mainly differ at the boundary between the Hassel and Kanguk formations, within the siltier intervals, and the facies associations within the upper member. Paper shales are absent at the base of the section at Sawtooth Range and instead consists of dark grey shales (Facies 2A; Figures 4 and 5). The silty intervals in the Sawtooth Range section are also generally coarser grained, except for the fine sandstone within the 23 to 63 m interval at Slidre Fiord (Figures 4 and 5). The rusty brown shale and mudstone dominates the upper member of the Slidre Fiord locality compared to the Sawtooth Range locality, which has more interbedded grey shale

intervals (Figures 4 and 5). Finally, the Sawtooth Range section is thinner, with a total thickness of 147.5 m compared to 287.5 m at Slidre Fiord.

4.2: Chemostratigraphy and Total Organic Carbon (TOC)

At both the Sawtooth Range and Slidre Fiord localities, five distinct $\delta^{13}\text{C}_{\text{org}}$ intervals were identified and are labelled A to E in Figure 7. Positive and negative excursions were established based on shifts in the isotopic values that were associated with more than one data point and were approximately ± 0.5 ‰. In the Slidre Fiord section $\delta^{13}\text{C}_{\text{org}}$ excursions were generally more gradual and TOC values were not as variable in comparison to Sawtooth Range.

In Interval A at the Slidre Fiord section, which occurs from 0 to 20.5 m, $\delta^{13}\text{C}_{\text{org}}$ values are initially more positive within the black paper shales (Facies 1A) at the base of the Kanguk Formation. Values then rapidly transition to between -26.2‰ and -25 ‰ for the rest of the interval (Figure 7). In the Sawtooth Range section, Interval A occurs from 0.6 to 25 m, and the initial positive $\delta^{13}\text{C}_{\text{org}}$ group of values is not seen, but the lowermost data point, which is the most positive value of the interval, may be correlated to the two initial values at the base of the Slidre Fiord section. The $\delta^{13}\text{C}_{\text{org}}$ values at Sawtooth Range vary between -25.8 ‰ to -24.3 ‰ for the interval (Figure 7). Total organic carbon is initially high at the base (approximately 10 % Slidre Fiord, 4 % Sawtooth Range) within both sections and then decreases upward, corresponding to a coarsening upwards trend in the lithology (Figure 7).

Figure 7: Carbon isotope stratigraphy ($\delta^{13}\text{C}_{\text{org}}$) and total organic carbon (TOC) content for the Slidre Fiord and Sawtooth Range localities. Intervals interpreted to be correlative between the $\delta^{13}\text{C}_{\text{org}}$ values of both localities are labelled A-E. For lithological descriptions see Figures 4 and 5 and Table 1.

Interval B is the first of two positive carbon isotope excursions recognized within both sections, characterized by an average + 0.5 ‰ and + 0.4 ‰ shift relative to the lower interval for Slidre Fiord and Sawtooth Range localities respectively (Figure 7). This excursion occurs from 20.5 to 34.5 m at Slidre Fiord, and from 25 to 32 m at Sawtooth Range. At Sawtooth Range the position of this excursion is better defined, with values ranging between -24.9 ‰ to -24.1 ‰. At Slidre Fiord the excursion occurs from 20.5 to 34.5 m and the values are slightly more negative than Sawtooth Range, varying from -25.6 ‰ to -24.6 ‰. TOC remains fairly constant within the interval, from approximately 2 to 4 % in Sawtooth Range and 1 to 4 % in Slidre Fiord (Figure 7). The lithology of the interval is silty shale to fine sandstone and fines upwards towards the top of the interval (Figure 7).

Interval C occurs from 34.5 to 117 m in the Slidre Fiord section and 32 to 80 m in the Sawtooth Range section between the two identified positive isotopic excursions within each section. At Slidre Fiord, the isotopic values range from -26.1 to -24.4 ‰, similar to Interval A. At Sawtooth Range, $\delta^{13}\text{C}_{\text{org}}$ values range from -26.9 to -24.9 ‰ in the interval, which are more negative than Slidre Fiord and Interval A. At Sawtooth Range, a rapid transition to fairly high TOC values occurs near the base of the interval (Figure 7). TOC values through the lower interval are fairly high but variable, ranging from 0.6 to 6.2 %, and correspond to very dark to dark grey shales to the last silty interval in the section (Figure 7). At 71 m, TOC rapidly decreases to around 1 % TOC, followed by a gradual increase through the rest of the interval (Figure 7). At Slidre Fiord, TOC values range from 0.5 to 3.6 %, with values initially decreasing in the interval, followed

by a rapid increase at 87 m (Figure 7.) Grey paper shales, silty shales and grey to very dark grey shales are associated with this interval at Slidre Fiord.

Interval D, which is the second positive excursion identified within both sections, occurs at 117 to 190 m in the Slidre Fiord section with values ranging from -25.35 to -24.32 ‰, with an average excursion of + 0.5 ‰ from the previous interval. At Sawtooth Range, Interval D is located from 80 to 96 m with a range of -25.8 to -22.4 ‰ and has an average excursion of + 0.8 ‰ from the previous interval. TOC in this interval is high and relatively constant within each interval, both ranging from around 1 to 4 %. The base of this interval lies close to the transition from the lower to upper member division at both localities (Figure 7).

Interval E occurs from 190 to 282 m in the Slidre Fiord locality and 96 to 190 m in the Sawtooth Range locality, with $\delta^{13}\text{C}_{\text{org}}$ values ranging from -25.2 to -24.7 ‰ and -25.6 to -23.9 ‰ respectively. The ranges recorded for both sections are similar to the ranges recorded in Interval A and C. The TOC content in this interval is relatively constant in the Slidre Fiord section, ranging between 1 to 4.6 %. The TOC content at Sawtooth Range is initially high from the base of the interval to 113 m, ranging from 1.4 to 5.1 %, and then rapidly decreases to a range of 0.5 to 2.9 % for the rest of the interval. Brown shale and mudstone (Facies 5) and dark grey shale (Facies 2) are found within this interval at both localities (Table 1, Figure 7).

4.3: Whole Rock Geochemistry

A total of 42 samples were analyzed for major (Ca, Fe, S, Al) and trace (V, Mo, Zn) elements to understand lithologic and paleoredox changes recorded within the Kanguk Formation at Slidre Fiord (Figure 8). The redox proxies V, Mo, and Zn, are expressed as excess concentrations in comparison to average crustal values of McLennan (2001) as well as the original concentration data (Figure 8). The trace metal excess and the concentration trends are similar (Figure 8). Two zones were established that correspond to the lower (GEOC-1) and upper (GEOC-2) member lithologies (Figure 8). Two subzones were established within GEOC-2 based on the varying Mo and Al concentrations. In the lower member, from 0 to 112 m, major elemental concentrations are generally low compared to the upper portion, ranging from 0.03 to 0.77 wt. % Ca, 1.1 to 3.5 wt. % Fe, 0.05 to 3.3 wt.% Σ S, and 0.2 to 1.4 wt. % Al. Al and Σ S values generally rise throughout the interval and V, Mo, and Zn, are generally low (Figure 8). Concentration data for each of these elements follows the same trends. V and Zn are generally not in excess throughout the lower interval, but Mo varies considerably. Excess concentrations of Mo greater than 2 ppm correspond to paper shale intervals of the lower member, in Facies 1A-B (Figure 8). The lower paper shale interval also corresponds to high TOC values of > 4 %. The upper paper shale interval of Facies 1B has generally low TOC values around 0.5 to 1.1% (Figure 8).

In the upper member (GEOC-2), ranging from 112 to 287.5 m, major elemental concentrations become more variable and generally higher than in the lower interval. The boundary between the two intervals lies at 188 m. In subzone GEOC-2A, Σ S and Al vary

Figure 8: Total organic carbon (A), carbon isotope stratigraphy (B), major element concentrations (C-F) and excess trace element concentrations (G-I) for the Kanguk Formation at Slidre Fiord. Trace element excess is based on average continental crust of McLennan (2001). Dashed line indicates boundary between subzones of GEOC-2. For lithological description refer to Figure 5 and Table 1.

from 0.2 to 2.9 wt. % and 0.6 to 1.8 wt.% respectively, which is similar to the previous interval. Fe and Ca are generally higher than in the lower member in this interval, varying from 0.6 to 6.2 wt. % and 0.2 to 1.3 wt. %. V increases slightly within the interval, reaching values of approximately > 10 ppm in excess and generally follows the trend of Al throughout the upper section (Figure 8). Zn and Mo are also elevated, with excess values of > 2 ppm for Mo and between approximately 30 to 200 ppm for Zn throughout the interval. This interval also corresponds to positive carbon isotope excursion of Interval D (Figures 7 and 8).

Subzone GEOC-2B is marked by the shift to the highest Al values of the section, ranging from 2.9 to 3.3% (Figure 8). These values lie within the interval of 188 to 237 m, followed by a slow decrease in the upper part of the interval. The excess V concentrations continue to follow the same trends as the Al curve, with highest excess concentrations of > 25 ppm from 188 to 237 m. Ca concentrations are lower within this interval, ranging from 0.01 to 0.6 wt.%. Fe values remain relatively high and similar to GEOC-2A, ranging from 0.9 to 7.3 wt. %, with a decrease in values occurring after 270 m. Σ S continues to remain low and within the same interval of GEOC-1, with values from 0.78 to 2.33 wt. %. Mo and Zn are generally lower in this interval, with Mo values all less than 2 ppm in excess and Zn values are generally in excess of 8 to 114 ppm, with one value reaching 232 ppm. TOC values are similar to the GEOC-2A, ranging from 1 to 4.6 % (Figure 8).

Major and trace elemental concentrations were also compared to Al to understand the influence of the sediment source on the geochemistry, as Al is largely unaffected by

Slidre Fiord

Figure 9: Element vs. Al plots for the Slidre Fiord locality for Fe (A), ΣS (B), Ca (C), V (D), Zn (E), and Mo (F). Grey line represents linear fit to data. R^2 and Spearman's rank correlation coefficient are recorded on plot.

biological processes and comes dominantly from a terrigenous source (Brumsack, 2006; Tribovillard *et al.*, 2006; Hofer *et al.*, 2013). Fe and V have strong positive correlations to Al ($R^2=0.599$, Spearman's Rank Coefficient = 0.828 and $R^2 = 0.882$, Spearman's Rank Coefficient = 0.895 for Fe and V respectively). ΣS and Ca are also positively correlated to Al, but values are more scattered ($R^2 = 0.254$, Spearman's Rank Coefficient = 0.567 for S; $R^2 = 0.064$, Spearman's Rank Coefficient = 0.446 for Ca). Zn and Mo have a weak positive to negative correlations to Al ($R^2 = 0.001$, Spearman's Rank Coefficient = 0.293 for Zn; $R^2 = 0.012$, Spearman's Rank Coefficient = -0.016 for Mo) (Figure 9).

4.4: Foraminiferal Abundance and Biostratigraphy

4.4.1: Sawtooth Range

In the 22 samples investigated, a total of 5660 foraminifera were identified in the Sawtooth Range section, which represented 39 different species and 20 genera (Figures 10 to 13). The section was split into two zones utilizing marker species after previous work from Wall (1983) and Schröder-Adams *et al.* (2014).

Zone 1: *Evolutinella boundaryensis* (0 – 78 m)

Zone 1 is characterized by the occurrence of *Evolutinella boundaryensis* throughout the interval (Figure 10). The boundary to the overlying zone was determined based on the last appearance of the zonal marker taxon *Evolutinella boundaryensis* at 76 m (Sample SR-13; Figures 4 and 10). The boundary was placed between Sample SR-13 and SR-14, at 78 m. A total of 31 species and 16 genera are represented in this zone. This zone was split into three subzones reflecting on major assemblage changes. The

Figure 10: Foraminifera biostratigraphy and relative abundance in the Kanguk Formation at the Sawtooth Range, showing the long ranging, *Evolutinella boundaryensis* Zone, and *Verneuilinoides bearpawensis*- *Glaphyrammina spirocompressa* Zone taxa. For lithological description see Figure 4.

Figure 12: Plate 1: See descriptions on pages 44 to 46.

Figure 12: Plate 1: Foraminifera from the Upper Cretaceous Kanguk Formation at Sawtooth Range, Ellesmere Island, Nunavut, Canada. Photos taken at 40 X magnification.

1. *Bathysiphon brosgiei* Tappan (1957), Sample SR-13, 80 m
2. *Bathysiphon vitta* Nauss (1947), Sample SR-13, 80 m
3. *Saccamina lathrami* Tappan (1960), Sample SR-14, 88 m
4. *Ammodiscus cretaceus* Reuss (1845), Sample SR-20, 135 m
5. *Reophax pepperensis* Loeblich (1946), Sample SR-5, 36 m
6. *Reophax* sp. A, Sample SR-14, 88 m
7. *Evolutinella boundaryensis* McNeil (1997b), Sample SR-1, 0.6 m
8. *Haplophragmoides bonanzaensis* Stelck and Wall (1954), Sample SR-14, 88 m
9. *Haplophragmoides collyra* Nauss (1947), Sample SR-7, 46 m
10. *Haplophragmoides glabra* Cushman and Waters (1927), Sample SR-20, 135 m
11. *Haplophragmoides kirki* Wickenden (1932), Sample SR-12, 76 m
12. *Haplophragmoides rota* Nauss (1947), Sample SR-13, 66 m
13. *Glaphyrammina spirocompressa* McNeil (1997b), Sample SR-20, 135 m
14. *Ammomarginulina* sp. A, Sample SR-20, 135 m
15. *Spiroplectammina mordenensis* Wickenden (1932), Sample SR-12, 76 m
16. *Spiroplectammina webberi* Tappan (1957), Sample SR-1, 0.6 m

Figure 12: Plate 1 (cont.)

17. *Pseudobolivina rollaensis* Stelck and Wall (1954), Sample SR-8, 54 m
18. *Trochammina albertensis* Wickenden (1932), spiral view (A) and umbilical view (B), Sample SR-20, 135 m
19. *Trochammina boehmi* Franke (1928), spiral view (A) and umbilical view (B), Sample SR-19, 125 m
20. *Trochammina diagonis* Carsey (1926), spiral view (A) and umbilical view (B), Sample SR-10, 65 m
21. *Trochammina globigeriniformis* var. *altiformis* Cushman (1910), spiral view (A) and umbilical view (B), Sample SR-14, 88 m
22. *Trochammina rainwateri* Cushman and Applin (1946), spiral view (A) and umbilical view (B), Sample SR-6, 42 m
23. *Trochammina ribstonensis* Wickenden (1932), spiral view (A) and umbilical view (B), Sample SR-8, 54 m
24. *Trochammina rutherfordi* Stelck and Wall (1955), spiral view (A) and umbilical view (B), Sample SR-1, 0.6 m
25. *Trochammina stefanssoni* Tappan (1957), spiral view (A) and umbilical view (B), Sample SR-10, 65 m
26. *Trochammina tukensis* McNeil (1997b), spiral view (A) and umbilical view (B), Sample SR-18, 115 m

Figure 12: Plate 1 (cont.)

27. *Trochammina umiatensis* Tappan (1957), spiral view (A) and umbilical view (B),
Sample SR-4, 27 m
28. *Trochammina whittingtoni* Tappan (1957), spiral view (A) and umbilical view
(B), Sample SR-6, 42 m
29. *Arenobulimina torula* Tappan (1957), Sample SR-4, 27 m
30. *Gaudryina irenensis* Stelck and Wall (1955), Sample SR-3, 17.1 m
31. *Uvigerinammina spiritensis* Stelck and Wall (1954), Sample SR-5, 36 m
32. *Verneuilina* sp. A, Sample SR-12, 76 m
33. *Verneulinoides bearpawensis* Wickenden (1932), Sample SR-18, 115 m
34. *Verneulinoides fischeri* Tappan (1957), Sample SR-14, 88 m
35. *Verneulinoides* cf. *perplexus* Loeblich (1946), Sample SR-20, 135 m
36. *Dorothia smokyensis* Wall (1960), Sample SR-18, 115 m

Figure 13: Plate 2: See descriptions on pages 48 to 49.

Figure 13: Plate 2: Foraminifera of the Upper Cretaceous Kanguk Formation at Sawtooth Range (1-3) and Slidre Fiord (4-19), Ellesmere Island, Nunavut, Canada. Photos taken at 40 X magnification.

1. *Textularia gravenori* Stelck and Wall (1955), Sample SR-5, 36 m
2. *Pseudoclavulina hastata* Cushman (1927), Sample SR-3, 17.1 m
3. *Quinqueloculina sphaera* Nauss (1947), Sample SR-6, 42 m
4. *Saccamina lathrami* Tappan (1960) Sample SF-14, 183 m
5. *Miliammina bisobscura* Stelck and Wall (1954), Sample SF-11, 160 m
6. *Reophax* sp. A, Sample SF-8, 100 m
7. *Haplophragmoides bonanzaensis* Stelck and Wall (1954), Sample SF-7, 85m
8. *Haplophragmoides glabra* Cushman and Waters (1927), Sample SF-14, 183 m
9. *Haplophragmoides kirki* Wickenden (1932), Sample SF-14, 183 m
10. *Haplophragmoides rota* Nauss (1947), Sample SF-18, 239 m
11. *Trochammina albertensis* Wickenden (1932), spiral view (A) and umbilical view (B), Sample SF-18, 239 m
12. *Trochammina boehmi* Franke (1928), spiral view (A) and umbilical view (B), Sample SF-14, 183 m
13. *Trochammina diagonis* Carsey (1926), spiral view (A) and umbilical view (B), Sample SF-14, 183 m

Figure 13: Plate 2 (cont.)

14. *Trochammina ribstonensis* Wickenden (1932), spiral view (A) and umbilical view (B), Sample SF-14, 183 m
15. *Trochammina tukensis* McNeil (1997b), spiral view (A) and umbilical view (B), Sample SF-14, 183 m
16. *Verneuilioides bearpawensis* Wickenden (1932), Sample SF-18, 239 m
17. *Verneuilioides fischeri* Tappan (1957), Sample SF-7, 85m
18. *Verneuilioides cf. perplexus* Loeblich (1946), Sample SF-7, 85m
19. *Dorothia smokyensis* Wall (1960), Sample SF-8, 100 m

Evolutinella boundaryensis Zone falls within the lower member of the Kanguk Formation at Sawtooth Range. The zone is also characterized by a high abundance of radiolarians occurring in samples SR-4 to SR-10 (27 – 65 m), with rare occurrences further up in the section. Algal cysts are found in the most basal sample and *Inoceramus* prisms are found throughout the zone (Figures 10 to 11).

Subzone EB-1 (0 - 44 m)

Within Subzone EB-1 foraminiferal concentration in samples are low compared to other portions of the section, ranging from 0 to 500 foraminifera per 150 g. The base of the subzone is marked by rare (<4 %) occurrences of *Trochammina rutherfordi*.

Pseudoclavulina hastata and *Spiroplectammina webberi* occur only within this subzone, ranging from 0 – 10 % of the assemblage. Sample SR-2 at 9 m was barren, and occurs within the siltier interval of Facies 3B. The first appearance of *Textularia gravenori*, *Evolutinella boundaryensis*, *Gaudryina irenensis*, *Arenobulimina torula*, *Trochammina umiatensis*, *Trochammina rainwateri*, and *Trochammina whittingtoni* all occur at the base of this interval, and all vary between 0 – 20 % of the assemblage (Figure 10).

Trochammina stefanssoni, which is observed in the basal sample, does not occur again until the upper part of the *Evolutinella boundaryensis* zone. *Reophax pepperensis* and *Saccammina lathrami* also are observed in the basal sample and continue throughout the subzone, but are rare (< 7 %). *Quinqueloculina sphaera*, the only calcareous taxa found at this locality, occurs within the uppermost portion of this subzone, along with *Uvigerinammina spiritensis*. Taxa which occur throughout the Kanguk Formation include *Haplophragmoides bonanzaensis*, *Haplophragmoides rota*, *Haplophragmoides kirki*,

Trochammina diagonis, *Dorothia smokyensis*, and *Verneuilinoides fischeri*.

Verneuilinoides cf. *perplexus* first appears in SR- 4 in high abundance, and is present throughout the rest of the Kanguk Formation. Both *Haplophragmoides bonanzaensis* and *Haplophragmoides rota* have their highest relative abundances in this subzone, between 30 to 40 % (Figure 10).

Subzone EB-2 (44 – 61.5 m)

In Subzone EB-2 foraminifera concentrations are high, dominated by the species *Trochammina ribstonensis* which first appears in Sample SR-7 and its abundance ranges between 40 to 70 % of the assemblage. Concentrations range from 3000 – 17,000 foraminifera per 150 g. *Trochammina albertensis* and *Trochammina globigeriniformis* var. *altiformis* appear at the end of the subzone at 58 m (Sample SR-9) with relative abundances both below 5%. *Haplophragmoides collyra* is found only within this interval at the Sawtooth Range locality. *Haplophragmoides bonanzaensis*, *Haplophragmoides rota*, *Haplophragmoides kirki*, *Dorothia smokyensis*, *Verneuilinoides* cf. *perplexus*, *Verneuilinoides fischeri*, *Evolutinella boundaryensis*, *Gaudryina irenensis*, *Textularia gravenori*, *Arenobulimina torula*, *Trochammina umiatensis*, and *Trochammina rainwateri* continue to occur throughout this subzone. The last appearance of *Reophax pepperensis*, *Gaudryina irenensis*, and *Trochammina whittingtoni* occur in this subzone. *Trochammina stefanssoni*, which had its first occurrence at the base of EB-1, reappears within this interval. The first appearance of *Bathysiphon brosgiei*, *Bathysiphon vitta*, *Saccammina lathrami*, and *Reophax* sp. A all occur in this interval, but form each less than 2% of the assemblage. (Figures 10 and 11).

Subzone EB-3 (61.5 – 78 m)

In Subzone EB-3 foraminifera concentrations decrease through the interval, ranging from 100 – 3200 foraminifera/sample. *Trochammina albertensis* increases throughout the subzone, varying in abundance from 10 to 25% of the assemblage (Figure 11). *Trochammina ribstonensis* is present, but is less than 8% for the rest of the subzone. *Spiroplectammina mordenensis* is found in the uppermost sample of this interval. The last appearance of *Evolutinella boundaryensis*, *Arenobulimina torula*, and *Uvigerinammina spiritensis* occur at the boundary of this subzone with the overlying *Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* Zone (Figures 10 and 11). Other species that have their last appearances in this subzone include *Pseudobolivina rollaensis*, *Trochammina umiatensis*, and *Trochammina rainwateri*. *Verneuilina* sp. first appears within this subzone. *Haplophragmoides bonanzaensis*, *Haplophragmoides rota*, *Haplophragmoides kirki*, *Dorothia smokyensis*, *Verneuilinoides* cf. *perplexus*, and *Verneuilinoides fischeri* continue to occur throughout this subzone.

Zone 2: *Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* (78 - 174 m)

Zone 2 is characterized by the occurrence of *Verneuilinoides bearpawensis* throughout the interval as well as rare (< 0.5 %) occurrences of *Glaphyrammina spirocompressa*, which also was recently identified at Glacier Fiord within the Kanguk Formation (Schröder-Adams *et al.*, 2014). Using this species here as zonal marker allows for correlation between these two localities. A total of 24 species are found in this interval that represent 11 genera. This zone was split into two subzones based on major

assemblage changes and subzone boundaries were placed between samples. The *Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* Zone is found in the upper 6 m of the lower member and the entire upper member. The late Santonian to early Campanian bivalve *Sphenoceras patootensis* occurs from 117.5 to 120 m within this zone.

Subzone VB-1 (78 – 111 m)

In Subzone VB-1 concentrations of foraminifera continue to decrease, ranging from 0 – 400 foraminifera/150 g. Samples SR-15 and SR-16 are barren. *Haplophragmoides kirki*, *Dorothia smokyensis*, *Verneuilinoides* cf. *perplexus*, *Verneuilinoides fischeri* *Haplophragmoides bonanzaensis*, and *Haplophragmoides rota* continue to occur through this subzone and range up from the *Evolutinella boundaryensis* Zone (Figure 10). The three *Verneuilinoides* species, *V.* cf. *perplexus*, *V. fischeri*, and *V. bearpawensis* are the major species of the zone constituting combined 25-40 % of the assemblage. Along with the first appearance of *Verneuilinoides bearpawensis*, *Haplophragmoides glabra*, and *Ammodiscus cretaceus* also first appear in this subzone. The last appearances of *Trochammina stefanssoni*, *Saccamina lathrami*, *Bathysiphon vitta*, and *Reophax* sp. A, are within this subzone. *Trochammina albertensis* is the main trochamminid species of the interval, at 8-10 % of the assemblage (Figure 11). *Trochammina globigeriniformis* var. *altiformis* and *Bathysiphon brosgiei* are also present within this subzone.

Subzone VB-2 (111 m – 174 m)

Within Subzone VB-2 concentrations increase in this interval, ranging from 400 – 1500 foraminifera/150 g. This interval is characterized by the appearance of *Trochammina boehmi*, *Trochammina tukensis*, *Ammomarginulina* sp. A, and *Glaphyrammina spirocompressa*. *Haplophragmoides kirki*, *Dorothia smokyensis*, *Verneuilinoides* cf. *perplexus*, *Verneuilinoides fischeri*, *Haplophragmoides bonanzaensis*, and *Haplophragmoides rota* continue to occur throughout this zone. Occurrences of *Quinqueloculina sphaera*, *Bathysiphon brosegi*, *Trochammina globigeriniformis* var. *altiformis*, *Verneulina* sp. and *Ammodiscus cretaceus* also occur in this subzone, all with less than 7% relative abundance. *Trochammina albertensis* continues to be the main trochamminid species, forming 10 -30 % of the assemblage. *Haplophragmoides glabra* continues to be present at 2 – 10 % (Figure 11). Sample SR-17 only contained seven foraminiferal specimens and so was not included in relative abundance calculations, but *Haplophragmoides kirki*, *Trochammina albertensis*, *Haplophragmoides glabra*, and *Verneuilinoides fischeri* were present in the interval. The uppermost sample of the subzone, SR-22, is barren of foraminifera.

4.4.2: Slidre Fiord

In the 20 samples investigated from the Slidre Fiord section, a total of 189 foraminifera were identified, which represented 16 species and 8 genera (Figures 13 and 14). The section was split into two zones utilizing marker species previously proposed by Schröder-Adams *et al.* (2014) and Wall (1983) and revised here as proposed for the Sawtooth Range locality. The limited number of foraminifera and numerous barren

Slidre Fiord

Figure 14: Foraminifera biostratigraphy in the Kanguk Formation at the Slidre Fiord locality. For lithological description see Figure 5 and Table 1.

samples within the Slidre Fiord section made placement of the zonal boundaries difficult. The upper boundary of the *Evolutinella boundaryensis* Zone was not identified but likely lies within the barren interval between 100 to 160 m, as above this interval is the first appearance of *Haplophragmoides glabra*, which only occurred in the *Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* Zone at the Sawtooth Range locality (Figure 10). Algal cysts also occur in the lowest most sample (SF-1) as at the Sawtooth Range locality. Radiolarians are found throughout the section, with higher abundances occurring in samples SF- 3 and SF-8 (27 and 100 m respectively).

Zone 1: *Evolutinella boundaryensis* (0 – 100 m ?)

The lower interval of the *Evolutinella boundaryensis* Zone is barren from sample SF-1 to SF-5 (between 0 – 50 m). The zone mainly consists of long ranging species *Verneuilinoides* cf. *perplexus*, *Verneuilinoides fischeri*, *Haplophragmoides bonanzaensis*, *Haplophragmoides kirki*, *Dorothia smokyensis*, and *Trochammina diagonalis*. *Trochammina ribstonensis* and *Trochammina albertensis* occur further up in the zone. *Reophax* sp. A also occurs in the uppermost sample of the zone (Figure 14).

Zone 2: *Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* (160 – 287.5 m)

In the Slidre Fiord section the first appearance of *Haplophragmoides glabra* defines the *Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* Zone. Boundary placement between the two zones remains undefined due to the low abundance of foraminifera within the section (Figure 14). *Trochammina tukensis*, *Trochammina*

boehmi, and *Verneulinoides bearpawensis*, all characteristic of this zone at Sawtooth Range, occur higher up in the section above 175 m (Figure 11). *Verneulinoides* cf. *perplexus*, *Verneulinoides fischeri*, *Haplophragmoides bonanzaensis*, *Haplophragmoides kirki*, *Dorothia smokyensis*, *Trochammina diagonis*, *Trochammina ribstonensis* and *Trochammina albertensis* all occur in this zone. *Miliammina bisobscura*, which was not found at the Sawtooth Range locality, is found at 160 m. (Figure 14). *Saccammina lathrami* also appears within this zone. The bivalve species *Sphenoceramus patootensis* of late Santonian to Campanian age is also found at the Slidre Fiord locality from 167 – 210 m (Figures 6F and 14).

4.5: Foraminiferal Morphogroups and Diversity

Using foraminiferal morphogroup analysis of van den Akker *et al.* (2000), Nagy *et al.* (2009), and Murray *et al.* (2011), a total of five distinct morphogroups were identified in the rich foraminiferal assemblages at Sawtooth Range as outlined in Tables 2 and 3. Taxa were assigned to a morphogroup based on chamber arrangement and overall test shape (Tables 2 and 3) and relative abundance of each morphogroup was calculated for the section. The calcareous genus *Quinqueloculina* was not included in the analysis as morphogroup assemblages are different for calcareous taxa (Murray *et al.*, 2011). Descriptions of each of the morphogroups and the changes in the relative abundance of each group are described below.

Table 2. Foraminiferal morphogroup categories A to C for the Upper Cretaceous Kanguk Formation at Sawtooth Range. Foraminifera genera were assigned to each morphogroup based on Murray *et al.* (2011), Nagy *et al.* (2009), Setoyama *et al.* (2011b) and van den Akker *et al.* (2000). Life mode, feeding strategy, and environments based on Murray *et al.* (2011), Setoyama *et al.* (2011b), Cetaan *et al.* (2011), and Nagy *et al.*, (2009, 2010).

Morphogroup	Life Mode/Feeding Strategy	Modern/Paleo-Environments (Previous Work)	Paleoenvironment (This Study)	Genera Included in this Study	Morphology
A	Epifaunal Suspension feeders	Bathyal to abyssal regions Low organic matter flux	Rare, transgressive and highstand stages	<i>Bathysiphon</i>	Tubular, one chamber
B	Epifaunal to shallow infaunal Suspension and/or deposit feeders	Common in bathyal to abyssal regions	Rare, transgressive and highstand stages	<i>Saccamina</i>	Circular, one chamber
C	Shallow to deep infaunal Deposit feeders	Shelf to bathyal regions High organic matter flux	Highest abundance in transgressive phases, dysoxic conditions	<i>Arenobulimina</i> <i>Dorothia</i> , <i>Gaudryina</i> <i>Pseudobolivina</i> <i>Reophax</i> <i>Spiroplectammina</i> <i>Textularia</i> <i>Uvigerinammina</i> <i>Verneuilina</i> <i>Verneuilinoides</i>	Elongate, multichambered

Table 3. Foraminiferal morphogroup categories D to F for the Upper Cretaceous Kanguk Formation at Sawtooth Range. Foraminifera genera were assigned to each morphogroup based on Murray *et al.* (2011), Nagy *et al.* (2009), Setoyama *et al.* (2011b) and van den Akker *et al.* (2000). Life mode, feeding strategy, and environments based on Murray *et al.* (2011), Setoyama *et al.* (2011b), Cetean *et al.* (2011), and Nagy *et al.*, (2009, 2010). U: umbilical view, S: spiral view.

Morphogroup	Life Mode/ Feeding Strategy	Modern/ Paleo- Environments (Previous Work)	Paleoenvironment (This Study)	Genera Included in this Study	Morphology
D	Epifaunal Deposit feeders	Common in marginal marine to outer shelf, often found in limited oxygen conditions or stressed environments	Highest abundance in highstand phases, limited oxygen content, high OM supply	<i>Trochammina</i>	U S Coiled/trochospiral, multichambered
E	Epifaunal to shallow infaunal Deposit feeders	Marginal to outer shelf (common) bathyal to abyssal (present)	Regressive to transgressive phases most abundant	<i>Ammomarginulina</i> <i>Evolutinella</i> <i>Glaphyrammina</i> <i>Haplophragmoides</i>	Coiled/planispiral, multichambered
F	Epifaunal Deposit feeders	Found in all marine environments	Rare, transgressive and highstand stages	<i>Ammodiscus</i>	Coiled/planispiral two chambers

4.5.1: Foraminiferal Morphogroups Descriptions for the Kanguk Formation at Sawtooth Range

Morphogroup A

Morphogroup A, which is represented by the genus *Bathysiphon* in this study, are tubular, single chambered foraminifera that typically have an epifaunal and suspension feeding lifestyle (Nagy *et al.*, 2009). They are typically found in deeper regions of the ocean, from bathyal to abyssal depths, as they are suspension feeders that need low organic matter flux to thrive (Tables 2 and 3).(Murray *et al.*, 2011). This morphogroup is only a minor part of the assemblage at Sawtooth Range, ranging from 0 to 2 % of the assemblage for the entire section. This morphogroup corresponds to Morphogroup A of Nagy *et al.* (2009) and Murray *et al.* (2011).

Morphogroup B

Morphogroup B is defined by globular and single chambered foraminifera represented by the genus *Saccamina* at Sawtooth Range. Like Morphogroup A, Morphogroup B is not a major component of the assemblage throughout the section, ranging from 0 to 6 %. This morphogroup is typically found from bathyal to abyssal regions of the ocean and are epifaunal deposit feeders (Nagy *et al.*, 2009; Murray *et al.*, 2011). This morphogroup corresponds to Morphogroup B in Nagy *et al.* (2009) and B1 in Murray *et al.* (2011).

Morphogroup C

Morphogroup C is characterized by elongate, multichambered foraminifera, which was well represented in the Sawtooth Range locality, and included the genera *Arenobulimina*, *Dorothia*, *Gaudryina*, *Pseudobolivina*, *Reophax*, *Spiroplectammina*, *Textularia*, *Uvigerinammina*, *Verneuilina*, and *Verneulinoides*. Foraminifera of Morphogroup C typically populate shelf to bathyal environments and are often associated with a higher organic matter flux (van den Akker *et al.*, 2000; Murray *et al.*, 2011). Their life mode is interpreted to be shallow to deep infaunal deposit feeders (Setoyama *et al.*, 2011b). Within the Sawtooth Range section this morphogroup ranges from 10 to 60 % of the assemblage. This morphogroup corresponds to Morphogroup C in Nagy *et al.* (2009) and Murray *et al.* (2011).

Morphogroup D

Morphogroup D is defined by multichambered trochospiral foraminifera, which is represented by the genus *Trochammina*. This morphogroup, and the genus *Trochammina* in general, is typical of stressed environments and high organic matter flux to the seafloor (e.g. Gooday *et al.*, 2000; Nagy *et al.*, 2010). This taxon represents epifaunal deposit feeders, and are most common in marginal marine to outer shelf environments (Nagy *et al.*, 2009; Murray *et al.*, 2011; Setoyama *et al.*, 2011b). The *Trochammina* genus is well represented in the Sawtooth Range locality, with a total of 11 species making up 6 to 75 % of the morphogroup assemblage. This morphogroup is equivalent to D1 in Nagy *et al.* (2009) and D in Murray *et al.* (2011).

Morphogroup E

Morphogroup E is defined as multichambered planispiral foraminifera and is represented by the genera *Ammomarginulina*, *Evolutinella*, *Glaphyrammina*, and *Haplophragmoides* in this study. This morphogroup includes typically epifaunal to shallow infaunal deposit feeders that are found most commonly from marginal to outer shelf regions (Nagy *et al.*, 2009; Murray *et al.*, 2011). At Sawtooth Range this morphogroup ranges in abundance from 10 to 52 % of the assemblage. This morphogroup is equivalent to D2 in Nagy *et al.* (2009) and B3 of Murray *et al.* (2011).

Morphogroup F

Morphogroup F is defined by planispiral multichambered tubular foraminifera, which is represented by the genus *Ammodiscus* in this study. This morphogroup includes epifaunal or attached deposit feeders that are found across all marine environments (Nagy *et al.*, 2009; Murray *et al.*, 2011; Setoyama *et al.*, 2011b). At Sawtooth Range this morphogroup is a minor component of the assemblage, ranging from 0 to 4 %. This morphogroup is equivalent to E in Nagy *et al.* (2009) and B2 in Murray *et al.* (2011).

4.5.2: Variation of Morphogroups and Diversity within the Kanguk Formation at Sawtooth Range

At the Sawtooth Range locality, the relative abundance of each morphogroup and diversity trends were characterized by four major assemblage types, which are labelled M-1 to M-4 in Figure 15. Assemblage types were based on changes in the relative abundance of Morphogroups C, D, and E, which are the main groups of the section.

Figure 15: Foraminiferal morphogroups and diversity indices for the Kanguk Formation at the Sawtooth Range locality. For lithologic description refer to Figure 4 and Table 1.

Overall, the diversity of the foraminiferal assemblage at Sawtooth Range is low, with only 4 to 20 species and 3 to 12 genera per sample. Species and generic diversity, recorded by the Shannon and Simpson indices, are fairly constant throughout the Kanguk Formation, except in intervals where either the assemblage is dominated by a certain taxon or foraminifera are absent from the interval (Figure 15). The dominance of a certain taxon is indicated by increased dominance and Berger-Parker indices and decreased evenness values (Figure 15). The diversity indices at the generic and species levels follow similar trends (Figure 15).

At the base of the section, from 0.6 to 22.1 m, a relatively even distribution of Morphogroups C, D, and E, is present, which defines the M-1 type assemblage (Figure 15). Epifaunal species of Morphogroups D and E each range from 20 to 50 % and infaunal species of Morphogroup C are an average of 25 % of the assemblage (Figure 15). The trochamminids of Morphogroup D are higher in the lower portion of this interval, corresponding to the high TOC values at the base of the formation, but one species of trochamminid does not dominate the interval (Figure 10). At both the species and generic level, the samples are fairly equitable (Equability: average 0.86 species, 0.70 generic level) and diversity is relatively high compared to the rest of the section (Shannon Index (H): average 2.34 species, 1.55 generic level). Decreasing TOC values and a coarsening upwards trend in the lithology also characterize this interval (Facies 2 to 3; Figure 15).

Above the basal M-1 interval, from 22.1 to 39 m, the percentage of infaunal species (Morphogroup C) increases to an average of 52 %, which defines the M-2

assemblage (Figure 15). The epifaunal Morphogroups D and E are also present, each accounting for 7 to 41 % of the assemblage respectively. Diversity remains similar to the previous interval (Equability: average species 0.82, genera 0.81 and Shannon Index: average species 2.07, genera 1.68) (Figure 15). TOC values increase within the interval from approximately 1 % to 4 %. The positive isotope excursion that defines Interval B in the $\delta^{13}\text{C}_{\text{org}}$ record is also within this interval (Figure 7) and the lithology transitions from light grey silty shales (Facies 3B) to dark grey shales (Facies 2A-B).

From 39 to 61.5 m, a sharp increase in the relative abundance of trochamminids (Morphogroup D) is noted, with an average of 62% of the assemblage in the interval. This dominance of Morphogroup D is what characterizes the M-3 assemblage. The dominant taxon is *Trochammina ribstonensis*, which accounts for 45 to 75% of the foraminiferal assemblage in this portion of the Kanguk Formation, and are quite small in comparison to the other trochamminid species of the Kanguk (Figures 11, 12, and 15). The first appearances of Morphogroups A and B also occur within this interval (Figure 15). Diversity in this interval is the lowest of the Sawtooth Range section, with an average Shannon Index of 1.88 for the species and 1.24 for the generic levels. Lowered diversity corresponds to the highest dominance (average 0.29 species level and 0.44 generic level) and lowest equability (average 0.64 species and 0.52 generic level) values of the section (Figure 15). Morphogroups C and E range from 10 to 40 % of the assemblage. Despite the dominance of *Trochammina* in the assemblage, the number of species found within the interval is higher than the previous two zones, with up to 20 different species, and concentrations of foraminifera are high, ranging from 150 to 17,000

foraminifera/150 g (Figures 11 and 15). TOC values fluctuate within the interval and are an average 3.5 %. This interval is associated with dark to very dark grey shales (Facies 2A-B) and in the upper portion light brown siltstone (Facies 3C).

The transition back to a higher relative diversity and a more even assemblage occurs between 61.5 to 74 m, and the relative percentages of Morphogroup C, D, and E is similar to the M-1 interval at the base. Epifaunal Morphogroups D and E range from 28 to 45 % and the infaunal species of Morphogroup C are an average of 24 % of the assemblage (Figure 15). Like at the base of the Kanguk Formation, TOC decreases in this interval from approximately 3.5 to 2 %. The lithology is initially the light brown siltstone of Facies 3C and transitions to dark grey and paper shales in upper portion.

Above the second M-1 interval, from 74 to 90.5 m, infaunal species of Morphogroup C again increase in relative abundance to an average of 44%, making it another M-2 assemblage type. Morphogroups A, B, and for the first time F also appear within this interval. Morphogroup D and E each range from 16 to 32 % of the assemblage (Figure 15). Diversity remains similar to the previous interval (Shannon Index (H): species average 2.27, generic average 1.45). Like in the previous M-2 assemblage, TOC values increase to an average of 3.5 % (Figure 15). The start of the positive $\delta^{13}\text{C}$ excursion of Interval D (Figure 7) also occurs at the top of this interval. The dark grey to rusty brown shales of Facies 2B and the rusty brown shale and mudstone of Facies 5B characterize this interval.

Foraminifera are largely absent in the M-4 interval from 90.5 to 111 m, with only seven specimens found in the uppermost sample of this interval at 107 m. The morphogroups present in that sample are C, D, and E, as in previous intervals (Figure 15). The upper part of the positive carbon isotope excursion of Interval D is contained within this interval and TOC values are high, around 3.5%. The lithology of the interval is dark grey and rusty brown shale and mudstone of facies 2B and 5B respectively.

The uppermost interval from 111 to 145 m is characterized by the reappearance of foraminifera and an initially high relative abundance of the infaunal Morphogroup C. This is followed by the return to a fairly even assemblage of Morphogroups C, D and E, as in previous M-1 intervals. Morphogroup C varies from 24 to 53 % in the zone, and D and E each range from 10 to 46% (Figure 15). Diversity also returns to similar values of previous intervals (Shannon Index: 2.11 average species and average 1.33 generic level). TOC values are relatively low within the interval, with an average of 1.8%. The lithology in this interval is dark grey to very dark grey shales (Facies 2A-B) with rusty brown shale and mudstone (Facies 5B) intervals.

Chapter 5: Discussion

5.1: Taphonomy

The microfossil assemblages of the two localities in this study have been influenced by taphonomic processes. Both sections are dominated by agglutinated taxa, with calcareous foraminifera being rare or absent (Figures 10 to 14). Dissolution of calcareous fauna within these localities has to be taken into account, as other Arctic localities (e.g. Tappan, 1962; Wall, 1983; McNeil, 1997b) have preserved calcareous taxa for the Late Cretaceous. The generally high values of total organic carbon content in the Kanguk Formation shales at both localities may have contributed to carbonate dissolution, as the breakdown of organic matter may cause acidic pore water conditions with the addition of CO₂ (Loubere *et al.*, 1993; Murray, 2006). The high frequency of bentonite beds throughout the section may also be responsible for calcareous microfossil dissolution, as they would also contribute to the acidic nature of the sediments (Balkwill and Hopkins, 1976).

The significant difference in abundance of foraminifera between the two localities might also be explained by taphonomy. Poor preservation of agglutinated foraminifera at Slidre Fiord versus the Sawtooth Range locality is likely due to silicification. Silicification occurs when tests are buried past depths of approximately 2400 - 3500 m and/or with temperatures of approximately 75 – 110 °C. Silicification causes secondary quartz precipitation on quartz grains in the agglutinated tests, filling the chambers and strengthening the test (McNeil, 1997a). The same burial and temperature differences are

responsible for the differences in colour of the foraminifera in each section, as the organic compound responsible for holding the grains together in agglutinated foraminifera produces volatiles with changing depth and temperature, causing foraminifera to darken with burial depth (McNeil, 1997a). Sawtooth Range was buried at greater depths with the colour being dark brown to black for the foraminifera observed in the study, while tests retrieved from sediments at Slidre Fiord have a white to pale yellow colour, and chambers are not filled with quartz. This means that these tests are more prone to breakage.

Abundant bentonites in the lower member would have enhanced the preservation of siliceous microfossils preservation, such as radiolarians and diatoms during deposition by increasing dissolved silica in the water column (e.g. Pugh *et al.*, 2014). Their presence in both sections suggest that burial depths were not deep enough for post depositional silica dissolution, which typically starts below 600 m depth (e.g. Hein *et al.*, 1978; Witkowski *et al.* 2011; Pugh *et al.* 2014).

The preservation of radiolarian and foraminiferal taxa also varies across the basin. Radiolaria are abundant at Hoodoo Dome on Ellef Ringnes Island (Pugh *et al.*, 2014) and at the two localities in this study, but no radiolarian taxa are found at Glacier Fiord (Schröder-Adams *et al.*, 2014). Variability in foraminiferal abundance is also seen, from rare (this study Slidre Fiord; Pugh *et al.*, 2014; Wall, 1983) to more common (this study Sawtooth Range, Schröder-Adams *et al.*, 2014) at different localities within the Sverdrup Basin. Not only silicification but also burial rates could have affected preservation of agglutinated foraminifera across the Sverdrup Basin, as the organic compounds that hold

the agglutinated particles together break down with prolonged exposure to oxygen (McNeil 1997a; Murray, 2006). The length of exposure time depends on bioturbation intensity, sedimentation rate, and the thickness of within the sediment (McNeil, 1997a; Murray, 2006). Overall the variation in microfossil preservation reflects differential burial and diagenetic regimes across the basin.

5.2: Criteria for Stage Boundary Placement within the Kanguk Formation

In order to assign ages and to relate the Kanguk Formation to global transgressive-regressive cycles of Gradstein *et al.* (2012), carbon isotope stratigraphy, microfossil abundances and compositions, macrofossil occurrences, and lithologic changes were utilized. The carbon isotopic curves ($\delta^{13}\text{C}_{\text{org}}$) of Sawtooth Range and Slidre Fiord were compared to the low-latitude composite $\delta^{13}\text{C}_{\text{carb}}$ reference curve from Jarvis *et al.* (2006). This reference curve is based on well-dated English Chalk sections and by comparing it to the Kanguk Formation at each locality, allows for the potential recognition of global events within the Arctic that can be assigned an age. The work of Jarvis *et al.* (2006) with the English Chalk sections and other reference curves were recently compared to a $\delta^{13}\text{C}_{\text{org}}$ record at Glacier Fiord, Axel Heiberg Island by Herrle *et al.* (2015), showing the correlation of the Arctic region to major global events from the Barremian to Turonian. This study extends that comparison into the Campanian. As in Herrle *et al.* (2015), the biostratigraphic marker ages within the Jarvis *et al.* (2006) reference curve were updated to the revised ages of Gradstein *et al.* (2012) and were recalibrated using the same age model as Jarvis *et al.* (2006). Recalibrated values are listed in Table 4.

Table 4: Biostratigraphic datum levels and stage boundaries used to recalibrate the Jarvis *et al.* (2006) with the revised ages of Gradstein *et al.* (2012). Bold datum levels were used in calculation of sedimentation rate, after model of Jarvis *et al.* (2006). *: Interpolated from age model used in Jarvis *et al.* (2006).

Datum Level	Age (Ma)		
	This Study	Jarvis <i>et al.</i> (2006)	Gradstein <i>et al.</i> (2012)
Campanian – Maastrichtian Boundary	72.05	70.60	72.05
Santonian – Campanian Boundary	83.64	83.53	83.64
Base <i>Marsupites</i> Zone	84.22*	84.11	-
upper Santonian Boundary (base <i>Uintacrinus socialis</i> Zone)	84.92*	84.71	-
middle Santonian (top <i>Micraster coranguinum</i> Zone)	84.93*	85.57	-
Coniacian – Santonian Boundary	86.26	85.85	86.26
upper Coniacian (base <i>Magadiceramus subquadratus</i> Zone)	86.97*	86.56	-
Turonian – Coniacian Boundary	89.77	89.27	89.77
upper Turonian Boundary (base <i>Subprionocyclus neptuni</i> Zone)	90.86*	90.36	-

At the base of both the Sawtooth Range and Slidre Fiord localities, the > 2‰ positive excursion of OAE 2 is not present (Figures 16 and 17). The absence of OAE 2 is supported by the diverse foraminiferal assemblages at the base of the Sawtooth Range locality section, marking full recovery from the oceanic anoxic event, and the lack of paper shales at the base (Figures 4 and 10) (Friedrich, 2010; Schröder-Adams *et al.*, 2014). Furthermore, the foraminiferal zone defined by Schröder-Adams *et al.* (2014) that includes the OAE 2 interval is characterized by an abundance of *Trochammina rutherfordi*, which occurs in the Sawtooth Range section, but is less than 4% of the assemblage. Slidre Fiord samples are barren until 50 m from the base of the section so foraminiferal data cannot be used to determine age, but black paper shales, more positive $\delta^{13}\text{C}$ isotopic values (Arthur *et al.*, 1988), and elevated Mo (Scott and Lyons, 2012) at the base may indicate that the uppermost portion of OAE 2 is preserved. The OAE 2 interval likely lies within the Hassel Formation sandstones at the Ellesmere Island localities, while the OAE 2 interval lies within the base of the Kanguk Formation on Axel Heiberg (Lenniger *et al.*, 2014; Schröder-Adams *et al.*, 2014; Herrle *et al.*, 2015) and Ellef Ringnes islands (Pugh *et al.*, 2014), demonstrating the diachronous nature of the Hassel – Kanguk boundary.

The first major positive $\delta^{13}\text{C}$ excursion (Interval B, Figure 7) in the record at both the Sawtooth Range and Slidre Fiord locality is identified as the late Turonian events within the Jarvis *et al.* (2006) reference curve (Figures 16 and 17). The late Turonian events of the Jarvis *et al.* (2006) reference curve are also recognized at Hoodoo Dome on Ellef Ringnes Island (Pugh *et al.*, 2014) which was recently constrained by Coniacian

Figure 16: Age assignments and transgressive-regressive framework for the Kanguk Formation at Sawtooth Range (A) with reference to the composite carbon isotope curve of Jarvis *et al.* (2006) and major transgressive-regressive cycles of Gradstein *et al.* (2012) (B) CTBE: Cenomanian-Turonian Boundary Event, SP: Occurrence of *Sphenocramus patootensis*, E: early, M: middle, L: late or lower, U: upper.

Figure 17: Age assignments and transgressive-regressive framework for the Kanguk Formation at Slidre Fiord (A) with reference to the composite carbon isotope curve of Jarvis *et al.* (2006) and major transgressive-regressive cycles of Gradstein *et al.* (2012) (B). CTBE: Cenomanian-Turonian Boundary Event, SP: Occurrence of *Sphenocramus patootensis*, E: early, M: middle, L: late or lower, U: upper.

bentonite ages above the interval in Davis *et al.* (2016), allowing for correlation across the Sverdrup Basin.

The second event recognized from the Late Cretaceous $\delta^{13}\text{C}_{\text{carb}}$ curve of Jarvis *et al.* (2006) is the Santonian-Campanian Boundary Event, which corresponds to the positive excursion of Interval D and has a latest Santonian to earliest Campanian age (Figures 16 and 17). This is the first time this event has been recognized in the Arctic and constrains the age of the transition from the informal upper and lower members of the Kanguk Formation to the upper Santonian (Figures 16 and 17). The occurrence of the latest Santonian to early Campanian boreal marker species *Sphenoceras patootensis* occurs within the Santonian-Campanian Boundary Interval at Slidre Fiord and just above at the Sawtooth Range locality, confirming the placement of this interval in both sections. A bentonite age below the first appearance of the rusty brown shale and siltstone of the upper member (83.80 ± 0.21 Ma) and the occurrence of *Sphenoceras patootensis* on Axel Heiberg Island also supports this interpretation (Schröder-Adams *et al.*, 2014; Davis *et al.*, 2016).

In order to compare the global transgressive-regressive cycles of Gradstein *et al.* (2012) to the Kanguk Formation, lithology, total organic carbon, and foraminiferal assemblage changes were utilized to place maximum regressive (MRS) and maximum flooding surfaces (MFS), and then these boundaries were compared to the global T-R cycles of Gradstein *et al.* (2012) that were constrained by the carbon isotope stratigraphy of Jarvis *et al.* (2006) (Figures 16 and 17). Two maximum flooding surface boundaries in the Sawtooth Range locality were tentatively placed where there was a shift from low to

high TOC values, as organic-rich shales are typically deposited during relative sea-level rise to highstand intervals (Figure 16) (Leckie and Olson, 2003; Bjerrum *et al.*, 2006). The foraminiferal concentration after the lower MFS increases rapidly at Sawtooth Range, confirming the approximate placement of the lower MFS, as foraminifera concentrations are high in highstand intervals with low sedimentation rate and high organic carbon supply to feed populations (Leckie and Olson, 2003; Friedrich, 2010). At the upper MFS of Sawtooth Range, foraminifera are absent, and so comparison of concentration cannot be made. In the Slidre Fiord locality, due to little variation in TOC content of the shales, the lower MFS was placed at the base of the grey paper shale unit (Facies 1B) and the upper MFS was placed within the dark grey to black shale unit (Facies 2A) of the Santonian-Campanian boundary interval (carbon isotope Interval D) (Figure 17). Maximum regressive surfaces were placed at the top of siltier intervals, before the transition back to shale or mudstone (Figures 16 and 17). Two MRS were placed within the Sawtooth Range section and three within the Slidre Fiord locality (Figures 16 and 17). Transgressive and regressive intervals were then placed between the MFS and MRS boundaries (Figures 16 and 17).

With the integration of lithostratigraphy and chemostratigraphy as outlined above, the global T-R cycles of the Late Cretaceous can be recognized in both localities and ages can be assigned to the formation (Figures 16 and 17). At each locality, the lowest MRS corresponds well with the onset of the $\delta^{13}\text{C}$ late Turonian events, which occur in the reference curve of Jarvis *et al.* (2006) within and after the late Turonian regression of Gradstein *et al.* (2012) (Figures 16 and 17). The top of the late Turonian events

corresponds to the start of the Coniacian in the reference curve of Jarvis *et al.* (2006), and so the Turonian-Coniacian boundary is placed just within the isotope excursion for both intervals, at approximately 32 m in Sawtooth Range and 46 m at Slidre Fiord.

Although the Slidre Fiord locality is barren of foraminifera throughout the late Turonian events interval (Interval B in Figure 7 and 17), at Sawtooth Range the foraminifera representing this interval are found within EB-1, which is characterized by *Trochammina rutherfordi* and *Pseudoclavulina hastata*. *Trochammina rutherfordi*, which was originally described by Stelck and Wall (1955) in the Cenomanian Dunvegan Formation of the Peace River Region, western Canada, has been previously described in Cenomanian to Turonian-aged deposits (McNeil and Caldwell, 1981; Tappan, 1962; Thomson *et al.*, 2011; Schröder-Adams *et al.*, 2014), which supports the boundary placement. *Pseudoclavulina hastata* defines the Turonian *Pseudoclavulina hastata* – *Arenobulimina torula* Zone within the Alaska slope (Tappan, 1962), which also correlates well to the eastern Sverdrup Basin.

The lower Santonian boundary is placed within the Sawtooth Range section based on the first occurrence of *Trochammina albertensis*, which occurs in the Santonian to Campanian on the Alaska Slope (Tappan, 1962). This assigns a Coniacian age to the lower MFS at both localities (Figures 16 and 17), which corresponds to the mid Coniacian transgression of Gradstein *et al.* (2012). At Slidre Fiord, the low abundance of foraminifera made placing the lower Santonian boundary based on *Trochammina albertensis* difficult, and here is tentatively placed between the lower MFS and upper

MRS in the section based on correlations with the Jarvis *et al.* (2006) curve to Gradstein *et al.*, (2012).

Within the Santonian-Campanian boundary interval of the Jarvis *et al.*, (2006) curve is a global transgression, which is also present in both intervals identified at Sawtooth Range and Slidre Fiord. The base of the Campanian is placed in both sections within the Santonian-Campanian boundary interval ($\delta^{13}\text{C}$ Interval D) and below the upper MFS, based on correlations between the Jarvis *et al.* (2006) curve and the global T-R cycles of Gradstein *et al.* (2012) (Figures 16 and 17). At Slidre Fiord, another MRS extends the record to the middle Campanian when compared to the T-R cycles of Gradstein *et al.* (2012) and transitions into dark grey shale above this surface (Figure 17). These shales are associated with the transgressive phase of the middle Campanian and extend to the base of the Expedition Formation (Figure 17).

5.3: Comparison of Kanguk Formation Foraminiferal Assemblages of the Sverdrup Basin

The established zonation, based mainly on the rich foraminiferal assemblages of the Sawtooth Range, shares indicator species with those zonations established by Wall (1983) and Schröder-Adams *et al.* (2014) in the eastern Sverdrup Basin (Figure 18). The high abundances and good preservation in the Sawtooth Range locality also allow for a more detailed biostratigraphic analysis, and each of the zones was split into several subzones (Figures 10 to 11). Detailed future analyses of foraminifera abundances in other localities are needed to confirm the validity of these subzones and to assign a biostratigraphic marker species to each, as environmental influences on relative

Stage	Wall (1983) Eastern Sverdrup Basin	Schröder-Adams <i>et al.</i> (2014) Glacier Fiord	This Study Sawtooth Range
Maastrichtian			
Campanian	<i>Verneuilinoides bearpawensis</i>		<i>Glaphyrammina spirocompressa</i> - <i>Verneuilinoides bearpawensis</i>
Santonian	<i>Dorothia smokyensis</i>	<i>Glaphyrammina spirocompressa</i>	
Coniacian		<i>Dorothia smokyensis</i> - <i>Evolutinella boundaryensis</i>	<i>Evolutinella boundaryensis</i>
Turonian			
Cenomanian		<i>Trochammina rutherfordi</i>	
		<i>Gaudryina irenensis</i>	

Figure 18: Foraminiferal biostratigraphy comparison chart of proposed foraminiferal zonation for the Kanguk Formation.

abundances of taxa have to be considered. The age of top of the *Evolutinella boundaryensis* Zone is assigned to the late Santonian, as the $\delta^{13}\text{C}$ Santonian -Campanian boundary event lies above the boundary (Figure 16). The assemblage change also corresponds to the boundary between the lower and upper member, reflecting a response to the change in basin setting that caused the lithological change.

***Evolutinella boundaryensis* Zone (Turonian to late Santonian)**

The *Evolutinella boundaryensis* Zone occurs from the base of the Kanguk Formation to the last occurrence of *E. boundaryensis* and in this study is assigned a Turonian to late Santonian age based on the Sawtooth Range locality. For the Turonian to late Santonian interval, Wall (1983) and Schröder-Adams *et al.* (2014) assigned *Dorothia smokyensis* as a zonal marker. This taxon was not included as a marker species in this study due to its abundance throughout the Kanguk Formation at Sawtooth Range, and its significant overlap in range with the upper zone's marker species *Verneuilioides bearpawensis*. It was also only a rare taxon in the Glacier Fiord locality of Schröder-Adams *et al.* (2014), and therefore may be an inconsistent marker species across the basin. The basal zonal boundary with the early to middle Turonian is placed based on the previous zonation of Schröder-Adams *et al.* (2014), where the interval of the latest Cenomanian OAE 2 was defined by the *Trochammina rutherfordi* Zone (latest Cenomanian to earliest Turonian). This taxon is rare in the Sawtooth Range section (< 4%) and the significant (> 2‰) positive isotope excursion of OAE 2 associated with the zonal marker in Schröder-Adams *et al.* (2014) is absent in the isotope curves at the base of both the Slidre Fiord and Sawtooth Range sections (Figures 16 and 17). The upper

boundary is placed above the last occurrence of *Evolutinella boundaryensis* at 76 m in Sawtooth Range. At Slidre Fiord, the upper boundary is likely within the barren section between 100 to 160 m, but there are no definitive indicator species for the interval located within the lower portion of the section, so the boundary could be lower than suggested here.

The species that define the zones proposed in this study are similar to the zonal markers from the original biostratigraphic framework of Wall (1983), which included *Dorothia smokyensis*, *Pseudoclavulina* sp., *Verneuilinoides fischeri*, *Pseudobolivina rollaensis*, *Uvigerinammina spiritensis*, *Trochammina ribstonensis* and *Spiroplectammina* sp. Recent work at Glacier Fiord in Schröder-Adams *et al.* (2014) also had similar taxa, including *Evolutinella boundaryensis*, *Trochammina ribstonensis*, *Pseudoclavulina* sp, and *Pseudobolivina rollaensis* for the Turonian to Coniacian interval exposed. Wall (1983) assigned a Turonian to early Campanian age to his *D. smokyensis* Zone. With the new stratigraphic framework in this study, it is proposed that the upper boundary of this zone is moved into the late Santonian (Figure 18). This change is supported by the common occurrence of *Trochammina albertensis* in EB-3 (Figure 11), which is a Santonian to Campanian marker in Alaska (Tappan, 1962).

Abundant radiolarians within the lower member and algal cysts in the basal unit of both localities in this study also could be other potential markers for this zone. Wall (1983) also recognized abundant radiolarians within the lower portions of numerous sections on Ellesmere and Axel Heiberg islands, as well as algal cysts. Pugh *et al.* (2014) also showed high radiolarian abundances within the lower member on Ellef Ringnes

Island, with highest abundances corresponding to the Coniacian transgressive interval, which is also seen at Sawtooth Range associated with the high abundance of *Trochammina ribstonensis* (Figure 11).

***Verneuilinoides bearpawensis* – *Glaphyrammina spirocompressa* Zone (late Santonian to Campanian)**

The *Verneuilinoides bearpawensis*- *Glaphyrammina spirocompressa* Zone is defined by the first appearance of *Verneuilinoides bearpawensis* at the base and rare (<0.5 %) occurrences of *Glaphyrammina spirocompressa* in Sawtooth Range. The lower boundary is not defined in the Slidre Fiord section, due to the barren interval between 100 -160 m. Common taxa reported by Wall (1983) include *Verneuilinoides bearpawensis* and *Trochammina albertensis*. *Arenobulimina* cf. *torula* in Wall (1983) is identified in this study as *Verneuilinoides* cf. *perplexus* after Mello (1971) and Stelck and Wall (1955) (there identified as *Verneuilinoides perplexus* var. *gleddiei*), due to only having three chambers per whorl for the entire test. This also allowed the distinction of this taxon from the *Arenobulimina torula* in this study, which was defined by having initially three chambers followed by four chambers per whorl as in Tappan (1962). *Haplophragmoides* cf. *howardense* is identified here as *Haplophragmoides glabra*, based on the curved sutures and six to eight chambers per whorl (North and Caldwell, 1970, Mello, 1971). *Miliammina bisobscura* was found at the Slidre Fiord locality only and is likely equivalent to *Miliammina* sp. 2 of Wall (1983). The age of this zone in Wall (1983) was based on the late Campanian Bearpaw Formation of the Western Interior Seaway assemblage that has many common faunal elements, including *Verneuilinoides*

bearpawensis, *Trochammina albertensis*, *Haplophragmoides glabra*, and *Trochammina boehmi*, but appears that these species occur later in the Western Interior Sea than in the Arctic region (North and Caldwell 1970, 1975; McNeil and Caldwell, 1981).

Verneuilinoides bearpawensis was not encountered in the Glacier Fiord assemblage by Schröder-Adams *et al.* (2014), but *Glaphyrammina spirocompressa* was identified for the first time in the Sverdrup Basin. This species was originally described from Campanian strata of the Beaufort-Mackenzie Delta region (McNeil, 1997b). The calcareous taxa identified in Wall (1983) for the Campanian interval including *Praebulimina venusae*, cf. *Anomalina* sp., *Gavelinella talaria*, and *Serovaina orbicella*, were not found in either of the sections of this study but there were rare (< 3%) occurrences of *Quinqueloculina sphaera* in the Sawtooth Range section.

5.4: Regional Biostratigraphic Correlations between the Arctic Region and North America

The two zones proposed for the Ellesmere localities, the Turonian to late Santonian *Evolutinella boundaryensis* and the late Santonian to Campanian *Glaphyrammina spirocompressa* – *Verneuilinoides bearpawensis* zones correlate well to other Arctic assemblages as well as the Western Interior Seaway. The Alaska slope assemblages of Tappan (1962) offer the most complete comparison, as the record there spans the entire Upper Cretaceous. Lithologies between these two regions are also broadly similar (Figure 2). The Turonian *Pseudoclavulina hastata* - *Arenobulimina torula* Zone and the lower portion of the *Trochammina ribstonensis* - *Neobulimina canadensis* Zone of the Alaska slope are the equivalent zones for the *Evolutinella*

boundaryensis Zone (Figure 19) based on common elements. Rare occurrences of *Pseudoclavulina hastata* in the Turonian to Coniacian EB-1 Sub-Zone was seen at Sawtooth Range, allowing for tentative correlations. The equivalent *Pseudoclavulina hastata* Zone of Turonian age was also reported by Thomson *et al.* (2011) in the Peel Plateau, Northwest Territories. Some of the specimens identified as *Trochammina whittingtoni* by Tappan *et al.* (1962) are *Evolutinella boundaryensis*, as noted by McNeil (1997b). The taxon *Trochammina whittingtoni* is mainly characteristic for the lowest *Pseudoclavulina hastata* – *Arenobulimina torula* Zone of early Turonian age. In the Beaufort – Mackenzie Basin, where *Evolutinella boundaryensis* was first described, the species is contained within the Cenomanian to Turonian *Trochammina superestes* Zone. *T. superestes* has not been recognized in the Sverdrup Basin, both in this study, and at Glacier Fiord (Schröder-Adams *et al.*, 2014).

In the Western Interior Sea, common species from the Turonian to Coniacian interval include *Dorothia smokyensis*, *Haplophragmoides bonanzaensis*, *Pseudobolivina rollaensis*, and *Pseudoclavulina* sp. which are included in the *Flabellamina gleddei* and *Hedbergella loetterlei* zones (Figure 19) (Caldwell *et al.*, 1978). The dominance of agglutinated taxa in the Kanguk Formation makes zone correlation difficult to the WIS, where the Tethyan influence supports calcareous planktic and benthic foraminifera, particularly during the early Turonian and Santonian sea-level highstand phases (Hay *et al.*, 1993; North and Caldwell, 1970, 1975; McNeil and Caldwell, 1981; Caldwell *et al.* 1978). The Tethyan influence had no impact on the Polar Sea as migration of Tethyan

Stage	Caldwell et al. (1978) / Nielsen et al. (2008) Western Interior	Tappan (1962) Alaska Slope	McNeil (1997b) Beaufort Mackenzie Region	Thomson et al. (2011) Peel Plateau	This Study Sawtooth Range
Maastrichtian	<i>Haplophragmoides excavata</i>		<i>Haplophragmoides bilobata</i>		
	<i>Anomalinoides</i> sp.				
	<i>Haplophragmoides fraseri</i>				
	<i>Eoeponidella linki</i>				
Campanian	<i>Glomospira corona</i>				
	<i>Trochammina ribstonensis</i>	<i>Trochammina ribstonensis</i> - <i>Neobulimina canadensis</i>	<i>Glaphyrammina</i> <i>spirocompressa</i>		<i>Glaphyrammina</i> <i>spirocompressa</i> - <i>Verneuilinoides</i> <i>bearpawensis</i>
	<i>Globigerinelloides</i> sp.				
Santonian					
Coniacian	<i>Bullopore laevis</i>				
	<i>Marssonella oxycona</i>				<i>Evolutinella boundaryensis</i>
	<i>Pseudoclavulina</i> sp.				
Turonian	<i>Hedbergella loefferlei</i>	<i>Pseudoclavulina hastata</i> - <i>Arenobulima torula</i>		<i>Pseudoclavulina hastata</i>	
	<i>Fiabellammina gleddiei</i>		<i>Trochammina superstes</i>		
Cenomanian	<i>Verneuilinoides perplexus</i>	<i>Gaudryina irenensis</i> - <i>Trochammina rutherfordi</i>		<i>Gaudryina irenensis</i>	
	<i>Textularia alcesensis</i>				

Figure 19: Regional correlations of foraminiferal biostratigraphic zones for the Polar and Western Interior Seas covering the Cenomanian to Maastrichtian interval.

taxa would have been restricted by water mass differences from the equatorial and polar regions (Hay *et al.*, 1993; Schröder-Adams, 2014).

The Coniacian to lower Santonian EB-2 at Sawtooth Range is characterized by over 60 % *Trochammina ribstonensis*, which correlates well with the base of the *Trochammina ribstonensis* - *Neobulimina canadensis* Zone of Tappan (1962). The late Santonian to Campanian *Verneuilinoides bearpawensis* - *Glaphyrammina spirocompressa* assemblage correlates well with the Campanian assemblage of the WIS, with common species including *Dorothia smokyensis*, *Verneuilinoides bearpawensis*, *Haplophragmoides glabra*, and *Trochammina albertensis* (North and Caldwell, 1970, 1975; Caldwell *et al.* 1978; McNeil and Caldwell; 1981). The *Glaphyrammina spirocompressa* Zone of the Beaufort Mackenzie Basin also correlates well with this zone described here. *Trochammina tukensis*, found in the Campanian portion of this zone (VB-2), was originally described from the Maastrichtian in the Beaufort-Mackenzie Basin by McNeil (1997b), but *Trochammina* aff. *T. tukensis* has also been identified in the Campanian of the Lomonosov Ridge by Setoyama *et al.* (2011a). Other Campanian species common to the Lomonosov Ridge locality include *Ammomarginulina* sp. 1 (*Ammomarginulina* sp. A in this thesis), *Glaphyrammina spirocompressa* and *Trochammina ribstonensis*.

The late Santonian age for the base of the *Verneuilinoides bearpawensis* Zone in the Arctic extends biostratigraphic ranges of these taxa downwards when compared to ranges recorded in the Western Interior Sea. This is also observed on the Alaska slope (Tappan, 1962). Species ranges are also generally long within the Kanguk Formation.

This along with the similar species assemblages across the Arctic region indicates that the pericratonic Polar Sea provided a more stable benthic paleoenvironment than the shallow, epicontinental WIS that was under the influence of Tethyan derived watermasses and frequent sea-level fluctuations (Hay *et al.*, 1993; Schröder-Adams, 2014). Species certainly would migrate periodically into the WIS under favourable conditions explaining diachronous first occurrences between the two seas (Schröder-Adams, 2014).

5.5: Temporal and Spatial Changes within the Kanguk Formation Across the Sverdrup Basin

Comparison between the studied Kanguk sections presented here with those of previous works by Pugh *et al.* (2014), Schröder-Adams *et al.* (2014), Lenniger *et al.* (2014), Herrle *et al.* (2015) and Davis *et al.* (2016) allow for a regional correlation of the temporal and spatial variations within the Sverdrup Basin. Ellef Ringnes Island (Pugh *et al.*, 2014) represents basin center and Axel Heiberg Island (Schröder-Adams *et al.*, 2014; Lenniger *et al.*, 2014; Herrle *et al.*, 2015; Davis *et al.*, 2016) and Ellesmere Island (this study) represent more distal and proximal shelf settings respectively. The base of the Kanguk Formation differs across the basin, as demonstrated by the carbon isotopic records (Figure 20). Axel Heiberg (Lenniger *et al.* 2014; Herrle *et al.* 2015) and Ellef Ringnes islands (Pugh *et al.*, 2014), which represent more distal settings in the basin, record the OAE 2 within the basal Kanguk Formation. Within the more proximal Ellesmere Island sections of this study, the large (> 2‰) positive isotopic excursion of the OAE 2 interval is not recognized and likely lies within the Hassel Formation

Figure 20: Comparison of lithologic, biostratigraphic, and chemostratigraphic changes across the Sverdrup Basin with study localities from Ellef Ringnes (Pugh *et al.*, 2014; Davis *et al.*, 2016), Axel Heiberg (Lenniger *et al.*, 2014; Schröder-Adams *et al.*, 2014; Herrle *et al.*, 2015; Davis *et al.*, 2016) and Ellesmere islands (this study). Ages are from Davis *et al.* (2016) for the Hoodoo Dome and Glacier Fiord localities. L: lower, M: middle, U: upper.

sandstones or is not represented due to an erosional contact. The bentonite ages of Davis *et al.* (2016) confirmed a late Cenomanian age of the OAE 2 interval in the Polar Sea with a bentonite dated at $> 93.03 \pm 0.21$ Ma at the top of the excursion at Glacier Fiord (Figure 20). Lenniger *et al.* (2014) also placed the base of the Kanguk Formation in the latest Cenomanian with dinoflagellate species *Isabelidinium magnum* and *Trithryodinium suspectum* as marker species. Therefore, at the more marginal locations of Sawtooth Range and Slidre Fiord fine-grained sandstone deposition lasted into the Turonian while the more distal localities of Ellef Ringnes and Axel Heiberg islands were characterized by deep water deposition during the same interval.

The upper Turonian is marked by the late Turonian $\delta^{13}\text{C}$ events in the Ellef Ringnes and Ellesmere Island sections, but at Glacier Fiord much of the late Turonian and Coniacian section is covered (Schröder-Adams *et al.*, 2014; Pugh *et al.*, 2014). Coniacian bentonite ages above the late Turonian interval of Hoodoo Dome in Davis *et al.* (2016), also confirm the placement of this interval within that section (Figure 20). The thickness of the Turonian interval increases basinward, indicating more accommodation space in the distal portions of the basin during this time interval.

The lithological change that marks the transition from the lower to upper member of the Kanguk Formation occurred during the late Santonian based on the age frameworks of each study, and coincides with a global regression of that time (Gradstein *et al.*, 2012). This lithology change is also marked by the increase in Fe and Al content in the shale and mudstone at Slidre Fiord (Figures 8 and 15). Al is often used as a proxy for proximity to the shoreline and so the lithologic changes may be indicative of being closer

to an iron-rich sediment source, giving the red colour (Brumsack, 2006). Campanian strata of the upper member at Slidre Fiord are thicker than at Sawtooth Range, indicating continued greater accommodation space basinward. The majority of the upper member at Glacier Fiord was not measured due to covered section (Schröder-Adams *et al.*, 2014), but is approximately 200 m (Figure 20), which is a similar thickness to Slidre Fiord. At Hoodoo Dome the Kanguk was not sampled up to the Expedition Formation (Pugh *et al.*, 2014).

The late Santonian to early Campanian inoceramid *Sphenoceras patootensis* is a widespread boreal marker species, found in Arctic Siberia (e.g. Sahagian *et al.*, 1994; Olfer'ev *et al.*, 2008) and North America (e.g. Jeletzky, 1970, Olsen and Pedersen, 1991). This inoceramid is found within the upper member across the Sverdrup Basin close to the lower boundary (Figure 20), making it a good marker species within the Sverdrup Basin as well. The first occurrence of *Sphenoceras patootensis* occurs in the uppermost Santonian interval in the more distal regions and within the lower Campanian in the proximal localities of this study.

5.6: Paleoenvironmental Conditions and Foraminiferal Response to Paleoredox Conditions of the Kanguk Formation

The Kanguk Formation at Ellesmere Island localities within this study is interpreted to represent offshore conditions, where siltier intervals represent increased sediment source proximity. Differences in the upper and lower member are reflected in the whole rock geochemistry of Slidre Fiord, where elemental concentrations are generally higher within the upper member (Figure 8). Al, which is an indicator of source

proximity, as it mainly comes from terrigenous sources, is higher within the upper Kanguk Formation, indicating closer proximity to source during Campanian time (Brumsack, 2006; Tribovillard *et al.*, 2006). A similar increase in Fe is consistent with a more proximal location (Brumsack, 2006; Lyons and Severmann, 2006). V and S is also positively correlated, but diagenetic processes may have influenced concentrations of these elements, including pyrite formation and the incorporation of V into clay minerals (Breit and Wanty, 1991; Tribovillard *et al.*, 2006; Brumsack, 2006). Furthermore, the trace elements, Zn, Mo, and V have different patterns within the Kanguk Formation records and do not always positively correlate with the total organic carbon content (Figure 8). Therefore, the trace elements are likely mainly sediment source derived and oxic to dysoxic conditions prevailed in the basin (Tribovillard *et al.*, 2006). Overall, the lower member is interpreted to represent lower to middle offshore conditions and the upper member middle to upper offshore, with increased source proximity.

From the morphogroup analysis of the Sawtooth Range locality, four major assemblage types were recognized, labelled M-1 to M-4 in Figures 15 and 21. When these groups are compared to the global transgressive-regressive (T-R) cycles of Gradstein *et al.* (2012) by using major lithological changes and carbon isotope stratigraphy for correlation, each group corresponds to a different portion of the global T-R cycles recognized within the Kanguk Formation (Figures 21 and 22). Morphogroup assemblage M-1 is associated with regressive to lowstand intervals of the lithology with a maximum regressive surface occurring in or near the top of the interval (Figure 21).

Figure 21: Summary of morphogroup response in relation to changes in transgressive - regressive cycles of Gradstein *et al.* (2012). Epifaunal % includes all epifaunal to shallow infaunal taxa (Morphogroups A, B, D, E) and infaunal % is represented by Morphogroup C. OMZ: oxygen minimum zone, TOC; total organic carbon content, OAE 2: Oceanic Anoxic Event 2. See Tables 2 and 3 for morphogroup descriptions.

Figure 22: Schematic of the major changes in the morphogroup assemblages in relation to transgressive-regressive cycles, after Leckie and Olson (2003) and Nagy *et al.* (2009). During a regression (A), the shelf has an even and relatively diverse assemblage with oxygenated conditions. During a transgressive phase (B) the erosion of the coastline brings in nutrients, which enhances primary production and increases organic matter flux. Dysoxic conditions form and infaunal species become more dominant with the expansion of the oxygen minimum zone (OMZ). During highstand (C) the oxygen minimum zone continues to expand, and may cause either anoxic conditions at the benthos and loss of benthic fauna or dysoxic low diversity assemblages dominated by trochamminids, both of which were recorded in the Kanguk Formation.

Assemblage M-2 is associated with lowstand to transgressive intervals with the top characterized by a maximum flooding surface. The final two morphogroup assemblage types, M-3 and M-4 are associated with highstand to early regression intervals (Figure 21).

Within the context of the transgressive-regressive framework proposed, the foraminiferal communities are responding to changing TOC values and therefore oxygen levels, which are controlled by T-R cycles (Leckie and Olson, 2003). During a transgression, erosion of the coastline causes increased nutrient flux to the ocean and enhances primary productivity, and therefore flux of organic matter to the ocean floor (Figure 22) (Nagy *et al.* 2009; Leckie and Olson, 2003). Increased organic matter flux promotes an increase in foraminiferal abundance with increased food supply, but also depletes oxygen conditions (Goody *et al.*, 2000; Friedrich, 2010; Murray *et al.*, 2011; Nagy *et al.*, 2009). Infaunal foraminifera, which are adapted to lower oxygen conditions within the sediments, tend to increase where organic matter flux high (Jorissen *et al.*, 1995; Reolid and Martinez-Ruiz, 2012). In the Sawtooth Range locality, during the late Turonian to Coniacian and late Santonian to early Campanian transgressive events, infaunal species dominate the intervals characterized by finer grained sediments with increased TOC content, where slightly dysoxic conditions likely prevailed. The dysoxic conditions on the shelf likely are caused by the expansion of the oxygen minimum zone during transgressive phases. On Ellef Ringnes Island rich radiolarian assemblages were associated with the Coniacian transgressive interval and an increase in marine type II organic matter, indicating increased primary productivity (Pugh *et al.*, 2014). An

abundance of radiolarians was also observed at the Sawtooth Range and Slidre Fiord localities (Figures 11 and 14). In the transgressive to highstand assemblages, foraminiferal Morphogroups A, B, and F in this study, which are typically found in bathyal to abyssal water depths also become minor portions of the assemblage (Figure 15, Tables 2 and 3) (Murray *et al.*, 2011).

During highstand to early regression interval of the Coniacian, TOC levels and foraminiferal abundance are high, but the diversity is reduced with the shift to the dominance of the genus *Trochammina* (Figures 15 and 21 to 22). The genus *Trochammina* has been shown to tolerate stressful conditions, such as salinity and oxygen changes (Nagy *et al.* 2010). Furthermore, the taxon that dominates this interval, *Trochammina ribstonensis*, has a small test, which is an adaptation to low oxygen conditions (Figure 12) (Reolid *et al.*, 2014). Depleted oxygen conditions also promote an opportunistic lifestyle, where small test size and fast reproduction are favourable (Sen Gupta and Castillo, 1993). Continued expansion of the OMZ with high primary productivity and organic matter flux to the benthos likely led to the stressful benthic conditions and resulted in the epifaunal *Trochammina*- dominated assemblage (Figure 21) (Leckie and Olson, 2003).

Variability in the benthic redox conditions in a given transgressive interval is shown by the dominance of *Trochammina ribstonensis* during the Coniacian transgression and complete loss of foraminifera within the Santonian/Campanian boundary interval (Figures 15 and 21). Within the Santonian-Campanian boundary interval at Slidre Fiord, redox elements such as Mo and Zn are enriched in the sediments,

which may indicate lowered oxygen conditions (Algeo and Rowe, 2012). Concentrations of > 25 ppm in shales typically indicate anoxic conditions using Mo, which are not recorded within this transgressive interval (GEOC -2A, Figure 8) (Scott and Lyons, 2012). The Mo enrichment could be associated with pyrite formation, which enriches Mo during early diagenesis in dysoxic sediments (Tribovillard *et al.*, 2008). Zn could also be associated with hydrothermal activity (Tribovillard *et al.*, 2006). Ca is also elevated within this interval, which may indicate higher primary production, but also has a weak correlation to Al (Figure 9). The correlation may be influenced by source rock geochemistry, as Paleozoic carbonates and volcanics associated with an extensive Silro-Devonian orogenic belt, including the Ellesmerian Orogeny, were the main sediment source to the basin during the Late Cretaceous (Patchett *et al.*, 2004; Embry and Beauchamp, 2008). Furthermore, a sediment source region that deviates highly from the average continental crust may also be why the calculations of excess trace metals (TM_{excess}) does not separate the redox influence vs. sediment source well in this study (Figure 8) (Brumsack, 2006). Overall, this interval was likely dysoxic during the late Santonian-early Campanian transgressive period at Slidre Fiord and may have reached anoxic conditions where there was a complete loss of foraminifera at Sawtooth Range.

Variation in oxygen levels across the shelf could be explained by the OMZ having reached the benthos (Levin, 2003), but terrestrial organic matter flux in the more proximal setting may have also played a role. This may have been the case especially in the Santonian-Campanian transgressive interval, as the section generally shows a more terrestrial influence up section with increased Al content in the shales and mudstones

(Figures 8). Other studies have also shown an increased terrestrial influence between the upper and lower Kanguk Formation, with terrestrial vs. marine palynomorphs and through the characterization of organic matter by rock-eval pyrolysis (Núñez-Betelu *et al.*, 1994; Pugh *et al.*, 2014).

With a regression, such as in the Turonian and Santonian intervals, the oxygenated bottom waters return and the foraminiferal assemblages recover to a fairly even and diverse assemblage. However, foraminiferal assemblages are lower in concentration with less food supply and increased clastic sedimentation rates that also dilute microfossil assemblages (Figure 11) (Leckie and Olson, 2003). This is likely why there are barren samples within the silty shale intervals in this study. The assemblages are still dominated by agglutinated taxa of generally small test size, which may indicate that a) the Arctic region was more restricted or b) freshwater run off promoting water column stratification within the basin made it prone to dysoxic to anoxic benthic conditions (Schröder-Adams *et al.*, 2014; Hay and Floegel, 2012). An overall increased terrestrially derived organic flux to the Cretaceous Polar Sea could also have contributed to overall reduced oxygen conditions with increased nutrient fluxes (Chin *et al.*, 2008).

Similar agglutinated low diversity benthic foraminifera communities controlled by transgressive-regressive cycles and dominated by the genus *Trochammina* found within the Sverdrup Basin have also been described in the Arctic regions of Svalbard and the Barents Sea region in Triassic to Jurassic intervals (e.g. Nagy *et al.* 2009, 2010; Reolid *et al.*, 2010). Within these studies, deltaic influence on organic matter flux and water stratification contributed to overall lower oxygen levels. High freshwater influx and

watermass stratification could have also been the case for the Sverdrup Basin, especially in the Campanian interval, with the initiation of the progradation of the Expedition Formation during that time (Embry and Beauchamp, 2008; Schröder-Adams, 2014).

In terms of oceanic anoxic events, the global OAE 2 has clearly been recognized within the more distal settings of the basin on Axel Heiberg (Schröder-Adams *et al.*, 2014; Lenniger *et al.*, 2014; Herrle *et al.*, 2015) and Ellef Ringnes islands (Pugh *et al.*, 2014), but little work on the “OAE 3” interval has been done to date. Within the Kanguk Formation, as seen in this study and previous work (Pugh *et al.*, 2014; Schröder-Adams *et al.*, 2014; Herrle *et al.*, 2015) deposition of dark organic-rich shales continues after the Cenomanian Turonian boundary OAE 2, similar to the Coniacian to Santonian within the Atlantic (Wagreich, 2009). Furthermore, within the Sverdrup Basin the deposition of the organic-rich shales is associated with transgressive intervals, as in the Western Interior Sea (Figure 21) (Tessin *et al.*, 2015), and a positive $\delta^{13}\text{C}$ isotope excursion at the Santonian-Campanian boundary (Figures 16 and 17). The reduced diversity and dominance of the trochamminid assemblage of the Coniacian and the loss of foraminifera at the Santonian-Campanian boundary are both consistent with the reported interval for OAE 3 in the Atlantic. Pugh *et al.* (2014) also recorded increased radiolarian abundance and marine type II organic matter within the Coniacian interval at the Hoodoo Dome Kanguk Formation locality during the Coniacian corresponding with the high radiolarian abundance at Sawtooth Range. Basin wide anoxia was likely not the case during either of these events however, as shown by high abundances of foraminifera (Friedrich, 2010) at Sawtooth Range during the Coniacian transgression (Figure 11) and limited paleo-redox

indicator element enrichments (Algeo and Rowe, 2012; Scott and Lyons, 2012) at Slidre Fiord in the latest Santonian to Campanian transgression (Figures 8, 11, and 21).

Therefore, the case can be made that these transgressive to highstand intervals did not record a true anoxic event (Wagreich, 2009).

The OAE 3 interval in regions outside the Atlantic had deposition of Cretaceous Oceanic Red Beds (CORBs), which were associated with cooling temperatures through the Late Cretaceous that were caused by the opening of the Atlantic and increased oxygen concentration in the oceans (Wang *et al.*, 2011). The rusty brown shales and siltstones of the upper member of the Kanguk Formation are not deposited until the latest Santonian, indicating that oxygen-poor conditions prevailed through the Coniacian to Santonian in the Sverdrup Basin as in the Atlantic regions (Hu *et al.*, 2012; Wang *et al.*, 2011).

Therefore, the Sverdrup Basin may have also contributed to the drawdown of CO₂, as in the Atlantic and WIS regions during transgressive intervals, with high primary production and dysoxic benthic conditions promoting organic carbon burial (Wagreich, 2009; Leckie and Olson, 2003). Continued cooling within the Late Cretaceous and relative sea-level fall promoted mixing within the Sverdrup Basin that could have contributed to the oxygenation of the benthic habitats and subsequent deposition of the rusty brown shales and mudstones of the upper member (Locklair *et al.*, 2011).

Chapter 6: Conclusions

6.1: Summary

Integration of faunal and geochemical data from the Slidre Fiord and Sawtooth Range localities delivered the following conclusions:

1. The lower Kanguk Formation boundary at both study localities is not characterized by the significant positive carbon isotopic excursion of the OAE 2 interval demonstrated in more distal sections on Ellef Ringnes (Pugh *et al.*, 2014) and Axel Heiberg islands (Lenninger *et al.*, 2014; Herrle *et al.*, 2015). At the Sawtooth Range locality this is further evidenced by the abundance of foraminifera at the base of the section and a lack of paper shales. Elevated Mo values at the base of the Slidre Fiord locality, paper shales, and more positive isotopic values at the base of the Slidre Fiord locality may record the top of the OAE 2 interval. This demonstrates the diachroneity associated with the Hassel-Kanguk boundary. Increased accommodation space basinward in the Sverdrup Basin in the lower Kanguk Formation made the Turonian to Coniacian section thicker in more distal sections.
2. Major and trace element values largely correspond to the lithology change between the black to grey siltstones and shales of the lower member and the red-brown mudrocks of the upper member. A general increasing trend in Al concentration indicates an increasingly closer shoreline position through the Late Cretaceous. This is corroborated by similar increases in S, Fe, Ca, and V, which

are suggestive of sediment source proximity (Brumsack, 2006) and diagenetic factors (Tribovillard *et al.*, 2006).

3. Two positive isotopic excursion intervals during the Late Cretaceous, consistent with the global composite curve of Jarvis *et al.* (2006), are recognized in the Kanguk Formation at the two study localities: the late Turonian events and the Santonian-Campanian boundary event. A sequence stratigraphic framework and age assignments were proposed using major changes in total organic carbon content and lithology, and were related to the global transgressive-regressive cycles of Gradstein *et al.* (2012) with the carbon isotope correlations.
4. Two benthic foraminiferal zones are proposed for the Kanguk Formation that correlate the Sawtooth Range with the Slidre Fiord locality and other more distal settings within the Sverdrup Basin. These are the Turonian to late Santonian *Evolutinella boundaryensis* Zone and the late Santonian to Campanian *Verneulinoides bearpawensis* - *Glaphyrammina spirocompressa* Zone. With the integration of carbon isotope stratigraphy to refine the age, the *Verneulinoides bearpawensis* marker is moved to the late Santonian rather than the late Campanian as previously proposed by Wall (1983). *Glaphyrammina spirocompressa* occurs in Sawtooth Range and at Glacier Fiord (Schröder-Adams *et al.*, 2014) and allows correlation to the Beaufort-Mackenzie Basin where it was first described (McNeil, 1997b). Many of the foraminiferal species found within the Late Cretaceous Alaska slope are common to the Sverdrup Basin, with similar ranges. Ranges within the

Arctic have longer duration than in the WIS, and may correspond to more stable conditions in the Arctic region.

5. Taphonomy played a role in the variability of fossil preservation across the Sverdrup Basin. At the Sawtooth Range locality, silicification during burial allowed for the preservation of abundant agglutinated foraminifera. At Slidre Fiord, silicification did not occur, and as a result the foraminifera may have been more susceptible to breakage and disintegration (McNeil, 1997a). Abundant bentonites in the lower portion of the Kanguk Formation may also have been responsible for the preservation of siliceous microfossils, including radiolarians (e.g. Pugh *et al.*, 2014).
6. By utilizing a combination of carbon isotopic, total organic carbon content and lithologic data to create a sequence stratigraphic framework, foraminiferal morphogroup assemblages of the Cretaceous Arctic are shown to have responded to the global transgressive regressive cycles of Gradstein *et al.* (2012). During transgressive phases, erosion of the coastline would have enhanced primary production with the flux of nutrients into the oceans, and therefore the organic matter flux to the seafloor. (Leckie and Olson, 2003). This would have promoted larger populations of foraminifera, but also limited oxygen conditions with oxygen minimum zone expansion (Friedrich, 2010). Elevated primary production is evidenced by the increased abundance of Radiolaria within the lower transgressive cycle. The infaunal species of Morphogroup C are elevated during the transgressive phases, as they are adapted to lower oxygen conditions below

the sediment water interface (e.g. Nagy *et al.*, 2010). Continued depletion of oxygen into the highstand phase eventually caused a switch to a trochamminid-dominated assemblage of Morphogroup D. *Trochammina* are known to be opportunistic taxa, and the small size of trochamminids in this interval may also have been an adaptation to stressed environmental conditions (Reolid *et al.*, 2014). In regions where the OMZ comes in contact with the shelf, anoxic conditions and loss of foraminifera can occur, as within the Santonian-Campanian boundary event recorded in Sawtooth Range (Leckie and Olson, 2003). Mo values are elevated in the same interval at Slidre Fiord, but are well below typical values of anoxic conditions (Scott and Lyons, 2012), indicating variability in oxygen across the shelf region. With the onset of regression, oxygenated conditions returned to the basin, promoting more diverse and even assemblages (e.g. Friedrich, 2010).

7. The Coniacian to Santonian “OAE 3” interval of the Atlantic region corresponds to the interval during which limited oxygen conditions of transgressive to highstand stages in the Sverdrup Basin occurred, but because anoxic conditions did not span the basin, they are likely not considered part of an oceanic anoxic event. Dysoxic conditions within the transgressive to highstand intervals would have still promoted carbon flux to the benthos, and therefore the Sverdrup Basin may have contributed to CO₂ drawdown and cooling in the Late Cretaceous.

6.2: Future Research

Although this study integrates multiple datasets to allow for a proposed stratigraphic framework and age assignment for the Kanguk Formation and the good preservation of foraminifera at Sawtooth Range allowed for a more detailed analysis of foraminiferal assemblage changes, continued work on refining the age of events within the Late Cretaceous is needed. In order to constrain the timing of the major boundaries, bentonites should be dated to confirm ages interpreted from the carbon isotope and foraminifera assemblages. Major boundaries to revisit would be the base of each of the sections to confirm the absence of OAE 2, the positive isotopic excursions identified at both localities, and the transition between the upper and lower members. Previous work on Ellef Ringnes Island has shown that the lower transgressive interval is characterized by dominantly marine type II organic matter, but rock-eval pyrolysis analysis of the samples at the study localities of this thesis, which are more proximal to the shoreline, is needed to understand the relative influence of terrestrial organic matter at these localities. In order to strengthen the interpretations of the paleoenvironment and diagenetic processes, which is based on lithology and whole rock geochemistry in this study, the identification of the clay mineralogy of the Slidre Fiord samples and the composition of the concretions in the upper member at both localities is needed. Finally, the integration of other microfossil groups such as dinoflagellates and diatoms, which are in preparation, would aid in the interpretation of what factors influenced primary productivity within the transgressive to highstand intervals interpreted in this study.

Appendices

Appendix A: Taxonomic List of Foraminifera for the Upper Cretaceous Kanguk Formation

Synonymy lists below contain original description reference and selected other references used in identification of specimens. Taxonomic classification after Loeblich and Tappan (1988). Figure numbers refer to the numbers assigned within Figure 12 for Plate 1 and Figure 13 for Plate 2.

Family BATHYSIPHONIDAE (Avnimelech, 1952)

Genus *Bathysiphon* (Sars, 1872)

***Bathysiphon brosgiei* (Tappan, 1957)**

Plate 1, Figure 1

- 1957 *Bathysiphon brosgiei* Tappan, p. 202, Pl. 65, Figs. 1-5
- 1962 *Bathysiphon brosgiei* Tappan, Tappan, p. 128, Pl. 29, Figs. 1-5
- 1970 *Bathysiphon brosgiei* Tappan, North and Caldwell p. 13, Pl. 1, Fig. 3
- 1978 *Bathysiphon brosgiei* Tappan, Chamney, p. 8, Pl. 1, Figs. 1-3
- 1981 *Bathysiphon brosgiei* Tappan, McNeil and Caldwell, pg. 129, Pl. 9, Fig. 1
- 2011 *Bathysiphon brosgiei* Tappan, Thomson *et al.*, Pl. 1, Figs. 1-3

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Bathysiphon vitta* (Nauss, 1947)**

Plate 1, Figure 2

- 1947 *Bathysiphon vitta* Nauss, p. 334, Pl. 48, Fig. 4
- 1962 *Bathysiphon vitta* Nauss, Tappan, p. 128, Pl. 29, Fig. 6-8
- 1975 *Bathysiphon vitta* Nauss, North and Caldwell, Pl. 6, Fig. 1
- 1981 *Bathysiphon vitta* Nauss, McNeil and Caldwell, p. 129, Pl. 9, Fig. 2

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Family SACCAMMINIDAE (Brady, 1884)

Genus *Saccamina* (Sars, 1869)

***Saccamina lathrami* (Tappan, 1960)**

Plate 1, Figure 3; Plate 2, Figure 4

- 1960 *Saccamina lathrami* Tappan, p. 289, Pl. 1, Figs. 1-2
1962 *Saccamina lathrami* Tappan, Tappan, p. 129, Pl. 29, Figs. 9-12
1970 *Saccamina lathrami* Tappan, North and Caldwell, p. 15, Pl. 1, Fig. 4
2011 *Saccamina lathrami* Tappan, Thomson *et al.*, Pl. 1, Figs 9-10

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuilinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Family AMMODISCIDAE (Reuss, 1862)

Genus *Ammodiscus* (Reuss, 1862)

***Ammodiscus cretaceus* (Reuss, 1845)**

Plate 1, Figure 4

- 1845 *Operculina cretacea* Reuss, p. 35, Pl. 13, Figs. 64-65
1946 *Ammodiscus cretaceus* Reuss, Cushman, p. 17, Pl. 1, Fig. 35
1962 *Ammodiscus cretaceus* Reuss, Tappan, p. 130, Pl. 30, Figs. 1-2
1975 *Ammodiscus cretaceus* Reuss, North and Caldwell, Pl. 6, Fig. 8
1981 *Ammodiscus cretaceus* Reuss, McNeil and Caldwell, p. 135, Pl. 9, Fig. 13

Occurrence: upper Santonian to Campanian *Verneuilinoides bearpawensis*-*Glaphyrammina spirocompressa* Zone

Family RZEHAKINIDAE (Cushman, 1933)

Genus *Miliammina* (Heron-Allen and Earland, 1930)

***Miliammina bisobscura* (Stelck and Wall, 1954)**

Plate 2, Figure 5

- 1954 *Miliammina bisobscura* Stelck and Wall, p. 29, Pl. 1, Fig. 1
1962 *Miliammina bisobscura* Stelck and Wall, Tappan, p. 160, Pl. 36, Fig. 19

Occurrence: upper Santonian to Campanian *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zone

Family TELAMMINIDAE (Loeblich and Tappan, 1985)

Genus *Reophax* (de Montfort, 1808)

***Reophax pepperensis* (Loeblich, 1946)**

Plate 1, Figure 5

1946 *Reophax pepperensis* Loeblich, p. 133, Pl. 22, Fig. 1

1962 *Reophax pepperensis* Loeblich, Tappan, p. 133, Pl. 30, Fig. 14

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Reophax sp. A

Plate 1, Figure 6; Plate 2, Figure 6

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Family HAPLOPHRAGMOIDIDAE (Maync, 1952)

Genus *Evolutinella* (Myatlyuk, 1971)

***Evolutinella boundaryensis* (McNeil, 1997b)**

Plate 1, Figure 7

1997b *Evolutinella boundaryensis* McNeil, p. 20-21, Pl. 1, Figs. 5-6

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Genus *Haplophragmoides* (Cushman, 1910)

***Haplophragmoides bonanzaensis* (Stelck and Wall, 1954)**

Plate 1, Figure 8; Plate 2, Figure 7

- 1954 *Haplophragmoides bonanzaensis* Stelck and Wall, p. 24, Pl. 2, Fig. 10
1962 *Haplophragmoides bonanzaensis* Stelck and Wall, Tappan, p. 133, Pl. 30, Figs. 16-19
1967 *Haplophragmoides bonanzaensis* Stelck and Wall, Wall, Pl. 4, Figs. 1-2
2011 *Haplophragmoides bonanzaensis* Stelck and Wall, Thomson *et al.*, Pl. 1, Figs. 27-28

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuilioides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Haplophragmoides collyra* (Nauss, 1947)**

Plate 1, Figure 9

- 1947 *Haplophragmoides collyra* Nauss, p. 337, Pl. 49, Figs. 2, 5
1960 *Haplophragmoides collyra* Nauss, Wall, p. 16, Pl. 3, Figs. 16-19
1981 *Haplophragmoides collyra* Nauss, McNeil and Caldwell, p. 147, Pl. 10, Figs. 20-21

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

***Haplophragmoides glabra* (Cushman and Waters, 1927)**

Plate 1, Figure 9, Plate 2 Figure 8

- 1927 *Haplophragmoides glabra* Cushman and Waters, p. 83, Pl. 10, Fig. 6
1970 *Haplophragmoides glabra* Cushman and Waters, North and Caldwell, p. 20, Pl. 1, Figs. 12-13
1971 *Haplophragmoides excavata forma glabra* Cushman and Waters, Mello, p. C33, Pl. 4, Fig. 5
1981 *Haplophragmoides glabra* Cushman and Waters, McNeil and Caldwell, p. 150, Pl. 11, Fig. 6

Occurrence: upper Santonian to Campanian *Verneuilioides bearpawensis*-*Glaphyrammina spirocompressa* Zone

***Haplophragmoides kirki* (Wickenden, 1932)**

Plate 1, Figure 10; Plate 2 Figure 9

- 1932 *Haplophragmoides kirki* Wickenden, p. 21-22, Pl. 2, Fig. 23
1960 *Haplophragmoides kirki* Wickenden, Wall, p. 18, Pl. 3, Figs. 11-12; Pl. 4., Fig. 10
1970 *Haplophragmoides kirki* Wickenden, North and Caldwell, p. 21, Pl. 1, Fig. 10
1981 *Haplophragmoides kirki* Wickenden, McNeil and Caldwell, p. 152, Pl. 11, Fig. 10
1983 *Haplophragmoides kirki* Wickenden, Wall, Pl. 7, Figs. 20-21

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Haplophragmoides rota* (Nauss, 1947)**

Plate 1, Figure 12; Plate 2, Figure 10

- 1947 *Haplophragmoides rota* Nauss, p. 339, Pl. 49, Figs. 1-3
1962 *Haplophragmoides rota* Nauss, Tappan, p. 134, Pl. 31, Figs. 16-18
1981 *Haplophragmoides rota* Nauss, McNeil and Caldwell, p. 153, Pl. 11, Fig 12
1983 *Haplophragmoides rota* Nauss, Wall, Pl. 7, Figs. 16-17
2011 *Haplophragmoides rota* Nauss, Thomson *et al.*, Pl. 2, Figs. 1-2

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Family DISCAMMINIDAE (Mikhalevich, 1980)

Genus *Glaphyrammina* Loeblich and Tappan, 1984

***Glaphyrammina spirocompressa* McNeil, 1997b**

Plate 1, Figure 13

- 1997b *Glaphyrammina spirocompressa* McNeil, p. 25, Pl. 4, Figs 3-6
2011a *Glaphyrammina spirocompressa* McNeil, Setoyama *et al.*, Pl. 5, Figs. 1-2

Occurrence: upper Santonian to Campanian *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zone

Family LITUOLIDAE (de Blainville, 1827)

Genus *Ammomarginulina* (Wiesner, 1931)

***Ammomarginulina* sp. A**

Plate 1, Figure 14

2011a *Ammomarginulina* sp. 1, Setoyama *et al.*, p. 516, Pl. 2, Fig.8; Pl. 3, Fig. 1

Occurrence: upper Santonian to Campanian *Verneuilioides bearpawensis*-*Glaphyrammina spirocompressa* Zone

Family SPIROPLECTAMMINIDAE (Cushman, 1927)

Genus *Spiroplectammina* (Cushman, 1927)

***Spiroplectammina mordenensis* (Wickenden, 1932)**

Plate 1, Figure 15

1932 *Spiroplectammina mordenensis* Wickenden, p. 86, Pl. 1, Fig. 4

1962 *Spiroplectammina mordenensis* Wickenden, Tappan, p. 140, Pl. 33, Fig. 6

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

***Spiroplectammina webberi* (Tappan, 1957)**

Plate 1, Figure 16

1957 *Spiroplectammina webberi* Tappan, p. 205, Pl. 66, Figs. 3-5

1962 *Spiroplectammina webberi* Tappan, Tappan, p. 140, Pl. 33, Figs. 1-3

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Family PSEUDOBOLIVINIDAE (Wiesner, 1931)

Genus *Pseudobolivina* (Wiesner, 1931)

***Pseudobolivina rollaensis* (Stelck and Wall, 1954)**

Plate 1, Figure 17

- 1954 *Textularia rollaensis* Stelck and Wall, p. 30, Pl. 1, Fig. 17
1967 *Pseudobolivina rollaensis* Stelck and Wall, Wall, p. 65, Pl. 4, Figs. 20-23; Pl. 7, Figs. 21-26
1983 *Pseudobolivina rollaensis* Stelck and Wall, Wall, Pl. 7, Figs. 7-8

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Family TROCHAMMINIDAE (Schwager, 1877)

Genus *Trochammina* (Parker and Jones, 1859)

***Trochammina albertensis* (Wickenden, 1932)**

Plate 1, Figure 18; Plate 2, Figure 11

- 1932 *Trochammina albertensis* Wickenden, p. 90, Pl. 1, Fig. 9
1962 *Trochammina albertensis* Wickenden, Tappan, p. 152, Pl. 39, Figs. 13-14
1970 *Trochammina albertensis* Wickenden, North and Caldwell, p. 29, Pl. 2, Figs. 15-16
1981 *Trochammina albertensis* Wickenden, McNeil and Caldwell, p. 167, Pl. 13, Fig. 6
1983 *Trochammina albertensis* Wickenden, Wall, Pl. 7, Figs. 26-28
2011 *Trochammina albertensis* Wickenden, Thomson *et al.*, Pl. 2, Figs. 31-34.

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuiliinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Trochammina boehmi* (Franke, 1928)**

Plate 1, Figure 19; Plate 2, Figure 12

- 1928 *Trochammina boehmi* Franke, p. 174, Pl. 15, Fig. 24
1975 *Trochammina boehmi* Franke, North and Caldwell, Pl. 7, Figs. 16-18
1981 *Trochammina boehmi* Franke, McNeil and Caldwell, p. 167, Pl. 13, Fig. 7

Occurrence: upper Santonian to Campanian *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zone

***Trochammina diagonis* (Carsey, 1926)**

Plate 1, Figure 20; Plate 2, Figure 13

- 1926 *Trochammina diagonis* Carey, p. 22, Pl. 3, Fig. 1
1962 *Trochammina diagonis* Carey, Tappan, p. 153, Pl. 38, Figs. 1-4
2011 *Trochammina diagonis* Carey, Thomson *et al.*, Pl. 2, Figs. 35-38

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Trochammina globigeriniformis* var. *altiformis* (Cushman, 1910)**

Plate 1, Figure 21

- 1910 *Trochammina globigeriniformis* Cushman, p. 124, Figs. 193-195
1970 *Trochammina globigeriniformis* Cushman, North and Caldwell, p. 30, Pl. 2, Fig. 14

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Trochammina rainwateri* (Cushman and Applin, 1946)**

Plate 1, Figure 22

- 1946 *Trochammina rainwateri* Cushman and Applin, p. 75, Pl. 13, Fig. 9
1962 *Trochammina rainwateri* Cushman and Applin, Tappan, p. 153, Pl. 39, Figs. 7-12
1981 *Trochammina rainwateri* Cushman and Applin, McNeil and Caldwell, p. 169, Pl. 13, Figs. 11-12.

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

***Trochammina ribstonensis* (Wickenden, 1932)**

Plate 1, Figure 23; Plate 2, Figure 14

- 1932 *Trochammina ribstonensis* Wickenden, p. 90, Pl. 1, Fig. 12
1947 *Trochammina ribstonensis* Wickenden, Nauss, p. 340, Pl. 49, Fig. 6
1962 *Trochammina ribstonensis* Wickenden, Tappan, p. 154, Pl. 39, Figs. 15-17
1981 *Trochammina ribstonensis* Wickenden, McNeil and Caldwell, p. 170, Pl. 14, Fig. 1
2011 *Trochammina ribstonensis* Wickenden, Thomson *et al.*, Pl. 3, Figs. 1-6
2011a *Trochammina ribstonensis* Wickenden, Setoyama *et al.*, p. 90, Pl. 1, Fig. 12

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Trochammina rutherfordi* (Stelck and Wall, 1955)**

Plate 1, Figure 24

- 1955 *Trochammina rutherfordi* Stelck and Wall, p. 56, Pl. 1, Figs. 11-12
1958 *Trochammina rutherfordi* Stelck *et al.*, p. 33, Pl. 4, Figs. 6-10
1962 *Trochammina ribstonensis ssp. rutherfordi* Stelck and Wall, Tappan, p. 155, Pl. 39, Figs. 18-20
1981 *Trochammina rutherfordi* Stelck and Wall, McNeil and Caldwell, p. 171, Pl. 14, Fig. 2
2011 *Trochammina rutherfordi* Stelck and Wall, Thomson *et al.*, Pl. 3, Figs. 7-9

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

***Trochammina stefanssoni* (Tappan, 1957)**

Plate 1, Figure 25

- 1957 *Trochammina stefanssoni* Tappan, p. 214, Pl. 67, Figs. 30-33
1962 *Trochammina stefanssoni* Tappan, Tappan, p. 156, Pl. 38, Figs. 11-14

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Trochammina tukensis* (McNeil, 1997b)**

Plate 1, Figure 26; Plate 2 Figure 15

- 1997b *Trochammina tukensis* McNeil, p. 32-33, Pl. 9, Figs. 6-8.
2011a *Trochammina aff. Trochammina tukensis* McNeil, Setoyama p. 518, Pl. 6, Fig 6

Occurrence: upper Santonian to Campanian *Verneuilinoides bearpawensis*-*Glaphyrammina spirocompressa* Zone

***Trochammina umiatensis* (Tappan, 1957)**

Plate 1, Fig. 27

- 1957 *Trochammina umiatensis* Tappan, p. 214, Pl. 67, Figs. 27-29
1962 *Trochammina umiatensis* Tappan, Tappan, p. 156, Pl. 38, Figs. 5-8
1981 *Trochammina wetteri* Stelck and Wall (1955), McNeil and Caldwell, p. 172-174, Pl. 13, Fig. 10
2011 *Trochammina umiatensis* Tappan, Thomson *et al.*, Pl. 3, Figs. 10-11

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

***Trochammina whittingtoni* (Tappan, 1957)**

Plate 1, Fig. 28

- 1957 *Trochammina whittingtoni* Tappan, p. 214, Pl. 68, Figs. 3-6
1962 *Trochammina whittingtoni* Tappan, Tappan p. 157, Pl. 39, Figs. 1-6
2011 *Trochammina whittingtoni* Tappan, Thomson *et al.*, Pl. 3, Figs. 13-15

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Family VERNEUILINIDAE (Cushman, 1911)

Genus *Arenobulimina* (Cushman, 1927)

***Arenobulimina torula* (Tappan, 1957)**

Plate 1, Figure 29

1957 *Arenobulimina torula* Tappan, p. 209, Pl. 67, Figs. 5-7

1962 *Arenobulimina torula* Tappan, p. 152, Pl. 36, Figs. 7-9

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Genus *Gaudryina* d'Orbigny, 1839

***Gaudryina irenensis*, Stelck and Wall, 1955**

Plate 1, Figure 30

1955 *Gaudryina irenensis* Stelck and Wall, p. 42-43, Pl. 2, Figs. 4-5

1962 *Gaudryina irenensis* Stelck and Wall, Tappan, p. 177, Pl. 14, Figs. 8-9

1975 *Gaudryina irenensis* Stelck and Wall, North and Caldwell, Pl. 3, Pl. 14, Figs. 12-15.

1981 *Gaudryina irenensis* Stelck and Wall, McNeil and Caldwell, p. 177, Pl. 14, Figs. 8-9

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Genus *Uvigerinammina* (Majzon, 1943)

***Uvigerinammina spiritensis* (Stelck and Wall, 1954)**

Plate 1, Fig. 31

1954 *Uvigerinammina spiritensis* Stelck and Wall, p. 31, Pl. 2, Figs. 12-14

1983 *Uvigerinammina spiritensis* Stelck and Wall, Wall, Pl. 7, Figs. 9-10

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Genus *Verneuilina* (d' Orbigny, 1839)

***Verneuilina* sp. A**

Plate 1, Fig. 32

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuilinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Genus *Verneulinoides* (Loeblich and Tappan, 1949)

***Verneulinoides bearpawensis* (Wickenden, 1932)**

Plate 1, Fig. 33; Plate 2, Figure 16

- 1932 *Verneulinoides bearpawensis* Wickenden, p. 87, Pl. 1, Fig. 8
- 1960 *Verneulinoides bearpawensis* Wickenden, Wall, p. 22, Pl. 4, Figs. 20-21
- 1967 *Verneulinoides bearpawensis* Wickenden, Wall, p. 75, Pl. 4, Figs. 31-34; Pl. 5, Figs. 21; Pl. 14, Figs. 13-15
- 1970 *Verneulinoides bearpawensis* Wickenden, North and Caldwell, p. 25, Pl. 2, Fig. 6
- 1983 *Verneulinoides bearpawensis* Wickenden, Wall, Pl. 7, Fig. 22

Occurrence: upper Santonian to Campanian *Verneulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zone

***Verneulinoides fischeri* (Tappan, 1957)**

Plate 1, Fig. 34; Plate 2 Figure 17

- 1957 *Verneulinoides fischeri* Tappan, p. 207, Pl. 66, Figs. 23-28
- 1962 *Verneulinoides fischeri* Tappan, Tappan, p. 143, Pl. 32, Figs. 12-17
- 1983 cf. *Verneulinoides fischeri* Tappan, Wall, Pl. 7, Fig. 6

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

***Verneuilinoides cf. perplexus* (Loeblich, 1946)**

Plate 1, Fig. 35; Plate 2, Figure 18

- 1946 *Verneuilina perplexa* Loeblich, p. 138, Pl. 22, Figs. 14-16
1955 *Verneuilinoides perplexus* var. *gleddiei* Stelck and Wall, p. 61, Pl. 2, Figs. 40-41
1971 *Verneuilinoides cf. perplexus* Loeblich, Mello p. C49, Pl. 7, Figs. 8-9

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuilinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Family EGGERELLIDAE (Cushman, 1937)

Genus *Dorothia* (Plummer, 1931)

***Dorothia smokyensis* (Wall, 1960)**

Plate 1 Fig. 36; Plate 2 Figure 19

- 1960 *Dorothia smokyensis* Wall, p. 23, Pl. 4, Figs. 22-28
1967 *Dorothia smokyensis* Wall, Wall, p. 81, Pl. 11, Figs. 25-28
1981 *Dorothia smokyensis* Wall, McNeil and Caldwell, p. 184, Pl. 15, Fig. 5
1983 *Dorothia smokyensis* Wall, Wall, Pl. 7, Figs. 3-5

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneuilinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Family TEXTULARIIDAE (Ehrenberg, 1838)

Genus *Textularia* (DeFrance, 1824)

***Textularia gravenori* (Stelck and Wall, 1955)**

Plate 2, Figure 1

- 1955 *Textularia gravenori* Stelck and Wall, p. 55, Pl. 2, Fig. 36
1962 *Textularia gravenori* Stelck and Wall, Tappan, p. 141, Pl. 33, Figs. 16-17

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Family PSEUDOGAUDRYINIDAE (Loeblich and Tappan, 1985)

Genus *Pseudoclavulina* (Cushman, 1936)

***Pseudoclavulina hastata* (Cushman, 1927)**

Plate 2, Figure 2

1927 *Pseudoclavulina hastata* Cushman, p. 131, Pl. 1, Fig. 9

1962 *Pseudoclavulina hastata* Cushman, Tappan, p. 151, Pl. 36, Figs. 10-11

2011 *Pseudoclavulina hastata* Cushman, Thomson *et al.*, Pl. 4, Figs. 5-6

Occurrence: Turonian to upper Santonian *Evolutinella boundaryensis* Zone

Family HAUERINIDAE (Schwager, 1876)

Genus *Quinqueloculina* (d'Orbigny, 1826)

***Quinqueloculina sphaera* (Nauss, 1947)**

Plate 2, Figure 3

1947 *Quinqueloculina sphaera* Nauss, p. 340, Pl. 48, Fig. 14

1962 *Quinqueloculina sphaera* Nauss, Tappan, p. 157, Pl. 37, Fig. 6

1970 *Quinqueloculina sphaera* Nauss, North and Caldwell, p. 30, Pl. 3, Fig. 1

1983 *cf. Quinqueloculina sphaera* Nauss, Wall, Pl. 7, Figs. 31-32.

Occurrence: Turonian to Campanian *Evolutinella boundaryensis* and *Verneulinoides bearpawensis*-*Glaphyrammina spirocompressa* Zones

Appendix B: Data Sheets

Table B-1: Foraminiferal counts for Sawtooth Range, Ellesmere Island

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Section Height (m)	0.6	9	17.1	27	36	42	46	54	58	65	72	76	80	88	93	97	107	115	125	135	145	184
<i>Bathysiphon broegei</i>	0	0	0	0	0	0	0	6	0	0	0	0	2	0	0	0	0	2	0	0	0	0
<i>Bathysiphon vitta</i>	0	0	0	0	0	0	0	0	2	0	0	0	1	1	0	0	0	0	0	0	0	0
<i>Ammodiscus cretaceus</i>	0	0	0	0	0	0	0	0	0	0	0	0	5	2	0	0	0	0	0	3	0	0
<i>Saccammina lathrami</i>	1	0	0	0	0	0	0	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0
<i>Reophax pepperensis</i>	2	0	0	0	2	1	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Reophax</i> sp. A	0	0	0	0	0	0	0	0	3	0	2	0	1	2	0	0	0	0	0	0	0	0
<i>Haplophragmoides bonanzaensis</i>	32	0	3	2	9	25	57	15	26	51	2	15	20	5	0	0	0	6	6	6	0	0
<i>Haplophragmoides collyra</i>	1	0	0	0	0	0	13	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Haplophragmoides glabra</i>	0	0	0	0	0	0	0	0	0	0	0	0	11	3	0	0	1	11	10	23	0	0
<i>Haplophragmoides kirki</i>	6	0	1	1	1	9	6	4	9	26	6	18	13	3	0	0	2	5	27	27	0	0
<i>Haplophragmoides rota</i>	22	0	12	12	1	2	10	21	14	32	5	24	23	2	0	0	0	11	18	7	0	0
<i>Evolutinella boundaryensis</i>	18	0	1	2	0	7	26	2	4	3	5	1	0	0	0	0	0	0	0	0	0	0
<i>Glaphyrammina spirocompressa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
<i>Ammomarginulina</i> sp. A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	22	0	0
<i>Textularia gravenori</i>	10	0	1	2	4	0	12	30	8	2	0	1	0	0	0	0	0	0	0	0	0	0
<i>Spiroplectammina webberi</i>	4	0	1	0	2	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Spiroplectammina mordenensis</i>	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
<i>Verneulinoides bearpavensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	21	2	0	0	0	17	7	5	0	0

Table B-1 (cont.)

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Section Height (m)	0.6	9	17.1	27	36	42	46	54	58	65	72	76	80	88	93	97	107	115	125	135	145	184
<i>Verneulinoides fischeri</i>	3	0	2	2	3	0	1	0	3	2	0	5	20	10	0	0	2	6	0	3	0	0
<i>Verneulinoides perplexus</i>	0	0	0	23	0	0	4	9	6	10	3	43	55	3	0	0	0	78	66	44	0	0
<i>Verneulina</i> sp. A	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0
<i>Gaudryina irenensis</i>	4	0	3	1	3	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Dorothia smokyensis</i>	52	0	0	0	1	3	25	18	53	47	10	7	31	0	0	0	0	67	4	21	0	0
<i>Pseudoclavulina hastata</i>	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Pseudobolivina rollaensis</i>	0	0	0	0	0	2	17	3	9	1	0	0	0	0	0	0	0	0	0	0	0	0
<i>Arenobulimina tortula</i>	6	0	0	36	0	4	3	6	1	12	7	5	0	0	0	0	0	0	0	0	0	0
<i>Uvigerinaminina spiritalensis</i>	0	0	0	0	2	0	0	4	7	2	0	2	0	0	0	0	0	0	0	0	0	0
<i>Trochammina albertensis</i>	0	0	0	0	0	0	0	0	14	38	19	31	25	4	0	0	2	30	45	71	0	0
<i>Trochammina boehmi</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	3	7	0	0
<i>Trochammina diagonis</i>	21	0	1	3	0	0	3	17	4	9	2	2	7	3	0	0	0	10	0	0	0	0
<i>Trochammina globigeriniformis</i>	0	0	0	0	0	0	0	0	2	0	0	1	2	2	0	0	0	2	1	0	0	0
<i>Trochammina rainwateri</i>	14	0	4	8	1	17	22	15	0	2	0	0	0	0	0	0	0	0	0	0	0	0
<i>Trochammina ribstonensis</i>	0	0	0	0	0	0	246	173	379	26	1	13	0	0	0	0	0	5	0	4	0	0
<i>Trochammina rutherfordi</i>	10	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Trochammina stefanssoni</i>	11	0	0	0	0	0	2	3	13	16	5	2	1	0	0	0	0	0	0	0	0	0
<i>Trochammina tukensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	8	0	0
<i>Trochammina umiatensis</i>	8	0	0	21	0	8	5	6	0	4	0	0	0	0	0	0	0	0	0	0	0	0
<i>Trochammina whittingtoni</i>	14	0	3	1	0	6	9	8	3	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Quinqueloculina sphaera</i>	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Table B-1 (cont.)

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Section Height (m)	0.6	9	17.1	27	36	42	46	54	58	65	72	76	80	88	93	97	107	115	125	135	145	184
<i>Trochammina</i> spp.	51	0	1	19	1	19	23	51	13	30	10	13	6	8	0	0	0	50	65	35	0	0
<i>Haplophragmoides</i> spp.	3	0	3	1	0	1	18	0	6	36	5	0	5	0	0	0	0	0	10	20	0	0
Unidentifiable	142	0	27	72	12	50	235	270	126	181	42	140	125	11	0	0	0	95	135	45	0	0
TOTAL	435	0	66	210	42	158	750	687	706	530	124	330	374	64	0	0	7	411	413	353	0	0
Multiplication Factor (From fraction of sample picked)	1	1	1	1	1	1	4	6	24	6	1	6	1	1	1	1	1	2	1	4	1	1

Table B-2: Foraminiferal counts for Slidre Fiord, Ellesmere Island

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Section Height (m)	2	15	27	35	48	64	85	100	120	140	160	172.5	183	193	205	215	225	239	260	280
<i>Saccammina lathrami</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
<i>Reophax</i> sp. A	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
<i>Miliammina bisobscura</i>	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
<i>Haplophragmoides bonanzaensis</i>	0	0	0	0	0	2	6	0	0	0	0	0	8	0	0	0	0	0	0	0
<i>Haplophragmoides glabra</i>	0	0	0	0	0	1	0	0	0	0	3	0	8	0	0	0	0	3	0	0
<i>Haplophragmoides kirki</i>	0	0	0	0	0	2	5	0	0	0	2	0	10	4	0	0	0	6	0	0
<i>Haplophragmoides rota</i>	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	1	0	5	0	0
<i>Verneulinoides bearpavensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
<i>Verneulinoides fischeri</i>	0	0	0	0	0	2	1	1	0	0	0	0	1	1	0	0	0	0	0	0

Table B-2 (cont.)

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Section Height (m)	2	15	27	35	48	64	85	100	120	140	160	172.5	183	193	205	215	225	239	260	280
<i>Verneuilinoides perplexus</i>	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	1	0	0	0	0
<i>Dorothia smokyensis</i>	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0
<i>Trochammina albertensis</i>	0	0	0	0	0	0	0	3	0	0	0	0	3	0	0	0	0	1	0	0
<i>Trochammina boehmi</i>	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
<i>Trochammina diagonalis</i>	0	0	0	0	0	2	0	0	0	0	0	0	7	0	0	0	0	0	0	0
<i>Trochammina ribstonensis</i>	0	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0	0	0
<i>Trochammina tulensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0	0	0	0
<i>Haplophragmoides</i> spp.	0	0	0	0	0	0	1	1	0	0	2	1	0	0	0	0	0	2	0	0
<i>Trochammina</i> spp.	0	0	0	0	0	3	4	0	0	0	0	0	3	0	0	0	0	0	0	0
Unknown	0	0	0	0	0	2	8	4	0	0	2	0	13	4	0	0	0	7	0	0
TOTAL	0	0	0	0	0	16	30	11	0	0	19	1	72	10	0	4	0	26	0	0

Table B-3: Concentrations of selected major and trace elements from Slidre Fiord, Ellesmere Island.

Element	Mo	Zn	V	Ca	Fe	S	Al	Element	Mo	Zn	V	Ca	Fe	S	Al
Unit	ppm	ppm	ppm	wt. %	wt. %	wt. %	wt. %	Unit	ppm	ppm	ppm	wt. %	wt. %	wt. %	wt. %
Detection Limit	0.01	1	2	0.01	0.01	0.05	0.01		0.01	1	2	0.01	0.01	0.05	0.01
Section Height (m)	Section Height (m)														
0	2.2	31	6	0.03	1.28	1.18	0.24		110	2.2	84	23	0.34	3.46	1.41
0.6	3.4	60	15	0.4	1.75	1.9	0.85		112.85	2.8	497	3	0.88	0.58	0.62
2	2.7	45	11	0.47	2.66	2.09	0.84		113.25	1.5	201	13	1.09	3.29	1.1
6	4.4	34	11	0.26	1.49	1.73	0.79		120	3.3	143	40	0.79	6.22	1.32
10	1.6	47	15	0.7	2.78	2.11	1.03		130	1.5	62	29	0.28	2.27	1.11
12	0.7	65	12	0.18	1.58	1.18	1.02		140	2.7	222	37	0.47	2.63	1.84
15	0.8	45	15	0.37	2.54	1.56	1.09		150	2.2	52	39	1.28	4.78	1.79
19	1.3	63	16	0.47	2.48	1.46	1.1		160	2.9	56	28	0.31	2.15	1.3
23	0.8	56	14	0.53	2.73	1.69	1.08		172.5	3.4	204	8	1	2.24	0.94
27	0.6	65	13	0.26	2.17	1.37	1.18		183	2.1	56	32	0.49	3.8	1.59
31	1	46	10	0.17	1.61	1.03	0.8		193	1.3	82	83	0.56	4.21	1.97
35	1	48	14	0.31	2.42	1.04	1.16		205	1.8	82	94	0.38	4.54	1.51
39	1.9	47	15	0.49	2.8	1.45	1.12		215	2.1	70	68	0.57	4.02	3.29
41	1.6	34	9	0.44	1.75	0.9	0.61		225	1	142	106	0.54	7.26	3.21
48	2.3	64	2	0.2	1.13	0.78	0.39		239	1.6	58	60	0.31	3.66	2.23
56	0.9	59	8	0.22	1.91	1.49	0.73		249	1.8	74	60	0.36	3.72	1.93
64	5.8	50	9	0.17	2.42	1.03	0.7		260	1.6	62	48	0.29	3.18	1.85
74.5	1.1	49	8	0.36	1.58	0.87	0.73		270	1.8	63	23	0.28	2.94	0.94
85	1.3	56	8	0.19	1.96	1.01	1.15		280	1.4	236	7	0.16	1.26	0.48
92.5	0.6	88	< 2	0.08	0.21	0.05	0.21		287.5	1.5	15	32	0.01	0.89	0.8
100	1.4	100	16	0.77	2.65	1.72	1.23		288	0.9	11	3	< 0.01	0.41	0.19

Table B-4: Carbon isotope ($\delta^{13}\text{C}_{\text{org}}$) and TOC data for the Slidre Fiord locality.

Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)
-0.2	-24.38	0.36	10	-25.35	5.1	21	-25.56	3.75	32	-24.80	1.62			
0	-24.45	10.38	10.5	-25.41	4.98	21.5	-25.37	3.24	32.5	-24.57	2.79			
0.5	-25.14	9.18	11	-25.13	3.66	22	-25.22	2.82	33	-24.56	2.46			
1	-25.65	7.59	11.5	-25.04	4.05	22.5	-25.22	2.16	33.5	-24.80	1.23			
1.2	-25.91	6.63	12	-25.00	3.84	23	-25.10	2.07	34	-24.80	1.44			
1.5	-25.73	5.28	12.5	-25.02	3.33	23.5	-25.59	2.07	34.5	-25.18	0.85			
2	-25.90	5.67	13	-25.06	3.69	24	-25.36	1.62	35	-25.37	1.74			
2.5	-25.80	5.82	13.5	-25.46	2.4	24.5	-25.07	2.22	35.5	-25.54	2.61			
3	-25.81	5.85	14	-25.50	2.7	25	-25.12	1.23	36	-25.32	2.46			
3.5	-25.98	5.79	14.5	-25.47	3.09	25.5	-25.15	1.71	36.5	-25.30	1.41			
4	-25.93	5.21	15	-25.44	2.61	26	-25.13	1.5	37	-25.06	1.97			
4.5	-25.91	5.51	15.5	-25.46	2.91	26.5	-24.86	2.34	37.5	-25.32	2.67			
5	-25.83	6.15	16	-25.58	2.81	27	-24.86	2.85	38	-25.23	3.06			
5.5	-25.85	6.27	16.5	-25.29	2.22	27.5	-24.84	2.67	38.5	-25.16	3.45			
6	-25.76	5.13	17	-25.60	2.16	28	-24.97	2.7	39	-25.21	2.82			
6.5	-25.77	4.14	17.5	-25.24	3.24	28.5	-24.96	2.61	39.5	-25.07	2.58			
7	-25.43	5.64	18	-25.55	3.42	29	-24.92	2.61	40	-25.19	2.61			
7.5	-25.50	4.17	18.5	-26.16	4.02	29.5	-24.94	2.7	41	-24.99	2.22			
8	-25.98	4.44	19	-25.44	2.7	30	-24.98	2.31	46.5	-25.80	0.63			
8.5	-25.72	4.62	19.5	-26.21	3.09	30.5	-25.04	2.43	50	-25.50	1.99			
9	-25.74	4.89	20	-25.67	2.1	31	-25.05	2.61	54	-25.65	2.34			
9.5	-25.35	4.35	20.5	-25.64	3.21	31.5	-25.04	1.59	58	-26.11	2.31			

Table B-4 (cont.)

Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)
62	-25.30	1.47	111.9	-25.55	2.55	167	-24.32	3.06	227	-24.86	4.59			
66	-25.32	0.72	117	-25.64	2.37	175	-24.89	1.32	232	-24.80	3.03			
71.5	-25.31	1.14	122	-25.37	3.33	180	-24.51	2.16	241	-24.71	3.36			
71.5	-25.53	0.9	124	-25.09	3.36	185	-24.70	3	246	-24.84	3.66			
76.5	-24.35	0.85	132	-24.78	2.25	190	-24.79	3.57	251	-24.87	3.78			
83	-25.44	0.46	137	-24.67	2.97	195	-24.84	2.82	257	-24.89	3.3			
87	-25.45	3.63	142	-24.85	2.22	202	-24.90	3.51	262	-24.91	3.9			
92	-25.18	3.48	147	-25.20	3.24	207	-24.72	3.81	267	-24.90	3.66			
97	-25.27	2.64	152	-24.73	3.3	212	-24.79	3.3	272	-25.06	2.13			
102	-25.00	1.98	157	-24.62	2.44	217	-24.79	3.1	277	-24.69	2.25			
107	-25.11	1.98	163	-24.69	2.79	222	-25.01	3.1	282	-25.16	1.17			

Table B-5: Carbon isotope ($\delta^{13}\text{C}_{\text{org}}$) and TOC data for the Sawtooth Range locality.

Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)
0.5	-24.25	0.87	33	-25.88	2.25	57	-25.26	2.43	78	-25.08	1.59			
0.6	-24.86	2.1	35	-26.47	1.77	58	-26.48	4.95	79	-25.07	2.82			
1.6	-25.78	3.96	36	-26.64	6.21	59	-26.43	4.59	80	-25.29	2.43			
2.6	-25.08	1.83	37	-26.42	5.34	60	-26.24	5.07	81	-25.10	1.65			
3.6	-24.72	1.54	38	-26.93	3.51	61	-25.61	4.71	82	-25.58	1.98			
4.6	-25.06	1.47	40	-26.42	3.45	62	-26.09	3.99	83	-25.81	2.01			
5.6	-24.81	1.98	42	-26.01	2.67	64	-26.26	3.06	84	-25.74	2.1			
9	-25.25	1.35	43	-25.60	1.86	65	-26.20	2.97	85	-25.42	2.94			
10	-25.06	1.23	44.1	-25.44	0.6	66	-26.09	2.55	85.1	-24.36	2.04			
11	-24.87	1.35	45	-24.88	2.34	67	-25.06	2.97	86	-24.34	2.55			
16	-25.24	1.14	46	-26.38	4.95	68	-26.34	4.38	87	-24.21	4.35			
17.1	-25.22	0.99	47	-26.16	4.23	69	-26.60	5.22	88	-24.03	4.05			
24	-25.04	0.39	48	-26.11	2.67	70	-26.24	5.19	89	-24.05	3.06			
25	-25.07	0.87	49	-25.67	3.18	71	-25.47	1.17	90	-23.95	4.08			
26	-24.88	0.75	50	-26.25	5.1	71	-25.65	1.35	91	-24.04	2.4			
27	-24.35	0.66	51	-26.01	3.21	72	-25.63	1.29	92	-23.98	4.11			
28	-24.40	0.84	52	-26.36	3.78	73	-26.01	2.73	93	-23.98	3.81			
29	-24.72	1.17	53	-25.48	3.12	74	-25.81	1.17	94	-23.58	2.91			
30	-24.72	0.84	54	-26.36	4.92	75	-25.35	1.11	95	-24.86	3.93			
31	-24.14	0.93	55	-26.42	4.98	76	-25.36	1.38	96	-24.77	3.51			
32	-24.76	0.96	56	-25.92	2.91	77	-25.43	1.32	97	-24.85	3.33			

Table B-5 (cont.)

Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)	Section Height (m)	$\delta^{13}\text{C}_{\text{org}}$ (‰ VPDB)	TOC (%)
98	-24.75	3.78	120	-25.27	2.04	143	-23.88	1.98			
99	-24.97	3.24	121	-25.25	2.16	145	-24.82	1.86			
100	-25.37	2.82	122	-25.09	1.32	146	-24.83	1.74			
101	-25.07	3.54	124	-25.40	1.56	147	-25.18	1.74			
102	-25.04	5.1	125	-25.18	2.01	148	-25.12	1.74			
103	-24.92	4.98	126	-24.94	2.46	182	-25.10	1.92			
104	-25.07	3.06	127	-24.94	2.55	183	-25.10	1.59			
105	-24.97	3.42	128	-24.90	2.07	184	-25.00	1.14			
106	-24.81	4.05	129	-24.82	2.25	185	-24.40	0.54			
107	-24.76	4.62	130	-24.80	2.29	186	-25.16	1.11			
108	-24.87	3.36	131	-24.79	1.98	187	-25.21	1.5			
109	-24.94	2.64	132	-24.86	2.91	188	-25.19	1.35			
110	-25.11	4.14	133	-24.91	2.91	189	-24.96	1.95			
111	-24.94	2.67	134	-24.76	2.64	190	-24.04	1.92			
112	-24.94	2.55	135	-24.65	1.77						
113	-25.00	1.41	136	-24.76	2.01						
114	-24.76	1.44	138	-25.04	0.99						
115	-25.03	2.01	139	-24.89	2.22						
117	-25.55	0.87	140	-24.84	2.28						
118	-25.50	1.08	141	-24.62	1.11						
119	-25.26	1.98	142	-24.83	2.43						

References

- Algeo, T.J. and Rowe, H., 2012, Paleooceanographic applications of trace-metal concentration data: *Chemical Geology*, v. 324-325, p. 6-18.
- Arthur, M.A., Dean, W.E., and Pratt, L.M., 1988, Geochemical and climatic effects of increased marine organic carbon burial at the Cenomanian/Turonian boundary: *Nature*, v. 335, p. 714-717.
- Balkwill, H.R. and Hopkins, W.S. Jr., 1976, Cretaceous stratigraphy, Hoodoo Dome, Ellef Ringnes Island, District of Franklin, *in* Report of Activities Part B: Geological Survey of Canada Paper 76-1B, p. 329 – 334.
- Balkwill, H.R., 1974, Structure and stratigraphy, Ringnes Islands and nearby smaller islands, District of Franklin *in* Report of Activities Part A: Geological Survey of Canada Paper 74-1A, p. 287 – 289.
- Balkwill, H.R., 1978, Evolution of the Sverdrup Basin, Arctic Canada: The American Association of Petroleum Geologists Bulletin, v. 62, n. 6, p. 1004-1028.
- Barclay, R.S., McElwain, J.C., and Sageman, B.B., 2010, Carbon sequestration activated by volcanic CO₂ pulse during Ocean Anoxic Event 2: *Nature Geoscience*, v. 3, p. 205- 208.
- Bice, K.L., Birgel, D., Meyers, P.A., Dahl, K.A., Hinrichs, K.U., and Norris, R.D., 2006, A multiple proxy and model study of Cretaceous upper ocean temperatures and atmospheric CO₂ concentrations: *Paleoceanography*, v. 21, n. 2, PA2002 p. 1-17.
- Bice, K.L., Huber, B.T., and Norris, R.D., 2003, Extreme polar warmth during the Cretaceous greenhouse? Paradox of the late Turonian $\delta^{18}\text{O}$ record at Deep Sea Drilling Project Site 511: *Paleoceanography*, v. 18, n. 2, p. 9-1 – 9-11.
- Bjerrum, C.J., Bendtsen, J., and Legarth, J.J.F., 2006, Modelling organic carbon burial during sea level rise with reference to the Cretaceous: *Geochemistry, Geophysics, Geosystems*, v. 7, n. 5, Q05008 p. 1-24.
- Breit, G.N. and Wanty, R.B., 1991, Vanadium accumulation in carbonaceous rocks; A review of geochemical controls during deposition and diagenesis: *Chemical Geology*, v. 91, p. 93-97.

- Brumsack, H.J., 2006, The trace metal content of recent organic carbon-rich sediments: Implications for Cretaceous black shale formation: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 232, p. 344-361.
- Caldwell, W.G.E., North, B.R., Stelck, C.R., and Wall, J.H., 1978, A foraminiferal zonal scheme for the Cretaceous system in the Interior Plains of Canada, *in* Stelck, C.R. and Chatterton, B.D.E, eds., *Western and Arctic Canadian Biostratigraphy: Geological Association of Canada Special Paper 18*, p. 495-575.
- Carsey, D.O., 1926, Foraminifera of the Cretaceous of central Texas: *Texas University Bulletin*, v. 2612, p. 1-56.
- Cetean, C., Bălc, R., Kaminski, M.A., and Filipescu, S., 2011, Integrated biostratigraphy and palaeoenvironments of an upper Santonian – upper Campanian succession from the southern part of the Eastern Carpathians, Romania: *Cretaceous Research*, v. 32, p. 575-590.
- Chamney, T.P., 1978, Albian foraminifera of the Yukon Territory: *Geological Survey of Canada Bulletin* 253, 61 p.
- Chin, K., Bloch, J., Sweet, A., Tweet, J., Eberle, J., Cumbaa, S., Witkowski, J., and Harwood, D., 2008, Life in a temperate Polar Sea: a unique taphonomic window on the structure of a Late Cretaceous Arctic marine ecosystem: *Proceedings of the Royal Society B*, v. 275, p. 2675-2685.
- Coffin, M.F., Duncan, R.A., Eldholm, O., Fitton, J.G., Frey, F.A., Larsen, H.C., Mahoney, J.J., Saunders, A.D., Schlich, R., and Wallace, P.J., 2006, Large igneous provinces and scientific ocean drilling: Status quo and a look ahead: *Oceanography*, v.19, n. 4, p. 150-160.
- Cushman, J.A., 1910, A monograph of the foraminifera of the North Pacific Ocean Part 1: *Astrorhizidae and Lituolidae: Bulletin of the United States National Museum*, v. 71, p. 1-108.
- Cushman, J.A., 1927, Some foraminifera from the Cretaceous of Canada: *Transactions of the Royal Society Canada Series 3*, v. 21, p. 127-132.
- Cushman, J.A., 1946, Upper Cretaceous foraminifera of the Gulf Coastal region of the United States and adjacent areas: *United States Geological Survey Professional Paper* 206, 241 p.
- Cushman, J.A., and Applin, E.R., 1946, Some foraminifera of Woodbine age from Texas, Mississippi, Alabama, and Georgia: *Contributions Cushman Laboratory Foraminiferal Research*, v. 22, p. 71-76.

- Cushman, J.A., and Waters, J.A., 1927, Some arenaceous foraminifera from the Upper Cretaceous of Texas: Cushman Laboratory for Foraminiferal Research, v. 4, p. 85-103.
- Davies, A., Kemp, A.E.S., and Pike, J., 2009, Late Cretaceous seasonal ocean variability from the Arctic: *Nature*, v. 46, p. 254-259.
- Davies, G.R. and Nassichuk, N.W., 1991, Carboniferous and Permian History of the Sverdrup Basin, Arctic Islands, *in* Trettin, H.P., ed., *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland*: Ottawa, Canada, Geological Survey of Canada, *Geology of Canada Series*, n. 3, p. 369-433.
- Davis, W.J., Schröder-Adams, C.J., Galloway, J.M., Herrle, J.O., and Pugh, A.T., 2016, U-Pb geochronology of bentonites from the Upper Cretaceous Kanguk Formation, Sverdrup Basin, Arctic Canada: constraints on sedimentation rates, biostratigraphic correlations and the late magmatic history of the High Arctic Large Igneous Province: *Geological Magazine*, p. 1-20.
- Dixon, J., 1999, Mesozoic-Cenozoic stratigraphy of the northern Interior Plains and Plateaux, Northwest Territories: *Geological Survey of Canada Bulletin* 536, 56 p.
- Døssing, A., Jackson, H.R., Matzka, J., Einarsson, I., Rasmussen, T.M., Olesen, A.V., and Brozena, J.M., 2013, On the origin of the Amerasia Basin and the High Arctic Large Igneous Province – Results from new aeromagnetic data: *Earth and Planetary Science Letters*, v. 363, p. 219-230.
- Embry, A., 2011, Petroleum prospectivity of the Triassic-Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago, *in* Embry, A.M., Gautier, A.F., Stoupakova, D.L., and Sørensen, K., eds., *Arctic Petroleum Geology*: Geological Society, London, *Memoirs*, v. 35, p. 545-558.
- Embry, A. and Beauchamp, B., 2008, Sverdrup Basin, *in* Miall, A.D., ed., *Sedimentary Basins of the World*, v. 5: Amsterdam, the Netherlands, Elsevier Science Limited, p. 451-471.
- Embry, A., 2009, Crockerland- The source area for the Triassic to middle Jurassic strata of northern Axel Heiberg Island, Canadian Arctic Islands: *Bulletin of Canadian Petroleum Geology*, v. 57, n. 2, p. 129-140.
- Embry, A.F. and Osadetz, K.G., 1988, Stratigraphy and tectonic significance of Cretaceous volcanism in the Queen Elizabeth Islands, Canadian Arctic Archipelago: *Canadian Journal of Earth Sciences*, v. 25, p. 1209-1219.

- Embry, A.F., 1991, Mesozoic history of the Arctic Islands, *in* Trettin, H.P., ed., *Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland*: Ottawa, Canada, Geological Survey of Canada, *Geology of Canada Series*, n. 3, p. 369-433.
- Embry, A.F., and Dixon, J., 1990, The breakup unconformity of the Amerasia Basin, Arctic Ocean: Evidence from Arctic Canada: *Geological Society of America Bulletin*, v. 102, p. 1526-1534.
- Emeis, K.C., and Weissert, H., 2009, Tethyan-Mediterranean organic carbon-rich sediments from Mesozoic black shales to sapropels: *Sedimentology*, v. 56, p. 247-266.
- Erbacher, J., Huber, B.T., Norris, R.D., and Markey, M., 2001, Increased thermohaline stratification as a possible cause for an ocean anoxic event in the Cretaceous Period: *Nature*, v. 409, p. 325-327.
- Estrada, S. and Henjes-Kunst, F., 2013, $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb dating of Cretaceous continental rift-related magmatism on the northeast Canadian Arctic margin: *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, v. 164, p. 107-130.
- Evenchick, C. and Embry, A.F., 2012, *Geology Ellef Ringnes Island North*, Geological Survey of Canada *Geoscience Map* 86, scale 1: 125,000.
- Falcon-Lang, H.J., MacRae, R.A., and Csank, A.Z., 2004, Palaeoecology of Late Cretaceous polar vegetation preserved in the Hansen Point Volcanics, NW Ellesmere Island, Canada: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 212, p. 45-64.
- Forster, A., Schouten, S., Moriya, K., Wilson, P.A., and Damsté, J.S.S., 2007, Tropical warming and intermittent cooling during the Cenomanian/Turonian oceanic anoxic event 2: Sea surface temperature records from the equatorial Atlantic: *Paleoceanography*, v.22, PA219 p. 1-14.
- Franke, A., 1928, *Die Foraminifera der oberen Kreide Nord- und Mitteldeutschlands*: *Abhandlungen Preussische Geologische Landesanstalt*, n.s., n. 111, 208 p.
- Fricker, P.E., 1963, *Geology of the Expedition Area: western central Axel Heiberg Island, Canadian Arctic Archipelago*: McGill University Axel Heiberg Island Research Reports *Geology*, n. 1, 156 pp.
- Friedrich, O., 2010, Benthic foraminifera and their role to decipher paleoenvironment during mid-Cretaceous Oceanic Anoxic Events- The “anoxic benthic foraminifera” paradox: *Revue de Micropaléontologie*, v. 53, p. 175- 192.

- Friedrich, O., Norris, R.D., and Erbacher, J., 2012, Evolution of middle to Late Cretaceous oceans- A 55 m.y. record of Earth's temperature and carbon cycle: *Geology*, v. 40, n. 2, p. 107 -110.
- Galloway, J.M., Sweet, A.R., Pugh, A., Schröder-Adams, C.J., Swindles, G.T., Haggart, J.W., and Embry, A.F., 2012, Correlating middle Cretaceous palynological records from the Canadian High Arctic based on a section from the Sverdrup Basin and samples from the Eclipse Trough: *Palynology*, v. 36, n. 2, p. 277-302.
- Gooday, A.J., Bernhard, J.M., Levin, L.A., and Suhr, S., 2000, Foraminifera in the Arabian Sea OMZ and other oxygen deficient settings: taxonomic composition, diversity, and relation to metazoan faunas: *Deep-Sea Research Part II*, v. 47, p. 25-54.
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M., 2012, *The Geologic Time Scale 2012*, v. 2: Oxford, UK, Elsevier, 1144 p.
- Granot, R. and Dymant, J., 2015, The Cretaceous opening of the South Atlantic Ocean: *Earth and Planetary Science Letters*, v. 414, p. 156-163.
- Hammer, Ø., Harper, D.A.T., and Ryan, P.D., 2001, PAST: Paleontological statistics software package for education and data analysis: *Palaeontologia Electronica*, v. 4, n. 1, p. 1-9.
- Hay, W.W. and Floegel, S., 2012, New thoughts about the Cretaceous climate and oceans: *Earth-Science Reviews*, v. 115, p. 262-272.
- Hay, W.W., 2008, Evolving ideas about the Cretaceous climate and ocean circulation: *Cretaceous Research*, v. 29, p. 725-753.
- Hay, W.W., 2011, Can humans force a return to a 'Cretaceous 'climate?': *Sedimentary Geology*, v. 235, p. 5-26.
- Hay, W.W., Eicher, D.L., Diner, R., 1993, Physical oceanography and water masses in the Cretaceous Western Interior Seaway, *in* Caldwell, W.G.E. and Kauffman, E.G., eds., *Evolution of the Western Interior Basin: Geological Association of Canada Special Paper 39*, p. 297 – 332.
- Hein, J.R., Scholl, D.W., Barron, J.A., Jones, M.G., and Miller, J., 1978, Diagenesis of late Cenozoic diatomaceous deposits and formation of the bottom simulating reflector on the southern Bering Sea: *Sedimentology*, v. 25, n. 2, p. 155-181.
- Herrle, J.O., Pross, J., Friedrich, O., Köbller, P., and Hemleben, C., 2003, Forcing mechanisms for mid-Cretaceous black shale formation: Evidence from the upper

- Aptian and lower Albian of the Vocontian Basin (SE France): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 190, p. 399-426.
- Herrle, J.O., Schröder-Adams, C.J., Davis, W., Pugh, A.T., Galloway, J.M., and Fath, J., 2015, Mid-Cretaceous high Arctic stratigraphy, climate, and oceanic anoxic events: *Geology*, published online March 19, G39439.1, 4 p.
- Hills, L.V. and Strong, W.L., 2007, Multivariate analysis of Late Cretaceous Kanguk Formation (Arctic Canada) palynomorph assemblages to identify nearshore to distal marine groupings: *Bulletin of Canadian Petroleum Geology*, v. 55, n. 2, p. 160-172.
- Hills, L.V., Braunberger, W.F., Núñez-Betelu, L.K., and Hall, R.L., 1994, Paleogeographic significance of *Scaphites depressus* in the Kanguk Formation (Upper Cretaceous), Axel Heiberg Island, Canadian Arctic: *Canadian Journal of Earth Sciences*, v. 31, p. 733-736.
- Hofer, G., Wagreich, M., and Neuhuber, S., 2013, Geochemistry of fine-grained sediments of the upper Cretaceous to Paleogene Gosau Group (Austria, Slovakia): Implications for paleoenvironmental and provenance studies: *Geoscience Frontiers*, v. 4, p. 449-468.
- Hu, X., Scott, R.W., Cai, Y., Wang, C., and Melinte-Dobrinescu, M.C., 2012, Cretaceous oceanic red beds (CORBs): Different time scales and models of origin: *Earth Science Reviews*, v. 115, p. 217-248.
- Huber, B.T., Norris, R.D., and MacLeod, K.G., 2002, Deep-sea paleotemperature record of extreme warmth during the Cretaceous: *Geology*, v. 30, n. 2, p. 123-126.
- Jarvis, I., Gale, A.S., Jenkyns, H.C., and Pearce, M.A., 2006, Secular variation in Late Cretaceous carbon isotopes: a new $\delta^{13}\text{C}$ carbonated reference curve for the Cenomanian-Campanian (99.6 – 70.6 Ma): *Geological Magazine*, v.143, n. 5, p. 561 – 608.
- Jarvis, I., Lignum, J.S., Gröcke, D.R., Jenkyns, H.C., and Pearce, M.A., 2011, Black shale deposition, atmospheric CO₂ drawdown, and cooling during the Cenomanian-Turonian Oceanic Anoxic Event: *Paleoceanography*, v.26, PA3201 p. 1-17.
- Jeletzky, J.A., 1970, Marine Cretaceous biotic provinces and paleogeography of western and Arctic Canada: Illustrated by a detailed study of ammonites: *Geological Survey of Canada Paper* 70-22, p. 1-52.

- Jenkyns, H.C., Forster, A., Schouten, S., and Sinninghe Damsté, J.S., 2004, High temperatures in the Late Cretaceous Arctic Ocean: *Nature*, v. 432, p. 888- 892.
- Jones, C.E. and Jenkyns, H.C., 2001, Seawater strontium isotopes, oceanic anoxic events, and seafloor hydrothermal activity in the Jurassic and Cretaceous: *American Journal of Science*, v. 301, p. 112-149.
- Jorissen, F.J., de Stigter, H.C., and Widmark, J.G.V., 1995, A conceptual model explaining benthic foraminiferal microhabitats: *Marine Micropaleontology*, v. 22, p. 3-15.
- Jowitt, S.M., Williamson, M.C., and Ernst, R.E., 2014, Geochemistry of the 130 to 80 Ma Canadian High Arctic Large Igneous Province (HALIP) event and implications for Ni-Cu-PGE prospectivity: *Economic Geology*, v. 109, n. 2, p. 281-307.
- Keller, G., 2008, Cretaceous climate, volcanism, impacts, and biotic effects: *Cretaceous Research*, v. 29, n., 5-6, p. 754-771.
- Leckie, R.M., and Olson, H.C., 2003, Foraminifera as proxies for sea-level change on siliciclastic margins, *in* Olson, H.C. and Leckie, R.M., eds., *SEPM Special Publication 75*, p. 5-19.
- Leckie, R.M., Bralower, T.J., and Cashman, R., 2002, Oceanic anoxic events and plankton evolution: Biotic response to tectonic forcing during the mid-Cretaceous: *Paleoceanography*, v. 17, n. 3, p. 13-1 – 13-29.
- Lenniger, M., Nøhr-Hansen, H., Hills, L.V., and Bjerrum, C.J., 2014, Arctic black shale formation during Cretaceous Oceanic Anoxic Event 2. *Geology* v. 42, p. 799-802.
- Levin, L.A., 2003, Oxygen minimum zone benthos: Adaptation and community response to hypoxia *in* Gibson, R.N., and Atkinson, J.A., eds., *Oceanography and Marine Biology: An Annual Review*, v. 41, p. 1-45.
- Locklair, R., Sageman, B., and Lerman, A., 2011, Marine carbon burial flux and the carbon isotope record of Late Cretaceous (Coniacian-Santonian) Oceanic Anoxic Event: *Sedimentary Geology*, v. 235, p. 38-49.
- Loeblich, A.R. Jr., 1946, Foraminifera from the type Pepper Shale of Texas: *Journal of Paleontology*, v. 20, p. 130-139.
- Loeblich, A.R. Jr., and Tappan, H., 1988, *Foraminifera Genera and their Classification*: New York, NY, Van Nostrand Reinhold Compant Inc., 970 p.

- Loubere, P. and Fariduddin M., 2002, Benthic foraminifera and the flux of organic carbon to the seabed, *in* Sen Gupta, B. K., ed., *Modern Foraminifera*: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 181-199.
- Loubere, P., Gary, A., and Lagoe, M., 1993, Generation of the benthic foraminiferal assemblage: Theory and preliminary data: *Marine Micropaleontology*, v. 20, p. 165-181.
- Lyons, T.W., and Severmann, S., 2006, A critical look at iron paleoredox proxies: New insights from modern euxinic marine basins: *Geochimica et Cosmochimica Acta*, v.70, p. 5698-5722.
- MacRae, R.A. 1992, Palynology of the Bastion Ridge and Strand Fiord formations, western Axel Heiberg Island, Canadian Arctic Islands, N.W.T.: Implications for stratigraphy, age, paleoenvironment, and *Nyktericysta* taxonomy [MSc. thesis]: University of Calgary, 346 p.
- Maher, H.T. Jr., 2001, Manifestations of the Cretaceous High Arctic Large Igneous Province in Svalbard: *The Journal of Geology*, v.109, n. 1, p. 91-104.
- McLennan, S.M., 2001, Relationships between the trace element composition of sedimentary rocks and upper continental crust: *Geochemistry, Geophysics, Geosystems*, v. 2, 1021.
- McNeil, D.H. 1997a, Diagenetic regimes and the foraminiferal record in the Beaufort-Mackenzie Basin and adjacent cratonic areas: *Annales Societatis Geologorum Poloniae*, v. 67, p. 271-286.
- McNeil, D.H., 1997b, New foraminifera from the Upper Cretaceous and Cenozoic of the Beaufort-Mackenzie Basin of Arctic Canada: *Cushman Foundation for Foraminiferal Research Special Publication 35*, 95 p.
- McNeil, D.H., and Caldwell, W.G.E., 1981, Cretaceous rocks and their foraminifera in the Manitoba Escarpment: *Geological Association of Canada Special Paper 21*, 439 p.
- Mello, J.F., 1971, Foraminifera from the Pierre Shale (Upper Cretaceous) at Red Bird, Wyoming: Stratigraphy, paleontology, and sedimentation of the classic reference locality of the Pierre Shale: *United States Geological Survey Professional Paper 393-C*, 54 p.
- Miall, A.D., 1979, Mesozoic and Tertiary geology of Banks Island, Arctic Canada: A history of an unstable craton margin, *Geological Survey of Canada Memoir 387*, 235 pp.

- Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: *Science*, v. 310, n. 5752, p. 1293-1298.
- Mull, C.G., Houseknecht, D.W., and Bird, K.J., 2003, Revised Cretaceous and Tertiary stratigraphic nomenclature in the Colville Basin, Northern Alaska, U.S. Geological Survey Professional Paper 1973, 51 pp.
- Murray, J., 2006, *Ecology and Applications of Benthic Foraminifera*: Cambridge, New York, NY, Cambridge University Press, 426 p.
- Murray, J.W., Alve, E., and Jones, B.W., 2011, A new look at modern agglutinated benthic foraminiferal morphogroups: their value in palaeoecological interpretation: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 309, p. 229-241.
- Nagy, J., 1992, Environmental significance of foraminiferal morphogroups in Jurassic North Sea deltas: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 95, p. 111-134.
- Nagy, J., Hess, S., and Alve, E., 2010, Environmental significance of foraminiferal assemblages dominated by small-sized *Ammodiscus* and *Trochammina* in Triassic and Jurassic delta-influenced deposits: *Earth-Science Reviews*, v. 99, p. 31-49.
- Nagy, J., Reolid, M., and Rodriguez-Tovar, F.J., 2009, Foraminiferal morphogroups in dysoxic shelf deposits from the Jurassic of Spitsbergen: *Polar Research*, v. 28, p. 214-221.
- Nauss, A.W., 1947, Cretaceous microfossils of the Vermilion Area, Alberta: *Journal of Paleontology*, v. 21, n. 4., p. 329-343.
- Neilsen, K.S., Schröder-Adams, C.J., Leckie, D.A., Haggart, J.W., Elberdak, K., 2008, Turonian to Santonian paleoenvironmental changes in the Cretaceous Western Interior Sea: The Carlile and Niobrara formations in southern Alberta and southwestern Saskatchewan, Canada: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 270, n. 1-2, p. 64-91.
- Norris, R.D., Bice, K.L., Magno, E.A., and Wilson, P.A., 2002, Jiggling the tropical thermostat in the Cretaceous hothouse: *Geology*, v. 30, no. 4, p.299-302.
- North, B.R. and Caldwell, W.G.E., 1970, Foraminifera from the Late Cretaceous Bearpaw Formation in South Saskatchewan River valley: Saskatchewan Research Council Geology Division Report 9, 117 p.

- North, B.R., and Caldwell, W.G.E., 1975, Illustrations of Canadian fossils: Cretaceous foraminifera from Saskatchewan and Manitoba: Geological Survey of Canada Paper 74-38, 35 p.
- Núñez-Betelu, L.K., Hills, L.V., MacRae, R.A., 1994, Palynostratigraphy and hydrocarbon potential of the Upper Cretaceous Kanguk Formation: An integrated multidisciplinary analysis of the northeastern Canadian Arctic Archipelago, *in* Proceedings, International Conference on Arctic Margins, 2nd, Magadan Russia: Bureau of Ocean Energy Management, p. 54-61.
- Olfer'ev, A.G., Beniamovski, N., Vishnevskaya, V.S., Ivanov, A.V., Kopaeovich, L.F., Ovechkina, M.N., Pervushov, E.M., Sel'tser, V.B., Tesakova, E.M., Kharitonov, V.M., and Shcherbinina, E.A., 2008, Upper Cretaceous deposits in the northwest of Saratov region, Part 2: Problems of chronostratigraphy and regional geological history: Stratigraphy and Geological Correlation, v. 16, n.3, p. 267-294.
- Olsen, T., and Pedersen, G.K., 1991, The occurrence of marine fossils in the Upper Cretaceous deltaic sediments at Pautût, central West Greenland: Bulletin of the Geological Society of Denmark, v. 39, p. 111-122.
- Patchett, P.J., Embry, A.F., Ross, G.M., Beauchamp, B., Harrison, J.C., Mayr, U., Isachsen, C.E., Rosenberg, E.J., and Spense, G.O., 2004, Sedimentary cover of the Canadian Shield through Mesozoic time reflected by Nd isotopic and geochemical results for the Sverdrup Basin, Arctic Canada; The Journal of Geology, v. 112, n.1, p. 39-57,
- Poulton, S.W., Henkel, S., Marz, C., Urquhart, H., Flögel, S., Kasten, S., Sinninghe Damsté, J.S., and Wagner, T., 2015, A continental-weathering control of orbitally driven redox-nutrient cycling during Cretaceous Oceanic Anoxic Event 2 Geology, v. 43, n. 11, p. 963-966.
- Pugh, A.T., Schröder-Adams, C.J., Carter, E.S., Herrle, J.O., Galloway, J., Haggart, J.W., Andrews, J.L., and Hatsukano, K., 2014, Cenomanian to Santonian radiolarian biostratigraphy, carbon isotope stratigraphy and paleoenvironments of the Sverdrup Basin, Ellef Ringnes Island, Nunavut, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 413, p. 101-122.
- Reolid, M. and Martínez-Ruiz, F., 2012, Comparison of benthic foraminifera and geochemical proxies in shelf deposits from the Upper Jurassic of the Prebetic (southern Spain): Journal of Iberian Geology, v. 38, n. 2, p. 449-465.
- Reolid, M., Nikitenki, B.L., and Glinskikh, L., 2014, *Trochammina* as opportunist foraminifera in the Lower Jurassic from north Siberia: Polar Research, v. 33, 21653.

- Reuss, A.E., 1845, Die Versteinerungen der böhmischen Kreideformation: Stuttgart, E. Schwizerbart, Abt. 1, 58 p.
- Ricketts, B., Osadetz, K.G., and Embry, A.F., 1985, Volcanic style in the Strand Fiord Formation (Upper Cretaceous), Axel Heiberg Island, Canadian Arctic Archipelago: *Polar Research*, v. 3, n.s, p. 107-122.
- Sahagian, D.L., Beisel, A.L., and Zakharov, V.A., 1994, Sequence stratigraphy enhancement of biostratigraphic correlation with application to the Upper Cretaceous of northern Siberia: A potential tool for petroleum exploration: *International Geology Review*, v. 36, p.359-372.
- Schlanger, S.O. and Jenkyns, H.C., 1976, Cretaceous Oceanic Anoxic Events: Causes and Consequences: *Geologie en Mijnboliw*, v.55, n. 3-4, p. 179-184.
- Schlanger, S.O., Arthur, M.A., Jenkyns, H.C., and Scholle, P.A., 1987, The Cenomanian-Turonian Oceanic Anoxic Event, I. Stratigraphy and distribution of organic carbon-rich beds and the marine $\delta^{13}\text{C}$ excursion *in* Brooks, J. and Fleet, A.J., eds., *Marine Petroleum Source Rocks*, Geological Society Special Publication, n. 26, p. 371 -399.
- Schröder-Adams, C.J., 2014, The Cretaceous Polar and Western Interior seas: paleoenvironmental history and paleoceanographic linkages: *Sedimentary Geology*, v. 301, p. 26-40.
- Schröder-Adams, C.J., Herrle, J.O., Embry, A.F., Haggart, J.W., Galloway, J.M., Pugh, A.T., and Harwood, D.M., 2014, Aptian to Santonian foraminiferal biostratigraphy and paleoenvironmental change in the Sverdrup Basin as revealed at Glacier Fiord, Axel Heiberg Island, Canadian Arctic Archipelago: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 413, p. 81-100.
- Scott, C. and Lyons, T.W., 2012, Contrasting molybdenum cycling and isotopic properties in euxinic versus non-euxinic sediments and sedimentary rocks: redefining the paleoproxies: *Chemical Geology*, v. 324-325, p. 19-27.
- Sen Gupta, B.K. and Machain-Castillo, M.L., 1993, Benthic foraminifera in oxygen poor habitats: *Marine Micropaleontology*, v. 20, p. 183-201.
- Setoyama, E., Kaminski, M.A., and Tyszka, J., 2011a, Campanian agglutinated foraminifera from the Lomonosov Ridge, IODP Expedition 302, ACEX, in the palaeogeographic context of the Arctic Ocean: *Micropaleontology*, v.57, n.6, p. 507-530.

- Setoyama, E., Kaminski, M.A., and Tyszka, J., 2011b, The Late Cretaceous-early Paleocene palaeobathymetric trends in the southwest Barents Sea- Palaeoenvironmental implications of benthic foraminifera assemblage analysis: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 307, p. 44-58.
- Stelck, C.R., and Wall, J.H., 1954, Kaskapau foraminifera from Peace River area of western Canada: Research Council of Alberta Report 68, 38 p.
- Stelck, C.R., Wall, J.H., and Wetter, R.E., 1958, Lower Cenomanian Foraminifera from Peace River Area, western Canada: Research Council of Alberta Geological Division Bulletin 2, Part I, p. 1-35.
- Stelck, C.R. and Wall, J.H., 1955, Foraminifera of the Cenomanian *Dunveganoceras* Zone from the Peace River Area of Western Canada, Research Council of Alberta Report 70, 81 pp.
- Stephenson, R.A., Embry, A.F., Nakiboglu, S.M., and Hastaoglu, M.A., 1987, Rift-initiated Permian to Early Cretaceous subsidence of the Sverdrup Basin *in* Beaumont, C. and Tankard, A.J., eds., *Sedimentary Basins and Basin-Forming Mechanisms*, CSPG Memoir 12: Calgary, Alberta, Canadian Society of Petroleum Geologists, p. 213-231.
- Stephenson, R.A., van Berkel, J.T., and Cloetingh, S.A.P.L., 1992, Relation between salt diapirism and tectonic history of the Sverdrup Basin, Arctic Canada: *Canadian Journal of Earth Sciences*, v. 29, p. 2695-2705.
- Takashima, R., Nishi, H., Huber, B.T., and Leckie, M., 2006, Greenhouse world and the Mesozoic ocean: *Oceanography*, v. 19, p. 82-92.
- Tapia, P.M., and Harwood, D.M., 2002, Upper Cretaceous diatom biostratigraphy of the Arctic Archipelago and northern continental margin, Canada: *Micropaleontology*, v. 48, n. 4, p. 303-342.
- Tappan, H., 1957, New Cretaceous index foraminifera from northern Alaska *in* Loeblich, A.R., ed., *Studies in Foraminifera*: United States National Museum Bulletin 215, p. 201-222.
- Tappan, H., 1960, Cretaceous biostratigraphy of northern Alaska: *American Association of Petroleum Geologists Bulletin*, v. 44, n. 3, p. 273-297.
- Tappan, H., 1962, Foraminifera from the Arctic slope of Alaska: Part 3, Cretaceous foraminifera: United States Geological Survey Professional Paper 236-C, p. 91-209.

- Tessin, A., Hendy, I., Sheldon, N., and Sageman, B., 2015, Redox-controlled preservation of organic matter during “OAE 3” within the Western Interior Seaway. *Paleoceanography*, v. 30, p. 702-717.
- Then, D.R. and Dougherty, B.J., 1983, A new procedure for extracting foraminifera from indurated organic shale, *in* Current Research Part B: Geologic Survey of Canada Paper 83-1B, p. 413-414.
- Thomson, D., Schröder-Adams, C.J., Hadlari, T., Dix, G., and Davis, W.J., 2011, Albian to Turonian stratigraphy and palaeoenvironmental history of the northern Western Interior Sea in the Peel Plateau Region, Northwest Territories, Canada: *Paleogeography, Palaeoclimatology, Palaeoecology*, v. 302, p. 270-300.
- Trettin, H.P. and Parrish, R., 1987, Late Cretaceous bimodal magmatism, northern Ellesmere Island: isotopic age and origin: *Canadian Journal of Earth Sciences* v. 24, p. 257-265.
- Tribovillard, N., Algeo, T.J., Lyons, T., and Riboulleau, A., 2006, Trace metals as paleoredox and paleoproductivity proxies: An update: *Chemical Geology*, v. 232, p. 12-32.
- Tribovillard, N., Lyons, T.W., Riboulleau, A., and Bout-Roumazelles, V., 2008, A possible capture of molybdenum during early diagenesis of dysoxic sediments: *Bulletin de la Société Géologique de France*, v. 179, n. 1, p. 3-12.
- Tyszka, J., 1994, Response of Middle Jurassic benthic foraminiferal morphogroups to dysoxic/anoxic conditions in the Pieniny Klippen Basin, Polish Carpathians: *Paleogeography, Palaeoclimatology, Palaeoecology*, v. 110, p. 55-81.
- van den Akker, T.J.H.A., Kaminski, M.A., Gradstein, F.M., and Wood, J., 2000, Campanian to Palaeocene biostratigraphy and palaeoenvironments in the Foula Sub-basin, west of the Shetland Islands, UK: *Journal of Micropaleontology*, v. 19, p. 23 – 43.
- van Helmond, N.A.G.M., Sluijs, A., Reichert, G.J., Damsté, J.S.S., Slomp, C.P., and Brinkhuis, H., 2013, A perturbed hydrological cycle during Oceanic Anoxic Event 2: *Geology*, online first 13 December 2013, G34929.1, 5 p.
- Wagreich, M., 2009, Coniacian-Santonian oceanic red beds and their link to oceanic anoxic event 3, *in* Hu, X., Wang, C., Scott, R.W., Wagreich, M., and Jansa, L., eds., *Cretaceous Oceanic Red Beds: Stratigraphy Composition, Origins, and Paleogeographic and Paleoclimatic Significance*: SEPM Special Publication 91, p. 235 -242.

- Wall, J.H., 1960, Upper Cretaceous foraminifera from the Smoky River area, Alberta: Research Council of Alberta Bulletin 6, 43 p.
- Wall, J.H., 1983, Jurassic and Cretaceous foraminiferal biostratigraphy in the eastern Sverdrup Basin, Canadian Arctic Archipelago: Bulletin of Canadian Petroleum Geology v. 31, p. 246-281.
- Wall, J.H., 1967, Cretaceous foraminifera of the Rocky Mountain Foothills, Alberta: Research Council of Alberta Bulletin 20, 185 p.
- Wang, C., Hu, Z., Huang, Y., Wagreich, M., Scott, R., and Hay, W., 2011, Cretaceous oceanic red beds as possible consequence of oceanic anoxic events: Sedimentary Geology, v.235, p. 27-37.
- Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., and Roest, W.R., 1996, Geological Map of Canada, Geological Survey of Canada Series map 1860 A, scale 1: 5,000,000.
- Wickenden, R.T.D., 1932, New species of foraminifera from the Upper Cretaceous of the prairie provinces: Transactions of the Royal Society of Canada Series 3, v. 26, p. 85-91.
- Witkowski, J., Harwood, D.M., and Chin, K., 2011, Taxonomic composition, paleoecology and biostratigraphy of Late Cretaceous diatoms from Devon Island, Nunavut, Canadian High Arctic: Cretaceous Research, v. 32, p. 277-300.