***Upper Cretaceous Dinocyst Assemblages from Ellef Ringnes
Island, Nunavut: Paleoecological changes within the Boreal
Sea***

by

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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

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Ottawa, Ontario

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Abstract

Ellef Ringnes Island, in the Canadian High Arctic, preserves the sedimentary and paleoenvironmental history of the Cretaceous phase of the Sverdrup Basin.

The study of dinoflagellate cysts (dinocysts) of the Late Cretaceous Kanguk Formation in combination with other fossil indicators, organic geochemistry and detailed correlation to global sea-level fluctuations provides the first stratigraphic framework for the undivided thick shaly Kanguk Formation. A new dinocyst range chart is developed consisting of mainly cosmopolitan species with a more tolerant temperature range that have invaded the Boreal realm. Extremely rich assemblages in the Boreal Sea resulted from the Cretaceous high sea level flooding terrestrial regions and delivering high supply of nutrients to shallow marine settings where plankton flourished. Ratios between benthic and pelagic dinocysts throughout the Kanguk Formation show a striking correlation to transgressive/regressive phases that are linked to global sea level. Their preservation was generally enhanced by anoxic bottom water conditions and expanded oxygen minimum zones as a result of high organic matter supply. Dinocyst radiation events took place during the late Turonian and late Santonian at times of low global sea level with incoming species preferring a shelf setting. This study demonstrates that dinocysts add a valuable proxy to depositional interpretations of the complex Cretaceous ecosystem of the Boreal Sea.

Acknowledgements

"I felt like I was seeing, woven together, the power and scale of the entire world."

--Kathryn D. Sullivan

I would like to express my sincere gratitude to my supervisor Dr. Claudia Schröder-Adams for support, encouragement and shared enthusiasm in the process of my work. Dr. Jennifer Galloway (Geological Survey of Canada, Calgary) is thanked for providing Rock Eval data; Drs. Steve Grasby and Keith Dewing (Geological Survey of Canada, Calgary) for logistical support in the field and Dr. Claudia Schröder-Adams, Adam Pugh and Dr. Jennifer Galloway for the measured section and field sampling. Finally, I like to thank Drs. Rob Fensome (Geological Survey of Canada, Darmouth) and Poul Schioler (GNS New Zealand) for taxonomic advice on the systematics of dinocysts; Dr. James Haggart (Geological Survey of Canada, Vancouver) for macrofossil identifications; Dr. Murray Hay (Université du Québec à Chicoutimi) for his diatom results and Dr. Jens Herrle (Goethe University, Frankfurt, Germany) for his carbon isotope data. I would also like to thank my mother for her kind words of understanding and love through the hard times, my friends for the laughter, and my animals that bring warmth and comfort to me every day.

Financial support to Claudia Schröder-Adams was provided by a Collaborative Research and Development Grant from the Natural Science and Engineering Research Council Canada with the Geological Survey of Canada's Geo-mapping for Energy and Minerals Program and ConocoPhillips Houston/Calgary as partners.

Table of Contents

Abstract	i
Acknowledgements	ii
Table of Contents	iii
List of Tables.....	iv
List of Figures	iv
List of Plates.....	iv
1 Chapter: Introduction	1
1.1 Dinocyst importance in paleoecological reconstructions	1
1.2 Background on the life cycle of dinoflagellates	4
1.3 Geological Setting.....	7
1.4 Biostratigraphy	10
2 Chapter: Materials and Methods	11
2.1 Collection of Material.....	11
2.2 Processing of Material	14
2.3 Taxonomic Approach.....	16
2.4 Counts	16
2.5 Taxonomy and Analysis	17
2.6 Supporting Data	18
3 Chapter: Results and Interpretations.....	18
3.1 Lithology and Stage Boundaries.....	18
3.2 Dinocyst Abundances	23
3.3 Benthic vs Pelagic Dinocyst Assemblages	24
3.4 Marine vs Terrestrial Components	27
3.5 Influence of Volcanic Activity on the Assemblages.....	28
3.6 Dinocyst Species and Ranges.....	30
4 Chapter: Discussion	36
4.1 Dinoflagellates of the Cretaceous Boreal Sea	36
4.2 Dinoflagellate Lifecycles and Paleoecology	37
4.3 Boreal Dinoflagellate Assemblages and Large-scale Cretaceous Changes	42
5 Chapter: Conclusions	44
References	52

List of Tables

Table 1 Physical characteristics of the samples taken from the Kanguk Formation.....	12
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List of Figures

Figure 1: Locality Map depicting Sverdrup Basin, Ellef Ringnes Island and Hoodoo Dome.....	3
Figure 2: Stratigraphic chart. Hoodoo Dome, Ellef Ringnes Island.....	9
Figure 3a: Photograph of macrofossil <i>Sphenoceras patootensis</i> (de Loriol).....	20
Figure 3b: Photographs of the Kanguk and Hassel formations outcrop.....	21
Figure 3c: Photographs of the Kanguk Formation outcrop.....	22
Figure 4: Abundance of dinocysts within the sampled section.....	23
Figure 5: Pelagic vs. benthic dinoflagellate species, terrestrial palynomorphs vs. marine dinocysts, total organic carbon content, Hydrogen Index compared to an upper Cretaceous sea level curve. Events (1 to 6) mark times of correlative changes. Note that sample intervals of the Rock Eval data do not correspond with the dinocyst sample intervals..	26
Figure 6a: Marine vs. Terrestrial % comparison within the Kanguk Formation.....	27
Figure 6b: Marine vs. Terrestrial % comparison within the uppermost Christopher and lowermost Hassel formations.....	28
Figure 7: Percent of marine dinocysts vs terrestrial spores and pollen in relationships to bentonite layers found in the measured section at Hoodoo Dome, Ellef Ringnes Island.....	29
Figure 8a: Lithographic column of section sampled and dinocyst range chart.	31
Figure 8b: Legend for the Lithographic column in 8a.....	31
Figure 9: Select Dinocyst specimen interpretive zones from Ellef Ringnes Island, Kanguk Formation compared to data from other North American and Greenland studies.....	35
Figure 10: Relative abundance of pelagic vs benthic dinocysts within the Kanguk Formation and resulting Late Cretaceous sea-level fluctuations within the Sverdrup Basin.....	40

List of Plates

Plate 1 Dinoflagellate cysts that are generally long ranging and make their first appearance in the lower Kanguk Formation, Hoodoo Dome, Ellef Ringnes Island.....	46
PLATE 1	47
Plate 2 Dinoflagellate cysts that have their first appearance in the early or middle Kanguk Formation (including the first radiation of dinocysts at the beginning of the Coniacian), Hoodoo Dome, Ellef Ringnes Island.	48
PLATE 2	49
Plate 3 Dinoflagellate cysts making first appearance to include the middle to upper Kanguk Formation (the second radiation near the end of the Santonian), Hoodoo Dome, Ellef Ringnes Island.	50
PLATE 3	51

Appendix

Authors used for Dinocyst identifications.....	61
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1 Chapter: Introduction

1.1 Dinocyst importance in paleoecological reconstructions

The Cretaceous was a time of significant paleoenvironmental extremes, where changes in climate and biosphere were rapid. Arid conditions may have affected continental life while maintaining productivity in marine settings. With the transition to humid conditions a net transfer of water to the continent allowed for development of an increasing continental vegetation cover (Föllmi, 2012). This together with flooding of coastal regions resulting from high sea levels delivered increasing amounts of organic matter to ocean basins. Phases of anaerobic conditions in deeper ocean waters developed leading to times of accelerated extinctions in oceans (Föllmi, 2012). These frequent periods of bottom water anoxia, known as oceanic anoxic events, are marked by positive excursions in carbon isotopes (eg. Leckie et al., 2002), and the lack of benthos such as foraminifera.

Biostratigraphy and paleo-environmental reconstructions are aided by the use of microfossil studies such as dinoflagellates; a diverse group of single-celled protists utilizing several life strategies, including in some species, the ability to form cysts. Dinoflagellates can be used as environmental proxies due to their requirements to temperature, salinity and nutrients (Vernal et al, 2007), but also oxygen (Pross, 2001). Therefore, they have important implications for reconstruction of paleoenvironments (Esper and Zonneveld, 2007). The use of pelagic microfossils such as organic walled dinocysts allows the closure of gaps in stratigraphic basin

analysis where tests made of calcium carbonate or silica might have been taphonomically removed.

Published information on Cretaceous Arctic dinocysts is limited and zonations are almost non-existent, especially for the upper Cretaceous strata. Cretaceous dinoflagellate assemblages have been described only from a few Arctic regions. Nunez-Betulu and Hills (1994) geologically characterized the Kanguk Formation in the central and northeastern part of the Sverdrup Basin based on outcrops on Axel Heiberg and Ellesmere islands. MacRae (1996) reported palynological data from Cretaceous strata in the central Sverdrup Basin as exposed on Axel Heiberg Island, and McIntyre (1995) addressed the Beaufort-Mackenzie area, northwestern Canada. Nohr-Hansen (1993 and 1996) compiled dinoflagellate ranges from eastern Greenland and Arhus (1991) from North Greenland, southeastern Spitsbergen and the Barents Sea.

This study documents dinocyst assemblages of the upper Cretaceous (upper Cenomanian to Campanian) Kanguk Formation exposed on Ellef Ringnes Island of the Queen Elizabeth Islands, Nunavut, Arctic Canada (Figure 1). The Kanguk Formation documents the Upper Cretaceous history of the Boreal Sea and remains undivided as it is expressed as a large package of mudrock with only bentonites that can be used as marker beds. These were sampled and await geochronological analysis. Ellef Ringnes Island is located near the depocentre of the Sverdrup Basin (Embry, 1991) and the Kanguk Formation represents deep water deposits.

Figure 1: Locality Map depicting Sverdrup Basin, Ellef Ringnes Island and Hoodoo Dome.

This study provides the first biostratigraphic zonation based on fossilized dinocysts for the Upper Cretaceous strata exposed on Ellef Ringnes Island and integrated with other bio- and chemostratigraphic proxies, diatom biostratigraphy (Murray et al., in prep.), radiolarian biostratigraphy (Pugh, 2013), sparse macrofossil occurrences (J. Haggart, pers. comm. 2012) and carbon isotope stratigraphy (J. Herrle, pers. comm.).

The establishment of dinocyst bio-stratigraphic markers will aid future stratigraphic correlations in the Cretaceous Sverdrup Basin. In addition, dinocyst turnover periods are compared to global sea-level fluctuations as proposed by Kominz et al. (2008) for the Atlantic in order to enhance our understanding of paleo-environmental changes within the Boreal Sea.

The specific objectives of this study include the establishment of an Arctic zonation for Ellef Ringnes Island based on Upper Cretaceous dinocysts, identification of valuable dinocyst bio-stratigraphic markers and documentation of significant dinocyst turnover periods and patterns in response to sea-level change. This allows integrating dinocyst biostratigraphy as an additional microfossil parameter to paleo-reconstructions that might ultimately increase accuracy in predictions for future climate changes and interactions. The Arctic climate and environmental warming has been a concern globally (e.g. Hay, 2011) but most importantly to the residents of the North who rely on this environment for cultural and economic sustainability.

1.2 Background on the life cycle of dinoflagellates

Using dinoflagellates in paleo-environmental and biostratigraphic studies requires knowledge of their life cycle as observed in extant species and their response to ecological changes. Dinoflagellates belong to the class Dinophyceae [Division Pyrrophyta (Algae)], are unicellular protists recognizable by a free swimming biflagellate stage in their life cycle (Williams and Bujak, 1985; Fensome et al,

1996a), and possess a unique nucleus in which the chromosomes remain continually condensed (termed a dikaryon). Dinoflagellates inhabit both marine and freshwater environments (Fensome et al, 1996a). Approximately half of known species are autotrophic, the remainder being heterotrophic (Fensome et al, 1996a). Some heterotrophic species can be parasitic or symbiotic (Williams and Bujak, 1985). They are generally asexual, however, there are several species that utilize sexual reproduction. Dinoflagellates have several stages in their life cycle including the 1) motile thecate form; 2) hypnozygote form; 3) theca-less naked form; and 4) the resting cyst form (that is left behind as part of the fossil record). The motile stage is quickly destroyed after death, but some species form resistant cysts comprised of sporopollenin-like organic walls (Williams and Bujak, 1985). When a dinoflagellate exits the cyst, it is surrounded by a gelatinous sheath which is shed at a later stage (Sarjeant, 1974). The cyst composition is organic and non-cellulose in nature, which resists decay from bacteria and fungi (and also resists breakage into the thecal plates of the motile form (Gilbert and Clark, 1983). The thecal plates are composed of cellulose and serve as structure for the motile cell (Lau et al, 2007).

It is generally accepted that cysts have resulted from the resting stage of a dinoflagellate, and bear resemblance to the motile form (Evitt, 1963), remaining in the sediment after the dinoflagellate has exited the cyst, and left behind as part of the fossil record. The fossil cyst can be identified if they retain tabulation patterns similar to the thecal plates of the motile organism (Gilbert and Clark, 1983), by the number or placement of the processes, or the shape of the excystment opening (the

archeopyle) (Fensome et al, 1996a; Evitt, 1967). Therefore dinoflagellates leave behind a selective record, since only cyst-forming species (approximately 10% of modern species) are represented biasing interpretations of the original diversity and surface productivity. The cyst-forming character may also be controlled by environmental fluctuations including temperature, salinity, or other stress (Gilbert and Clark, 1983), or may be the result of other life stages of a dinoflagellate or a means of survival. For the purposes of this study, the term dinocyst will be used to refer to organic-walled fossilized dinoflagellate cysts. Cysts that are not fully formed suggest evidence of disturbance such as oxygen depletion in the upper zone of the water column (Pross, 2001), although other types of disturbance are also possible. Fossil 'hystrichospheres' also include Acritarchs that are not classified as dinoflagellates due to the missing archeopyle (Williams and Bujak, 1985).

Although dinoflagellates are classified as eukaryotic algae, they are unique organisms which exploit both marine and lacustrine environments. They are very sensitive to temperature changes, salinity, depth, and other environmental factors. Most take advantage of photosynthesis when possible and are primary producers, therefore are part of the flora that exists within phytoplankton, which many other species rely on for sustenance. If an environment is lacking in dinoflagellates, it is lacking in a substantial component for the food chain (Fensome et al, 1996a).

1.3 Geological Setting

The study area is located at Hoodoo dome, on the southeastern side of Ellef Ringnes Island, which is located near the axis of the Sverdrup Basin (Figure 1). The Sverdrup Basin is a large sedimentary basin in the Canadian High Arctic covering approximately 300,000 km² (about 1300 km in WE direction and 350 km in NS direction); approximately half is now exposed on land as part of the Queen Elizabeth Islands (figure 1). The Sverdrup Basin documents the depositional history of the Arctic Islands from the Carboniferous to the Paleogene, a package of up to 13 km thickness (Balkwill, 1978). The basin developed as a rift basin in the Early Carboniferous and its development can be described in eight phases that are bound by major angular unconformities caused by tectonic events (Embry and Beauchamp, 2008). During Cretaceous time the basin was bordered to the North by the Sverdrup Rim as a result of early Cretaceous uplift. This rim served as a source of sediment for the basin and when it emerged, connections were severed between the Sverdrup Basin and the Chukchi Basin of Northern Alaska. During the earliest Cretaceous subsidence rates increased due to renewed rifting and extension and with increasing sea levels during the Cretaceous a new seaway formed connecting the Sverdrup Basin with the Western Interior Seaway (Embry and Beauchamp, 2008). These marine connections are important for faunal and floral migration.

Cretaceous strata are associated with an initial rifting phase during the early Cretaceous followed by a phase of seafloor spreading in the Amerasian Basin (Embry, 1991). During the Jurassic to Early Cretaceous, regressive deltaic

sandstones and transgressive marine shales were deposited (Davies, 1983). These include in ascending order the shelf mudstones and siltstones of the Upper Jurassic to lowermost Cretaceous Deer Bay Formation, the fluvial to deltaic coarse grained sandstones of the Isachsen Formation, the distal shelf mudstones of the Christopher Formation and the deltaic and shoreface deposits of the Hassel Formation. The Christopher Formation consists of either prodelta or offshore marine sediments from transgressive and regressive cycles that occurred during the late Aptian to early Albian (Embry, 1991). The deltaic deposits of the Hassel Formation rest conformably on the Christopher Formation, while the Kanguk Formation lies comfortably over the Hassel Formation (Galloway et al, 2012). A sequence boundary in the uppermost Hassel Formation separates floodplain deposits with prominent coal beds from returning shoreface sands (Figure 2).

Volcanics of the Strand Fiord Formation that interfinger with the Hassel Formation have delivered a U/Pb radiometric date of 95.3 ± 0.2 Ma (Trettin and Parrish, 1987). The Bastion Ridge Formation located on Axel Heiberg Island overlies the Strand Fiord Formation and was suggested to be correlative with the basal beds of the Kanguk Formation elsewhere (Fricker, 1963).

The Sverdrup basin went through slow subsidence during the Late Cretaceous and combined with increasing global sea levels (Kominz et al., 2008) resulted in deposition of the shale and mudrock dominated Kanguk Formation. Frequent volcanism provided ash beds that transformed subsequently into bentonites that

were sampled for future radiometric dating. The Eastern section of the basin was uplifted and deformed in the Late Paleogene (Embry and Beauchamp, 2008); therefore, the deeper basin location of our section provides an ideal location for our study. The overlying Eureka Sound Formation places sandstones on top of the mudstone dominated Kanguk Formation.

Figure 1: Stratigraphic chart. Hoodoo Dome, Ellef Ringnes Island. The black vertical bar shows the measured stratigraphic interval.

1.4 Biostratigraphy

The following studies deliver relevant biostratigraphic work for comparison with the Cretaceous strata on Ellef Ringnes Island. Nohr-Hansen and McIntyre (1998) studied part of the Isachsen and Christopher formations (Lower Cretaceous) from three locations (Melville Island, Axel Heiberg Island and Ellesmere Island) that fall within the Sverdrup basin. These shale/siltstone deposits yielded 83 dinocyst species that date the strata from Barremian to early/late Albian. Wall (1983) studied benthic foraminifera and proposed a Late Aptian to Albian age for the Christopher Formation. Jeletzky (1983) dated macrofossils from the Christopher Formation as early to middle Albian. Doerenkamp et al. (1976) described Cretaceous and Tertiary palynomorph assemblages from Banks Island, west of the Sverdrup Basin, and adjacent areas in the Northwest Territories and dated the upper part of the Isachsen Formation as Aptian. Brideaux and McIntyre (1975) dated the Christopher Formation from Banks Island as Aptian to late Albian. Palynofloras of Barremian to Albian age were described from the Mackenzie Delta area by Brideaux and McIntyre (1975), Brideaux (1977), Brideaux and Myhr (1976), Brideaux and Fisher (1976) and by Dixon et al. (1973). Nunez-Betelu and Koldo (1991) described the palynology of the Kanguk Formation on Ellesmere Island. Nunez-Betelu et al. (1994a) developed a palynostratigraphy for the Upper Cretaceous Kanguk Formation for the Eastern Sverdrup Basin. These published records show that most studies have addressed lower Cretaceous strata, whereas few concentrated on the upper Cretaceous of the Arctic region. Dinoflagellates are becoming increasingly valuable tools in paleoenvironmental reconstructions. Since

their organic walls can be sometimes found in intervals where macrofossils or other microfossils of calcareous nature are few or non-existent due to dissolution, their use in biostratigraphic studies is important.

2 Chapter: Materials and Methods

2.1 Collection of Material

In 2010 a composite section including the uppermost Christopher, the Hassel and Kanguk formations was sampled on Ellef Ringens Island at Hoodoo Dome (general locality: N78°13.483', W101°03.880') by C. Schröder-Adams, A. Pugh and J. Galloway. A subsample set was put aside for dinocyst analysis and samples revealed a high occurrence of well-preserved paleo-flora and fauna including dinoflagellate, spore-pollen, radiolarian, and diatom assemblages; however, foraminifera appear to be rare (Pugh, 2013). The sampled section covers 294 m of strata of the Kanguk Formation collected mostly from dark organic rich mudrock and shales which I focus on in this study, but also 186 m of the underlying Hassel and Christopher formations. From the 138 samples recovered, 99 were selected specifically for dinocyst recovery; a sub-sample of material was removed from each of the sample bags using a metal spoon which was cleaned between bags to avoid contamination. Samples were put in small plastic bags, sealed and labeled. Processing and mounting on slides were performed in the laboratory of Global Geolab Limited (care of ConocoPhillips). A total of 96 of these samples contained dinocysts and three were barren. Slides were labeled with the location, year and sample number which corresponds to a functional meterage of the section (e.g. ER 2010 E 54 refers to

Ellef Ringnes 2010, section E #54). See Table 1 for complete descriptions of the samples and the corresponding functional meterage.

Table 1: Physical characteristics of the samples taken from the Kanguk Formation.

<i>Metres</i>	<i>Sample ID</i>	<i>Colour perceived by eye</i>	<i>Description perceived by eye</i>
480.0	E108 + E109	Med brown	Thickly parted shale, some sand present
474.0	E106	Very dark brown	Very fine clay/mud
472.5	E107	Med grey - green	Thickly parted shale with sulphur present
450.0	E105	Dark red - brown	Coarse grained with rust present
436.5	E104	Dark brown	Fine silt with sulfur present
433.5	E103	Black - grey	Granular / slightly shaly
430.5	E102	Dark brown - green	Silty, slightly shaly, some sulphur present
427.5	E101	Med brown	Fine grained
426.0	E100	Med grey	Silty / smooth
425.0	E63	Light grey	Silty / chalky / smooth
424.5	E64	Dark brown	Loamy
422.0	E92	Dark brown	Silty / very thin shale partings
413.5	E91	Black	Shale
410.5	E90	Dark grey	Shaly
405.0	E89	Grey - dark brown	Large shaly partings
400.5	E88	Dark brown - green	Medium parted shale with sulphur
396.0	E87	Med brown - green	Medium parted shale with sulphur
392.8	E86	Med brown - green	Medium parted shale / silty with sulphur
389.0	E85	Dark brown - green	Thickly parted shale with sulphur
384.0	E84	Light brown - green	Medium parted shale with sulphur
381.0	E62	Grey - yellow	Thickly parted shale with sulphur
380.5	E61	Grey - yellow	Thickly parted shale with sulphur
379.0	E60	Grey - yellow	Thin parted shale with sulphur
375.5	E82	Med brown - green	Medium parted shale with sulphur
373.0	E81	Very dark brown - yellow	Medium parted shale
367.0	E80	Very dark brown	Thin parted shale with sulphur
364.0	E79	Dark brown	Very fine grained clay / mud
358.5	E78	Med-dark brown	Thin parted shale
340.0	E121	Dark brown	Muddy shale with fine grains
329.0	E120	Grey-brown - green	Some partings with sulphur
323.0	E119	Rusty dark - brown	Medium parted shale with rust

311.0	E118	Med-brown - yellow	Thin parted shale with some sulphur
305.0	E117	Dark brown - green	Shale / granular with sulphur
298.5	E77	Light grey - green	Shale with sulphur
292.5	E76	Light brown - green	Med-thin partings with sulphur
284.0	E75	Light brown - yellow	Silty with some partings, some sulphur
280.5	E74	Light brown - green	Thin parted shale with sulphur
278.2	E57	Light brown - green	Medium parted shale with sulphur
277.8	E56	Dark grey - green	Medium parted shale with sulphur
277.0	E58	Dark brown - green	Thickly parted shale with sulphur
276.0	D130	Medium grey	Shale / silty
275.0	E73	Grey - brown - green	Thickly parted shale with sulphur
270.0	E72	Med - brown - green	Medium parted shale with sulphur
268.5	D129	Dark brown	Thinly parted shale
265.5	E71	Dark grey	Shaly mud
263.0	D128	Black	Granular / minor platyness
262.5	E70	Light brown - green	Crumbly shale with sulphur
255.0	D127	Dark grey - green	Fine grained with sulphur
250.0	D126	Med brown - green	Thinly parted shale with sulphur
247.0	D125	Very dark brown	Fine textured clay / mud
239.0	D99	Dark brown - green	Thinly parted shale with sulphur
234.5	D98	Med-dark brown - yellow	Thinly parted shale with sulphur
216.0	D97	Dark grey-brown - yellow	Thin-med parted shale with sulphur
209.5	D96	Dark brown	Thinly parted shale / silty
205.0	D95	Dark grey	Thinly parted shale / silty
200.5	D94	Dark grey	Silty
196.0	D93 + D69	Dark grey	Silty shale
193.0	D68	Medium brown-green	Thinly parted shale with sulphur
191.5	D67	Medium brown-green	Thinly parted shale with sulphur
190.0	D66	Medium brown-green	Thinly parted shale with sulphur
188.3	D54	Light grey-brown	Thinly parted shale / silty
188.2	D51	Dark brown	Granular / salty
188.0	D52 + D50	Light grey	Sandy clay
186.0	D53	Light grey	Shale

2.2 Processing of Material

The subsample set was processed for dinocysts by Global Geolab Limited using the following procedure for isolating dinocysts, staining and mounting on slides:

Acid Digestion/Cleaning process: 25-55 grams of sample was placed in a 250 ml polypropylene beaker. The specific weight for each sample was measured and recorded. A 10% solution of HCl was added, watching for an overly violent reaction, which was dampened with an atomized spray of distilled water from a spray bottle. Time was allowed for carbonates to dissolve. The spent HCl was decanted. Distilled water was added, allowed to settle, and decanted again. The sample was diluted and decanted three times to remove any remaining calcium ions (which can produce a precipitate when HF is added). 70% HF was added by watching for any violent reaction which was dampened with distilled water as above. The sample in HF was oscillated for up to four hours until digestion was completed. The digested sample was poured into a 50 ml Polypropylene test tube and centrifuged for five minutes at 2000RPM. The top $\frac{3}{4}$ of the spent HF was carefully decanted. Distilled water was added to the tube while vortexing, and centrifuged for two minutes. This process was repeated until the solution was neutral. This washing/centrifuging was repeated until the fine material was removed. To allow for a better heavy liquid separation, a few drops of concentrated HCl was added to the vortex while adding water and centrifuged for four minutes.

Heavy Liquid Separation: Approximately 25 ml of ZnBr₂ specific Gravity -2.0 was added to the tube, and was vortexed thoroughly. Each test tube was placed in an

ultrasonic bath for approximately 10 seconds. The samples were allowed to sit for 10 minutes before being centrifuged for 15 minutes at 2000RPM (the 10 minute wait allows for better separation). The “float” was poured off into another 50 ml tube, washed and centrifuged for two minutes at 2000RPM, and repeated three times. The remaining residue was transferred to a 20 ml glass tube. A small smear of the residue was examined to determine the amount of oxidation required.

Oxidation: Approximately 3ml of Shultz solution was placed on the residue, vortexed and the tube placed in a hot bath for approximately 30 seconds. The spent Schultz solution was removed by washing and centrifuging until neutral. A small smear of residue was checked to see if the oxidation is sufficient. A 10% solution of NH_4OH was added and the tube was placed in hot water bath for two minutes. The sample was then centrifuged and washed three times. The residue was examined to determine if the desired level of oxidation has been achieved.

Mounting of Slides: With a pipette each of the sieved fractions were mixed in one drop of polyvinyl alcohol using a glass stirring rod. When the polyvinyl alcohol residue had dried, one drop of clear casting resin was added to the slide and the cover slip was turned onto the residue and sealed. Permanent curing occurs in approximately one hour.

2.3 Taxonomic approach

Using a Leica light microscope DM 2500 at x1000 magnification under the oil immersion lens 5017 photographs of all different species found were taken from the 96 samples that contained dinocysts. Selected photographs of species found within three different zones of the Kanguk Formation (lower, middle and upper) that correspond to the biostratigraphic chart, were imaged for the plates. Dinocysts on the plates are labeled by genus and species where known. A total of 37 different taxa were identified to genus level and 24 to species level. Based on high abundance and continuous but limited biostratigraphic ranges, species were selected for biostratigraphy, a new established zonation, and plates. To facilitate comparison attention was also given to species described in other studies in the Boreal realm. In general, dinocysts are characterized by a large phenotypic variability (many specimens appeared phenotypically between two species or might possibly represent new species) making taxonomic identifications difficult.

2.4 Counts

Due to the large number of specimens in each of the samples, counting was done by selecting 5 specific subdivisions via 'fields of view' per slide under the 400x magnification. This magnification was chosen as a larger number of specimens could be viewed while still able to make the determination as to dinocyst versus spore-pollen. Dinocysts and spore-pollen were counted within each area and sums within areas were added to determine a ratio between dinocysts and spore-pollen per sample, for a total count of 6085 dinocysts specimens versus a total of 938 spore-

pollen specimens overall, and with an average of 63 dinocysts versus 8 spore-pollen per slide (this number includes slides that were near barren). Counts per slide were mainly greater than 60 (median 62, range 1 to 208) for dinocysts and 7 (median 7.5, range 0 to 48) for spore-pollen. Dinocysts were significantly more abundant than spore-pollen in the Kanguk Formation samples; where many samples were almost completely barren of terrestrial influence. In samples from the Hassel and uppermost Christopher formations, dinocyst and spore-pollen amounts were more equally distributed.

2.5 Taxonomy & Analysis

Analyses of spore-pollen (terrestrial) and dinocysts (marine), and between benthic and pelagic dinocysts are based on the relative abundance of each group, using percentages of the total number found in each sample. We still do not fully understand the life histories of fossil dinoflagellates. However, Helenes (1986) has pointed out that morphological characters of the cyst are consistent with tabulation patterns of the motile cell, which are often used to identify genera and species of dinocysts. Therefore, the use of these characters would provide a way to develop an identification system when looking at non-tabulated genera of dinocysts, which occur frequently in the fossil record. Tabulated species were not found in the Kanguk Formation, therefore in this study, identifications were done by comparing key morphological characteristics of specimens to named species in the literature. Two studies including Fensome et al. (1993) and Evitt (1985) were particularly helpful for my initial taxonomic studies.

2.6 Supporting data

Rock Eval Pyrolysis was performed at the Geological Survey of Canada, Calgary using the method of Espitalié et al. (1977) in order to measure the Hydrogen Index (HI) and the Total Organic Carbon (TOC) values measured in % for comparison to my data. HI is a parameter used to characterize the origin of organic matter in a sample, and is measured in mg HC/g OC. Marine organisms and algae, in general, are composed of lipid- and protein-rich organic matter, where the ratio of H to C is higher than in the carbohydrate-rich constituents of land plants. HI typically ranges from ~100 to 600 mg HC/g OC in geological samples. Over 300 mg HC/g TOC is corresponding to kerogen derived from marine organisms (plankton, algae, and bacteria) in sediments, however, over time and with burial the HI values may decrease (Peters et al, 2005), therefore the values of these samples may not be as high as expected even if the material is marine derived. A global sea-level curve developed by Kominz et al. (2008) was also utilized for comparison to floral and geochemical patterns.

3 Chapter: Results

3.1 Lithology and Stage Boundaries

The outcrop at Hoodoo Dome, Ellef Ringnes Island, consists of non-consolidated uppermost Albian to Campanian aged deposits including the sandy/silty mudrock dominated Christopher Formation, the sand dominated Hassel Formation and the shale dominated Kanguk Formation. The term sand is used here instead of sandstone due to the nearly unconsolidated nature of the Hassel Formation. One bivalve *Sphenoceras patootensis* (de Loriol) was found near the top of our section

in the Kanguk Formation (figure 3a). The boundary between the Hassel and Kanguk formations forms a distinctive sharp transition from sand to shale (figure 3b). The Kanguk Formation is a thick undivided package of silty shale that lacks marker beds with the exception of bentonites that can be traced over considerable distances (Figure 3 c). These were used to stratigraphically piece together measured sections. Bentonites were sampled for geochronology and await analysis. A total of 480 m of outcrops were sampled, including 294 m that belong to the Kanguk Formation.

This study is part of a multidisciplinary project aiming to develop a stratigraphic framework for the Kanguk Formation and an improved understanding of the paleoenvironmental history that is hidden in the thick package of monotonous mudrock. Stage boundaries, as presented here, are therefore based on several disciplines. Some of these results will be published separately, but will be referred to here. Taking into account a multi-fossil framework, carbon isotope trends and a comparison to the global sea-level curve of Kominz (2008) the entire Kanguk Formation spans from the late Cenomanian to Campanian. Carbon isotope stratigraphy ($\delta^{13}\text{C}_{\text{org}}$) and the recognition of the Oceanic Anoxic Event 2 (OAE2) straddling the Hassel/Kanguk boundary confirmed the placement of the Cenomanian/Turonian stage boundary at 205 m within the section (J. Herrle, pers. comm.). With that the Kanguk Formation reaches into the uppermost Cenomanian.

The Turonian/Coniacian boundary is identified based on a combination of sea-level controlled surface productivity changes as determined with radiolarian

assemblages (Pugh, 2013). Global sea level drops within the middle Turonian and stays low until the early Coniacian (Kominz et al., 2008). The Turonian/Coniacian boundary is placed at about 275 m right below a change in lithology towards a silt-rich unit and a change in the Hydrogen Index towards increasing terrestrial derived organic matter. At the same interval radiolaria diversify up section.

The Coniacian/Santonian boundary is placed at 310 m based on increasing HI values. The Santonian signals a return to high sea level and is coupled at this interval with an increase in the TOC values and Hydrogen Index. The Santonian/Campanian boundary is based on a diatom turnover (M. Hay, pers. comm.) and is bracketed by the interval 385 to 391 m. The occurrence of the macrofossil *Sphenoceras patootensis* (de Loriol) (figure 3a) suggests a late Santonian/Campanian age for the top of the section (J. Haggart, pers. comm.).

Figure 3a: Photograph of macrofossil *Sphenoceras patootensis* (de Loriol).

Figure 3b: Photographs of the Kanguk and Hassel formations outcrops. Upper photograph: mudrock exposure of the Kanguk Formation. Lower photograph: Dark mudrock exposures of the Kanguk Formation in contrast to the light coloured sands of the Hassel Formation.

Figure 3c: Photographs of the Kanguk Formation outcrop. Upper photograph: prominent rusty yellow weathered bentonite bed. Lower photograph: Platy shales of the Kanguk Formation.

3.2 Dinocyst Abundances

Abundance of dinocysts (numbers counted on five fields of view) significantly vary throughout the Kanguk Formation (figure 4). Relatively high numbers occur throughout the late Cenomanian to early Turonian and during the late Santonian. Intervals with reduced numbers of dinocysts occur during the middle Turonian, middle Santonian and late Campanian. Beside this general pattern dinocyst numbers vary considerably between individual samples.

Figure 4: Abundance of dinocysts based on individual counts within the sampled section.

3.3 Benthic vs Pelagic Dinocyst Assemblages

Preservation of dinocysts was excellent mainly in samples from the transgressive Christopher and Kanguk formations where dinocysts are numerous and are rarely disintegrated or broken. The high preservation is likely due to: a) unconsolidation of sediment in this outcrop; and b) anoxic conditions in the case of the Kanguk Formation where organic matter is not degraded after deposition, but largely preserved. Fine grained texture of the sediments also contributes to the anoxic conditions, inhibiting oxygen from downward circulation into the porewaters of the sediment (Stow et al, 2001). In contrast, dinocysts in the deltaic Hassel Formation showed evidence of re-working. Low dinocyst numbers and poor preservation of specimens (<10 identifiable individuals) were found at 6.8 m, 8.8 m, 10.3 m, 13.9 m (17% of 21 samples from the Christopher Formation were poorly preserved) and 154.5 m, 171.8 m, 173.0 m (approximately half of the samples from the Hassel Formation were poorly preserved). All samples taken from the Kanguk Formation yielded abundant dinocysts. The Kanguk samples included a total of 5881 counted specimens, of which 91.5 % were marine palynomorphs and 8.5 % were terrestrial palynomorphs. A total of 3141 dinocyst specimens were classified (not too badly damaged or preserved) of which 43.3% were pelagic (deep water) dinocysts and 56.7 % were benthic (shallow water) dinocysts.

Dinocysts can be subdivided into two groups based on their phenology; simple forms (without many processes) generally fall in the category of dinoflagellates with peridinoid tabulation, and are found in shelf settings, lakes and benthic environments (here named benthic species). Their simple forms allow them to sink into the sediment once they form

cysts (P. Shioler, pers. comm. 2012). When the dinoflagellate emerges from the cyst, they are in a shallow zone and able to photosynthesize. The more complex forms with gonyaulacoid tabulation are associated with the photic-zone of deep water settings (here named pelagic species). When the pelagic dinoflagellate cysts the processes enable suspension in the water (P. Shioler, pers. comm., 2012). Thus, when the dinoflagellate emerges from the cyst, they are still in the photozone. Therefore, by counting the number of benthic and pelagic individuals in any particular sample, one can generate a curve that may associate with transgressive and regressive phases within the Boreal Sea (Figure 5). The changes in ratio of pelagic vs. benthic species show four distinctive segments within the Kanguk Formation. Segment 1 is characterized by high numbers of pelagic taxa covering the interval from the uppermost Cenomanian to approximately the middle Turonian. Segment 2 is a short segment of increasing benthic species and follows up section to the lower Coniacian. A return to high pelagic species abundance corresponds to the upper Santonian at segment 3, and the uppermost Santonian to Campanian is characterized by increasing benthic species at segment 4 (Figure 5).

Figure 5 (next page) Pelagic vs. benthic dinoflagellate species, terrestrial palynomorphs vs. marine dinocysts, total organic carbon content, Hydrogen Index compared to an upper Cretaceous sea level curve. Events (1 to 6) mark times of correlative changes. Note that sample intervals of the Rock Eval data do not correspond with the dinocyst sample intervals.

3.4 Marine versus Terrestrial components

The terrestrial component of the samples (spore/pollen) was minimal throughout the Kanguk Formation, with the exception of a few peaks of terrestrial influence, including a large peak found at the end of the Santonian (figure 6a). In contrast to the marine dominated Kanguk Formation, the uppermost Christopher and lower Hassel formations contained a higher count of terrestrial spore/pollen. There, dinocysts (both benthic and pelagic types) only accounted for approximately 50% of the organic micropalynoflora found in samples (figure 6b).

Figure 6a: Percent of marine vs. terrestrial palynomorphs within the Kanguk Formation.

Figure 6b: Percent of marine vs. terrestrial palynomorphs within the uppermost Christopher and lowermost Hassel formations.

3.5 Influence of volcanic activity on dinocyst assemblages

Cretaceous volcanic activity appear to have had relatively minor biotic effects at the generic level, but caused dramatic changes at the species level, forcing the extinction of larger planktonic foraminifera, the temporary disappearances of other larger species, and the rapid increase in small and thin-walled species due to eutrophication of surface waters from volcanism (Keller, 2008). The section of the upper Kanguk Formation shows two distinct peaks in the abundance of spores and pollen (Figure 5). Looking more closely at the lithology at these peaks, at 376 m, 380 m and 425.5 m, bentonites are found (figure 7). Ash falls must have negatively influenced the marine productivity signal by briefly transporting the marine

biomass with the ash to the ocean floor and possibly delivering a higher pollen count from the air. On the other hand, ash falls also provide eutrophication feeding primary productivity. The gradual increase of spores and pollen towards the position of the bentonites could be explained by a bentonite swarm starting earlier than actually measured in. Thin bentonite beds are not easily identified in these shales that are heavily altered through cryoturbation. After a final eruption the sea would return to normal and the dinoflagellate numbers would again increase (figure 7). Alternatively, the late Santonian and Campanian is also known for lower sea-levels where the influence of terrestrial sediment sources could have played a greater role.

Figure 7: Percent of marine dinocysts vs terrestrial spores and pollen in relationships to bentonite layers found in the measured section at Hoodoo Dome, Ellef Ringnes Island.

3.6 Dinocyst species and ranges

Taxonomic identification of dinocysts is challenging due to phenotypic similarities among different species that are reported in the literature. Consequently the species richness is significantly higher than what is showcased here. I selected species based on access in the literature, abundance, and range. A full taxonomic treatment of the encountered rich assemblages of this section and naming of new species was beyond the scope of this study.

The dinocyst assemblages had many long ranging species, however, there are notable radiations of new species at two time intervals; the first speciation event takes place over the Turonian / Coniacian boundary whereas the second speciation event occurs during the late Santonian. These two events are characterized by a larger number of incoming benthic species (figures 8a, b), including *Apteodinium* sp., *Laciniadinium* sp., *Chatangiella spectabilis*, *Chatangiella granulifera*, *Isabelidinium cooksoniae*, *Spinidinium echinoideum*, which occur near the Turonian / Coniacian boundary, and *Chatangiella ditissima*, *Chatangiella tanamaensis*, *Phelodinium* sp., and *Alterbidinium* sp., which occur near the Santonian / Campanian boundary, of which most also appear to be fairly short ranging species. The long ranging species tend to be pelagic species including *Heterospaeridium difficile*, *Spiniferities ramosus*, *Callaiosphaeridium asymmetricum*, and *Cometodinium* sp. (figures 8a, b). This can be explained by the fact that distal deep-water settings and their respective biota are paleoecologically less affected by sea-level change than shallow water regions.

Figure 8a (next page): Lithographic column of sampled section and dinocyst range chart.

Figure 8b: Legend for the Lithographic column in 8a.

Previously published dinocyst zonation from Cretaceous Arctic sections are limited. A dinocyst zonation chart was derived using data available in the literature (figure 9), by determining established first and last appearance datums of dinoflagellate species based on other arctic studies, but where no zonations were proposed. One western Canadian example from the Beaufort-Mackenzie region was also included. Using the newly established range chart of dinocysts within the Kanguk Formation of Ellef Ringnes Island several species can be correlated to the species found in the Kanguk Formation in other regions.

Nohr Hansen (1996) found that dinocyst assemblages from the upper Cretaceous sediments of Western Greenland are characterised by a large number of specimens of *Chatangiella*, which is also found here in large numbers (Figure 8a) and are categorized here as a benthic cyst species. Many studies acknowledge that *Chatangiella* ranges from late Cenomanian to late Maastrichtian, and therefore not useful as a biostratigraphic marker for this study. *O. octopus* appears to be restricted to the late Coniacian and is therefore an important biostratigraphic marker within the Kanguk Formation within the Northeastern section of the Sverdrup Basin (Nunez-Betelu and Hills, 1998), however this species was not recovered from the Kanguk Formation at Ellef Ringnes Island, suggesting that the species may have had a restricted paleogeographic range.

In order to build a dinocyst zonation, species with clear first and last appearance datums within the studied section were chosen. Data from other studies were then

used to compare biostratigraphic ranges. Several correlations across the study regions could be made with *Isabelidium cooksoniae*, *Spinidium echinoideum*, *Oligoshaeridium complex*, *Chatangiella ditissima*, *Chatangiella spectabilis*, *Chatangiella granulifera*, *Odontonchitina costata* *Spiniferities ramosus ramosus*, and *Heterosphaeridium difficile* (figure 9). The dominance of the benthic species *Isabelidium cooksoniae* on Axel Heiberg Island (Nunez-Betelu and Hills, 1994b) reflects the more marginal position of this locality compared to the deep water locality of Ellef Ringnes Island where the dominance of this species is reduced. *Spinidium echinoideum*, another benthic species, was found in West Greenland to begin in the middle Coniacian (Nohr-Hansen, 1996) while on Ellef Ringnes this species did not make an appearance until the late Middle Santonian when sea levels were lower.

Oligoshaeridium complex, a pelagic species, was found at Axel Heiberg (Nunez-Betelu and Hills, 1994b), ranging from early Turonian to well into the Campanian. However, Nohr-Hansen (1996) found the species appearing in the middle Coniacian, and here, it appears in the early Coniacian, with several other new species. Sea level at this point was low, and many benthic species were making first appearances correlating to an increasing dinoflagellate population (Figure 5). *Chatangiella ditissima*, a benthic species was found by McIntyre (1995) to begin in the late Turonian in the Beaufort-Mackenzie region, in the late middle Coniacian by Nunez-Betelu and Hills (1994) at Axel Heiberg, and here it was not observed until the latest Santonian. *Chatangiella spectabilis*, a benthic species, had very similar ranges across

Axel Heiberg, West Greenland and this study, ranging from the late Turonian/early Coniacian to the late Santonian. *Chatangiella granulifera*, another benthic species, also has comparable ranges from the late Turonian into the Campanian in the high Arctic and in the Beaufort-Mackenzie region. *Odontonchitina costata* is classified in this study as a pelagic species, was found to start early in the section during the late Cenomanian and ending at the early Coniacian, but had a late Turonian to late Santonian range where it was found on Axel Heiberg Island. There is a high abundance of *Odontonchitina* phenotypes in the samples from Ellef Ringnes and one cannot exclude that some of the specimens were misnamed. *Spiniferities ramosus ramosus*, a long ranging pelagic species, showed similar ranges between Ellef Ringnes and Axel Heiberg, ranging from the Cenomanian to the Campanian. Finally, *Heterospaeridium difficile*, another pelagic species, was not found until the late Turonian in the Beaufort-Mackenzie area (McIntyre, 1995), but was found on Ellef Ringnes in the late Cenomanian (figure 9).

Figure 9: Select Dinocyst specimen interpretive zones from Ellef Ringnes Island, Kanguk Formation compared to data from other North American and Greenland studies.

4 Chapter: Discussion

4.1 Dinoflagellates of the Cretaceous Boreal Sea

The Kanguk Formation of the Sverdrup Basin on Hoodoo Dome, Ellef Ringnes Island in the Canadian Arctic remains still relatively unexplored and the internal stratigraphic framework is poorly understood. The section focused on in this study covers 294 metres of mainly silty shales of these deep water deposits. The relationships between dinocyst phenology, productivity, and radiation/evolution to oceanic anoxic events and sea-level changes provide a relatively unexplored area of paleoecology in the Boreal realm. In this context, I examined mid to late Cretaceous dinocyst assemblages to add to biostratigraphic results. Paleoenvironmental interpretations are refined by establishing ratios of pelagic vs benthic species as a paleoecological indicator. Abundance of dinocysts versus spore-pollen act as a marine vs terrestrial indicator, and in turn allows for climatic interpretations in addition to detecting regressive/transgressive cycles. These dinocyst parameters are then compared to geochemical proxies such as TOC and HI values which also distinguish between marine and terrestrially dominated systems. The depositional and paleoenvironmental history of this superficially monotonous section of the Kanguk Formation needed to be studied with a multidisciplinary approach and as a result a complex record can be revealed. Pattern of evolution and radiation of dinocysts are strongly linked to this history.

4.2 Dinoflagellate Lifecycles and Paleoecology

It is generally accepted that cysts have resulted from the resting stage of a living dinoflagellate, but can also occur with environmental fluctuations such as temperature, salinity, or other stressors (Gilbert and Clark, 1982). The cyst often will bear resemblance to the motile form (Evitt, 1963), as well, the shape of the cyst wall opening (the archeopyle) is consistent within species (Evitt, 1967). Species identifications can be determined based on this parameter, when the archeopyle is visible. After the dinoflagellate has exited through the archeopyle the cyst in the sediment is left behind as part of the fossil record. Since more and more studies of modern dinoflagellate assemblages are appearing, there is a wider array of modern analogues to compare to fossil species (Head, 1996) and their encystment strategies become better understood. The extremely high abundance of dinocysts encountered in this study might be the result of significant paleoecological changes through the Cretaceous that stimulated the encystment of many dinoflagellate species. Extreme climates, sea level changes, volcanic eruptions and subsequent ash falls and CO₂ enrichment are some of these large events that dominated the Cretaceous period. In addition, frequent periods of anoxia have contributed to the high preservation of dinocysts in the sedimentary record. The anoxic conditions are evidenced by the presence of the OAE 2 at the base of the section (J. Herrle, pers. comm.) and the persistent lack of benthic foraminifera throughout the section with the exception of the upper Santonian (Pugh, 2013).

Marine dinoflagellates are most diverse in tropical regions and most numerous in neritic, temperate, waters. Cosmopolitan species are temperature tolerant, whereas temperature sensitive species are restricted to warmer water (Williams et al., 2012). The Boreal assemblage studied here is predominantly composed of such cosmopolitan species due to their tolerance to Boreal temperatures, although much warmer than compared to today's Arctic climate. Future work on the unnamed dinocysts components would possibly discover also an endemic species community associated with the Boreal Sea.

Ecological variables of dinoflagellates consist of light, temperature, salinity, nutrients, oceanic currents, water depth, upwelling, tidal influence, pollution and predation. Seasonally, abundance fluctuates; dinoflagellates multiply rapidly in the late spring and summer in mid and high latitudes, when nutrients are most abundant and the amount of light increases. Species that prefer shelf zones are more abundant than those that prefer the open ocean (Williams et al, 2012). In a study of modern northern dinoflagellates at Nunatsiavut fiords (Labrador, Canada), it was revealed that summer sea-surface temperature and salinity, sea-ice cover duration, radiation and food availability (nutrients and diatoms) play an important role in the distribution of most dinoflagellate taxa (Richerol et al, 2012). In the Cretaceous Boreal Sea, dinoflagellates productivity was supported by ice-free summers and high nutrient availability due to high humidity and/or transgressions, flushing nutrients into the system. In contrast, primary producers have short times to bloom

due to annual winter darkness in the Polar Regions. It would seem likely that dark winter conditions with ice-cover (Davies et al, 2009) would have contributed to increased encystment resulting in large numbers found in the samples studied here.

By comparing dinocyst assemblage changes, TOC and HI values and a global sea-level curve six events can be distinguished (Figure 10). Events 1 and 2 represent a sea level highstand during late Cenomanian to early Turonian time corresponding to OAE 2 and correlate to increasing pelagic dinocysts. TOC and HI values are also elevated at these points, corresponding to an increase of primary productivity.

Event 2 also matches with the highest abundance of dinocysts found in the samples studied here (Figure 10) and to a dark, medium platy, sulphur-rich shale (Table 1).

Event 3 relates to the sea-level lowstand that spans the middle Turonian to early Coniacian and is linked to a large increase in benthic dinocysts (Figure 10). A shift from deep to shallow water settings triggered a facies change to light brown, silty mudrock with sulphur (Table 1) and an assemblage response characterized by a dinocyst radiation of mainly benthic species (Figure 8a). Event 4 is marked by a brief sea-level highstand followed by a lowstand and correlates to a significant change to lower TOC and HI values that then persist through the section. Event 5 signals the early Santonian sea-level highstand and translates to a brief increase in HI values and increasing numbers of pelagic dinocysts. Event 6 correlates to the sea-level fall towards the end of the Santonian and a pronounced shift to benthic species corresponding to increased terrestrially derived organic matter and low TOC values.

Figure 10: Relative abundance of pelagic vs benthic dinocysts within the Kanguk Formation and resulting Late Cretaceous sea-level fluctuations within the Sverdrup Basin.

At this interval the lithology changes again to light sulphuric shale, the lighter colour being related to reduced amounts of organic carbon, but also possible influx of ash.

The late Santonian is the time of the second dinoflagellate radiation event as recorded in the Kanguk section (figure 8a), again composed of mainly benthic species. This assemblage change is also consistent with high abundances (figure 4)

that might have been stimulated by increased nutrients through ash falls and fluviially derived inputs through closer shorelines. These linkages demonstrate the influence of sea level on primary productivity and its preservation in the fossil record. Arthur et al (1987) suggested that sea level is the driving force for organic carbon deposition globally in sedimentary basins under different climatic and ocean circulation regimes.

Benthic-cyst (shallow water) species are viable down to only about 200 m water depth, and therefore are likely to have widely radiated during times of continental separation and formation of increasing shelf space (Fensome et al, 1996b). While marine palynomorphs dominate most of the samples throughout the Kanguk Formation, benthic dinocyst species become dominant in the late Santonian; while pelagic dinocysts decrease below 50%. The upper Hassel Formation was not sampled for dinocyst recovery in this study, but samples from near the Christopher/Hassel boundary showed a vast change in the proportions of marine versus terrestrial palynomorphs (Figure 5). These results compare well to the studies of Nunez- Betelu et al. (1994b) who reported a drastic change from a terrestrial dominated to a marine assemblage at the Hassel/Kanguk Formation boundary. They also found that marine palynomorphs dominated the lower part of the Kanguk Formation while terrestrial palynomorphs dominated the upper part in sections sampled on Ellesmere Island. No comparison was made between benthic versus pelagic dinocysts in their study. However, the broad assemblage change from pelagic to benthic dinocyst assemblages during the late Santonian in the Ellef

Ringnes section corresponds to the assemblage change from marine to terrestrial dominated palynomorphs on Ellesmere Island (Nunez- Betelu et al., 1994b). These broad subdivisions correspond well with TOC and HI values; where the pelagic assemblage corresponds with increased TOC and HI values, and the benthic assemblage correlates with decreased TOC and HI values (Figure 10).

4.3 Boreal Dinoflagellate assemblages and Large-scale Cretaceous Changes

In the Late Cretaceous, a Central Atlantic spreading system propagated northward into the Labrador Sea between Greenland and North America. Eurasia, Greenland and North America were drifting northwestward, but differential velocities led to sea-floor spreading in the Labrador Sea and continued extension between Greenland and Eurasia (Torsvik et al, 2012) opened migration pathways for marine plankton. Migration could account for the taxonomic differences between the Albian aged dinocyst assemblage of the Christopher Formation (although not studied here in detail) and the Upper Cretaceous Kanguk assemblages. The Cretaceous is also characterized by increased global volcanism resulting from the final breakup of Pangea, and faster mid-ocean ridge spreading when compared to today. These changes resulted in raising global sea levels, which pushed marine waters up onto the continents (e.g. Hay, 2011). Sea level was 100-200 meters higher than today. The Cretaceous climate was also considerably warmer, and mild climatic conditions were in part due to the fact that shallow seaways covered the continents during the Cretaceous (e.g. Friedrich et al, 2012; Torsvik et al, 2012). The late Cenomanian/early Turonian temperature maximum (Friedrich et al, 2012) falls

together with the OAE 2, now documented in the Boreal Sea straddling the base of the Kanguk Formation. Warm water from the equatorial regions was transported northward, warming the Polar Regions (Torsvik et al, 2012). Given the warmer waters, current flow, and the addition of nutrients from submerged coastlines, cosmopolitan as well as some more typical warm water dinoflagellate species were likely able to invade the Late Cretaceous Boreal Sea. Bujak and Williams (1979) noted overall high dinoflagellates species diversity for the Albian which reduces towards the Turonian only to increase again during the Santonian. My findings from Ellef Ringnes Island show an increase in species richness throughout the Kanguk Formation confirming their observations. A consistently increasing species richness during the entire Cretaceous was also reported by Keller et al. (2008) who described a sequence of extinctions followed by speciation events related to OAEs. This phenomenon can certainly be partly observed within the studied Kanguk section where a dinocyst radiation occurs after the OAE 2.

5 Chapter: Conclusions

Dinocyst biostratigraphy is an important proxy for reconstructions of marine paleoenvironments. This study addresses the Cretaceous Boreal Sea as exposed in outcrop on Ellef Ringnes Island, Canadian High Arctic, and in particular the Upper Cretaceous Kanguk Formation. The following conclusions are made:

- In the upper Cenomanian to Campanian Kanguk Formation, as sampled in outcrop on Ellef Ringnes Island, dinocysts are extremely abundant and well preserved. Abundances and species richness fluctuate throughout the section.
- High dinocyst vs pollen/spore ratios in the Kanguk Formation indicate the deep water nature of the Kanguk Formation in contrast to even proportions of marine and terrestrial palynomorph components in the prodelta sediments of the uppermost Christopher and lowermost Hassel formations.
- High sea levels during the upper Cretaceous flooded terrestrial areas resulting in increased nutrient supply stimulating the primary productivity. This increased supply of organic matter resulted in anoxic bottom water conditions and thus excellent preservation of dinocysts and elevated values of TOC. Reduced TOC values in the upper half of the Kanguk Formation could signalize reduced primary productivity, enhanced by reduced preservation

resulting from returning bottom water oxygenation that in turn is confirmed by rare benthic foraminifera.

- A remarkable positive correlation between a global sea level curve and changing ratios between benthic and pelagic dinocysts species suggests a clear influence of global sea level on the Cretaceous Boreal Sea.
- The relationships between dinocyst phenology, productivity, and radiation/evolution to oceanic anoxic events and sea-level changes provide a relatively unexplored area of dinocyst paleoecology of the Cretaceous Boreal Sea and can be used as a model that requires future testing.

Plate 1:

Dinoflagellate cysts that are generally long ranging and make their first appearance in the lower Kanguk Formation, Hoodoo Dome, Ellef Ringnes Island. 1000X Magnification. Scale bar applies to all specimens.

A] *Odontonchitina costata*; Pelagic. Sample D96 [209.5 m].

B] *Arvalidinium scheii*; Benthic. Sample E62 [381.0 m].

C] *Spiniferities ramosus ramosus*; Pelagic. Sample D51 [188.2 m].

D] *Paleohysrichophora infusorioides*; Benthic. Sample E118 [311.0 m].

E] *Heterospaeridium difficile* Pelagic. Sample D98 [234.5 m].

F] *Isabelidinium acuminatum*; Benthic. Sample E70 [262.5 m].

G] *Callaiosphaeridium assymmetricum*; Pelagic. Sample E118 [311.0 m].

Plate 2:

Dinoflagellate cysts that have their first appearance in the early or middle Kanguk Formation (including the first radiation of dinocysts at the beginning of the Coniacian), Hoodoo Dome, Ellef Ringnes Island. 1000X Magnification. Scale bar applies to all specimens.

A] *Oligospaeridium complex*; Pelagic. Sample E119 [323.0 m]

B] *Apteodinium* sp. Benthic. Sample E119 [323.0 m]

C] *Laciniadinium arcticum*. Benthic. Sample E81 [373.0 m]

D] *Odontochitina porifera*; Pelagic. Sample E118 [311.0 m]

E] *Cometodinium whitei*; Pelagic. Sample D97 [216.0 m]

F] *Chatangiella spectabilis*; Benthic. Sample E118 [311.0 m]

G] *Areoligera senonensis*; Pelagic. Sample D95 [205.0 m]

H] *Caninginopsis denticulata*; Benthic. Sample D54 [188.3 m]

Plate 3:

Dinoflagellate cysts making first appearance to include the middle to upper Kanguk Formation (the second radiation near the end of the Santonian), Hoodoo Dome, Ellef Ringnes Island. 1000X Magnification. Scale bar applies to all specimens.

- A] *Chatangiella granulifera*; Benthic. Sample E80 [367.0 m]
- B] *Chatangiella ditissima*; Benthic. Sample E102 [430.5 m]
- C] *Isabelidinium cooksoniae*; Benthic. Sample E76 [292.5 m]
- D] *Odontochitina* sp. Pelagic. Sample E61 [380.5 m]
- E] *Glapyrocysta* sp. Pelagic. Benthic. Sample E102 [430.5 m]
- F] *Alterbidinium* sp. Benthic. Sample E90 [410.5 m]
- G] *Spinidinium echinoideum*; Benthic. Sample E62 [381.0 m]
- H] *Phelodinium* sp. Benthic. Sample E84 [384.0 m]
- I] *Chatangiella bondarenkoi*; Benthic. Sample E87 [396.0 m]

A

B

C

D

E

F

G

H

I

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Appendix

Authors used for Dinocyst identifications

<i>Odontonchitina costata</i>	Alberti, 1961, pl. 6, fig. 1, 2
<i>Arvalidinium scheii</i>	Manum, 1963, pl. 1, figs. 1-4; text-fig. 1
<i>Spiniferities ramosus ramosus</i>	Davey and Williams , 1966a, p.32
<i>Paleohysrichophora infusorioides</i>	Deflandre, 1936b, pl. 9, fig. 7
<i>Heterospaeridium difficile</i>	Manum and Cookson, 1964, pl. 3, fig. 1
<i>Isabelidinium acuminatum</i>	Cookson and Eisenack, 1958, pl. 4, fig. 5
<i>Callaiosphaeridium assymmetricum</i>	Fensome et al., 1993a, fig. 1 - p.9 49.
<i>Oligospaeridium complex</i>	Davey and Williams, 1966b, pl. 7, fig. 1
<i>Laciniadinium arcticum</i>	Nohr-Hansen, 1996. pl. 4, fig. 1
<i>Odontochitina porifera</i>	Cookson, 1956, pl. 1, fig. 17
<i>Cometodinium whitei</i>	Deflandre and Courteville, 1939, pl. 3, fig. 5
<i>Chatangiella spectabilis</i>	Alberti, 1959, pl. 9, fig. 78
<i>Areoligera senonensis</i>	Lejeune-Carpentier, 1938a, text-fig. 2
<i>Caninginopsis denticulata</i>	Cookson and Eisenack, 1962b, pl. 1, fig. 16
<i>Chatangiella granulifera</i>	Manum, 1963, pl. 3, figs. 5-6
<i>Chatangiella ditissima</i>	McIntyre, 1975, pl. 1, figs. 1-2
<i>Isabelidinium cooksoniae</i>	Alberti, 1959, pl. 9, fig. 2
<i>Spinidinium echinoideum</i>	Cookson and Eisenack, 1960a, pl. 1, figs. 5-6
<i>Chatangiella bondarenkoi</i>	Lentin and Williams, 1976, p. 53