Late Cretaceous (Cenomanian to Campanian) Dinoflagellate Cyst
Assemblages and Palaeoproductivity Signals from the Kanguk
Formation, Sverdrup Basin, Nunavut, Canada

by

Gregory Paul Froude

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Abstract

The response of the polar sea to Cretaceous carbon perturbations is poorly understood and palaeotemperature data from the Arctic are limited. To help understand high latitude palaeoceanographic dynamics, sediment samples containing dinoflagellate cysts (dinocyst) assemblages were collected from a composite Cenomanian to Campanian section from the Bastion Ridge and Kanguk formations within the Sverdrup Basin at Glacier Fiord, Axel Heiberg Island, and at Slidre Fiord, Ellesmere Island. Dinocyst assemblages were compared to recent carbon isotope and benthic foraminiferal age data taken from the same lithographic section. These multiproxy correlations allowed for a more constrained placement of dinocyst biozones, palaeoenvironmental changes, planktic/benthic coupling, and indicate that local age ranges for several Late Cretaceous dinocyst taxa need regional revision within the Sverdrup Basin. At Glacier Fiord a change from a restricted marine to an open marine setting before the Cenomanian/Turonian boundary and a polar expression of the globally recognized OAE 2 is revealed through a turnover in dinocyst and acritarch assemblages, an increase in relative abundance of angiosperm and bisaccate pollen, and an increase in amounts of gelified, dark amorphous organic matter derived from microbial degraded terrestrial material. At Slidre Fiord, depositional settings transition from open marine to deltaic; recognized by an overall increasing sporomorph index trend. Taxa-specific dinocyst peaks are recognized in the Coniacian (*Chatangiella* sp.), late Santonian (*Heterosphaeridium difficile*) and middle Campanian (*Manumiella* sp.). The Coniacian *Chatangiella* acme is a correlative event across the Canadian Arctic that likely contributed to an increased organic matter supply, causing dysoxic to anoxic benthic redox conditions, which resulted in an increase in the benthic foraminifera

Trochammina. Correlations between $\delta^{13}\text{C}_{\text{org}}$, peridinioid dinoflagellate cysts occurrences and cooling global sea-surface temperatures, calculated from the tropical Atlantic, indicate an increase in palaeoproductivity during a Coniacian to Campanian cooling trend. Multiproxy correlations allow for accurate dinocyst first and last occurrences dates, which resulted in newly proposed biozonations for the Sverdrup Basin. In ascending order, these include the Cenomanian to Turonian *Surculosphaeridium longifurcatum* Zone, Coniacian to Santonian *Chatangiella ditissima* Zone and the Upper Santonian to Middle Campanian *Arvalidinium scheii* Zone. These will aid future regional pan-Arctic biostratigraphic event correlations and studies of paleobiogeographic pattern.

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Chapter 1: Introduction

1.1 Background

Over the past forty years extensive research has been centred on upper Cretaceous organic-rich black shales that are associated with Oceanic Anoxic Events (OAEs) located in low-to-mid latitude marine basins that were first recognized by Schlanger and Jenkyns (1976). One outcome of these studies was the recognition that sea-surface temperatures reached their maximum during the greenhouse conditions of the Cenomanian/Turonian boundary event, coinciding with OAE 2 (e.g., Foster et al., 2015). The geographically more restricted OAE 3, which occurred during the Coniacian-Santonian cooling trend, was observed within low latitude Atlantic and adjacent marginal basins (e.g., Wagreich, 2012). The response of polar regions to Cretaceous carbon perturbations is less understood, and palaeotemperature data from the Arctic are limited (Jenkyns et al., 2004; Herrle et al., 2015). Hence, in order to improve our understanding of these understudied palaeoceanographic dynamics in high latitudes, sediment samples were collected from the Kanguk Formation within the Sverdrup Basin at Glacier Fiord, Axel Heiberg Island and Slidre Fiord, Ellesmere Island; as part of a larger research project that addresses large-scale biostratigraphic correlations and palaeoenvironmental reconstructions of the Cretaceous Canadian Arctic (Schröder-Adams, 2014). The Kanguk Formation in the Sverdrup Basin represents a well-exposed, conformable sequence of Cenomanian to Maastrichtian bituminous deposits of dominantly claystone to siltstone. Sections at Glacier Fiord and Slidre Fiord have previously been studied for foraminiferal biostratigraphy, carbon isotope stratigraphy, whole rock geochemistry, burial rates of total organic carbon (TOC) and benthic

palaeoecology (Schröder-Adams et al., 2014 and Davies et al., 2018, respectively). This thesis will add information on the dinocyst and acritarch assemblages and their response to palaeoproductivity signals that marked palaeoenvironments of the late Cretaceous polar sea to the previously collected inventory of data. Dinocyst assemblages represent organic-walled plankton; these are known to respond to changes in water depth, temperature, light levels, oxygen levels and nutrient availability (e.g., Hoppenrath et al., 2014). Paleoclimatic conditions can also be defined using the presence of certain peridinialean dinoflagellate cyst taxa which indicate global climatic suites; an idea first concluded by determining provincialism in Campanian dinocysts (Lenin & Williams, 1980). Therefore, analysis of dinoflagellate cyst assemblages will improve our understanding of planktonic response to late Cretaceous polar environmental changes; and will also provide insight into the examination of pelagic/benthic coupling processes.

1.2 Oceanic Anoxic Events

Results from the early years of the Deep Sea Drilling Project (DSDP), during late 1960s to early 1970s, resulted in the discovery of globally correlative organic-carbon-rich black shales in sedimentary settings that varied from continental margins and shelf seas to oceanic plateaus and basins (Schlanger and Jenkyns, 1976). These discoveries led Schlanger and Jenkyns (1976) to propose that the Cretaceous went through intervals of widespread, perhaps global, poor oceanic mixing that they dubbed “Oceanic Anoxic Events” (OAEs). Originally, Schlanger and Jenkyns (1976) recognized two of these events, an Aptian-Albian event, referred to as OAE 1, and a Cenomanian/Turonian event, referred to as OAE 2. Black shale deposits of the OAE 2 were also known to correlate with a major positive carbon isotope $\delta^{13}\text{C}$ excursion. Recognition

of a third, less pronounced Cretaceous OAE during the Coniacian-Santonian (OAE 3) followed, based on evidence from sites around the low latitude Atlantic and marginal basins (Ryan & Cita, 1977; Jenkyns, 1980; Wagreich, 2012; Joo & Sageman, 2014). There has also been acknowledgement of a Jurassic OAE occurring during the early Toarcian (Jenkyns, 2003).

Schlanger and Jenkyns (1976) proposed two main causes for OAE 1 and OAE 2. The first was an increase in primary production as a result of an increased availability of suitable habitat as transgressions extended the area and volume of shallow epicontinental and marginal seas and brought nutrients into the marine basins. The second factor was an almost uniform high global temperature, which decreased oceanic circulation and increased water column stratification; resulting in a decrease in cold oxygenated bottom waters. These conditions would have created a situation where the oxygen minimum-zone would have expanded and preserved organic-rich deposits where it reached the sediment-water interface.

Recently, carbon perturbations of the Cenomanian/Turonian boundary interval have been described from Cretaceous strata within the Arctic Sverdrup Basin (Pugh et al., 2014; Lenniger et al., 2014; Herrle et al., 2015; Davies, 2016). Less pronounced positive carbon isotope signals, from the Santonian, were detected on Ellef Ringens and Ellesmere islands have been cited as possible signals for “OAE 3” within the Canadian Arctic (Pugh et al., 2014; Davies, 2016).

1.3 Application of Dinoflagellate Cysts as Palaeoenvironmental Indicators

Dinoflagellates are single-celled eukaryotic protists. Most modern dinoflagellate species are free-living planktonic organisms, living mainly in either marine or freshwater habitats, during

some stage of their life cycle. The ecological mode in modern dinoflagellates is quite diverse. About 50 % of modern dinoflagellates are photosynthetic autotrophs, while the rest are either photosynthetic symbionts or heterotrophs. Among the heterotrophic dinoflagellates there are those that ingest whole food particles (holozoic) while others absorb dissolved food material (saprophytic) (Williams et al., 2012).

About 15 % of modern dinoflagellate species produce a hypnozygotic resting cyst (Head, 1996) during the diploid phase of their lifecycle (Evitt, 1985). The cellular walls of these cysts are usually composed of the highly resistant organic material, the biopolymer dinosporin. However, some species are known to produce vegetative calcium carbonate or, in rare cases, silica cysts (Williams et. al., 2012). Dinoflagellate cysts are quite variable in size, shape and ornamentation. Most dinocysts have a diameter which ranges between 25 to 200 μm and their morphologies can be spherical, ovoidal, ellipsoidal, elongate or peridinioid. Some species are have long spines or processes (chorate cysts), some have short spines or processes (proximochorate cysts) and others lack processes or spines (proximate cysts) (Williams et. al, 2012). The cysts produced by dinoflagellates are widely preserved in the MesozoicCenozoic sedimentary record. The earliest appearance of a definitive, unquestioned dinoflagellate cyst within the fossil record is *Sahulidinium ottii* during the late Anisian (Middle Triassic) (Nicoll & Foster, 1994). Following this first occurrence, dinoflagellate cysts are particularly abundant in Mesozoic and Cenozoic marine shales, claystones and marlstones (Williams et. al, 2012).

During the haploid phase, dinoflagellate motile cells emerge from the cyst (excystment) via an opening that appears in the cyst once a particular set of plates, the archaeopyle, either fully or partially detach from the rest of the cyst. The motile cell then migrates from either the sea floor or the water column to the photic zone after excystment (Evitt, 1985). As a result, the

maximum water depth above the cyst is a limiting environmental factor for where the dinocyst can be deposited, so that the motile cell can reach the photic zone after excystment. Hence, most dinocysts are found within shallow marine to shelf deposits; with the highest diversities located in continental shelf and rise deposits (Williams et. al, 2012). Within these environments, the absolute frequency, or abundance, increases with distance from the shore; up to the point where a proportionate decline is connected to a land-derived nutrient decrease (Williams & Sarjant, 1967). Modern dinoflagellate studies have shown that oxygen availability is a major control on cyst germination; with excystment being inhibited during anoxic conditions (Anderson et al., 1987). Therefore, fossil dinocyst assemblages may preserve benthic anoxic to dysoxic oxygenation signals in shelf settings through observed reduced cyst diversities and shifts within assemblages with the onset of low oxygen conditions (Pross, 2001; Pross & Brinkhuis, 2005).

1.4 Dinoflagellate Cysts as Biostratigraphic Markers

The rate of dinoflagellate cyst evolution, as reflected in the fossil record, was rapid from the Triassic to early Pliocene. Therefore, it is possible to correlate precise regional biostratigraphic zones which are comparable to those derived from other fossil taxa (Sarjant, 1974). For example, within the Canadian Arctic, Pocock (1976) established ten dinocyst biozones from the Tithonian to Albian based on mostly subsurface sections. These zonations were compared to the Arctic Canadian ammonite-pelecypod zonation of Jeletzky (1971) as well as the standard European ammonite succession (Williams & Bujak, 1985).

Globally, dinocyst diversity was variable throughout the Mesozoic, but remained high within the Late Cretaceous. A peak of about 750 species in the Albian gradually decreased to

about 600 species in the Coniacian. Following this decrease, dinocyst diversity then increased until reaching a climax of about 800 species in the Maastrichtian (MacRae et al., 1996b; Williams et al., 2012). These diversity fluctuations roughly correspond to the global long-term relative sea-level fluctuations, that characterize the Late Cretaceous (Haq et al., 1987; MacRae et al., 1996b; Williams et al., 2012). During phases of high diversity, dinocyst assemblages are widely distributed across different lithologies (Williams & Bujak, 1985). Given the cosmopolitan distribution of many dinocyst taxa, a generalized worldwide Cretaceous dinocyst biozonation with nine range zones and five subzones was erected by Williams (1977) in an attempt to create a globally useful stratigraphic tool. Dinocysts biostratigraphic changes in: 1) assemblage composition, 2) diversity and 3) abundance signals within assemblages can also be applied to establish changes in local transgressive-regressive phases and global sequence stratigraphy (Pross & Brinkhuis, 2005).

Within the Arctic realm, but outside of the Sverdrup Basin (see chapter 2.3), dinocyst biozones were established for western and eastern Greenland (Nøhr-Hansen, 1993, 1996, 2012). The western Greenland dinocyst biozonation schemes of Nøhr-Hansen (1993, 1996) are temporally separated into two main age ranges. The first group of biozones range from the Aptian to the early Cenomanian and consists of three biozones, subdivided into nine subzones. The second group of biozones ranges from the early Coniacian to the late Campanian, leaving a late Cenomanian to Turonian gap; and consist of four palynological biozones. The Coniacian to early Santonian biozone within this scheme is unique in that it is defined by a dinocyst assemblage rather than single species. Another unique aspect of this biozone scheme is that due to the lack of dinocysts, the early to middle Campanian biozone is defined by a terrestrial palynomorph as opposed to a dinoflagellate cyst species (Nøhr-Hansen, 1996). For eastern

Greenland, Nøhr-Hansen (2012) published a limited dinocyst biozonation scheme, which consists of two middle Albian to early Cenomanian biozones with one subzone; as well as a single Turonian biozone defined by an acme of the dinocysts *Heterosphaeridium difficile*.

Establishment of dinoflagellate biozonation schemes for the northern Atlantic was mostly conducted during the 1960's to 1970's. Williams (1975) defined 11 biozones for offshore eastern Canada which range from the Berriasian to the Maastrichtian. Clarke and Verdier (1967) determined two biozonation schemes for the north Atlantic offshore England. Their biozonation ranges from the early Cenomanian to early Coniacian, with three biozones and three subzones. This is followed by a Coniacian gap and two middle Santonian to late Campanian biozones and subzones.

1.5 Research Objectives and Significance

Early studies of the palynology of the Kanguk Formation dealt mostly with identification of marine and terrestrial palynomorph species found within the formation (Felix and Burbridge 1973, 1976; Núñez-Betelu and Hills 1992, 1992b). Later investigations provided marine to terrestrial input ratios for the Kanguk Formation at Remus Creek, Ellesmere Island (Núñez-Betelu and Hills 1992, 1992b; Núñez-Betelu 1994). Núñez-Betelu (1994) addressed Glacier Fiord, Axel Heiberg Island and Mount Bridgeman, Ellesmere Island and established marine and terrestrial palynomorph biostratigraphic age ranges, long ranging biostratigraphic zonations (biozones 1-4), and marine to terrestrial input ratio changes. Most subsequent Kanguk Formation palynological data published after Núñez-Betelu (1994) simply list dinocysts collected at specific horizons for the purposes of: 1) age-constraining vertebrate material (Hills et al., 1999; Núñez-

Betelu et al., 2005; Vavrek et al., 2014); 2) describing the assemblage of dinocysts with which a newly described dinocyst species is associated (Núñez-Betelu & Hills, 1998); and 3) the identification of the Cenomanian/Turonian boundary interval and OAE 2 (Lenniger et al., 2014). The present study is based on the entire Kanguk Formation as exposed at Slidre Fiord (Ellesmere Island) supplemented by a short section exposed at Glacier Fiord (Axel Heiberg Island), where the OAE 2 is clearly identified (Herrle et al., 2015). From this composite section, of the Cenomanian to Campanian interval in the Sverdrup Basin, this study attempts to answer the following questions:

- 1) How did dinocyst assemblages change throughout the Cenomanian to Campanian polar sea?
- 2) What information do dinocysts add to our palaeoecological understanding of the Arctic Cretaceous photic zone?
- 3) What do dinocyst and acritarch assemblage changes add to the palaeoenvironmental interpretation of the Cretaceous Sverdrup Basin in respect to sea-level history, probable climatic changes, as well as associated carbon burial histories?
- 4) What do dinocyst assemblages add to our understanding and recognition of OAEs in the polar sea?
- 5) Can newly defined biostratigraphic zonations for the Arctic Late Cretaceous be defined based on dinoflagellate cysts occurrences?
- 6) Can these new dinocyst biozones refine future correlations to the eastern Atlantic and other Arctic basins such as the Beaufort-Mackenzie Basin?
- 7) Can previously established dinocyst biostratigraphic ranges for the upper Cretaceous Sverdrup Basin be revised?

- 8) Can we recognize correlations between dinocyst acmes and changes in benthic foraminiferal assemblages to investigate planktonic/benthic coupling?

Chapter 2: Geological Setting of Study Region

2.1 Sverdrup Basin

Figure 1a, b: a) Overview map of Arctic Canada with rectangle showing the general study b) region within the Queen Elizabeth Islands. Stars indicate the study localities at Glacier Fiord, Axel Heiberg Island and Slidre Fiord, Ellesmere Island. Modified from Schröder-Adams et al., (2014).

Sediment samples were collected from the Kanguk Formation of the Sverdrup Basin at Slidre Fiord, Ellesmere Island and Glacier Fiord, Axel Heiberg Island (Fig. 1). The Sverdrup Basin is an approximately east-west-trending, pericratonic, extensional, sedimentary basin which underlies the Queen Elizabeth Islands and inter-island channels of the Canadian Arctic Archipelago (Stephenson et al., 1987, 1992). It covers a, roughly triangular, 300,000 km² basin which has an approximately 13-kilometre sedimentary record (Embry & Beauchamp, 2008). It originated as a north-south rifting basin on the pre-existing Siluro-Devonian Ellesmerian Orogenic Belt, as older thrust faults reactivated within the Franklinian Basement (Balkwill, 1978; Harrison, 1995; Embry & Beauchamp, 2008). The sediments within the basin record a depositional and tectonic history that spans the interval from the Early Carboniferous (Viséan) to the Eocene which was subdivided into eight phases by Embry and Beauchamp (2008). This study encompasses the latest part of phase 6 and most of phase 7, together spanning the Cenomanian to Campanian interval. Within the Sverdrup Basin, the Early Cretaceous to earliest Late Cretaceous (Phase 6) was an interval of tectonic uplift followed by subsidence due to extensional normal faulting; during this time the Deer Bay, Isachsen and Christopher formations were deposited (Fig. 2). The overlying Hassel Formation is the result of renewed uplift, and in turn is regionally overlain by the volcanics of the Strand Fiord Formation that interfingers with the Bastion Ridge Formation (Fig. 2; Embry & Beauchamp, 2008). Following this interval of increased tectonic activity, a major transgression covered the Sverdrup Basin (Phase 7) and led to the deposition of deeper fine-grained marine sediment of the Kanguk Formation, which is characterized by frequent bentonites reflecting to the upper Cretaceous Arctic volcanic history.

Towards the end of Kanguk Formation deposition, shallow marine and deltaic sands prograded into the basin, resulting in the overlying Expedition Formation (Embry & Beauchamp, 2008).

2.2 Stratigraphic Framework

Figure 2: Lower to Upper Cretaceous lithostratigraphic units for the Sverdrup Basin. 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. Lithostratigraphic sections examined in this study at Glacier Fiord, Axel Heiberg Island and Slidre Fiord, Ellesmere Island are highlighted in yellow.

The Kanguk Formation overlies the Hassel Formation in most parts of the Sverdrup Basin, with the exception of Axel Heiberg Island where it overlies either the Strand Fiord Formation or the Bastion Ridge Formation (Fig. 2), which interfingers with the Strand Fiord Formation. The Strand Fiord Formation, which consist of mafic volcanics and pyroclastics, is part of the High Arctic Large Igneous Province (HALIP) (Embry & Osadetz, 1988; Embry & Beauchamp, 2008). At Slidre Fiord, the Kanguk Formation disconformably overlies the Hassel Formation (Davies et al., 2018). Throughout the Sverdrup Basin, the Hassel Formation has been described as uppermost Albian to lower Cenomanian shoreface, deltaic and shallow-shelf sand deposits with palaeosols at the very top of the formation (Núñez-Betelu, 1994; Embry & Beauchamp, 2008; Schröder-Adams et al., 2014). The Kanguk Formation is a Cenomanian to Maastrichtian marine dominated deposit with diachronous basal and top boundaries (Fig. 2; Davies et al., 2018). This formation consists of dark bituminous shale and mudrock with interbedded siltstone to coarse sandstone and bentonites throughout the Sverdrup Basin and the southern Canadian Arctic Archipelago (Núñez-Betelu 1994; Embry & Beauchamp, 2008; Schröder-Adams et al., 2014). The type locality was first described based on material from the Kanguk Peninsula of Axel Heiberg Island, along the shore of Strand Fiord (Souther, 1963).

At both, the Slidre Fiord and Glacier Fiord sections, the Kanguk Formation is disconformably overlain by the uppermost Campanian to lower Paleocene Expedition Formation (Fig. 2) of the Eureka Sound Group (Schröder-Adams et al., 2014; Davies et al., 2018). In the Expedition Formation, sandstones again reflect a deltaic and shallow to marine depositional setting (Núñez-Betelu, 1994; Embry & Beauchamp, 2008). Choi (1983) described this unit at

Axel Heiberg and Ellesmere islands as white to light grey, medium to coarse-grained, arkosic to quartzose, cross-bedded sandstone which is separated by tan sandstone to mudstone units.

2.3 Biostratigraphic Framework of the Kanguk Formation

Biostratigraphic analyses of the Cenomanian/Turonian to Campanian/Maastrichtian Kanguk Formation is based on various microfossils groups, including dinoflagellate cysts, pollen, spores (Núñez-Betelu, 1994), diatoms (Tapia & Hardwood, 2002), foraminifera (Wall, 1983; Schröder-Adams et al., 2014), chrysophyte statocysts (McCarthy et al., 2011) and radiolarians (Pugh et al., 2014). Macrofossil analysis based on both invertebrate (Jeletzky, 1971; Jeletzky pers. com. in Balkwill & Hopkins, 1976; Jeletzky pers. com. in Wall, 1983; Tapia & Hardwood, 2002; Schröder-Adams et al., 2014) and vertebrate material (Wilson, 1978; Hills et al., 1999; Núñez-Betelu et al., 2005; Vavrek et al., 2013) also confirm this age range. The following summary is based on previous palynological, foraminiferal, radiolarian, ammonite and bivalve assemblages, as they have the most relevance to this study.

Palynomorphs

The first palynological analysis of Kanguk Formation sediments was performed on grayish black shale that was collected on May 2, 1900; during the second Norwegian “Fram” Expedition (Manum, 1963; Manum & Cookson, 1964). Although there is no reliable geographic and stratigraphic reference point for this sample, the holotypes of many common dinocyst species published in Manum (1963) and Manum and Cookson (1964) are from this material which was placed, at the time, in the Hassel Formation. Given the high dinocyst diversity and unique assemblages described by Manum (1963) and Manum and Cookson (1964), Felix and

Burbridge (1976) later moved the provenance of this sample within the Kanguk Formation and rather than Hassel Formation.

Ioannides (1986) published marine palynomorph assemblages sampled from the Kanguk Formation on Bylot Island, from both the South Coast and the “Twosnout Creek” sections. He provided for the Kanguk Formation the first terrestrial versus marine palynomorph analysis and developed a dinocyst biostratigraphic scheme.

The first detailed biostratigraphic marine palynomorph work for the Kanguk Formation in the Sverdrup Basin was derived from Remus Creek, Ellesmere Island (Núñez-Betelu and Hills 1992a; Núñez-Betelu and Hills 1992b; Núñez-Betelu et al., 1992). Due to limited outcrop exposure, samples were taken from only a 39 m section of the Kanguk Formation. These samples yielded 103 taxa of well-preserved dinocysts and acritarchs, which comprised 51% of the palynomorphs assemblage, thereby, indicating a marine environment. The stratigraphic occurrence of 36 selected marine palynomorph taxa (Núñez-Betelu and Hills 1992a) and 36 selected terrestrial palynomorph taxa (Núñez-Betelu and Hills 1992b) were provided. Based on these studies, the Kanguk Formation was informally subdivided into a lower marine-dominated member and an upper terrestrial-dominated member. It was also noted that the Kanguk Formation has taxa that were regarded as reworked from the underlying Hassel Formation (Núñez-Betelu et al., 1992).

Núñez-Betelu (1994) presented a summary of palynological, sedimentological, and Rock-Eval data for the Hassel and Kanguk formations and Eureka Sound Group as at Glacier Fiord, Axel Heiberg Island and Mount Bridgeman, Ellesmere Island. From the Kanguk Formation he listed 428 taxa, 226 of which were marine and 202 were terrestrial. Among the marine palynomorph species, 147 were known dinoflagellate cysts with and 13 taxa of debated dinocysts

or acritarch affinity. The remaining 66 taxa were known acritarchs. For the Glacier Fiord and Mount Bridgeman sections, Núñez-Betelu (1994) contributed: 1) detailed plots of marine and terrestrial palynomorph biostratigraphic ranges; 2) a long-ranging, informal biostratigraphic zonation (biozones 1-4); and 3) marine to terrestrial input ratios. Addressing the Mount Bridgeman section of the Fosheim Peninsula, Ellesmere Island, Núñez-Betelu et. al (1994) illustrated the range charts of 67 marine palynomorphs and 82 terrestrial palynomorphs, which span the interval from the Hassel and Kanguk formations to the base of the Expedition Formation. These palynological assemblages indicate the presence of major disconformities between the Hassel and Kanguk formations and between the Kanguk and Expedition formations.

MacRae (1996) developed a biozonation of the Albian-Cenomanian Bastion Ridge Formation of the Glacier Fiord section on Axel Heiberg Island as studied here. His four biozones are defined as follows: 1) biozone 1 is based on the presence of a diverse assemblage of marine dinocysts; 2) biozones 2-4 are characterized by the dominance of euryhaline taxa, of which biozone 2 is dominated by *Nyktericysta davisii*, biozone 3 by *Nyktericysta tripenta*, and biozone 4 by the first occurrence of *Limbicysta octopediformes*.

Andrews (2012) examined palynomorphs collected from the Kanguk Formation, Hoodoo Dome locality, Ellef Ringens Island; representing a basin-centre locality. In her study, she determined the ratios of dinocysts with gonyaulacoid to peridinioid tabulation, the marine to terrestrial palynomorph percentage, and stratigraphic ranges for selected dinocyst taxa. It was concluded that the lower 200 m of the Kanguk Formation was dominated by gonyaulacoid dinocysts with marine palynomorphs making up approximately between 85 to 99 % of the assemblages examined. The upper approximately 130 m were dominated by peridinioid dinocysts, and marine palynomorphs making up from about 80 to 95 % of the assemblages. One

notable terrestrial signal was located at 375.5 m above the base of the section where the marine palynomorph percentage only reached slightly above 60 %. This was attributed to a decrease in marine productivity due to volcanic activity, an interpretation supported by the presence of bentonite deposit. The appearance of two distinct peridinioid dinocyst assemblages was identified as speciation events 1 and 2 (Andrews, 2012). The appearance of the first dinocyst group occurred at the Turonian/ Coniacian boundary, and the second speciation event occurred during the late Santonian. These two distinct assemblages coexisted with a long-ranging assemblage of cosmopolitan dinocysts found throughout the majority of the section. Andrews (2012) also compared the peridinioid-goyaulacoid ratio curve to a global sea-level curve (Kominz et al., 2008) and noted a positive correlation between global highstands and increased amounts of goyaulacoid dinocysts. This correlation, along with TOC and Hydrogen Index (HI) values (see below), was then used as evidence to interpret a series of six palaeoenvironmental events within the Kanguk Formation.

Foraminifera

Wall (1983) established 11 informal Jurassic to Cretaceous microfaunal zones for the Sverdrup Basin based mostly on benthic foraminifera, with additional data from diatoms and radiolarians. This microfaunal zonation was also compared to ammonite and bivalve occurrences (Jeletzky, 1971; Jeletzky in Wall 1983). Within the Kanguk Formation, Wall (1983) established two foraminiferal zones; the Turonian to early Campanian *Dorothia smokyensis* Zone and the late Campanian *Verneuilinoides bearpawensis* Zone. These zones were based on material collected from four drill sites and two outcrops on the Fosheim Peninsula, Ellesmere Island, with additional data coming from May Point, Axel Heiberg Island. The age of the *Dorothia smokyensis* Assemblage was based on comparisons to similar foraminiferal assemblages from

northern Alaska and western Canada. *Uvigerinammina spiritensis* was used as an index fossil for the lower Turonian at the base of the Kanguk Formation, which indirectly correlates to the presence of ammonites of the same age found within the lowest section of the Kanguk Formation as studied on Amund Ringnes Island by Jeletzky (Jeletzky pers. com. in Wall, 1983). The index foraminifera taxa *Pseudoclavulina* sp. was used by Wall (1983) as a marker for late Turonian. Wall (1983) also noted a transition from the deeper-water *Dorothia smokyensis* Assemblage to the shallower *Verneuilinoides bearpawensis* Assemblage.

The Kanguk foraminiferal assemblages of Wall (1983) were redefined by Schröder-Adams et al., (2014), with the description of three foraminiferal zones based on material from the Kanguk Formation, Glacier Fiord, Axel Heiberg Island. At the base of the Kanguk Formation is the latest Cenomanian to earliest Turonian *Trochammina rutherfordi* Zone; which occupies the upper part of the OAE 2 interval (Herrle et al., 2015). The genus *Trochammina* has a tolerance for low-oxygen benthic conditions and high organic-matter input (e.g., Gooday et al., 2000). The Turonian to late Santonian portion of the section is placed within the *Dorothia smokyensis*-*Evolutinella boundaryensis* Zone. The latest Santonian to early Campanian *Glaphyrammina spirocompressa* Zone is at the top of the measured section. Assemblages are characterized by foraminifera with minute tests, a result of from dysoxic conditions. Towards the top of the section, the species richness of benthic forms increases.

Foraminiferal assemblages of the Kanguk Formation at Slide Fiord (the section studied here) and Sawtooth Range, Ellesmere Island, a section positioned further to the eastern margin of the Sverdrup Basin, were studied by Davies et al. (2018). It was determined that two benthic foraminiferal zones, the Turonian to late Santonian *Evolutinella boundaryensis* Zone and the late Santonian to Campanian *Verneuilinoides bearpawensis* - *Glaphyrammina spirocompressa* Zone

could be used to correlate between different localities both on Ellesmere Island and within the Sverdrup Basin. The *Trochammina rutherfordi* Zone was not described from the Slidre Fiord section due to a position of the basal Kanguk boundary above the OAE 2 interval (Davies et al., 2018). Four foraminiferal assemblages, labelled M-1 to M-4 were recognized from Sawtooth Range, where foraminifera were abundantly preserved. This allowed morphogroup analysis in support of palaeoenvironmental interpretations. The faunal turnovers were associated with sequence stratigraphic boundaries.

Radiolarians

Radiolarians are understudied in Cretaceous sediments of the Sverdrup Basin. Wall (1979; 1983) documented that the radiolarian taxa *Spongodiscus* cf. *multus* and *Dictyomitra* sp. were unaltered and preserved alongside the Turonian to lower Campanian *Dorothia smokyensis* Assemblage of the Kanguk Formation during his foraminiferal assemblage study of the Cretaceous rocks of eastern Axel Heiberg Island and the Fosheim Peninsula of west-central Ellesmere Island. Recently, Pugh et al. (2014) made a first attempt to produce a radiolarian range chart for the lower member of the Kanguk Formation within the central portion of the Sverdrup Basin, at Hoodoo Dome, Ellef Ringnes Island. Radiolarians are abundant within the Kanguk Formation: they documented 12 spumellarian genera and nine nassellarian genera and proposed two zones.

Invertebrates

Several mollusc index fossils were described from the Kanguk Formation from multiple islands within the Canadian Arctic Archipelago (Jeletzky, 1971; Jeletzky in Balkwill & Hopkins 1976; Jeletzky in Wall, 1983; Tapia & Hardwood, 2002). In the lower Turonian, the ammonites

Scaphites delicatulus, *Watinoceras* sp. and the bivalve *Mytiloides labiatus* were collected 45 m above the base of the Kanguk Formation of western Amund Ringnes Island (Balkwill and Hopkins 1976; Tapia & Hardwood, 2002). Early Santonian ammonites were found from material without stratigraphic reference at Slidre Fiord, Ellesmere Island (Wall 1893). Jeletzky (1971) noted that the Coniacian to mid-Santonian ammonites *Scaphites depressus*, *Clioscapites* aff. *montanensis*, and bivalves *Inoceramus couthardi* as being present in the Kanguk Formation (Jeletzky, 1971; Wall 1983). The middle Santonian to earliest Campanian bivalve *Inoceramus* cf. *lobatus* and similar-aged ammonites were collected 15 m above the base of the Kanguk Formation of Ellef Ringes Island (Jeletzky, 1971; Wall 1983). Núñez-Betelu (1994) stated that no marine invertebrate macrofossils were recovered from the Hassel and Bastion Ridge formations or from the Eureka Sound Group. Therefore, marine macrofossils were exclusively restricted to the Kanguk Formation within the sections studied by Núñez-Betelu (1994) at Axel Heiberg and Ellesmere Islands. Hills and Núñez-Betelu (1994) collected three specimens of the late Coniacian ammonite *Scaphites depressus* from a sideritic bed 193.5 m above the base of the Kanguk Formation on a tributary at the head of Glacier Fiord, Axel Heiberg Island. Other observations on the western side of Alex Heiberg Island included an inoceramid-rich interval within the upper Kanguk, and a single lobster claw, along with some small unidentified bivalves and gastropods. The Remus Creek section, Ellesmere Island, yielded large decimetre- to metre-scale inoceramids, identified as *Sphenoceras* aff. *cardissoides* (Núñez-Betelu, 1994).

Schröder-Adams et al. (2014) collected several molluscs from the Kanguk Formation of Glacier Fiord, Axel Heiberg Island. The two latest Turonian age ammonite species *Scaphites nigricollensis* and *Scaphites corvensis* were collected from scree about 130 m above the boundary to the underlying Bastion Ridge Formation. The good preservation of the specimens

pointed towards a position close to its original stratigraphic level. The late Santonian to lower Campanian bivalve *Sphenoceras patootensis* was collected from both scree and outcrop between 660–682 m above base of section. This pan-Arctic marker for the Santonian-Campanian boundary interval was also collected from both Ellef Ringnes Island and Slidre Fiord (Pugh 2014; Davies et al., 2018, respectively).

2.4 Chemostratigraphic Frameworks of the Kanguk Formation

Pugh et al. (2014) conducted Rock-Eval pyrolysis on 65 samples from the upper Christopher, Hassel and lower Kanguk formations from Hoodoo Dome, Ellef Ringnes Island. The results for the Kanguk Formation samples suggest that there were two distinct segments based on kerogen sources. The basal 100 m, was marked by increased TOC content dominated by type II kerogen, which is marine derived organic matter. This marine dominated segment mainly spanned the Cenomanian/Turonian interval. The upper segment, the overlying approximately 110 m, was dominated by type III kerogen, terrestrially derived organic matter, and reduced TOC values. The terrestrial-dominated segment spanned the Coniacian to Santonian interval. A positive carbon-isotope excursion was identified in the basal Kanguk Formation placing the Cenomanian/Turonian boundary near the top of the OAE 2. Within the Coniacian of the Kanguk Formation, the interval from 360 m to 400 m, was tentatively interpreted as OAE 3 due to the presence of finely laminated black shales and a switch to increasingly positive carbon-isotope values (Pugh et al., 2014).

Lenniger et al. (2014) performed a chemostratigraphic analysis of a Cenomanian/Turonian boundary interval at May Point, Axel Heiberg Island, using Rock Eval

Pyrolysis proxies including TOC (wt%) and Hydrogen Index (HI), carbon isotope data ($\delta^{13}\text{C}_{\text{org}}$); carbon sulphur/iron systematics and other palaeoredox proxies to determine the position of the OAE 2 at that locality. Herrle et al. (2015) published a carbon-isotope record of the Barremian to Coniacian record at Glacier Fiord, Axel Heiberg Island. The Cenomanian/Turonian boundary was indicated for the top of the finely laminated organic-rich grey ‘paper’ shale of the lowermost Kanguk Formation. Supporting evidence for the OAE 2 at this position included a positive excursion of $>2\text{‰}$ in the $\delta^{13}\text{C}_{\text{org}}$ stratigraphy, co-occurring with the *Trochammina rutherfordi* Zone of Schröder-Adams et al. (2014), and an approximately 20 m interval of TOC values of up to 10 %. Lenniger et al. (2014) and Herrle et al. (2015) both compared the polar carbon isotope records with the reference section of lower latitudes. Davies et al. (2018) conducted $\delta^{13}\text{C}_{\text{org}}$ and TOC stratigraphy for the Kanguk Formation at both Slidre Fiord and Sawtooth Range, Ellesmere Island. These chemostratigraphic analyses revealed two positive isotopic excursions that are consistent with the late Turonian event and the Santonian-Campanian boundary event of Jarvis et al. (2006) and the global transgressive-regressive cycles of Gradstein et al. (2012). Their record of Slidre Fiord is directly comparable to data presented here since both studies share the same section and sample intervals. Davies (2016) noted that elements such as Al, Fe, S, Ca and V increase in concentrations within the upper member of the Kanguk Formation indicating increased proximity to the sediment source.

Chapter 3: Materials and Methods

3.1 Collection and Processing of Material

Samples were collected during the field seasons of 2011 and 2014 by Dr. C.Schröder-Adams, Dr. Jens Herrle, Mr. Alex Quesnel and Mr. Adam T. Pugh. The sections sampled were located at Glacier Fiord, Axel Heiberg Island, and Slidre Fiord, Ellesmere Island, Nunavut. A total of 98 samples were collected; 80 at Slidre Fiord and 18 at Glacier Fiord. These samples were then processed, stained and mounted for palynological analysis by Global Geolab LTD, Medicine Hat, Alberta, Canada, using the following accepted standard techniques.

Acid Digestion

Identification and study of palynomorphs require extraction of fossils from sediment. To facilitate this, approximately 25-55 grams of each the samples were placed in a 250 ml polypropylene beaker. The specific weight of each sample was recorded, and *Lycopodium* tablets added. In order to remove any carbonates within the sediment, as well as the added *Lycopodium* tablets, the samples were treated in a 10% hydrochloric acid (HCl) solution for an extended period of time until complete carbonate dissolution. In an attempt not to dilute the acid, any violent reactions observed were dampened with an atomized spray of distilled water from a spray bottle. The spent HCl was decanted, then the samples were allowed to settle, washed with distilled water and decanted three times before a hydrofluoric acid (HF) treatment. This removed calcium ions and reduced precipitation of fluorite crystals which can obstruct palynomorphs during transmitted light microscopy. The samples are then treated in a 70% hydrofluoric acid (HF) solution. The samples in HF solutions were then oscillated for up to four hours until

complete silicate dissolution. Any violent reactions were dampened using the method above. The samples, still in HF solution, were poured into a 50 ml Polypropylene test tube and centrifuged for five minutes at 2000 RPM. The top approximately 75 % of the spent HF was carefully decanted. Distilled water was added while vortexing and centrifuged for two minutes. This process was repeated until a neutral pH was obtained. This washing and centrifuging was repeated until the fine caustic material was removed.

Heavy Liquid Separation

To allow for a better heavy liquid separation, a few drops of concentrated HCl and water was added while the samples were being vortexed, then the samples were centrifuged for four minutes. Approximately 25 ml of ZnBr_2 , which has a -2.0 specific Gravity, was added and vortexed thoroughly. Each test tube was placed in an ultrasonic bath for approximately 10 seconds. In order to allow for better separation, the samples were allowed to sit for 10 minutes before being centrifuged for 15 minutes at 2000 RPM. The organic matter floating at the top of the samples was poured off into another 50 ml tube, washed and centrifuged for two minutes at 2000 RPM; this procedure was repeated three times. Each of the remaining residues was transferred to a 20 ml glass tube. A small smear of the residue was examined to determine the amount of oxidation required in the next step.

Oxidation

Inside each 20 ml glass tube, approximately 3 ml of Schultz's solution was placed on the residue and vortexed. Each tube was 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 was sufficient. A 10% solution of NH_4OH was added

to each tube, which were then placed in hot water bath for two minutes. Each sample was then centrifuged and washed three times. The residues were examined to determine if the desired level of oxidation had been achieved.

Slide Preparation

After oxidation and washing, each sample is then sieved with a 30 and 10 micrometre sieve. This removes insoluble clay minerals and fine-grained organic particles. Each of the sieved fractions were pipetted onto a microscope slide and mixed with one drop of Safranin O stain and one drop of polyvinyl alcohol using a glass stirring rod. After the polyvinyl alcohol residue had dried, one drop of clear casting resin was added, the cover slip was turned and sealed. Permanent fixing occurred in approximately one hour.

3.2 Transmitted Light Microscopy and Digital Photography

In this study, standard palynology techniques were used to identify and count dinoflagellate cysts, acritarchs and terrestrial palynomorphs. Whereas dinoflagellate cysts and acritarch were identified to species or genus level, terrestrial palynomorphs are separated into bisaccates, spores and pollen. Slides containing all these palynomorph types extracted from the Kanguk Formation were transversed and examined using a Leica DM 2500 microscope at 200x magnification. Upon finding marine palynomorph fossil taxa, specimen identification and preservation were more carefully examined at 400x magnification. Identification to species level was also aided by photographing specimens using a Leica DFC 425 digital camera with Leica Application Suite version 3.6 software and then additional digital magnification was provided by cropping photographs using Adobe Photoshop CC 2018. Photographs of taxa with either

biostratigraphic or palaeoenvironmental value were cropped and contrast was enhanced using Adobe Photoshop before being figured in plates. In plate captions, the taxon name is followed by the slide number. The magnification of all illustrated specimens is 400x.

3.3 Palaeontological Data Analysis

A minimum of 300 marine palynomorphs, when available, was counted per slide. Any terrestrial palynomorphs encountered were also recorded. The overall composition of the assemblage was analyzed through the relative percentage abundance of terrestrial and marine palynomorphs. This was calculated through the sporomorph/dinocyst index $I = s / (d + s)$; with s being the number of terrestrial palynomorphs and d being the number of marine palynomorphs. This determined the relative contribution of terrigenous organic material to the marine depositional environment (Núñez-Betelu, 1992a, b; Versteegh, 1994; Pross, 2001).

Actuopalaeontological studies of modern dinocyst taxa that biostratigraphically extend into the Quaternary have illustrated that palaeoproductivity variation can be detected through calculating the ratio of heterotrophic peridinioid (P) cysts to autotrophic gonyaulacoid (G) cysts (Powell et al., 1992). The relative abundance of peridinioid dinocysts was calculated as # peridinioid dinocysts/ total dinocysts counted per slide. This gave a relative abundance percentage that expressed the dominance of peridinioids randomly encountered on each slide. This percentage was then calculated to a decimal. For example, if 86% of the dinocysts randomly encountered on the slide were peridinioids, then in the figure it would be expressed as 0.86. In times of abundant nutrients resulting in siliceous algae blooms, heterotrophic peridinioids thrive. Even though it is known that not all pre-Quaternary peridinioids are heterotrophs (Dale &

Fjellsa, 1994), this technique has been used to interpret approximate palaeoproductivity signals dating as far back as the Palaeogene (Sluijs et al., 2005; Pross & Brinkhuis, 2005) and even Aptian (Sánchez-Pellicer, 2017). Therefore, the P-cyst: G-cyst ratio is also calculated for this study in order to determine approximate variation of palaeoproductivity during Kanguk deposition. Peridinioid (P) relative abundance was also plotted against $\delta^{13}\text{C}_{\text{org}}$ (Davies et al., 2018) in order to determine possible correlations between carbon perturbations and phases of palaeoproductivity increases. Relative abundance of selected dinocyst and acritarch species with palaeoecological interpretative value (i.e., Sluijs et al., 2006) are plotted adjacent to lithostratigraphy, in order to: 1) establish possible palaeoproductivity signals with respect to sea-level change; and 2) determine if signals for the OAE 2 and OAE 3 can be detected within the palaeoproductivity profile of these sections. In addition, palaeoproductivity records of Slidre Fiord are compared to a low latitude palaeotemperature TEX₈₆ curve, a record missing for the polar region, to determine possible relationships between climate phases, nutrient input and dinocyst acme responses.

Chapter 4: Results

4.1 Lithostratigraphy

Glacier Fiord

An approximately 75 m thick section covering the Cenomanian/Turonian boundary interval (Schröder-Adams et al., 2014) was studied at Glacier Fiord. The upper Bastion Ridge Formation, extending, from 85 m to 110 m, studied here, consists of light grey siltstones with several concretion beds which can be found at 105 m and 110 m. The lowermost Kanguk Formation consists of alternating dark grey ‘paper’ shale and grey shale with concretion beds at 120 m and 133 m. Four bentonites are observed in the interval ranging from 129 m to 149 m.

Glacier Fiord

Figure 3: Stratigraphic section of the upper Bastion Ridge Formation and lower Kanguk Formation at the Glacier Fiord locality that involved in the present palynological studied. Stage boundary after Herrle et al. (2015). The black and blue sample numbers were collected from the 2014 and 2011 field seasons, respectively.

Slidre Fiord

The lithology of the Slidre Fiord section (Fig. 4) can be summarized as consolidated to unconsolidated bioturbated quartz sand of the Hassel Formation (not measured for this study) overlain predominately by shales and siltstones of the Kanguk Formation (Davies et al., 2018). The Kanguk Formation is subdivided into two informal members which are separated by a thick bentonite. The lower member, a light grey shale, extending from the top boundary with the Hassel Formation (0 m) to approximately 115 m. The upper member is a brown siltstone extending from 115 m to 287.5 m. The Kanguk Formation is overlain by sandstones of the Expedition Formation.

Lower Member

The basal 2 m of the Kanguk Formation is non-bioturbated black ‘paper’ shale (Fig. 5A). This is overlain, from approximately 2 to 6 m in this section, by a light brown sandy shale unit which is the result of an intermixing of the underlying Hassel Formation sand and black shale (Fig. 5B). This basal unit is overlain by a lithology dominated by light to dark grey shale with portions that are sulphur-rich. Several thick bentonites characterize this lower member (Fig. 5C). A light-coloured off-white to light grey quartz- and muscovite-rich deposit with fossilized wood occurs at 35 m.

Upper Member

The base of the upper member, from 115 m to 140 m, is a yellow and brown shale that weathers to a rust colour; concretion beds are present. Thick bentonites occur at 135 m, 150 m, 170 m, 255 m, 265 m, and 273 m; with thicknesses ranging between 30 to 60 cm. Between 140 m to 225 m, the section changes to a mottled brown to light brown shale to siltstone. Within this

section there are a few notable features: 1) at 145 m there are siderite concretions with *Nereites* ichnosp. traces within one of the concretions; 2) large individual concretions occur at 160 m; 3) a sulphur-rich deposit appears at 185 m; 4) rusty brown, sulphur-rich, concretion beds can be found at approximately 190 m and 210 m and 5) shells of the mollusc *Sphenoceras* *patootensis* occur between 165 m to 167 m, 180 m and 200 to 210 m (Fig. 5E). Siderite concretions are occur between 225 m and 275 m. The uppermost 7 m of the Kanguk Formation consists of a black shale. The boundary with the Expedition Formation is at approximately 287.5 m (Fig. 5F). The overlying Expedition Formation is a medium to coarse-grained, quartz dominated pebbly sandstone.

Figure 4: Stratigraphic section of the Kanguk Formation at the Slidre Fiord locality. Stage boundaries after Davies et al., (2018). Photo designations refer to images found in Figure 5.

Slidre Fiord

Legend	
Lithology	
	Massive coarse-grained sandstone
	Grey shale with brown alteration at the top
	Dark grey soft shale
	Brown siltstone with sulphur enrichment near the top
	Mottled brown to light shale to siltstone
	Yellow to brown shale to siltstone with rusty weathering
	Grey 'platy' shale
	Grey siltstone to very fine sandstone
	Mottled sulphur-rich light grey shale with increasing silt near the top
	Mottled sulphur-rich dark grey shale
	Sulphur-rich black shale
	Light brown shale to very fine sand
	Black 'paper' shale
Symbols	
	30 Bentonite deposit (thickness in cm)
	Quartz and muscovite deposit
	Concretions
	Sidrite concretions
	Fossilized wood
	<i>Nerites ichnosp.</i> in concretion
	<i>Sphenoceramus patoonensis</i> shell

Figure 5: Images of the Kanguk Formation at the Slidre Fiord locality, courtesy of C. Schröder-Adams. A: Black ‘paper’ shales at the base of the Kanguk Formation; note the platy appearance. B: Interfingered contact at the Hassel-Kanguk formational boundaries. C: Frequent bentonite deposits 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 marked by an

80 cm thick bentonite. E: Bed of *Sphenoceras patootensis* shells. F. Sharp boundary between the shale-rich Kanguk Formation and the sand-rich Expedition Formation.

4.2 Sporomorph Index and Palaeoproductivity Signals

Glacier Fiord

A palynological analysis was conducted on 18 samples taken from the Cenomanian/Turonian boundary interval at Glacier Fiord, Axel Heiberg Island. The samples studied were taken from between 90 m and 160 m of a larger 250 m section (Schröder-Adams et al., 2014). This section was targeted to determine palaeoenvironmental information and observe the planktonic response to the OAE 2 carbon perturbation (Herrle et al., 2015). The sporomorph index of the 90 m to 160 m section of Glacier Fiord has an overall strong terrestrial input, with values ranging from 0.69 to 0.93 (Fig. 6). The Bastion Ridge Formation section, from 90 m to 130 m, has a strong, but variable, terrestrial input signal with the sporomorph index ranging from 0.69 to 0.83 (Fig. 6). The Kanguk Formation section, from 130 m to 160 m, has a more consistent dominant terrestrial signal, with sporomorph index values for most of the samples being 0.90 or higher (Fig. 6). This high terrestrial input signal within the Kanguk Formation is the result of increasing amounts of pollen with a peak abundance in bisaccates (Fig. 7). A notable acme in peridinioid dinoflagellate cysts occurs just above 110 m, which reflects the boundary between the Bastion Ridge and Kanguk formations.

Glacier Fiord

Figure 6: Sporomorph index and peridinioid relative abundance (percentages of peridinioids randomly encountered per slide calculated as decimal points) for the section of Glacier Fiord palynologically examined here. Blue area indicates a marine dominated sporomorph index, green area indicates terrestrial dominated sporomorph index. Note the peridinioid acme at the transition between the Bastion Ridge and Kanguk formations (yellow highlighted area). OAE 2 interval indicated by grey highlighted area. See Figure 3 for lithology explanation.

Glacier Fiord

Figure 7: Relative abundances of palynological components at Glacier Fiord. Note increasing amounts of pollen and peak abundance in bisaccates within the Kanguk Formation (grey area).

See Figure 3 for lithology explanation.

Slidre Fiord

The sporomorph index was determined for 70 samples taken from a 290 m section located at Slidre Fiord, Ellesmere Island. The sporomorph index is variable throughout the Slidre Fiord section (Fig. 8). However, the overall trend towards increased terrestrial influence upsection. The lower member, from 0 to 110 m, has sporomorph index values that mostly range from 0.4 to 0.65; thereby suggesting a dominant marine influence. A brief terrestrial excursion with an index value of 0.79-0.84 is located just above the base of the section where the Kanguk Formation interfingers with the underlying sandstones of the Hassel Formation. The upper member, from 110 m to 290 m, ranges from 0.7 to 0.98. However, an interval of a dominant marine influence occurs from approximately 155 m to about 190 m, where the sporomorph index declines to 0.63 to 0.45, before once again becoming a dominantly terrestrial influenced system with a sporomorph index of 0.9 to 0.98. As the overall sporomorph index increases from dominantly marine influenced to dominantly terrestrial influenced, the abundance of dinocysts present on each slide decreases. From 0 m to 60 m the relative abundance of peridinioids is less than 0.5. The remaining section, from 60 m to 290 m, is overall a peridinioid dominated system.

4.3 Dinocyst and Acritarch Abundances and Biostratigraphy

Glacier Fiord

At Glacier Fiord, a diverse dinocyst and acritarch assemblage is present within the 70 m section that was palynological examined within the present study. The assemblage consists of 55 dinoflagellate cyst taxa and 10 acritarch taxa. Overall, specimens are very poorly to well preserved. The samples from 132 to 160 m are thermally mature and have abundant dark amorphous organic matter (AOM), which obstructed the view of the palynomorphs. Therefore, levels of taxonomic identification varied between each individual specimen. There is a notable assemblage change with lithological change. The siltstones of the Bastion Ridge Formation are dominated by the non-marine to marginal marine dinocysts *Nyktericysta* spp. and *Vesperopsis* spp. (MacRae, 1996; Mao et al., 1999). The non-marine acritarch *Limbicysta* sp. (MacRae et al., 1996b) also has a common occurrence within this interval. As the lithology changes to ‘paper’ shale at the base of the Kanguk Formation assemblage changes begin to occur: 1) the dominant and abundant taxa *Limbicysta* sp., *Nyktericysta* sp. and *Vesperopsis* sp. disappear (Fig. 9); 2) a variety of marine dinocyst and acritarch genera start to occur (Fig. 10; 11); and 3) the marine palynomorph assemblage is diverse, but each taxon is rare. For example, *Florentinia deanei* and *Palaeotetradinium silicorum* are each represented by a single specimen (Fig. 11). The following taxa were identified from the Cenomanian/Turonian boundary interval at Glacier Fiord.

Apteodinium reticulatum

Apteodinium sp.

Batioladinium jaegeri

?*Batioladinium* sp.

Baltisphaeridium sp.

Callaiosphaeridium asymmetricum

Cauveridinium membraniphorum

Canningia sp.

<i>Chatangiella</i> sp.	<i>Chlamydophorella nyei</i>
<i>Circulodinium distinctum</i>	<i>Cometodinium whitei</i>
<i>Coronifera oceanica</i>	<i>Cribroperidinium edwardsii</i>
<i>Cribroperidinium exilicristatum</i>	<i>Cribroperidinium tensiftense</i>
<i>Dapsilidinium daveyi</i>	<i>Dinopterygium alatum</i>
<i>Dinopterygium</i> sp.	<i>Downiesphaeridium aciculare</i>
<i>Exochosphaeridium phragmites</i>	<i>Florentinia deanei</i>
<i>Florentinia ferox</i>	<i>Fromea amphora</i>
<i>Fromea fragilis</i>	<i>Hystrichodinium pulchrum</i>
<i>Isabelidinium acuminatum</i>	<i>Kleithriasphaeridium loffrense</i>
<i>Kiokansium unituberculatum</i>	<i>Lejeunecysta</i> sp.
<i>Limbicysta octopediformis</i>	<i>Limbicysta quadriformis</i>
<i>Limbicysta</i> sp.	<i>Manumiella</i> sp.
<i>Nyktericysta</i> sp.	<i>Nyktericysta tripenta</i>
<i>Odontochitina costata</i>	<i>Odontochitina nuda</i>
<i>Odontochitina</i> sp.	<i>Oligosphaeridium albertense</i>
<i>Oligosphaeridium complex</i>	<i>Oligosphaeridium totum</i>
<i>Oligosphaeridium</i> sp.	<i>Ovidinium?</i> sp. 1

<i>Palambages</i> sp.	<i>Palaeohystrichophora infusorioides</i>
<i>Palaeoperidinium cretaceum</i>	<i>Palaeoperidinium pyrophorum</i>
<i>Palaeotetradinium silicorum</i>	<i>Prolixosphaeridium parvispinum</i>
<i>Pseudoceratium retusum</i>	<i>Pterospermella aureolata</i>
<i>Samlandia</i> sp.	<i>Sepispinula</i> sp.
<i>Sirmiodinium grossii</i>	<i>Solisphaeridium</i> sp.
<i>Spiniferites</i> sp.	<i>Stanfordella fastigiata</i>
<i>Stiphrosphaeridium</i> sp.	<i>Subtilisphaera</i> sp.
<i>Surculosphaeridium?</i> <i>longifurcatum</i>	<i>Tanyosphaeridium variecalamum</i>
<i>Trithyrodinium suspectum</i>	<i>Vesperopsis fragilis</i>
<i>Vesperopsis</i> sp.	<i>Wallodinium krutzschii</i>
<i>Wallodinium luna</i>	<i>Wuroia</i> sp.
<i>Xenascus ceratioides</i>	<i>Xenascus sarjeantii</i>

Glacier Fiord

Figure 9: Relative abundances (percentages of each taxa randomly encountered per slide calculated as decimal points) expressed of euryhaline dinoflagellate cysts and acritarch genera. *Nyktericysta* and *Limbicysta* are freshwater-to-brackish tolerant. *Vesperopsis* is brackish to marine tolerant. Data points on lines represent 10 or less specimens per count. *Wuroia* and *Fromea* are morphologically similar and, therefore, difficult to distinguish; thus, they are plotted

together. OAE 2 interval indicated by grey highlighted area. See Figure 3 for lithology explanation.

Glacier Fiord

Figure 10: Biostratigraphy of palaeoenvironmentally significant, restricted marine to open marine, dinocyst and acritarch genera within the Glacier Fiord section palynologically examined within this current studied. Note the assemblage change associated with the formational boundary between the Bastion Ridge and Kanguk formations (blue highlighted area). See Figure 3 for lithology explanation.

Glacier Fiord

Figure 11: Continuation of palaeoenvironmentally significant dinocyst and acritarch genera within the Glacier Fiord section palynologically studied. See Figure 3 for lithology explanation. Note the stepwise first appearance of taxa that show limited occurrences. These ranges are obscured by abundant amorphous organic matter.

Slidre Fiord

The marine palynomorph assemblage sampled throughout the 290 m section of the Kanguk Formation is diverse, with 93 dinoflagellate taxa and 16 acritarch taxa identified in this study. However, some genera, such as *Spiniferites*, were considered one taxon and not separated into species, or subspecies, due to the current complex taxonomic status of the genus.

Approximately five particularly rare taxa remain in open nomenclature. Two taxa are either yet undescribed or under taxonomic revision (R. Fensome, pers. com. 2016); and are, therefore, not reported on here. Slides 58 as well as 65 to 11 had extremely high densities of marine palynomorphs; with up to hundreds to possibly thousands of dinoflagellate cysts per slide.

Consequently, the count of 300 dinocysts per sample does not represent the entire diversity of the assemblage. The following taxa were identified from the Turonian to Campanian deposits at Slidre Fiord.

Alterbidinium sp.

Areoligera sp.

Arvalidinium scheii

Baltisphaeridium sp.

Callaiosphaeridium asymmetricum

Cauveridium membraniphorum

Cerebrocysta sp.

Chatangiella cf. *bondarenkoi*

Chatangiella ditissima

Chatangiella granulifera

Chatangiella cf. *madura*

Chatangiella mcintyreii

Chatangiella spectabilis

Chatangiella verrucosa

<i>Chlamydomophorella nyei</i>	<i>Circulodinium distinctum</i>
<i>Cometodinium whitei</i>	<i>Cribroperidinium apione</i>
<i>Cribroperidinium edwardsii</i>	<i>Cribroperidinium exilicristatum</i>
<i>Coronifera oceanica</i>	<i>Cyclopsiella sp.</i>
<i>Dapsilidinium daveyi</i>	<i>Deflandrea galeata</i>
<i>Desmocysta plekta</i>	<i>Dinopterygium alatum</i>
<i>Dinopterygium sp.</i>	<i>Distatodinium sp.</i>
<i>Dorocysta litotes</i>	<i>Downiesphaeridium aciculare</i>
<i>Exochosphaeridium major</i>	<i>Exochosphaeridium phragmites</i>
<i>Florentinia deanei</i>	<i>Fromea amphora</i>
<i>Fromea fragilis</i>	<i>Halophoridia xena</i>
<i>Hapsocysta? Benteae</i>	<i>Heterosphaeridium difficile</i>
<i>Hystrichodinium pulchrum</i>	<i>Hystrichodinium ramoides</i>
<i>Impagidinium sp.</i>	<i>Isabelidinium acuminatum</i>
<i>Isabelidinium cooksoniae</i>	<i>Isabelidinium cretaceum</i>
<i>Isabelidinium svartenhukense</i>	<i>Kallosphaeridium helbyi</i>
<i>Kallosphaeridium? ringnesiorum</i>	<i>Kiokansium unituberculatum</i>
<i>Kleithriasphaeridium cooksoniae</i>	<i>Kleithriasphaeridium loffrense</i>

<i>Kleithriasphaeridium perforatum</i>	<i>Laciniadinium arcticum</i>
<i>Laciniadinium biconiculum</i>	<i>Limbicysta quadriformis</i>
? <i>Litosphaeridium</i> sp.	<i>Manumiella</i> sp.
<i>Michystridium</i> cf. <i>breve</i>	<i>Michystridium fragile</i>
<i>Muderongia</i> sp.	<i>Nyktericysta</i> sp.
<i>Odontochitina corpucorna</i>	<i>Odontochitina costata</i>
<i>Odontochitina singhii</i>	<i>Odontochitina striatoperforata</i>
<i>Oligosphaeridium albertense</i>	<i>Oligosphaeridium complex</i>
<i>Oligosphaeridium pulcherrimum</i>	<i>Oligosphaeridium totum</i>
<i>Palambages deflandrei</i>	<i>Palambages</i> sp.
<i>Palaeohystrichophora infusorioides</i>	<i>Palaeoperidinium cretaceum</i>
<i>Palaeoperidinium pyrophorum</i>	<i>Paralecaniella</i> sp.
<i>Pareodinia</i> sp.	<i>Pervosphaeridium pseudhystrichodinium</i>
<i>Pervosphaeridium granulosum</i>	<i>Phelodinium pentagonale</i>
? <i>Pierceites pentagonus</i>	<i>Pterodinium</i> sp.
<i>Pterospermella aureolata</i>	<i>Pterospermella australiensis</i>
<i>Raphidodinium fucatum</i>	<i>Schizocystia rugosa</i>
<i>Schizocystia</i> sp.	<i>Scriniodinium crystallinum</i>

<i>Sentusidinium</i> sp.	<i>Sirmiodinium grossii</i>
<i>Spiniferites ramosus</i>	<i>Spiniferites scabrosus</i>
<i>Spiniferites</i> sp.	<i>Spinidinium echinoideum</i>
<i>Spongodinium delitiense</i>	<i>Stiphrosphaeridium anthophorum</i>
<i>Stiphrosphaeridium dictyophorum</i>	<i>Subtilisphaera</i> sp.
<i>Surculosphaeridium? longifurcatum</i>	<i>Tanyosphaeridium salpinx</i>
<i>Tanyosphaeridium variecalamum</i>	<i>Trichodinium castanea</i>
<i>Trigonopyxidia fiscellata</i>	<i>Trithyrodinium suspectum</i>
<i>Trithyrodinium vermiculatum</i>	<i>Veryhachium rhomboidinium</i>
<i>Veryhachium valiente</i>	<i>Vesperopsis</i> sp.
<i>Wallodinium luna</i>	<i>Wuroia</i> sp.
<i>Xenascus ceratioides</i>	<i>Xenascus sarjeantii</i>
<i>Xenascus</i> sp.	

Dinocyst assemblages in the basal Kanguk Formation reveal an irregular boundary between the Hassel and Kanguk formations. The basal assemblage briefly disappears due to soft sediment folding of the soft Kanguk Formation shales that resulted into an interbedded layer of Hassel Formation sands (Fig. 12). Many taxa range through the entire section and are, therefore, not reliable biostratigraphic indicators (Figs. 13, 14). Figure 16 shows taxa that have long ranges,

but become particularly prevalent within the Campanian interval of the Kanguk Formation. A few taxa such as *Chatangiella ditissima*, *Laciniadinium biconiculum*, *Spinidinium echinoideum*, *Chatangiella mcintyreii*, *Cerebrocysta* sp., *Arvalidinium scheii*, and *Isabelidinium svartenhukense* have their first appearance in the upper Santonian and, therefore, have greater biostratigraphic value. Several specific appearances outside of the reported biostratigraphic ranges were noted (Fig. 17), and tended to cluster in the lower part of the lower and upper members.

Figure 14: Continued biostratigraphic ranges of dominant to common dinocysts and acritarchs found through the majority Kanguk Formation in the Slidre Fiord section. See Figure 4 for lithology explanation.

Figure 15: Biostratigraphic ranges of uncommon dinocysts and acritarchs found sporadically through the Kanguk Formation in the Slidre Fiord section. See Figure 4 for lithology explanation.

Figure 16: Biostratigraphic ranges of dinoflagellate cysts that are prevalent in the Campanian part of the Kanguk Formation in the Slidre Fiord section. Note several taxa appear in the upper Santonian. See Figure 4 for lithology explanation.

Figure 17: Biostratigraphic occurrences of dinoflagellate cysts and acritarchs which might be present as a result of contamination or reworking. These partly seem to cluster at the bases of the lower and upper member1.3. See Figure 4 for lithology explanation.

4.4 Biozonations

Glacier Fiord

Two dinoflagellate biozones and one subzone were identified at Glacier Fiord, Axel Heiberg Island (Fig. 18); the Cenomanian *Nyktericysta* sp. Biozone and the late Cenomanian to Turonian *Surculosphaeridium? longifurcatum* Biozone with the Turonian *Xenascus* sp. subzone.

Nyktericysta sp. Biozone - Cenomanian

This zone is defined by the last occurrence of the dinocyst genus *Nyktericysta* in the lowermost Kanguk Formation; and it spans the siltstones of the upper Bastion Ridge Formation and the ‘paper’ shale base of the Kanguk Formation. The majority of this zone is located within the Bastion Ridge Formation which is dominated by the dinocysts *Nyktericysta* sp. and *Vesperopsis* sp.; with both of these genera having a relative abundance of 40-50%. The acritarchs *Fromea* sp. and *Wuroia* sp. are also dominate to common (65% to 10% relative abundance). The acritarch genus *Limbicysta* sp. is present at 5% to 20% relative abundance (Fig. 9).

Glacier Fiord

Figure 18: Biostratigraphic ranges for selected dinocyst and acritarch taxa and biozonation for Glacier Fiord. See Figure 3 for lithology explanation.

Surculosphaeridium? longifurcatum Biozone – Late Cenomanian to Turonian

This zone is defined by the first occurrence of the dinoflagellate *Surculosphaeridium? longifurcatum* in the Cenomanian. This species is used as a zonal marker in offshore eastern Canada, where it ranges from the Turonian to Coniacian (Williams, 1975). As the lithology changes to ‘paper’ shale at the base of the Kanguk Formation, a distinct assemblage change occurs as a diverse variety of marine dinocyst and acritarch taxa enter the system (Fig. 10; 11). Many of these taxa are represented by only one individual specimen. Many of the common dinoflagellate cysts, such as *Isabelidinium acuminatum*, *Surculosphaeridium? longifurcatum*, *Palaeohystrichophora infusorioides* and *Downiesphaeridium aciculare* are also found in the lower member at Slidre Fiord.

Xenascus sp. Subzone -Turonian

The *Xenascus* sp. Subzone, within the *Surculosphaeridium? longifurcatum* Zone, is established since its subzonal indicator has its first occurrence within the early Turonian.

Slidre Fiord

Many of the dominant to common dinoflagellate cysts found at Slidre Fiord have long and overlapping biostratigraphic ranges, unsuitable for zonal markers.

Figure 19: Biostratigraphic ranges of selected dinocyst taxa and biozonation for the Slidre Fiord section. See Figure 4 for lithology explanation.

Surculosphaeridium? longifurcatum Biozone – Late Cenomanian to Turonian

This biozone is defined by the last occurrence of *Surculosphaeridium? longifurcatum* in the lower member. Two specimens of this species were found in a Campanian sample collected at 230 m (Fig. 14). These specimens are broken and could possibly represent sampling contamination since no other specimens were found in the interval between the upper zonal boundary and this questionable occurrence. This zone is characterized by a high abundance of marine dinocysts and reduced number of pollen. The assemblage is dominated by various well-to-very well preserved chorate gonyaulacoid dinoflagellate cysts. The dominant gonyaulacoid taxa include *Exochosphaeridium phragmites*, *Downiesphaeridium aciculare*, *Surculosphaeridium? longifurcatum*, *Chlamydophorella nyei*, *Spiniferites* sp., and *Oligosphaeridium* sp. Common gonyaulacoid taxa include *Dapsilidinium daveyi*, *Pervosphaeridium pseudhystrichodinium*, *Florentinia* sp. and *Kleithriasphaeridium* sp. Common non-gonyaulocoid dinocysts taxa include *Palaeohystrichophora infusorioides*, *Isabelidinium* sp., and *Xenascus* sp. (Figs. 12, 14).

The lowermost base of the dark ‘paper’ shale is a distinctive unit with a very diverse assemblage of very well-preserved dinoflagellate cysts. In addition to the dominant to common dinoflagellate cysts already mentioned within the *Surculosphaeridium? longifurcatum* Zone (above), taxa such as *Cauveridinium membraniphorum*, *Scriniodinium crystallinum*, *Areoligera* sp. and *Dinopterygium* sp. occur (Fig. 12). These taxa were encountered in the basal samples (slides 58 to 82) and from samples around 95 m to 110 m (slides 11 to 17). Their disappearance is the result of the interfingering of the Hassel Formation and Kanguk Formation lithologies from about 2 to 4 m within the section. The Hassel Formation contaminated section is characterized by an abundance of dark, thermally mature, amorphous organic matter, poor-to-moderate dinocyst

preservation, and a high terrestrial sporomorph index. Typical marine Albian dinoflagellate cyst species such as *Hapsocysta? benteae*, *Odontochitina singii* and *Oligosphaeridium totum* (Nøhr-Hansen et al., 1996), occur in this interval (Fig. 12). *Oligosphaeridium totum* occurs in both lithologies, thereby, indicating that this species was present during the deposit of the shale. Hence, extending the local biostratigraphic range for this species into the Turonian.

Chatangiella ditissima Biozone – Coniacian to Late Santonian

The *Chatangiella ditissima* Zone is defined by the first occurrence of *Chatangiella ditissima* at 58 m (slide 4). This zone is interpreted as having a continually increasing terrestrial input. The preservation of dinoflagellate cysts within this section to moderately to well preserved. This interval is notably dominated by species of the peridinioid genus *Chatangiella* (Fig. 20). The relative abundance of *Chatangiella ditissima*, *C. verrucosa*, and *C. granulifera* increases to the point where the system switches to being peridinioid dominated. At 60 m the genus *Chatangiella* reaches an acme, with its relative abundance being 82% of the dinoflagellate cysts present. Other common dinoflagellate cysts within this assemblage are *Heterosphaeridium difficile*, *Chlamydochorella nyei* and *Exochosphaeridium phragmites*. This zone persists to the upper member boundary at about 110 m.

Arvaladinium scheii Biozone – late Santonian to middle Campanian

The *Arvaladinium scheii* Zone is marked by the first occurrence of *Arvaladinium scheii* at the Santonian lower/upper member boundary (slide 19). *Arvaladinium scheii* first occurs at 115 m and becomes one of the most abundant taxa present at 125 m (slide 23), accompanied by an increase in relative abundance of *Palaeoperidinium pyrophorum* and *Heterosphaeridium difficile*. The dominance of *A. scheii* provides an easily recognizable indicator for the late Santonian. This

species has correlative value as it is wide-spread within northern high latitudes, having been reported at Hoodoo Dome, Ellef Ringnes Island (Andrews, 2012) and western Greenland (Nøhr-Hansen, 1996). *Chatangiella mcintyreii* and *Isabelidinium svartenhukense* co-occur in this interval, making them also good index fossils for this biozone, when *Arvalidinium scheii* was not found due to very low marine palynomorph input.

Figure 20: Relative abundances of dinoflagellate cysts and acritarch genera (percentages of each taxa randomly encountered per silde calculated as decimal points) which had notable acmes (indicated with grey shading) within the Kanguk Formation at Slidre Fiord. Stage boundaries after Davies et al., (2018). See Figure 4 for lithology explanation.

Manumiella sp. and *Kiokansium unituberculatum* both, first occur above the major lithological change and member boundary (slide 22), contributing less than 1 % of the overall assemblage with only a few individuals per slide. At 200 to 290 m the assemblage is dominated by the dinocyst genus *Manumiella*, which makes up between 45 to 55 % of the assemblage (Fig. 20). The species *Kiokansium unituberculatum* is the second most common marine palynomorph, with 15 to 20 % abundance. *Pervosphaeridium granulosum*, *Exochosphaeridium bifidum*, *Callaiosphaeridium asymmetricum*, *Spongodinium delitiense*, a small form of *Circulodinium distinctum*, and specimens of the genera *Stiphrosphaeridium* and *Oligosphaeridium* are very common and typical members of the rest of the assemblage. *Chatangiella mcintyreii*, *Arvalidinium scheii* and *Isabelidinium svartenhukense* are rare to uncommon within this terrestrially dominated upper part of this section (slides 37 to 52) but are still present as indicated by their abundant occurrence in the topmost part of the section (slide 54).

4.5 Photographic Plates of Dinocysts and Acritarchs

The following plates represent the diversity of the dinoflagellate cysts and acritarchs. Some additional images are added representing linings of foraminifera, gelified amorphous organic matter and the pollen taxon *Aquilapollenites*. Some taxa are presented using the best-preserved specimen found within this study. Other images were selected to illustrate how certain taxa typically appear so that future workers can have a variety of visual references for the various taphonomic appearance of a taxon. The magnification of all illustrated specimens is 400x. All black or white scale bars are 50 μm unless otherwise indicated.

Plate 1: Glacier Fiord

Fig. 1: *Apteodinium reticulatum*

Comment: oblique apex view.

Slide: C9

Fig. 2: *Apteodinium* sp.

Comment: oblique antapex view.

Slide: C9

Fig. 3: *Batioladinium jaegeri*

Comment: dorsal view.

Slide: H8

Fig. 4: ?*Batioladinium* sp.

Comment: dorsal view.

Slide: C55

Fig. 5: *Baltisphaeridium* sp.

Comment: dorsal view.

Slide: H8

Fig. 6: *Callaiosphaeridium asymmetricum*

Comment: apex view.

Slide: H1

Fig. 7: *Callaiosphaeridium* sp.

Comment: apex view.

Slide: C48

Fig. 8: *Cauveridinium membraniphorum*

Comment: dorsal view.

Slide: C54

Fig. 9: *Canningia* sp.

Comment: dorsal view.

Slide: C48

Fig. 10: *Canningia* sp.

Comment: dorsal view.

Slide: H12

Fig. 11: *Chatangiella* sp.

Comment: dorsal view.

Slide: H1

Fig. 12: *Chatangiella* sp.

Comment: dorsal view.

Slide: C48

Fig. 13: *Chlamydophorella nyei*

Comment: dorsal view.

Slide: H1

Fig. 14: *Circulodinium distinctum*

Comment: dorsal view. Obscured by AOM.

Slide: C55

Fig. 15: *Cometodinium whitei*

Comment: oblique apex view.

Slide: H12

Fig. 16: *Coronifera oceanica*

Comment: dorsal view.

Slide: H4

Fig. 17: *Cribroperidinium edwardsii*

Comment: dorsal view. Obscured by AOM.

Slide: H31

Fig. 18: *Cribroperidinium exilicristatum*

Comment: oblique dorsal view

Slide: H4

Fig. 19: *Cribroperidinium exilicristatum*

Comment: dorsal view.

Slide: C9

Fig. 20: *Cribroperidinium* sp.

Comment: oblique dorsal view.

Slide: C15

Glacier Fiord

Plate 1

Plate 2: Glacier Fiord

Fig. 1: *Cribroperidinium tensiftense*

Comment: oblique dorsal view.

Slide: C9

Fig. 3: *Cribroperidinium tensiftense*

Comment: ventral view.

Slide: C15

Fig. 5: *Dapsilidinium daveyi*

Comment: dorsal view.

Slide: C48

Fig. 7: *Dinopterygium* sp.

Comment: apex view.

Slide: H4

Fig. 9: *Exochosphaeridium phragmites*

Comment: apex view.

Slide: H4

Fig. 11: *Florentinia deanei*

Comment: oblique apex view.

Slide: H4

Fig. 13: *Fromea amphora*

Comment: dorsal view.

Slide: C6

Fig. 2: *Cribroperidinium tensiftense*

Comment: oblique dorsal view.

Slide: C9

Fig. 4: *Cribroperidinium tensiftense?*

Comment: oblique dorsal view.

Slide: C19

Fig. 6: *Dinopterygium alatum*

Comment: dorsal view.

Slide: H4

Fig. 8: *Downiesphaeridium aciculare*

Comment: dorsal view.

Slide: H1

Fig. 10: *Florentinia deanei*

Comment: dorsal view.

Slide: H4

Fig. 12: *Florentinia ferox*

Comment: dorsal view.

Slide: H4

Fig. 14: *Fromea fragilis*

Comment: dorsal view.

Slide: C9

Fig. 15: *Fromea fragilis*

Comment: dorsal view.

Slide: H28

Fig. 16: *Hystrichodinium pulchrum*

Comment: dorsal view

Slide: H8

Fig. 17: *Isabelidinium acuminatum*

Comment: dorsal view. Obscured by AOM.

Slide: H28

Fig. 18: *Kiokansium unituberculatum*

Comment: oblique apex view.

Slide: H12

Fig. 19: *Kleithriasphaeridium loffrense*

Comment: oblique dorsal view.

Slide: H4

Fig. 20: *Lejeunecysta* sp.

Comment: dorsal view.

Slide: H28

Glacier Fiord

Plate 2

Plate 3: Glacier Fiord

Fig. 1: *Lejeunecysta* sp.

Comment: dorsal view. Poor preservation.

Slide: H31

Fig. 2: *Limbicysta octopediformis*

Comment: oblique dorsal view.

Slide: C6

Fig. 3: *Limbicysta octopediformis*

Comment: dorsal view.

Slide: C9

Fig. 4: *Limbicysta octopediformis?*

Comment: dorsal view.

Slide: C6

Fig. 5: *Limbicysta quadriformis*

Comment: dorsal view.

Slide: C6

Fig. 6: *Manumiella* sp.

Comment: dorsal view.

Slide: H1

Fig. 7: *Nyktericysta* sp.

Comment: dorsal view.

Slide: C6

Fig. 8: *Nyktericysta* sp.

Comment: oblique dorsal view.

Slide: C9

Fig. 9: *Nyktericysta* sp.

Comment: dorsal view.

Slide: C9

Fig. 10: *Nyktericysta* sp.

Comment: dorsal view..

Slide: C9

Fig. 11: *Nyktericysta tripenta?*

Comment: dorsal view.

Slide: C9

Fig. 12: *Nyktericysta tripenta*

Comment: dorsal view.

Slide: C9

Fig. 13: *Nyktericysta tripenta*

Comment: dorsal view.

Slide: C9

Fig. 14: *Nyktericysta tripenta*

Comment: dorsal view. No archeopyle.

Slide: C9

Fig. 15: *Odontochitina costata*

Comment: dorsal view.

Slide: H12

Fig. 16: *Odontochitina costata*

Comment: dorsal view. No archeopyle.

Slide: H8

Fig. 17: *Odontochitina nuda*

Comment: dorsal view. No archeopyle.

Slide: C47

Fig. 18: *Odontochitina* sp.

Comment: dorsal view.

Slide: C55

Fig. 19: *Oligosphaeridium albertense*

Comment: dorsal view.

Slide: H16

Fig. 20: *Oligosphaeridium complex*

Comment: dorsal view. No archeopyle.

Slide: C15

Plate 4: Glacier Fiord

Fig. 1: *Oligosphaeridium complex*

Comment: dorsal view. Obscured by AOM.

Slide: C55

Fig. 2: *Oligosphaeridium totum*

Comment: dorsal view.

Slide: C55

Fig. 3: *Oligosphaeridium* sp.

Comment: dorsal view.

Slide: H4

Fig. 4: *Ovidinium?* sp. 1

Comment: dorsal view.

Slide: H31

Fig. 5: *Palambages* sp.

Slide: H4

Fig. 6: *Palambages* sp.

Slide: C48

Fig. 7: *Palaeohystrichophora infusorioides*

Comment: dorsal view.

Slide: H4

Fig. 8: *Palaeoperidinium cretaceum*

Comment: dorsal view.

Slide: C15

Fig. 9: *Palaeoperidinium pyrophorum*

Comment: dorsal view.

Slide: H20

Fig. 10: *Palaeotetradinium silicorum*

Comment: dorsal view.

Slide: H8

Fig. 11: *Prolixosphaeridium parvispinum*

Comment: dorsal view. No archeopyle.

Slide: H4

Fig. 12: *Prolixosphaeridium parvispinum*

Comment: dorsal view. No archeopyle.

Slide: H1

Fig. 13: *Pseudoceratium retusum*

Comment: dorsal view.

Slide: H2

Fig. 14: *Pterospermella aureolata*

Comment: Obscured by AOM.

Slide: C47

Fig. 15: *Sepispinula* sp.

Comment: dorsal view.

Slide: C19

Fig. 16: *Sepispinula* sp.

Comment: dorsal view.

Slide: C19

Fig. 17: *Sirmiodinium grossii*

Comment: dorsal view

Slide: H1

Fig. 18: *Solisphaeridium* sp.

Comment: incomplete specimen.

Slide: H12

Fig. 19: *Spiniferites* sp.

Comment: dorsal view.

Slide: H4

Fig. 20: *Spiniferites* sp.

Comment: oblique ventral view.

Slide: H1

Plate 5: Glacier Fiord

Fig. 1: *Spiniferites* sp.

Comment: dorsal view.

Slide: H1

Fig. 2: *Spiniferites* sp.

Comment: dorsal view.

Slide: H4

Fig. 3: *Spiniferites* sp.

Comment: dorsal view.

Slide: H1

Fig. 4: *Stanfordella fastigate*

Comment: dorsal view.

Slide: C6

Fig. 5: *Stiphrosphaeridium* sp.

Comment: dorsal view.

Broken and obscured by AOM.

Slide: H24

Fig. 6: *Subtilisphaera* sp.

Comment: dorsal view.

Slide: C9

Fig. 7: *Surculosphaeridium? longifurcatum*

Comment: antapex view.

Slide: H12

Fig. 8: *Surculosphaeridium? longifurcatum*

Comment: dorsal view. Obscured by AOM.

Slide: H28

Fig. 9: *Tanyosphaeridium variecalamum*

Comment: incomplete specimen.

Slide: C15

Fig. 10: *Trithyrodinium suspectum*

Comment: dorsal view.

Slide: H1

Fig. 11: *Vesperopsis fragilis*

Comment: dorsal view.

Slide: C6

Fig. 12: *Vesperopsis fragilis*

Comment: dorsal view. No archeopyle.

Slide: C6

Fig. 13: *Vesperopsis fragilis*

Comment: dorsal view.

Slide: C6

Fig. 15: *Vesperopsis* sp.

Comment: dorsal view.

Slide: C9

Fig. 17: *Wuroia* sp.

Comment: antapex view.

Slide: H12

Fig. 19: *Wuroia* sp.

Comment: dorsal view.

Slide: C6

Fig. 14: *Vesperopsis* sp.

Comment: dorsal view.

Slide: C9

Fig. 16: *Wallodinium luna*

Comment: dorsal view.

Slide: H16

Fig. 18: *Wuroia* sp.

Comment: dorsal view.
Obscured by AOM.

Slide: H28

Fig. 20: *Xenascus ceratioides*

Comment: dorsal view.

Slide: C55

Plate 6: Glacier Fiord

Fig. 1: *Xenascus sarjeantii*

Comment: dorsal view.

Slide: C54

Fig. 2: *Xenascus sarjeantii*

Comment: dorsal view.

Slide: C54

Fig. 3: Unknown Dinocyst

Comment: dorsal view.

Slide: C6

Fig. 4: Unknown Dinocyst

Comment: dorsal view.

Slide: C6

Fig. 5: Unknown Dinocyst

Comment: ventral view.

Slide: H4

Fig. 6: Unknown Dinocyst

Comment: dorsal view.

Slide: H1

Fig. 7: Unknown Dinocyst

Comment: dorsal view.

Slide: H8

Fig. 8: Unknown Dinocyst

Comment: dorsal view.

Slide: H4

Fig. 9: Unknown Dinocyst

Comment: dorsal view.

Slide: C55

Fig. 10: Foraminifera test lining

Slide: C50

Fig. 11: Foraminifera test lining

Slide: H8

Fig. 12: Foraminifera test lining

Slide: C50

Fig. 13: Foraminifera test lining

Side: C54

Fig. 14: Gelified amorphous organic matter

Comment: typical of degraded terrestrial material

Slide: H8

Fig. 15: Gelified amorphous organic matter

Comment: typical of degraded terrestrial material.

Slide: H8

Plate 1: Slidre Fiord

Fig. 1: *Alterbidinium* sp.

Comment: dorsal view.

Slide: 6

Fig. 2: *Alterbidinium* sp.

Comment: dorsal view.

Slide: 32

Fig. 3: *Areoligera* sp.

Comment: dorsal view.

Slide: 58

Fig. 4: *Areoligera* sp.

Comment: dorsal view.

Slide: 82

Fig. 5: *Arvalidinium scheii*

Comment: dorsal view.

Slide: 23

Fig. 6: *Baltisphaeridium* sp.

Comment: dorsal view.

Slide: 17

Fig. 7: *Callaiosphaeridium asymmetricum*

Comment: apex view.

Slide: 48

Fig. 8: *Cauveridinium membraniphorum*

Comment: dorsal view. No archeopyle.

Slide: 76

Fig. 9: *Cauveridinium membraniphorum*

Comment: dorsal view.

Slide: 82

Fig. 10: *Cerebrocysta* sp.

Comment: archeopyle.

Slide: 47

Fig. 11: *Chatangiella* cf. *bondarenkoi*

Comment: oblique dorsal view.

Slide: 23

Fig. 12: *Chatangiella* cf. *bondarenkoi*

Comment: dorsal view.

Slide: 1

Fig. 13: *Chatangiella ditissima*

Comment: dorsal view.

Slide: 43

Fig. 14: *Chatangiella ditissima*

Comment: dorsal view.

Slide: 32

Fig. 15: *Chatangiella ditissima*

Comment: dorsal view.

Slide 9

Fig. 16: *Chatangiella granulifera*

Comment: dorsal view.

Slide: 9

Fig. 17: *Chatangiella granulifera*

Comment: dorsal view.

Slide: 32

Fig. 18: *Chatangiella granulifera*

Comment: dorsal view.

Slide: 18

Fig. 19: *Chatangiella* cf. *madura*

Comment: dorsal view.

Slide: 32

Fig. 20: *Chatangiella* cf. *madura*

Comment: dorsal view. Same specimen.

Slide: 32

Plate 2: Slidre Fiord

Fig. 1: *Chatangiella* cf. *madura*

Comment: dorsal view.

Slide: 19

Fig. 2: *Chatangiella mcintyre*

Comment: dorsal view.

Slide: 32

Fig. 3: *Chatangiella mcintyre*

Comment: dorsal view.

Slide: 32

Fig. 4: *Chatangiella mcintyre*

Comment: dorsal view.

Slide: 32

Fig. 5: *Chatangiella* sp.

Comment: dorsal view.

Slide: 41

Fig. 6: *Chatangiella tripartita*

Comment: dorsal view.

Slide: 19

Fig. 7: *Chatangiella tripartita*

Comment: dorsal view.

Slide: 75

Fig. 8: *Chatangiella* cf. *verrucosa*

Comment: dorsal view.

Slide: 52

Fig. 9: *Chatangiella spectabilis*

Comment: dorsal view.

Slide: 19

Fig. 10: *Chatangiella verrucosa*

Comment: dorsal view

Slide: 75

Fig. 11: *Chatangiella verrucosa*

Comment: dorsal view.

Slide: 9

Fig. 12: *Chlamydophorella nyei*

Comment: dorsal view.

Slide: 18

Fig. 13: *Chlamydophorella nyei*

Comment: dorsal view. Broken.
Typical appearance.

Slide: 58

Fig. 15: *Circulodinium distinctum*

Comment: dorsal view. No archeopyle.

Slide: 37

Fig. 17: *Cribroperidinium apione*

Comment: dorsal view.

Slide: 9

Fig. 19: *Cribroperidinium edwardsii*

Comment: dorsal view.

Slide: 81

Fig. 14: *Circulodinium distinctum*

Comment: dorsal view.

Slide: 82

Fig. 16: *Cometodinium whitei*

Comment: dorsal view.

Slide: 58

Fig. 18: *Cribroperidinium edwardsii*

Comment: ventral view.

Slide: 19

Fig. 20: *Cribroperidinium exilicristatum*

Comment: ventral view.

Slide: 18

Plate 3: Slidre Fiord

Fig. 1: *Cribroperidinium* sp.

Comment: archeopyle.

Slide: 18

Fig. 3: *Cyclopsiella* sp.

Comment: dorsal view.

Slide: 52

Fig. 5: *Deflandrea galeata*

Comment: oblique apex view.

Slide: 18

Fig. 7: *Desmocysta plekta*

Comment: dorsal view.

Slide: 32

Fig. 9: *Dinopterygium* sp.

Comment: dorsal view.

Slide: 17

Fig. 11: *Dorocysta litotes*

Comment: dorsal view.

Slide: 69

Fig. 13: *Exochosphaeridium bifidum*

Comment: dorsal view.

Slide: 46

Fig. 2: *Coronifera oceanica*

Comment: dorsal view.

Slide: 36

Fig. 4: *Dapsilidinium daveyi*

Comment: dorsal view.

Slide: 1

Fig. 6: *Desmocysta plekta*

Comment: oblique antapex view.

Slide: 82

Fig. 8: *Dinopterygium alatum*

Comment: dorsal view.

Slide: 19

Fig. 10: *Distatodinium* sp.

Comment: dorsal view.

Slide: 1

Fig. 12: *Downiesphaeridium aciculare*

Comment: dorsal view.

Slide: 19

Fig. 14: *Exochosphaeridium bifidum*

Comment: apex view.

Slide: 46

Fig. 15: *Exochosphaeridium phragmites*

Comment: dorsal view.

Slide: 19

Fig. 16: *Exochosphaeridium phragmites*

Comment: ventral view. Same specimen.

Slide: 19

Fig. 17: *Florentinia deanei*

Comment: dorsal view.

Slide: 31

Fig. 18: *Fromea amphora*

Comment: dorsal view.

Slide: 58

Fig. 19: *Fromea fragilis*

Comment: dorsal view.

Slide: 18

Fig. 20: *Fromea fragilis*

Comment: dorsal view.

Slide: 18

Plate 4: Slidre Fiord

Fig. 1: *Halophoridia xena*

Slide: 18

Fig. 2: *Hapsocysta? benteae*

Comment: apex view.

Slide: 62

Fig. 3: *Hapsocysta? benteae*

Comment: apex view. Deformed?

Slide: 36

Fig. 4: *Heterosphaeridium difficile*

Comment: dorsal view.

Slide: 26

Fig. 5: *Hystrichodinium pulchrum*

Comment: oblique dorsal view.

Slide: 72

Fig. 6: *Hystrichodinium ramoides*

Comment: dorsal view.

Slide: 72

Fig. 7: *Impagidinium* sp.

Comment: dorsal view.

Slide: 19

Fig. 8: *Impagidinium* sp.

Comment: oblique view.

Slide: 19

Fig. 9: *Isabelidinium acuminatum*

Comment: dorsal view.

Slide: 61

Fig. 10: *Isabelidinium cooksoniae*

Comment: dorsal view.

Slide: 1

Fig. 11: *Isabelidinium cretaceum*

Comment: dorsal view.

Slide: 19

Fig. 12: *Isabelidinium svartenhukense*

Comment: dorsal view.

Slide: 32

Fig. 13: *Isabelidium svartenhukense*

Comment: dorsal view.

Slide: 32

Fig. 14: *Kallosphaeridium? helbyi*

Comment: dorsal view.

Slide: 82

Fig. 15: *Kallosphaeridium? ringnesiorum*

Comment: dorsal view.

Slide: 1

Fig. 16: *Kallosphaeridium? sp.*

Comment: dorsal view.

Slide: 61

Fig. 17: *Kiokansium unituberculatum*

Comment: dorsal view.

Slide: 36

Fig. 18: *Kiokansium unituberculatum*

Comment: oblique apex view.

Slide: 47

Fig. 19: *Kleithriasphaeridium cooksoniae*

Comment: dorsal view.

Slide: 9

Fig. 20: *Kleithriasphaeridium loffrense*

Comment: oblique dorsal view.

Slide: 10

Plate 5: Slidre Fiord

Fig. 1: *Kleithriasphaeridium perforatum*

Comment: dorsal view.

Slide: 22

Fig. 2: *Laciniadinium arcticum*

Comment: dorsal view.

Slide: 75

Fig. 3: *Laciniadinium arcticum*

Comment: dorsal view.

Slide: 82

Fig. 4: *Laciniadinium biconiculum*

Comment: oblique view.

Slide: 32

Fig. 5: *Laciniadinium biconiculum*

Comment: dorsal view.

Slide: 32

Fig. 6: *Laciniadinium biconiculum*

Comment: dorsal view.

Slide: 32

Fig. 7: *Limbicysta quadriformis*

Comment: dorsal view.

Slide: 61

Fig. 8: ?*Litosphaeridium* sp.

Comment: dorsal view.

Slide: 75

Fig. 9: *Manumiella* sp.

Comment: dorsal view.

Slide: 52

Fig. 10: *Manumiella* sp.

Comment: dorsal view.

Slide: 52

Fig. 11: *Manumiella* sp.

Comment: dorsal view.

Slide: 52

Fig. 12: *Michystridium* cf. *breve*

Comment: dorsal view.

Slide: 82

Fig. 13: *Michystridium fragile*

Comment: dorsal view.

Slide: 75

Fig. 15: *Nyktericysta* sp.

Comment: dorsal view.

Slide: 24

Fig. 17: *Odontochitina corpucorna*

Comment: dorsal view.

Slide: 58

Fig. 19: *Odontochitina costata*

Comment: dorsal view.

Slide: 18

Fig. 14: *Muderongia* sp.

Comment: dorsal view.

Slide: 19

Fig. 16: ?*Nyktericysta* sp.

Comment: dorsal view.

Slide: 22

Fig. 18: *Odontochitina costata*

Comment: dorsal view.

Slide: 45

Fig. 20: *Odontochitina singhii*

Comment: dorsal view.

Slide: 62

Slidre Fiord

Plate 5

Plate 6: Slidre Fiord

Fig. 1: *Odontochitina singhii*

Comment: dorsal view.

Slide: 62

Fig. 2: *Odontochitina striatoperforata*

Comment: dorsal view.

Slide: 18

Fig. 3: *Odontochitina striatoperforata*

Comment: dorsal view.

Slide: 23

Fig. 4: *Oligosphaeridium albertense*

Comment: dorsal view.

Slide: 58

Fig. 5: *Oligosphaeridium complex*

Comment: dorsal view.

Slide: 72

Fig. 6: *Oligosphaeridium complex*

Comment: dorsal view.

Slide: 13

Fig. 7: *Oligosphaeridium pulcherrimum*

Comment: dorsal view.

Slide: 37

Fig. 8: *Oligosphaeridium totum*

Comment: dorsal view.

Slide: 65

Fig. 9: *Oligosphaeridium totum*

Comment: dorsal view.

Slide: 58

Fig. 10: *Palambages deflandrei*

Slide: 58

Fig. 11: *Palambages* sp.

Slide: 82

Fig. 12: *Palambages* sp.

Slide: 82

Fig. 13: *Palambages* sp.

Slide: 58

Fig. 14: *Palaeohystrichophora infusorioides*

Comment: dorsal view. Very well preserved.

Fig. 15: *Palaeohystrichophora infusorioides*

Comment: dorsal view. Well preserved.

Slide: 76

Fig. 17: *Palaeoperidinium cretaceum*

Comment: dorsal view.

Slide: 1

Fig. 19: *Palaeoperidinium pyrophorum*

Comment: dorsal view.

Slide: 4

Slide: 58

Fig. 16: *Palaeohystrichophora infusorioides*

Comment: dorsal view. Moderately preserved.

Slide: 76

Fig. 18: *Palaeoperidinium cretaceum*

Comment: dorsal view.

Slide: 1

Fig. 20: *Palaeoperidinium pyrophorum*

Comment: dorsal view.

Slide: 82

Plate 7: Slidre Fiord

Fig. 1: *Paralecaniella* sp.

Comment: dorsal view.

Slide: 82

Fig. 2: *Pareodinia* sp.

Comment: dorsal view.

Slide: 26

Fig. 3: *Pervosphaeridium pseudhystrichodinium*

Comment: apex view.

Slide: 70

Fig. 4: *Pervosphaeridium granulosum*

Comment: oblique view.

Slide: 52

Fig. 5: *Phelodinium pentagonale*

Comment: dorsal view.

Slide: 43

Fig. 6: ? *Pierceites pentagonus*

Comment: dorsal view.

Slide: 58

Fig. 7: *Pterodinium* sp.

Comment: oblique view.

Slide: 32

Fig. 8: *Pterodinium* sp.

Comment: oblique dorsal view

Slide: 18

Fig. 9: *Pterospermella aureolata*

Slide: 18

Fig. 10: *Pterospermella australiensis* .

Slide: 58

Fig. 11: *Raphidodinium fucatum*

Comment: dorsal view.

Slide: 1

Fig. 12: ?*Samlandia* sp

Comment: dorsal view.

Slide: 58

Fig. 13: *Schizocystia rugosa*

Slide: 37

Fig. 14: *Schizocystia* sp.

Slide: 49

Fig. 15: *Schizocystia* sp.

Slide: 43

Fig. 17: *Sentusidinium* sp.

Comment: oblique antapex view.

Slide: 24

Fig. 19: *Sirmiodinium grossii*

Comment: dorsal view.

Slide: 42

Fig. 16: *Scriniodinium crystallinum*

Comment: oblique view.

Slide: 82

Fig. 18: *Sepispinula* sp.

Comment: dorsal view

Slide: 62

Fig. 20: *Spiniferites scabrosus*

Comment: dorsal view.

Slide: 58

Plate 8: Slidre Fiord

Fig. 1: *Spiniferites* sp.

Comment: dorsal view.

Slide: 82

Fig. 3: *Spiniferites* sp.

Comment: antapex view.

Slide: 69

Fig. 5: *Spiniferites* sp.

Comment: dorsal view.

Slide: 19

Fig. 7: *Spiniferites* sp.

Comment: dorsal view.

Slide: 75

Fig. 9: *Spiniferites* sp.

Comment: dorsal view.

Slide: 19

Fig. 11: *Spiniferites* sp.

Comment: dorsal view.

Slide: 1

Fig. 13: *Spinidinium echinoideum*

Comment: dorsal view.

Slide: 17

Fig. 2: *Spiniferites* sp.

Comment: dorsal view.

Slide: 58

Fig. 4: *Spiniferites* sp.

Comment: oblique view

Slide: 75

Fig. 6: *Spiniferites* sp.

Comment: dorsal view.

Slide: 75

Fig. 8: *Spiniferites* sp.

Comment: oblique dorsal view.

Slide: 58

Fig. 10: *Spiniferites* sp.

Comment: oblique dorsal view.

Slide: 32

Fig. 12: *Spinidinium echinoideum*

Comment: dorsal view.

Slide: 32

Fig. 14: *Spongodinium delitiense*

Comment: oblique view.

Slide: 18

Fig. 15: *Stiphrosphaeridium anthophorum*

Comment: dorsal view.

Slide: 18

Fig. 16: *Stiphrosphaeridium dictyophorum*

Comment: dorsal view.

Slide: 9

Fig. 17: *Stiphrosphaeridium dictyophorum*

Comment: dorsal view.

Slide: 36

Fig. 18: *Subtilisphaera* sp.

Comment: dorsal view.

Slide: 62

Fig. 19: *Surculosphaeridium? longifurcatum*

Comment: oblique dorsal view.

Slide: 32

Fig. 20: *Surculosphaeridium? longifurcatum*

Comment: dorsal view.

Slide: 43

Plate 9: Slidre Fiord

Fig. 1: *Tanyosphaeridium salpinx*

Comment: dorsal view.

Sample: 18

Fig. 2: *Tanyosphaeridium variecalamum*

Comment: dorsal view.

Sample: 72

Fig. 3: *Trichodinium* sp.

Comment: oblique antapex view.

Sample: 72

Fig. 4: *Trichodinium* sp.

Comment: ventral view.

Sample: 75

Fig. 5: *Trithyrodinium suspectum*

Comment: dorsal view.

Sample: 58

Fig. 6: *Trithyrodinium vermiculatum*

Comment: dorsal view.

Sample: 18

Fig. 7: *Trithyrodinium vermiculatum*

Comment: ventral view.

Sample: 32

Fig. 8: *Trithyrodinium vermiculatum*

Comment: apex view.

Sample: 32

Fig. 9: *Veryhachium valiente*

Sample: 18

Fig. 10: *Wallodinium luna*

Sample: 58

Fig. 11: *Wallodinium* cf. *luna*

Sample: 58

Fig. 12: *Wallodinium* cf. *luna*

Sample: 18

Fig. 13: *Wallodinium krutzschii*

Sample: 18

Fig. 14: *Xenascus ceratioides*

Comment: dorsal view. No archeopyle.

Sample: 82

Fig. 15: *Xenascus sarjeantii*

Comment: dorsal view.

Sample: 82

Fig. 16: *Xenascus* sp.

Comment: dorsal view. No archeopyle.

Sample: 69

Fig. 17: *Aquilapollenites* sp.

Comment: Often used as a Campanian terrestrial
biozonation maker (Nøhr-Hansen, 1996).

Sample: 54

Chapter 5: Discussion

5.1 Palaeoproductivity Signals and Response to Palaeoclimatic Changes

Glacier Fiord

The siltstones of the Bastion Ridge Formation are dominated by the brackish and freshwater dinocysts *Nyktericysta* sp. and *Vesperopsis* sp. (e.g., Mao et al., 1999); with the freshwater acritach *Limbicysta* sp. (MacRae et al., 1996b) also having a common occurrence within this interval. This clearly confirms a freshwater influence in the paleoenvironmental setting represented by the Bastion Ridge Formation. As the lithology changes to ‘paper’ shale at the base of the Kanguk Formation, a turnover from brackish to marine palynomorphs occurs (Fig.10). The lowermost Kanguk Formation shows an acme of peridinioid dinoflagellate cysts (Fig. 6), thereby, suggesting that this interval is where palaeoproductivity is at a maximum (Harland, 1973). This is likely due to increased input of terrestrially derived nutrients driven by the initial transgression. Peridinioids decrease towards the Cenomanian/Turonian boundary responding to the global temperature maximum of this time (Huber et al., 2002). A low abundance of peridinioids is often associated with warm conditions (Reichart & Brinkhuis, 2003) supporting the influence of this global temperature rise on the biota of the Sverdrup Basin in Arctic Canada.

Slidre Fiord

At Slidre Fiord, the Turonian to lower Coniacian is marked by a low abundance of peridinioid dinocysts (Fig. 8), which suggests warm polar oceans continued to dominate marine ecosystems throughout this time interval. This correlates to paleotemperature curves based on

TEX₈₆ data from mid-latitudes that indicate warm sea surface temperatures during the Turonian to early Coniacian (Fig. 21; Forster et al., 2007).

Globally, *Heterosphaeridium difficile* and peridinioid cavate dinoflagellate cysts are considered typical cold-water species (e.g., Lamolda & Mao, 1999). This would connect the sudden increase and consistent dominance of *Chatangiella* species and *Heterosphaeridium difficile* within the Coniacian to lowermost Campanian interval (55 to 150 m) to the global general cooling trend which occurred from the Coniacian to the Campanian (Fig. 21; Forster et al., 2007). The sudden abundance and dominance of the peridinioid genus *Chatangiella* in the late Cretaceous was recognized across the Canadian High Arctic (McIntyre, 1974; Ioannides, 1986; Núñez-Betelu, 1994). Núñez-Betelu (1994) suggested a late Coniacian age for this *Chatangiella* acme based on the co-occurrence of the late Coniacian ammonite, *Scaphites depressus* (Hills et al., 1994). The widely recognized sudden diversification and abundance increase in *Chatangiella* points towards a basin-wide increase in primary productivity. This *Chatangiella* acme event (Fig. 20) could have developed as a result of both local and global influences. The sporomorph index indicates an increasing terrestrial input into the system at this time, resulting in an influx of continental nutrients, which could increase primary productivity. Increase in the heterotrophic peridinioids, such as *Chatangiella*, is often interpreted as an increase in primary productivity (Harland, 1973). Increased production of organic matter in the Coniacian to Santonian interval at Sawtooth Range, on Ellesmere Island, supports a rich benthic foraminiferal community that is dominated by the genus *Trochammina*; which is known to adapt to high organic matter input, with dysoxic benthic redox conditions (Davies et al., 2018). The acme of the heterotrophic *Chatangiella* (slide 8) correlates with a positive excursion in $\delta^{13}\text{C}_{\text{org}}$

and a peak in low latitude temperatures (Fig. 21 blue area), suggesting that during this time the heterotrophic ability of this taxon might have driven its abundance despite warmer temperatures.

The dinocyst genera *Manumiella* and *Isabelidinium* are often associated with cool water conditions (e.g., Askin 1988; Thorn et al., 2009). The lower to middle Campanian occurrence of *Isabelidinium svartenhukense* (Fig. 16), as well as the increasing relative abundance of *Manumiella* to the point where a middle Campanian acme occurs (Fig. 21), suggests decreasing sea surface temperatures in the middle Campanian as the Kanguk Formation continued to be deposited.

Figure 21: Comparison of sporomorph index, peridinioid relative abundance, biozonations, $\delta^{13}\text{C}_{\text{org}}$ (‰VPDB) (Davies et al., 2018) and paleoseasurface temperature from the tropical Atlantic (Demerara Rise) (Forster et al., 2007). The blue area highlights the correlation between 1) high abundances of the heterotrophic *Chatangiella* in the Sverdrup Basin, 2) positive excursions in $\delta^{13}\text{C}_{\text{org}}$ in the Sverdrup Basin and 3) a switch to cooler sea surface temperatures at Demerara Rise. See Figure 4 for lithology explanation.

It is recognized that *Manumiella* and *Isabelidinium* show increased abundance in the high-latitude northern and southern hemisphere in response to the Santonian to Maastrichtian global cooling (Nøhr-Hansen and Dam, 1997; Bowman et al., 2012; Nøhr-Hansen et al., 2016). This can explain the introduction of *Isabelidinium cretaceum*, together with *Manumiella*, at Slidre Fiord in the upper Santonian. The cooling could also account for the lower Campanian introduction and common occurrence of *Isabelidinium svartenhukense* preceding and during the middle Campanian *Manumiella* acme within the Sverdrup Basin (Figs. 15,21).

There are three climatic belts defined using dinoflagellate cyst suites that were first identified by Lenin and Williams (1980) using provincialism in Campanian peridinialean dinocysts. These dinocyst suites are: the Malloy suite (subtropical to tropical), the Williams suite (warm to temperate), and the McIntyre suite (boreal). Mao and Mohr (1992) expanded on this concept and added a fourth, Campanian to Maastrichtian, Helby suite for the higher latitudes of the Southern Hemisphere. The Williams suite is characterized by *Alterbidinium*, *Isabelidinium*, *Spinidinium* and *Trithyrodinium*. *Laciniadinium* and the large taxa of *Chatangiella* are diagnostic dinocysts of the McIntyre suite. The Helby suite is similar to the McIntyre suite with *Chatangiella* and *Isabelidinium* being common. The McIntyre suite is commonly found in Arctic localities (Arctic Canada, the Mackenzie Delta, the northern North Sea and West Greenland) as well as the Western Interior Seaway (Saskatchewan, Alberta, South Dakota, Wyoming) (Costa & Davey 1992; Nøhr-Hansen 1996; Nøhr-Hansen et al., 2016). These climatic suites were originally used to define Campanian assemblage provincialism. However, it is interesting to note that: 1) the Turonian *Surculosphaeridium? longifurcatum* Zone is similar to the Williams suite, reflecting a warm Arctic phase; 2) the assemblage defining the Coniacian to early Santonian *Chatangiella ditissima* Zone resembles that of the McIntyre suite, suggested cooling during that

time; and 3) the assemblage defining late Santonian to middle Campanian *Arvalidinium scheii* Zone has characteristics of the Helby suite. Nøhr-Hansen et al., (2016) studied the Campanian of the Labrador-Baffin Seaway and recognized the Williams suite associated with warm to temperate climates and the presence of large specimens of *Chatangiella* typical of the McIntyre suite. Their analysis, in addition to this study, shows that the Campanian bioprovinces track the dynamic, cooling, climate history of the late Cretaceous.

5.2 Response of Dinoflagellate Cysts and Acritarchs to Sea-level Changes within the Sverdrup Basin

Glacier Fiord

Previous studies of the Glacier Fiord section have identified a transition from a restricted marine Bastion Ridge Formation to a fully marine Kanguk Formation (MacRae et al., 1996b; Schröder-Adams et al., 2014). The lowermost siltstones of the uppermost Bastion Ridge Formation are dominated by the euryhaline dinocysts *Nyktericysta* sp. and *Vesperopsis* sp., which occur in freshwater and brackish habitats (Mao et al., 1999; Harris & Tocher, 2003). The non-marine acritach *Limbicysta* sp. (MacRae et al., 1996b) also has a common occurrence within this interval, supports a freshwater setting. The transition between the Bastion Ridge Formation and Kanguk Formation shows a stepwise change in the dinocyst assemblage: 1) the genus *Apteodinium*, which is closely connected with sea-level increases associated with transgression (Lebedeva, 2009), becomes common within the euryhaline assemblage; 2) *Limbicysta* sp., *Nyktericysta* sp. and *Vesperopsis* sp. disappear; and 3) a variety of marine dinocyst and acritarch

genera appear. These assemblage changes clearly show a brackish environment which is flooded and replaced by marine conditions during a late Cenomanian transgression.

Slidre Fiord

The main part of the Turonian *Surculosphaeridium? longifurcatum* Zone at the base of the Slidre Fiord section, has a moderate sporomorph index (Fig.8) and is dominated by a high diversity of chorate gonyaulacoid dinoflagellate cysts (Figs. 12, 13, 14). A higher relative abundance of chorate, gonyaulacoid cysts is often interpreted as being associated with a more open marine environment (Harland, 1973; Lamolda & Mao, 1999). *Surculosphaeridium? longifurcatum* is a predominantly offshore species which is found in high abundances in deep-water deposits, but is also known to be commonly found in low abundances in all other marine settings (Harris & Tocher, 2003). Other genera found in this interval, such as: *Cribroperidinium*, *Kallosphaeridium*, *Circulodinium*, *Laciniadinium* and *Dorocysta*, also have a wide habitat range (Lebedeva, 2009). The Slidre Fiord assemblage also includes taxa such as *Exochosphaeridium phragmites*, *Downiesphaeridium aciculare* and *Spiniferites* sp., which are known from coastal environments (Harris & Tocher, 2003; Sluijs et al., 2005). Specimens of *Impagidinium* sp., a open ocean genus (e.g., Sluijs et al., 2005), is also found within this zone. This diversity of the dinocysts suggest that the Turonian paleoenvironment is a normal-salinity, proximal continental shelf under coastal and open ocean influences (Harris & Tocher, 2003).

The various species of *Chatangiella* and *Heterosphaeridium difficile* remain very abundant, respectively, below and above the lithological change from grey shale to brown siltstone, which marks the boundary between the lower to upper member (Fig. 20). However, a

notable assemblage change at the Santonian-Campanian boundary can be observed. The first occurrences of the species *Spinidinium echinoideum* and *Laciniadinium biconiculum* are found in the 100m to 110 m interval (slide 17) (Fig. 16). The taxa *Arvalidinium scheii*, *Manumiella* sp., *Kiokansium unituberculatum*, *Isabelidinium svartenhukense* and *Chatangiella* cf. *madura* have their first occurrences in the 110 m to 120 m interval. A rapid series of diverse first dinocysts occurrence datums is common during the beginning of transgressive system tracts (Habib et al., 1992).

The Santonian-Campanian boundary interval is also marked by an increased occurrence of the open ocean dinocyst genus *Impagidinium* (e.g., Sluijs et al., 2005) (Fig. 14) suggesting a deepening of the basin at that time. Other observations supporting this late Santonian-early Campanian transgression include the presence of deep water foraminiferal indicators at the time-equivalent section at Sawtooth Range (Davies et al., 2018). These include *Ammodiscus* and the suspension feeder *Bathysiphon*.

The lower Campanian interval (150 to 190 m) is marked by a lower sporomorph index, suggesting another brief marine incursion (Fig.8). It would also explain the presence of the *Nereites* ichnosp., since this ichnotaxon can be found in pro-delta environments (Försich et al., 2007). Once the sporomorph index switches back to a terrestrial dominated input system, connected with shallowing, the mollusc *Sphenoceras patootensis* starts to occur (Fig. 4).

A high abundance of *Manumiella* is associated with regressive sea level changes (Habib and Saeedi, 2007). Davies et al. (2018) established transgressive/regressive cycles for the Slidre Fiord section, and postulated regressions peaking at the end of the Turonian, lower Upper Santonian and middle Campanian. *Manumiella* appears at the Santonian/Campanian boundary, but has an acme in the middle Campanian corresponding to the sea-level lowstand reported by

Davies et al. (2018). This event, in the 200 m to 280 m interval, is indicated the dominance of *Manumiella*, with an increase to a 55 % relative abundance, a 0.90-0.98 sporomorph index and the disappearance of the marine bivalve *Sphenoceras patootensis*, a species that avoids high sediment input regions. *Manumiella* is often associated with *Isabelidium* (e.g., Askin, 1988; Thorn et al., 2009), which also occurs at Slidre Fiord section. Both genera have been interpreted as indicators for relative near-shore, inner shelf marine environments within Antarctic Santonian and Maastrichtian deposits (Thorn et al., 2009; Castro and Carvalho, 2015), confirming paleoenvironmental interpretations suggested here.

5.3 Dinocyst assemblages and Oceanic Anoxic Events

Glacier Fiord

At Glacier Fiord, Herrle et al. (2015) reported a distinct OAE 2 signal marking the Cenomanian/Turonian boundary interval that falls into the lower Kanguk Formation. The OAE 2 interval is characterized by: 1) a very diverse, albeit with low abundance, marine dinocysts assemblage; 2) an abundance of dark, gelified (Pacton et al., 2011), amorphous organic matter; and 3) high sporomorph index values of 0.9 or above for most of the interval. The presence of gelified amorphous organic matter within the OAE 2 interval indicates the continued input of terrigenous derived organic matter in addition to marine productivity. The terrestrial portion was microbially degraded and preserved as dark, gelified, amorphous organic matter which is typical of anoxic marine environments (Pacton et al., 2011). The mixed composition of marine and terrestrially derived organic matter in this interval is also confirmed by the Hydrogen Index (Schröder-Adams et al., 2014).

5.4 Comparison of Kanguk Formation Dinoflagellate Assemblages of the Sverdrup Basin

McIntyre (1974) established three Campanian to Maastrichtian stage divisions based on the biostratigraphic ranges of pollen, spores and microplankton found within the Kanguk Formation at Horton River, District of Mackenzie. The lower Campanian division H1 (Fig. 22) is characterized by a high relative abundance of *Chatangiella victoriensis* and *Chatangiella spectabilis*. The beginning of the upper Campanian division H2 (Fig.22) is characterized by a high relative abundance of *Deflandrea* sp.3, now known as *Chatangiella ditissima*, and *Chatangiella spectabilis*. McIntyre (1974) also discovered the dinoflagellate cyst *Deflandrea* sp. 5, later named in his honour *Chatangiella mcintyre*i (Nøhr-Hansen, 1996), within division H2. The increase in abundance of *C. mcintyre*i marks the beginning of the Maastrichtian H3 division. Within this study at Slidre Fiord, *Chatangiella ditissima* was found to have an upper Coniacian to middle Campanian range, and *Chatangiella mcintyre*i was found to have an upper Santonian to middle Campanian range (Fig. 16). Therefore, the biostratigraphic age ranges of both species discovered by McIntyre (1974) can be extended within the Canadian High Arctic.

Ioannides (1986) determined the Santonian to early Paleocene Intervals I-IV and Ia-Iva at the South Coast and “Twosnout Creek” sections, respectively, of Bylot Island. Intervals I and Ia (Fig.22) were determined and correlated by a shared diverse dinoflagellate cyst assemblage which included *Odontochitina costata*, *Dinopterygium alatum*, *Isabelidinium acuminatum*, *Laciniadinium arcticum*, *Xenascus ceratioides* and *Chlamydothorella* sp. In this current study it was found that at Slidre Fiord this particular shared assemblage was present and has a Turonian to lower Campanian range (Figs, 14,16.), thereby, making a precise correlation difficult.

Figure 22: Regional correlations of dinoflagellate cyst biostratigraphic zones for the Sverdrup Basin from the Aptian to the Campanian. Cenomanian to lower Campanian biozones of Ellesmere Island and Axel Heiberg Island (Núñez-Betelu, 1994; Lenniger et al. 2014) Upper Albian to lower Cenomanian biozones of Axel Heiberg Island (MacRae, 1996). Upper Coniacian to Upper Campanian zones of Bylot Island (Ioannides, 1986). Campanian Divisions of Horton River, Mackenzie, North West Territories (McIntyre, 1974). Aptian to Albian Biozones, sensu, of samples taken from various localities within the Canadian Arctic (Pocock, 1976).

Canadian Arctic									
		Ellesmere Island & Axel Heiberg Island	Axel Heiberg Island	Bylot Island South "Twosnout Coast Creek"	Mackenzie, N.W.T	Canadian Arctic Islands	Axel Heiberg Island	Ellesmere Island	
Gradstein, 2012		Núñez-Betelu, 1994		Ioannides, 1986	McIntyre, 1974	Pocock, 1976	This Study		
72	Campanian	Upper		I	Ia	H2			
74									
76									
78	Middle								Arvaldinium scheii Zone
80									
82	Lower	Zone 4 <i>Aquilapollenites</i>				H1			
84									
86	Santonian	Zone 3 "Ibaidinium spp." <i>Odontochitina octopus</i> <i>Palaeoperidinium pyrophorum</i>	Lenniger et al., 2012						Chatangiella ditissima Zone
88									
90	Coniacian	Zone 2 <i>Chatangiella</i> spp. <i>Spinidinium echinoideum</i>	<i>Trithyrodinium vermiculatum</i> <i>Spinidinium echinoideum</i>						
92									
94									
96	Turonian	Zone 1 <i>Cribroperidinium exilicristatum</i> <i>Isabelidinium? globosum</i> <i>Apteodinium</i> spp. <i>Kallosphaeridium ringnesiorum</i> <i>Nyktericysta</i> spp.	<i>Heterosphaeridium difficile</i> <i>Chatangiella</i> spp. <i>Trithyrodinium suspectum</i>						Surculosphaeridium longifurcatum Zone
98									
100									
102	Cenomanian		MacRae, 1996						
104									
106									
108	Albian	Upper	Zone 4 <i>Limbicysta octopodiformis</i> 4B <i>Nyktericysta</i> sp. B 4A <i>N. tripenta</i> Zone 3 <i>Nyktericysta tripenta</i> 3B "5 prong" 3A "3-4 prong" Zone R Terrestrial "Regressive" Zone 2 <i>Nyktericysta davisi</i> Zone 1 Diverse assemblage <i>Subtilisphaera kalaalliti</i> , <i>Chichaouadinium vestitum</i>						Lunatadinium dissolution
110									
112									
114	Aptian	Lower							
116									
	Upper								<i>Subtilisphaera terrula</i> - <i>Muderongia</i> sp.

MacRae (1996) developed a biozonation for the Bastion Ridge Formation exposed at Glacier Fiord, Axel Heiberg Island, and proposed an Albian to early Cenomanian age for this interval (Fig. 22). The Albian biozone 1 of MacRae (1996) correlates with the top of the *Lunatadinium dissolution* zone of Pocock (1976) (Fig. 22); since they both state that *Gardodinium trabeculosum* and *Oligosphaeridium complex* are common members of their marine zonation assemblages. Biozones 3 and 4 (MacRae, 1996) were based on the dominance of the genus *Nyktericysta* sp., while his subzone 4B including the first occurrence of the acritarch *Limbicysta octopediformes* (MacRae, 1996). Recent foraminiferal data (Schröder-Adams et al., 2014), in combination with carbon isotope stratigraphy (Herrle et al., 2015) and geochronology (Davis et al., 2016), places a Cenomanian age for the Bastion Ridge Formation at the Glacier Fiord section. The present study recovered the same taxa that defined MacRae (1996) biozones 3 and 4; but utilized the revised age placement (Fig. 22).

Núñez-Betelu (1994) recognized four informal palynomorph biozones (biozone 1-4) within the Kanguk Formation at Mount Bridgman, Ellesmere Island and Glacier Fiord (Fig 22). These biozones were based on first occurrences of select taxa, terrestrial versus marine palynomorph input and dinoflagellate cyst acmes. The base of his Cenomanian to Turonian biozone 1 is noted by high abundances of poor-to-well preserved *Nyktericysta* sp.; which were interpreted as reworked material from the lower Albian to Cenomanian based on how common this euryhaline genus occurred within the lower Bastion Ridge Formation mudstones (MacRae, 1992). With the new age placement of the Bastion Ridge Formation, the amount of inferred reworking in the Glacier Fiord section becomes questionable. The remainder of biozone 1 (Núñez-Betelu, 1994) is marked by an increasing diversity of marine dinoflagellate cysts up section; which is also confirmed in this present study. Núñez-Betelu (1994) noted that the

Coniacian biozone 2, dated by the ammonite *Scaphites depressus* (Hills et al., 1994), could be recognized across the Glacier Fiord, Mount Bridgman and Remus Creek sections. It was characterized by an abundance and dominance of *Chantangellia*.

Biozone 3 (Núñez-Betelu, 1994) ranges from late Coniacian to either late Santonian or early Campanian. It is recognized by the basin-wide appearance of “*Ibaidinium* spp.”, *Odontochitina octopus* and *Spindinium* spp. “*Ibaidinium* spp.” was not published. In this author’s opinion, it is a junior taxonomic synonym of *Arvalidinium scheii* (Nøhr-Hanson, 1993). Therefore, biozone 3 (Núñez-Betelu, 1994) is correlative to the upper Santonian to middle Campanian *Arvalidinium scheii* zone of this present study. *Odontochitina octopus* was not encountered in this present study. Núñez-Betelu (1994) also characterized biozone 3 as transitional from a palynologically marine dominated to a terrestrial dominated input system with multiple new terrestrial and marine palynomorphs appearing in this interval. The description of Núñez-Betelu (1994) corresponds to the upper Santonian lower/upper member boundary of the Kanguk Formation (slide 19) of this present study (Figs. 8, 22)

The Campanian biozone 4 (Núñez-Betelu, 1994) is unique among his biozonations as being based entirely on dominance of terrestrial palynomorphs. It was noted for high abundance of the angiosperm pollen *Aquilapollenites*, *Expressipollis* spp. and *Fibulapollis* spp. Although, terrestrial palynomorphs were not a primary focus of this present study, these taxa were easily recognized and found within the Campanian of the Slidre Fiord section (e.g., Pl. 9 Fig. 17).

Núñez-Betelu (1994) attempted to further correlate his findings with those of McIntyre (1974) and Ioannides (1986) based on shared common species. However, Núñez-Betelu (1994) admitted that these correlations were difficult and only approximate. During the present study it was found that many of the taxa which were used for tentative correlations within the Kanguk

Formation by previous authors, are common long-ranging taxa that are found throughout much of the section (Figs. 13, 14,16). Therefore, attempting to use them for biostratigraphic correlations might yield confusing results.

Doerenkamp et al. (1976). reported that *Laciniadinium arcticum* and *Spongodinium delitiense* were common within the Santonian to Campanian on Banks Island. This present study found *L. arcticum* at Slidre Fiord from the Turonian to middle Campanian (Fig. 12), thus extending the high latitude occurrence of *L. arcticum* into the Turonian. This study also extended the first high latitude occurrence of *S. delitiense* down into the Coniacian (slide 4) (Fig.16).

Lenniger et al. (2014) placed biostratigraphic importance on the first occurrences of *Trithyrodinium suspectum* and *Heterosphaeridium difficile* as the markers for the upper Cenomanian and the Cenomanian/Turonian boundary, respectively. Within this study, both *T. suspectum* and *H. difficile* are present in lowermost Turonian base (slide 58), thus confirming the age of this part of the section. Both of species are present up to the middle Campanian at Slidre Fiord, hence indicating that the first co-occurrence is the most biostratigraphy useful datum, especially considering the long range of both.

The overlapping of ranges of *Trithyrodinium suspectum* and *Trithyrodinium vermiculatum* at May Point, Axel Heiberg Island, was cited as an indicator of the Coniacian (Lenniger et al., 2014). This overlap can be correlated to the upper Coniacian at Slidre Fiord (slide 6) (Fig. 13). The Coniacian first occurrence of *Spinidinium echinoideum* at May Point is in the uppermost Bituminous Member (Lenniger et al., 2014). In this study, *S. echinoideum* had an upper Santonian first occurrence at 112 m in the uppermost part of the lower member (slide 17 Fig. 16).

Given the uncertain dating techniques of the past, and that each previous study within the Canadian Arctic has reported a *Chatangiella* sp. acme, it is likely that the Divisions H1 and H2 (McIntyre, 1974), Interval I (Iodinnides, 1986), biozone 2 (Núñez-Betelu, 1994) and the *Chatangiella ditissima* zone of this study represent a correlative Coniacian to Santonian event defined by an acme in the relative abundance of *Chatangellia*.

5.5 Regional Biostratigraphic Correlations between the Arctic Region, North America and Europe

Clarke and Verdier (1967) established a biozonation for the Cenomanian to Campanian of the north Atlantic, offshore England (Fig. 23). *Cauveridinium membraniphorum* was used as Turonian biozone species for the offshore England. At Slidre Fiord, this species is also a common Turonian marker (Fig. 12). Clarke and Verdier (1967) used the first occurrence *Spinidinium echinoideum* as a late Santonian to early Campanian biomarker. *S. echinoideum* also has an upper Santonian to lower Campanian first occurrence at Slidre Fiord, which corresponds to the lower member/upper member boundary change (Fig. 16).

Figure 23: Regional correlations of dinoflagellate cysts biostratigraphic zones for the Arctic and transitional (offshore Canada and Europe) regions from the Aptian to the Campanian. Upper Albian to lower Cenomanian biozones of Axel Heiberg Island (MacRae, 1996). Cenomanian to lower Campanian biozones of Ellesmere Island and Axel Heiberg Island (Núñez-Betelu, 1994). Aptian to Albian Biozones, sensu, of samples taken from various localities within the Canadian Arctic (Pocock, 1976). Aptian to Albian and Coniacian to Upper Campanian Biozones of western Greenland (Nøhr-Hansen, 1993, 1996). Albian to Coniacian Biozones of eastern Greenland (Nøhr-Hansen, 2012). Aptian to upper Campanian Biozones of offshore eastern Canada (Williams, 1975). Lower Cenomanian to upper Campanian of Isle of Wight, England (Clarke and Verdier, 1967).

			Arctic Region			Transitional		Arctic				
			Arctic Canada		Western Greenland	Eastern Greenland	Eastern Canada	England	Slidre Fiord & Glacier Fiord			
Gradstein, 2012			Núñez-Betelu, 1994	Pocock, 1976	Nøhr-Hansen, 1993 & 1996	Nøhr-Hansen, 2012	Williams, 1975	Clarke & Verdier, 1967	This Study			
72	Campanian	Upper			<i>Isabelidium cooksoniae</i>		<i>Odontochitina operculata</i>	<i>Xenascus ceratioides</i>				
74												
76												
78	Middle				<i>Aquilapollenites</i>			<i>Pterospemopsis spinosa</i>	<i>Arvaldinium scheii</i>			
80												
82	Lower		Zone 4 <i>Aquilapollenites</i>				<i>Raetiaedinium truncigerum</i>	<i>Callaiosphaeridium asymmetricum</i>				
84												
86	Santonian	U.	Zone 3 "Ibaidinium spp." <i>Odontochitina octopus</i>		<i>Dinogymnium cf. sibiricum</i> ?		<i>Oligosphaeridium pulcherrimum</i>	<i>Spinidinium echinoideum</i>	<i>Chatangiella ditissima</i>			
88	Coniacian	U.	Zone 2 <i>Chatangiella</i> spp.									
90	Turonian	U.	Zone 1 <i>Cribrerodinium exilicristatum</i> <i>Apteodinium</i> spp. <i>Isabelidium?</i> <i>globosum</i> <i>Nyktericysta</i> spp.									
92		M.		<i>Heterosphaeridium difficile</i>	<i>Surculosphaeridium longifurcatum</i>	<i>Cauveridinium membraniphorum</i>	<i>Scrinodinium campanula</i>	<i>Surculosphaeridium longifurcatum</i>				
94		L.										
96	Cenomanian	U.							<i>Subtilisphaera kalaallitii</i>	<i>Kiokansium unituberculatum</i>	<i>Sepispinula huguonioti</i>	<i>Surculosphaeridium longifurcatum</i>
98		M.		<i>Oligosphaeridium</i> sp. 1	<i>Atopodinium perforatum</i>	<i>Nyktericysta</i> sp.						
100		Lower										
102	Albian	Upper	MacRae, 1996				<i>Lunatadinium dissolution</i>	<i>Subtilisphaera kalaallitii</i>	<i>Epelidosphaerota spinosa</i>	<i>Spindinium cf. S. vestitum</i>		
104			Zone 4 <i>Limbicysta octocodiformis</i> 4A "5 prong" Zone 3 <i>Nyktericysta hyperta</i> 3A "3-4 prong" Zone R "Tenellia" "regressive" Zone 2 <i>Nyktericysta davisii</i> Zone 1 Diverse assemblage <i>Subtilisphaera kalaallitii</i> <i>Chichauadinium vestitum</i>	<i>Rigaudella paucispina</i>	<i>Ovalidium?</i> sp. 1	<i>Odontochitina ancala</i>						<i>Wigginsiella grandstandica</i>
106												
108												
110												
112												
114	Aptian	Upper		<i>Subtilisphaera terrula-Muderongia</i> sp.	<i>Circulodinium brevispinosum</i>	<i>Leptodinium?</i> <i>hyalodemopse</i>	<i>Subtilisphaera perlucida</i>					
116												

An Aptian to Campanian biozonation scheme for offshore eastern Canada was established by Williams (1975). The first occurrence and peak abundance of *Surculosphaeridium longifurcatum* within the Turonian of offshore eastern Canada established it as a biozone defining species (Williams 1975). Williams (1975) also listed *Litosphaeridium siphoniphorum*, *Coronifera oceanica*, *Callaiosphaeridium asymmetricum* and *Areoligera* sp. as taxa which are characteristic of the eastern Canadian Turonian *Surculosphaeridium longifurcatum* biozone. Within the Sverdrup Basin, this present study found *Surculosphaeridium longifurcatum* to be common within the Cenomanian to Turonian deposits at Glacier Fiord and Slidre Fiord. The taxa listed to be common within the Turonian *Surculosphaeridium longifurcatum* offshore eastern Canada biozone by Williams (1975) are also common within the Turonian aged deposits of Slidre Fiord; thereby, indicating a similar palaeoenvironmental in offshore eastern Canada and Arctic Canada during the Turonian. Williams (1975) used *Cleistosphaeridium polypes*, now known under its senior synonym *Kiokansium unituberculatum*, as a Cenomanian biomarker for offshore of eastern Canada. During this study, one specimen was found within the Cenomanian of Glacier Fiord (Fig. 11, Bastion Ridge Pl. 2 Fig. 18). At Slidre Fiord, *Kiokansium unituberculatum* had its first occurrence during the uppermost Santonian (slide 22), but then reaches an acme in the middle Campanian, where it comprises approximately 15% relative abundance of the total dinocyst assemblage counted (Fig. 20). This would suggest that the palaeoenvironmental conditions which allowed this species to thrive in the offshore eastern Canada during the Cenomanian also occurred within the Sverdrup Basin during the middle Campanian.

The palynological biozonation for eastern and western Greenland have been determined (Nøhr-Hansen, 1993, 1996, 2012) and can be correlated to the Sverdrup Basin (Fig. 23). *Subtilisphaera kalaallitii* is a late Albian to early Cenomanian marker for both eastern and western Greenland (Nøhr-Hansen, 1993, 2012). *Subtilisphaera kalaallitii* is also common within the biozone 1 marine zone assemblage at Glacier Fiord (MacRae, 1996). Nøhr-Hansen (2012) reported a Turonian acme of the species *Heterosphaeridium difficile* within western Greenland. This study found *Heterosphaeridium difficile* present from the Turonian to the Campanian with an acme occurring in the lower Campanian (Fig. 20). Nøhr-Hansen (1996) considered the first occurrences of *S. echinoideum* and *A. scheii* as Coniacian to Santonian events within western Greenland. In this current study at Slidre Fiord, the first occurrences of these species was identified in the upper Santonian to lower Campanian, in the transition from the uppermost lower member to lowermost upper member. This suggests that the palaeoenvironmental event which created this boundary change produced a habitat within the Sverdrup Basin similar to the conditions which existed on western Greenland during the prior stages. The palaeoenvironmental conditions which allowed the introductions of these species into the Sverdrup Basin could reflect an end to the dysoxic to anoxic conditions; which appears to correlate to the Canadian Arctic-wide *Chatangiella* event discussed above.

Due to a lack of dinoflagellate cysts, and the high abundance of terrestrial palynomorph input, the angiosperm pollen genus *Aquilapollenites* spp. was used as the index fossil for the Campanian biozone for western Greenland (Nøhr-Hansen, 1993). Núñez-Betelu (1994) also noted a lack of middle Campanian diagnostic dinocysts within the uppermost part of the upper member of the Kanguk Formation sections that he examined. Therefore, Núñez-Betelu (1994) also listed *Aquilapollenites* spp. as an Early Campanian biomarker for the top of the Kanguk Formation.

This study also found a terrestrial-palynomorph-dominated section at the top of the upper member (slides 37 to 43), which contained *Aquilapollenites* spp. However, using age data established by Davies et al. (2018), this would extend the range of this zone of high terrestrial palynological input into the middle Campanian. Given the high presence of the angiosperm pollen *Aquilapollenites* spp. in both western Greenland and the Sverdrup Basin, it is likely that palaeoenvironmental conditions during the lower to middle Campanian were similar across northern high latitude areas during this time.

Chapter 6: Conclusions

Palynological studies of Cenomanian to Campanian strata within the high Arctic Sverdrup Basin were based on exposures at Glacier Fiord, Axel Heiberg Island, and Slidre Fiord, Ellesmere Island. The Glacier Fiord section represents the Cenomanian to lower Turonian interval, and the Slidre Fiord section covers the Turonian, just above the OAE 2, to middle Campanian interval. This composite section reveals a dynamic polar paleoclimate and sea-level history that influenced brackish to marine dinocyst and acritarch assemblages. This study provides the following conclusions:

1. The Glacier Fiord section exposes a Cenomanian/Turonian boundary interval with a polar expression of the globally recognizable OAE 2. The marginal marine to terrestrial environment of the Bastion Ridge Formation is defined by a high abundance of brackish-water acritarchs and dinocysts. A rapid late Cenomanian transgression deposited the ‘paper’ shales of the Kanguk Formation accompanied by a diverse assemblage of marine dinocysts. The depleted oxygen

conditions during the OAE 2 interval allows for microbial degradation of terrestrial material now preserved as gelified dark amorphous organic matter.

2. The sporomorph index suggests strong terrestrial input at Glacier Fiord within the lowermost Kanguk Formation. Whereas, at Slidre Fiord the terrestrial palynomorph input into the marine system is lower overall; but increases throughout the section as the depositional environment approaches the deltaic environment that led to the deposition of the overlying Eureka Sound Group. This increase in terrestrial influence is also reflected in the transition from bisaccate-dominated to angiosperm-dominated assemblages.

3. Dinocyst assemblage changes allowed the establishment of four biozones that are defined by first and last occurrences of zonal indicators. In ascending order, these zones include the Cenomanian to Turonian *Surculosphaeridium longifurcatum* Zone, Coniacian to Santonian *Chatangiella ditissima* Zone and the Upper Santonian to Middle Campanian *Arvalidinium scheii* Zone. These are now correlated with ages derived from carbon isotope stratigraphy and benthic foraminiferal biozones (Davies et al., 2018), adding a more refined age placement of a dinocyst zonation for the Upper Cretaceous of the Sverdrup Basin.

4. Palaeoproductivity signals are measured by increases in both peridinioid dinocysts as well as the gonyaulocoid *Heterosphaeridium difficile*. Peaks are recognized in the Coniacian (*Chatangiella* sp.), late Santonian (*Heterosphaeridium difficile*) and middle Campanian (*Manumiella* sp.); and occur after the global temperature maximum of the Cenomanian/Turonian boundary event. The Coniacian-aged peak in the relative abundance of the peridinioid genus *Chatangiella* appears to be a correlatable event across the Canadian Arctic (McIntyre, 1974; Iodinnides, 1986; Núñez-Betelu 1994). This productivity increase contributed to an increased organic-matter supply causing dysoxic to anoxic benthic redox conditions that resulted in a

dominance of the genus *Trochammina*, an agglutinated genus adapted to high organic matter input and depleted oxygen (Davies et al., 2018).

5. The integration of these new palynological results into a biostratigraphic and chemostratigraphic framework of the same sections, allows for a more constrained placement of dinocyst biozones, palaeoenvironmental changes and planktic/benthic coupling. This will aid future regional pan-Arctic biostratigraphic and event correlations and studies of paleobiogeographic pattern.

Future Work

This project was unique when compared to previous thesis which studied dinoflagellate cyst assemblages within the Sverdrup Basin, in that dinoflagellate cyst data can be directly compared to carbon isotope and benthic foraminifera data from the same section. Within the scope of this thesis it allowed for a more constraint temporal placement of dinocyst first and last occurrence datums, and high relative abundances of certain taxa, in order to establish biozones. This dinocyst biostratigraphic data will be re-examined in order determine an event stratigraphic record for the Sverdrup Basin which can be compared to more modern dinocyst biostratigraphic studies in the Arctic regions of both Canadian and Europe, eastern Canada and the Western Interior Seaway.

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Appendix A: Palynomorph Counts

Table 1: Palynomorph counts from Glacier Fiord.

Glacier Fiord							
Slide Number	Dinocysts	Acritarchs	Pollen	Spores	Bisaccates	Lycopodium	Total Palynomorphs Counted
AH 2011 C55	60	6	301	60	78	0	505
AH 2011 C54	55	6	357	28	340	0	786
AH 2011 C50	23	5	284	70	19	0	401
AH 2011 H31	29	14	320	71	123	0	557
AH 2014 H28	43	8	471	36	300	0	858
AH 2014 H24	13	7	205	33	294	0	552
AH 2014 H20	48	4	195	32	219	0	498
AH 2014 H16	12	6	222	12	245	0	497
AH 2014 H12	33	4	268	29	204	0	538
AH 2014 H8	161	8	459	35	321	0	984
AH 2014 H4	158	7	405	7	300	2	877
AH 2014 H1	118	10	398	11	468	2	1005
AH 2011 C48	102	17	453	15	213	2	800
AH 2011 C47	51	6	217	25	63	0	362
AH 2014 C19	201	146	287	8	869	2	1511
AH 2014 C15	251	91	318	26	1141	7	1827
AH 2014 C9	347	40	200	42	603	3	1232
AH 2014 C6	122	263	766	61	859	2	2071

Table 2: Palynomorph counts from Slidre Fiord.

Slidre Fiord							
Slide Number	Dinocysts	Acritarchs	Pollen	Spores	Bisaccates	Lycopodium	Total Palynomorphs Counted
AH 2014 54	342	14	1094	25	501	4	1976
AH 2014 52	141	13	1339	34	691	18	2218
AH 2014 50	378	23	972	25	575	17	1973
AH 2014 49	84	7	913	155	482	2	1641
AH 2014 48	105	2	439	19	522	2	1087
AH 2014 47	175	11	740	94	635	6	1655
AH 2014 45	327	12	709	92	364	11	1504
AH 2014 44	188	3	585	38	421	2	1235
AH 2014 43	109	13	1175	26	836	8	2159
AH 2014 42	40	4	441	33	280	4	798
AH 2014 41	83	4	2994	83	1759	9	4923
AH 2014 40	12	1	305	10	217	2	545
AH 2014 39	36	1	893	44	523	0	1497
AH 2014 38	17	2	279	17	309	1	624
AH 2014 37	324	34	2106	38	1191	35	3693
AH 2014 36	334	23	709	16	334	2	1419
AH 2014 35	339	8	439	18	138	1	942
AH 2014 34	375	13	311	30	136	1	865
AH 2014 33	435	16	219	23	120	0	813
AH 2014 32	347	18	704	31	455	13	1555

Table 3: Palynomorph counts from Slidre Fiord continued.

Slidre Fiord							
Slide Number	Dinocysts	Acritarchs	Pollen	Spores	Bisaccates	Lycopodium	Total Palynomorphs Counted
AH 2014 31	465	16	478	35	166	0	1160
AH 2014 28	315	24	380	31	165	0	915
AH 2014 26	395	10	727	69	424	3	1625
AH 2014 25	344	17	335	33	372	2	1101
AH 2014 24	486	30	647	57	537	1	1757
AH 2014 23	422	9	624	38	322	3	1418
AH 2014 22	135	17	757	159	471	2	1541
AH 2014 19	590	33	933	42	367	48	2013
AH 2014 18	408	48	1055	20	467	234	1998
AH 2014 17	423	10	757	47	427	0	1664
AH 2014 16	307	7	702	76	453	0	1545
AH 2014 15	360	8	215	23	215	0	821
AH 2014 14	374	13	608	27	337	0	1359
AH 2014 13	362	3	426	15	541	5	1347
AH 2014 11	600	22	348	100	382	0	1452
AH 2014 10	380	32	413	41	315	1	1181
AH 2014 9	401	10	381	83	148	0	1023
AH 2014 8	460	6	313	5	232	1	1016
AH 2014 7	458	4	223	13	177	0	875
AH 2014 6	471	5	136	33	143	1	788

Table 4: Palynomorph counts from Slidre Fiord continued.

Slidre Fiord							
Slide Number	Dinocysts	Acritarchs	Pollen	Spores	Bisaccates	Lycopodium	Total Palynomorphs Counted
AH 2014 4	340	29	599	88	199	0	1255
AH 2014 3	138	16	230	18	39	0	441
AH 2014 2	58	6	85	6	2	0	157
AH 2014 1	63	5	57	0	11		136
AH 2014 82	478	33	671	139	111	0	1432
AH 2014 76	76	0	41	0	45	5	16
AH 2014 75	423	45	608	45	196	0	1317
AH 2014 73	350	35	451	31	219	0	1086
AH 2014 70	378	10	367	111	114	0	980
AH 2014 69	366	10	304	35	85	1	800
AH 2014 65	680	15	896	223	495	2	2309
AH 2014 62	309	33	904	367	550	2	2163
AH 2014 61	300	22	704	123	401	0	1550
AH 2014 58	325	54	353	176	129	0	1037