AN EARLY PERMIAN SUBTROPICAL CARBONATE SYSTEM: SEDIMENTOLOGY AND DIAGENESIS OF THE RAANES AND GREAT BEAR CAPE FORMATIONS, SVERDRUP BASIN, ARCTIC CANADA

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ABSTRACT

The Early Permian (Sakmarian to Kungarian) Raanes and Great Bear Cape formations of the Sverdrup Basin were deposited at a time of ocean cooling, and are interpreted to reflect a subtropical setting. Pelmatozoans, bryozoans, and brachiopods are the predominant fossils throughout the extent of these two units, with local occurrences of large fusulinids and colonial corals. This mixed photozoan-heterozoan assemblage is similar to the sediments of modern-day subtropical settings. Although the Raanes and Great Bear Cape have warm-water rocks below, and cool-water rocks above, the fossil assemblages in these formations were dependent upon changes in oceanography and sea-level. Three distinct phases, as determined by water depth and temperature, occur. First, the rocks of the Raanes and lower Great Bear Cape are deep water and heterozoan in nature. Second, the middle Great Bear Cape limestones record a time of shallow, subtropical waters. Finally, the upper Great Bear Cape is shallow-water, but cooling had progressed to a point that precluded the occurrence of any photozoan components, regardless of depth. Due to evolutionary changes in other subtropical biota, the most reliable fossil indicator of subtropical deposition in the rock record is large benthic foraminifera (including fusulinids) in an otherwise heterozoan assemblage. The identification of limestones representative of these conditions should, therefore, be identifiable at times in the Earth's history when large benthic foraminifera lived in shallow marine environments.

The Great Bear Cape Formation subtropical facies underwent post-depositional changes that are manifest as calcite cements, iron-oxides, glauconite, and silica. Isopachous calcite cements precipitated in intraskeletal pore spaces as well as around the

outside of grains. Glauconite, which is an authigenic marine mineral, has been oxidized to iron oxide, and both minerals post-date, or are included within, the isopachous cements. The isopachous cements must, therefore, have also formed in the marine environment. Where they are precipitated around pelmatozoan fragments, these originally high magnesium calcite cements have been neomorphosed to single-crystal epitaxial cements at the same time as mineral stabilization of the biofragments. These cements then seeded the growth of further epitaxial cement in the meteoric environment.

COAUTHORSHIP

The following thesis represents the original work of the author. Credit, however, is due to Dr. Noel P. James and Dr. Benoit Beauchamp who contributed both scientifically and editorially.

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PREFACE:

THESIS OBJECTIVES

The purpose of this thesis is to describe the sedimentology and diagenesis of the Raanes and Great Bear Cape formations (Permian) in the Sverdrup Basin in detail. In particular, this work focuses on the mixed photozoan and heterozoan (‘subtropical’) assemblage of the Great Bear Cape Formation, the information this assemblage provides regarding the paleoceanographic conditions under which the sediments were deposited, and how these conditions changed through time and in response to changes in sea level. These rocks represent a critical stage of interpreted ocean cooling in the Sverdrup Basin during the Paleozoic, and therefore an understanding of these rocks is important to unlocking Permian paleoceanography.

The post-depositional changes of the subtropical facies of the Great Bear Cape are also addressed in this work. The fabrics and relative timing of the diagenetic features present are used to constrain the environment in which cements were precipitated, and can be utilized further to understand alteration processes at work on subtropical carbonates in general. Epitaxial cements are scrutinized in this study in order to shed new light on the origin of these diagenetic features. Recent work has suggested that early epitaxial cements are a phenomenon of cooler-water settings in aragonite sea times (Knoerich and Mutti, 2006). Therefore, epitaxial cements in the subtropical rocks of the Great Bear Cape, which were formed in the aragonite-saturated Permian seas, are a natural test for the above hypothesis. Understanding paragenesis, from deposition to present day, of the Raanes and Great Bear Cape formations provides further insight into limestones not readily categorized into the traditional divisions of carbonate sedimentology.

CHAPTER 1:

GENERAL INTRODUCTION

THESIS STRUCTURE

Introduction—Chapter 1 is an overall introduction to this work and provides the necessary geological background. The Sverdrup Basin is introduced and a brief history of the environmental and sedimentary changes of the basin through time is reviewed. Important background information regarding current practice of carbonate sedimentology, as it pertains to paleoenvironmental interpretations, are discussed as this is the framework for this thesis.

Sedimentology and Depositional Setting—Chapter 2 is taken from a manuscript currently in press with the *Journal of Sedimentary Research*, and describes the sedimentary facies, interpreted environmental settings, and relation to changing sea level of the Raanes and Great Bear Cape formations. The rocks are compared to rocks and sediments of Cenozoic and modern environments. The occurrence of photosymbiont-bearing large benthic foraminifera in an otherwise heterozoan assemblage are interpreted to represent a subtropical environment, and are therefore key to the identification of similar conditions throughout the rock record. Furthermore, some discrepancies between recent to modern subtropical rocks and similar rocks of the Paleozoic are addressed. In addition to the environmental interpretation of the rocks, the complexity of the carbonate facies due to sea-level fall and ocean cooling is explained. Although the rocks represent a subtropical system, the occurrence of facies representative of these environments is dependent on the presence of warm-water in shallow settings. The progression of ocean cooling, to even the inner ramp, precludes the occurrence of subtropical biota in all rocks formed in shallow waters.

Diagenesis—Chapter 3 is a description of the post-depositional history and paragenesis of the Great Bear Cape Formation subtropical facies, and has been submitted to *Sedimentary Geology* for publication. The origin of epitaxial cements around pelmatozoan fragments is considered. Early-stage pelmatozoan overgrowths were not originally single crystal cements, but were rather precipitated as isopachous rinds in the marine environment, similar to those around other bioclasts in the Great Bear Cape. The transformation of the pelmatozoan overgrowths to their current state occurred during synchronous neomorphism and mineral stabilization of bioclasts and marine cements.

Summary and Conclusions—Chapter 4 summarizes the main conclusions of the two manuscripts which comprise the bulk of the original research. The contribution of this work to the field of carbonate sedimentology and potential application of these findings to other areas forms the final segment of the thesis.

Appendix A—The appendix to the main body of this work consists of graphical representations and step-by-step descriptions for each stratigraphic section. These original field observations, combined with further data from collected samples, are the foundation of this work.

GEOLOGIC BACKGROUND

Sverdrup Basin—The Sverdrup Basin is a 1200 km long and 400 km wide rift basin located in the Canadian Arctic Archipelago. The basin contains up to 12 km of Early Carboniferous to Middle Tertiary terrigenous clastic, carbonate, and evaporite sediments deposited during eight second-order transgressive-regressive sequences

(Thorsteinsson, 1974; Beauchamp, 1994). The Sverdrup Basin was a semi-isolated tongue of the Paleopacific Ocean (Beauchamp et al., 1987). Formation of the Sverdrup Basin resulted from the faulting and collapse of highly deformed Precambrian to Devonian rocks of the Franklinian Mobile Belt (Thorsteinsson, 1974). The first marine invasion of the Sverdrup Basin occurred toward the end of the Carboniferous (Beauchamp et al., 1987). At the conclusion of active rifting and extension in Middle Permian time (Artinskian), the basin underwent passive regional subsidence until Early Cretaceous. Throughout deposition the Sverdrup Basin migrated northward from a position of about 25^{o}N during the Late Carboniferous to 45^{o}N by Latest Permian (Beauchamp and Desrochers, 1997). The Eurekan Orogeny of the Middle Tertiary deformed and uplifted the Sverdrup Basin succession, which is now exposed on Ellesmere and Axel Heiberg Islands (Thorsteinnson, 1974; Beauchamp and Desrochers, 1997). These rocks remain in the subsurface in the western Arctic, as Tertiary deformation did not significantly affect this area.

Paleoceanography—Late Paleozoic rocks of the Sverdrup Basin display a cooling upward trend (Beauchamp, 1994; Beauchamp and Desrochers, 1997; Beauchamp and Baud, 2002) that is accompanied by increasing nutrient flux (Reid et al., 2007). Carboniferous to Lower Permian (Sakmarian) rocks were deposited under warm-water conditions. Lower Permian to Middle Permian (Artinskian to Wordian) rocks accumulated in cool-water, and likely are the coolest water deposits of the Sverdrup Basin (Reid et al., 2007). The transition from warm- to cool-water in the Sverdrup Basin was geologically rapid (Beauchamp and Henderson, 1994). Finally, Middle Permian (post-Wordian) to Lower Triassic rocks were deposited in cool water with elevated nutrients (Reid et al. 2007), with bedded chert deposits throughout (Gates et al., 2004).

Ecological turnover related to cooling occured in shallow-water environments. Organisms living in colder, deep waters during deposition of warm-water shelf carbonates migrated onto the shallower shelf during times of shallow cool-water carbonate deposition (Beauchamp and Henderson, 1994). Closure of the gateway connecting the Sverdrup Basin to warm waters of the Paleo-Tethys Ocean was also responsible for the apparent cooling (Reid et al., 2007).

CARBONATE REALMS

Until the landmark works of Chave (1967) and Lees and Buller (1972), which documented carbonates accumulating in nontropical conditions, limestones were considered a tropical phenomenon. It is now accepted that carbonates can form in both tropical and nontropical settings, and are generally referenced as photozoan or heterozoan, respectively (James, 1997). Although temperature is the most often referenced control on the dominance of photozoan or heterozoan sediment accumulation, other factors such as salinity, terrigenous input, nutrients, and light are also important (Lees and Buller, 1972; Nelson, 1988; Hallock and Schlager, 1986; James, 1997; Mutti and Hallock, 2003). Regardless of the primary control, photozoan and heterozoan carbonates can be easily identified in the rock record, and further subdivided as detailed below.

Biotic Paleotemperature Indicators—Of particular importance to this study are Late Paleozoic biotic associations (Fig. 1.1). Paleozoic photozoan limestones have highly diversified chloroforam (phylloid and daycladacean algae, foraminifers, and fusulinaceans) and chlorosponge (chloroforam + calcisponges) assemblages. Heterozoan limestones have poorly diversified bryonoderm (bryozoans, echinoderms, and brachiopods) and bryonoderm extended (bryonoderm + lesser chloroforam and chlorosponge components) assemblages (Beauchamp, 1994). Cold-water or polar rocks have siliceous sponge-dominated hyalosponge assemblages, with chert being the dominant lithology (Beauchamp, 1994), but may also represent cool-water carbonates with elevated nutrients (Reid et al., 2007). The principle difference in biotic components between warm- and cool-water carbonates is the paucity or organisms dependent upon photosynthesis (Nelson, 1988).

Other Paleotemperature Indicators—Mineralogy, abiotic components, and sedimentary structures also record evidence of paleotemperature (Fig 1.1). The occurrence of aragonitic components, both biotic and abiotic, of warm-water environments is replaced by the occurrence of low magnesium calcite and siliceous components in cool-water environments (Nelson, 1988; Beauchamp, 1994). There is also a marked increase in glauconite in cool-water carbonates (Nelson, 1988; Beauchamp, 1994) which may be a reflection of slow sedimentation rates, increased trophic resources or both. Ooids and oncoids are absent from cool and cold-water deposits, whereas their presence in warm-water carbonates is common (Lees and Buller, 1972). The presence of peloids is also greatly reduced in the cool-water deposits (Lees and Buller, 1972; Nelson, 1988). Carbonates formed under cooler-water conditions lack carbonate buildups (reefs and mud mounds), and submarine cements (Nelson, 1988; Beauchamp and Desrochers, 1997).

Figure 1.1: Representation of biotic and abiotic components and mineralogy of Paleozoic rocks of Sverdrup Basin. Note changes in mineralogy and components with changing temperature. From Beauchamp, 1994.

Diagenesis—Differing characteristics of cool- and warm-water carbonates cause these units to respond differently to the influence of diagenesis. Because cool-water carbonates were originally mostly low magnesium calcite, they had a lower diagenetic potential than their originally aragonitic and high magnesium calcite warm-water counterparts. Cool-water carbonates have minimal early submarine cements compared to their warm-water counterparts. Lower seawater temperature allows for greater CO_2 content, which lowers the likelihood of precipitation of early submarine cements, and can drive carbonate dissolution (Nelson et al., 1988). When marine cements are precipitated in cool-water environments, they are likely originally intermediate magnesium calcite, precipitated at times of lowered sea level (Nelson and James, 2000). Submarine cementation is facilitated by lowered sea level because there is a relative increase in temperature and carbonate saturation of the waters (Nelson and James, 2000). The lower diagenetic potential of low magnesium calcitic cool-water carbonates, and a marine environment not conducive to abundant submarine cementation lead to a diagenetic fabric dominated by features formed during later diagenesis associated with burial (Nelson et al., 1988). The majority of porosity occlusion in cool-water carbonates is from mechanical and chemical compaction, as well as precipitation of burial cements sourced from calcite dissolved during chemical compaction (Nelson et al., 1988; James and Bone, 1989; Nicholaides and Wallace, 1997).

CHAPTER 2:

CARBONATE DEPOSITION DURING A TIME OF MID-LATITUDE OCEAN COOLING: EARLY PERMIAN SUBTROPICAL SEDIMENTATION IN THE SVERDRUP BASIN, ARCTIC CANADA*

ABSTRACT

Carbonate rocks of the Lower Permian (Sakmarian to Kungarian) Raanes and Great Bear Cape formations accumulated in the Sverdrup Basin during a critical transition period when ocean waters cooled dramatically. These rocks have many attributes similar to sediments deposited in modern subtropical zones. The biota is dominated by a heterozoan assemblage of pelmatozoans, bryozoans, and brachiopods with the addition of photozoan elements such as fusulinids and colonial corals. Associated with the change in the Sverdrup Basin from a tropical to subtropical environment is the first occurrence of glauconite, iron oxides, and storm deposits. The shift in depositional conditions is interpreted to reflect decreased seawater temperature that was brought about by a northward migration to a mid-latitude position frequented by storms. Oceanographic change, however, was not unidirectional, but was complicated by concomitant variations in sea level and oceanography recorded as three distinct phases determined by water depth and temperature. (1) Rocks of the Raanes and lower Great Bear Cape are deep-water and heterozoan. (2) The middle Great Bear Cape records shallow-water subtropical conditions with fusulinids and large colonial corals. (3) The upper Great Bear Cape is entirely heterozoan in all locations, and by implication, all depths. All post-Raanes and Great Bear Cape rocks of the Sverdrup Basin are entirely

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*From Bensing et al. (in press).

heterozoan. Taking caution for possible evolutionary changes, subtropical carbonates can be recognized in rocks much older than previously believed. The most important components for identifying subtropical carbonates of the past are large benthic foraminfers in an otherwise heterozoan assemblage, and, as such, the ability to delineate this carbonate realm in the past is currently restricted to times when large benthic foraminifers grew in shallow-marine environments.

INTRODUCTION

Carbonate deposition can be broadly divided by water temperature into two realms, warm-water photozoan carbonates and cool- to cold-water heterozoan carbonates (James, 1997). In modern environments, cool-water carbonates are those accumulating in waters colder than ~ 20^{o}C, and can be differentiated from warm-water carbonates by characteristics of their biotic associations, abiotic grains, and mineralogy (Lees and Buller, 1972; Nelson, 1988; James, 1997). The study of modern carbonates in subtropical zones that are transitional between warm- and cool-water depositional environments reveals that sediments deposited in these areas have characteristics of both photozoan and heterozoan associations (Carannante et al., 1988; Betzler et al., 1997; James et al., 1999; Halfar et al., 2006). Although these subtropical carbonates have been identified in the modern and the Cenozoic, it is yet unclear how to identify these rocks in much older rocks, such as those from the Paleozoic. The Sverdrup Basin, in the Canadian Arctic, is a prime location for studying an ancient subtropical carbonate system, inasmuch as this basin underwent oceanographic cooling through the late Paleozoic (Beauchamp et al., 1989a; Beauchamp, 1994; Beauchamp and Desrochers, 1997; Beauchamp and Baud, 2002). This study examines Lower Permian (Sakmarian-Kungurian) rocks that are transitional between Upper Carboniferous and lowermost Permian warm-water limestones and Middle to Upper Permian cool- to cold-water rocks, and, thereby record a subtropical environment of the Paleozoic.

GEOLOGIC BACKGROUND

Sverdrup Basin—The Sverdrup Basin is a 1200 km-long and 400 km-wide rift basin located in the Canadian Arctic Archipelago that contains up to 12 km of Lower Carboniferous to Middle Tertiary terrigenous clastic, carbonate, evaporite, and siliceous sedimentary rocks representing eight second-order transgressive–regressive sequences (Fig. 2.1; Beauchamp et al., 1989b; Beauchamp, 1994). Formation of the Sverdrup Basin resulted from faulting and collapse of deformed Precambrian to Devonian rocks of the Franklinian Mobile Belt by rifting during Carboniferous to Permian time, with the first marine deposition in the Middle Carboniferous (Thorsteinsson, 1974; Beauchamp et al., 1987). At the conclusion of active rifting and extension in Middle Permian time (Artinskian), the basin underwent passive regional subsidence until the earliest Cretaceous. Over the course of late Paleozoic deposition the Sverdrup Basin migrated northward from a position of about 25^{o} N during the Late Carboniferous to $35–40^{o}$ N by latest Permian (Ogg and Steiner, 1991; Golonka et al., 1994). The Middle Tertiary Eurekan Orogeny deformed and uplifted the eastern Sverdrup Basin succession, which is now exposed on Ellesmere and Axel Heiberg islands (Thorsteinsson, 1974).

This study was conducted in the northeasterly trending Fosheim–Hamilton sub-basin at the eastern margin of the Sverdrup Basin (Fig. 2.2). The sub-basin is separated from the Sverdrup Basin proper by the Elmerson high to the northwest, the Bay Fiord high to the southwest, and the Tanquary high to the northeast (Scott et al., 1991).

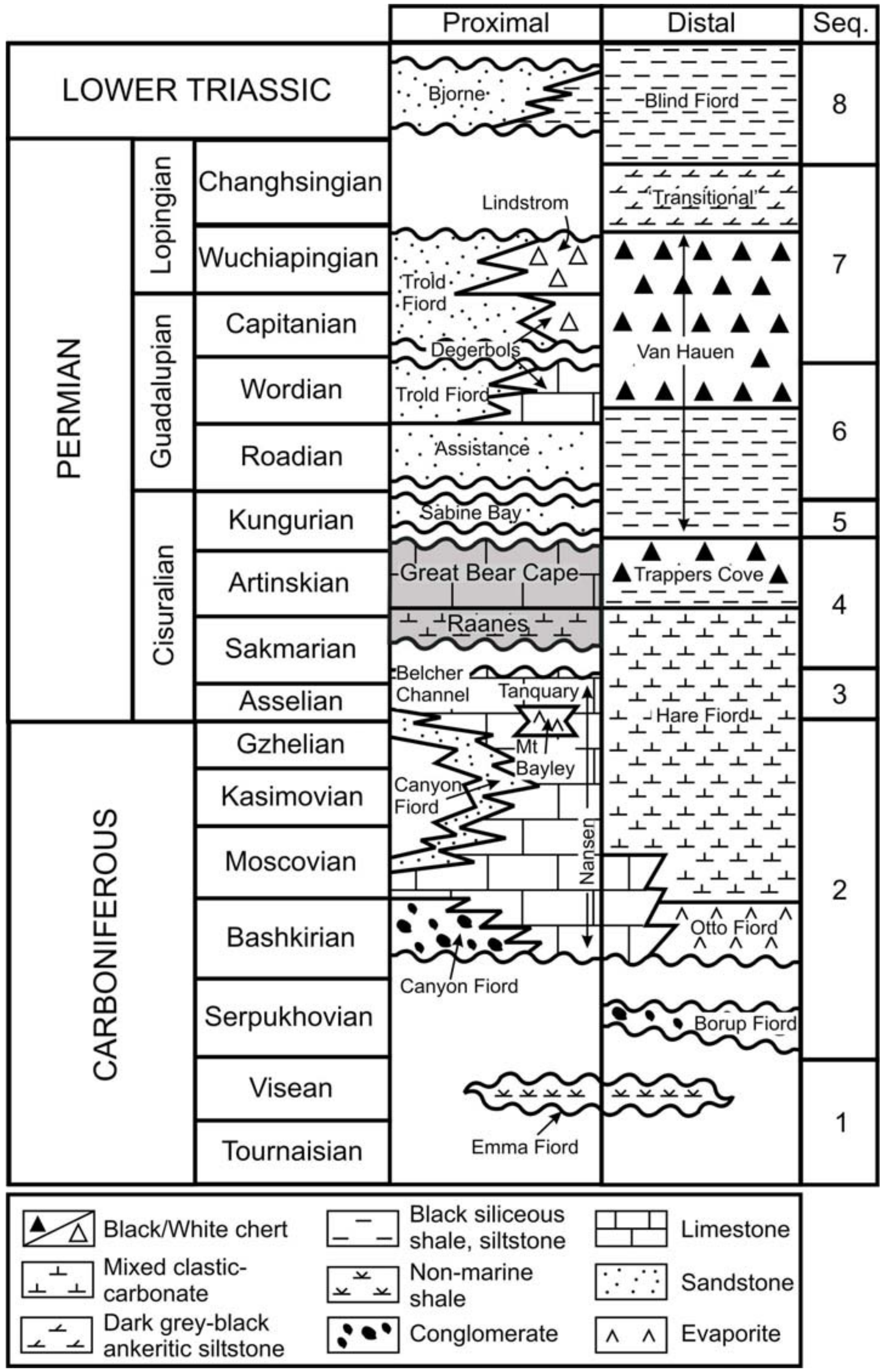

Figure 2.1: Stratigraphic section of the Paleozoic rocks of the Sverdrup Basin. Modified from Beauchamp et al., 1989a; Beauchamp and Baud, 2002. Rocks of this study are highlighted in grey. Sequence numbers (Seq.) refer to 2nd-order transgression-regression sequences. Chronostratigraphic ages are based on conodont biostratigraphy of Henderson and Mei (2000).

Evaporites in this sub-basin indicate that it was periodically enclosed or partially isolated from the Sverdrup Basin (Morin et al., 1991; Beauchamp and Olchowy, 2003). This sub-basin also lacks deeper-water rock units that are present in the Sverdrup Basin.

Limestone Associations—Biotic and abiotic components of late Paleozoic rocks in the Sverdrup Basin record a cooling-upward trend (Beauchamp et al., 1989a; Beauchamp, 1994; Beauchamp and Desrochers, 1997; Beauchamp and Baud, 2002). Carboniferous to Lower Permian (Sakmarian) rocks contain originally aragonitic components such as synsedimentary marine cements, calcareous algal reefs, micritized fossil fragments, ooids, and a fossil assemblage with tabulate and rugose colonial corals, calcareous algae, and larger foraminifera that accumulated under warm-water conditions (Beauchamp et al., 1989a; Beauchamp, 1994; Beauchamp and Desrochers, 1997). Post-Sakmarian to Upper Permian rocks formed in cool-water marine waters with calcite-dominated assemblages rich in brachiopods, bryozoans, and echinoderms with common to abundant glauconite (Beauchamp, 1994). Upper Permian rocks are dominated by spiculitic chert in all ramp locations (Gates et al., 2004). The rocks of interest in this study are those of the Raanes and Great Bear Cape formations, which were deposited from Middle Sakmarian to Early Kungurian time and are the transitional units between truly warm and truly cool-water carbonates (Fig. 2.1; Beauchamp, 1994; Beauchamp and Desrochers, 1997).

STRATIGRAPHY

Raanes Formation—In the type area on southwestern Ellesmere Island, the Raanes is an onlapping and deepening-upward unit comprising a series of meter-scale shallowing-upward rock packages representing the transgressive systems tract (TST) of a second-order transgressive-regressive sequence that spans a time period of ~ 8 My

(Beauchamp et al., 1989; Beauchamp and Henderson, 1994). In the Sverdrup Basin it ranges in thickness from a few meters to 325 meters, and is 167 meters thick at the type section on Raanes Peninsula (Beauchamp and Henderson,1994). In the Fosheim–Hamilton sub-basin the Raanes ranges in thickness from ~ 25 meters to ~ 325 meters (Scott, 1991; Beauchamp and Henderson, 1994), and is composed of recessively weathering shale, siltstone, moderately fossiliferous argillaceous limestone, and fossiliferous limestone.

The lower contact of the Raanes (Middle Sakmarian) with the underlying Upper Carboniferous to Lower Sakmarian Nansen Formation, or the Asselian to Lower Sakmarian Belcher Channel or Tanquary Formation, is locally unconformable. Where it is unconformable, the underlying unit shows signs of subaerial exposure (Beauchamp and Henderson, 1994). The upper contact of the Raanes with the Great Bear Cape Formation is conformable and marked by a gradual decrease in mudstone. Deposition occurred when terrestrial conditions were semiarid to tropical at a position of approximately 25-35^{o} N (Beauchamp and Henderson, 1994; Beauchamp and Desrochers, 1997).

Great Bear Cape Formation—The Great Bear Cape Formation (Artinskian to Early Kungurian) ranges in thickness from a few meters to 300 meters in the Sverdrup Basin, and is a resistant-weathering, pure to locally sandy and silty, highly fossiliferous limestone with local silicification (Beauchamp and Henderson, 1994). In the Fosheim-Hamilton sub-basin the Great Bear Cape ranges in thickness from ~ 17 meters to ~ 153 meters (Scott, 1991). In the type area, this unit makes up the regressive systems tract (RST) in the same second-order transgressive–regressive sequence of which the Raanes is the TST (Beauchamp and Henderson, 1994). The Great Bear Cape was deposited after active rifting during passive subsidence when the Sverdrup Basin was located at approximately 35^{o} N. The top of the Great Bear Cape is a subaerial unconformity with calcrete (Beauchamp and Desrochers, 1997), above which is the siliciclastic Sabine Bay Formation deposited in a deltaic environment.

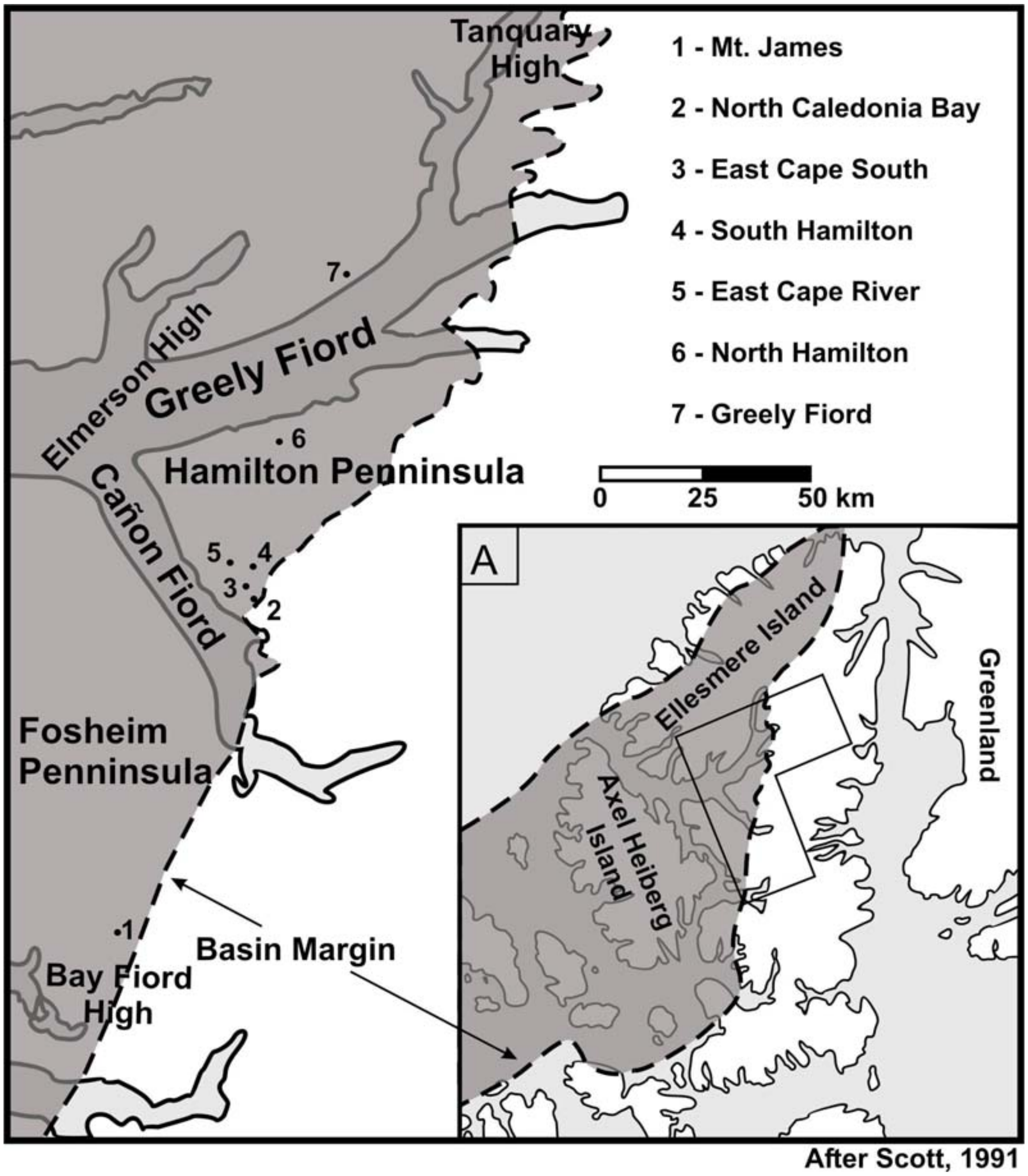

Figure 2.2: Location of study area and measured sections on Ellesmere Island, Canada. Dashed lines indicate the margins of the Sverdrup Basin.

METHODS

This study is based on six measured stratigraphic sections, and observations made at a seventh locality (Mt. James), on northeast Ellesmere Island (Figs. 2.2, 2.3) in the Fosheim–Hamilton sub-basin of the Sverdrup Basin. A total of 70 selected samples were analyzed using standard thin-section petrographic procedures. Following the procedures of Dravis and Yurewicz (1985), cathodoluminescence (CL) and fluorescence microscopy (FL) were used on neomorphosed rocks in order to better understand the original depositional character. Rocks were divided into facies based on similar lithologies and fossil assemblages. These characteristics were then used to interpret the depositional environment and water depths with regard to wave base.

LITHOFACIES

Rocks of the Raanes and Great Bear Cape formations are composed of siliciclastic mudstone, calcisiltite, limestone, and calcrete (Table 2.1). Siliciclastic mudstone is most abundant in the Raanes and is poorly fossiliferous and friable. Limestones range from silty wackestone to skeletal grainstone and floatstone of the Bryonoderm and Bryonoderm Extended assemblages of Beauchamp (1994). Descriptions of lithofacies are given below and in Table 2.1.

Raanes Formation—Siliciclastic mudstone and wackestone comprise the Raanes (RF-1; RF-2; Table 2.1). Siliciclastic-mudstone (RF-1; Fig. 2.4A) is green-weathering and poorly consolidated with rare fossil fragments. The rocks are interbedded with more resistant silty wackestone containing small pelmatozoans and brachiopods, as well as large cystoporate bryozoans. Colonial rugose corals are present at one location (South Hamilton Peninsula; Fig. 2.3). Noncarbonate material consists of siliceous sponge spicules and quartz silt. Graded bedding is rare and hummocky cross-stratification is absent.

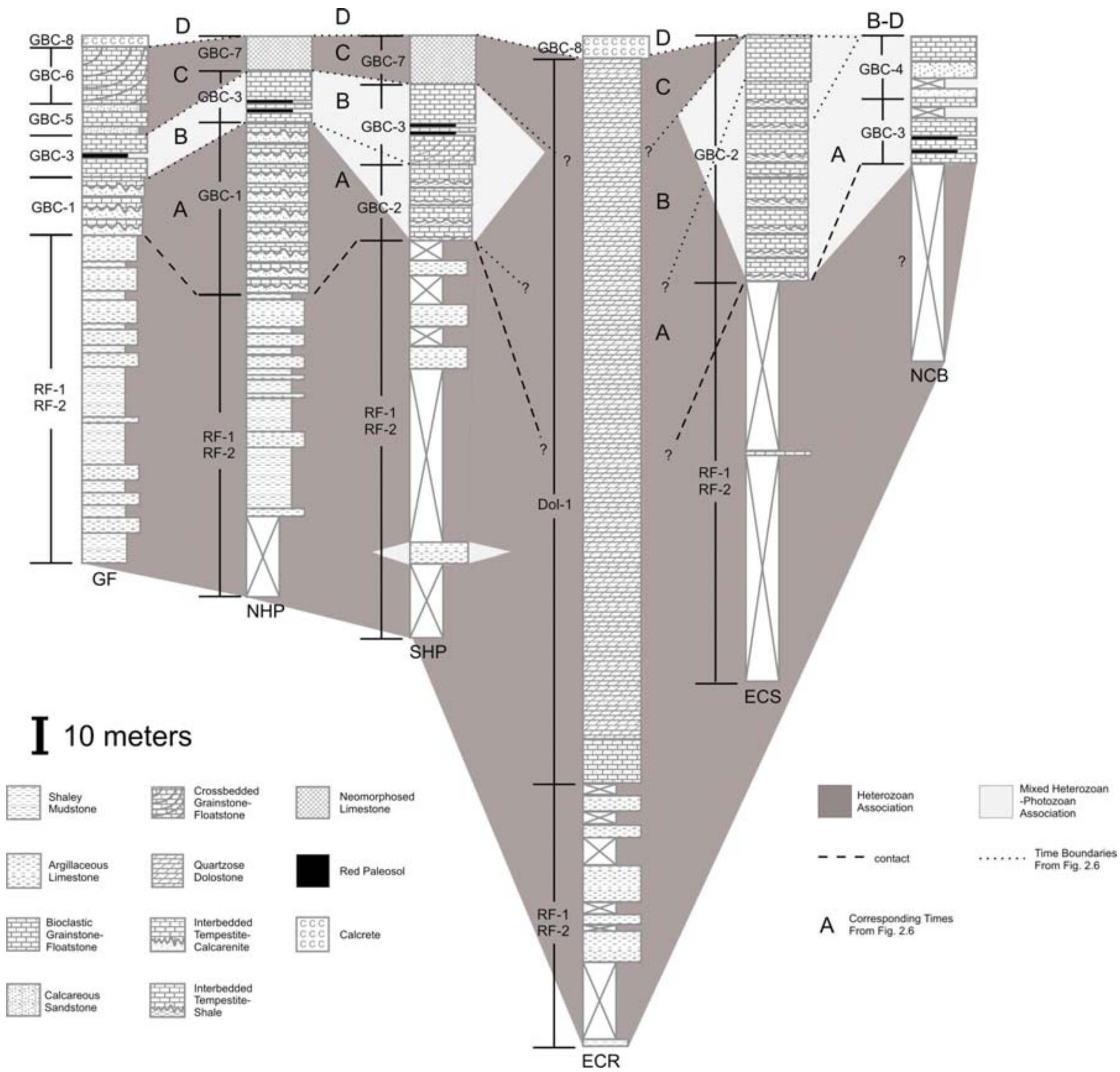

Figure 2.3: Measured sections of Raanes and Great Bear Cape formations. Locations of sections are shown in Figure 2.2. Times corresponding to those of Figure 2.6 are marked by dotted lines. Descriptions of lithofacies are found in Table 2.1.

Great Bear Cape—Rocks of the Great Bear Cape can be divided into three broad units based on biota, sedimentary features, and stratigraphic position.

Lower Great Bear Cape rocks are bioclastic grainstone and floatstone with interbedded siliciclastic units (GBC-1; GBC-2) with pelmatozoan ossicles, bryozoan fragments, brachiopods, solitary rugose corals, and siliceous sponge spicules. Colonial rugose corals (Fig. 2.4C) are found locally (GBC-2). Individual centimeter-scale grainstone and floatstone beds fine upwards (GBC-1; GBC-2; Fig. 2.5A). These beds have scoured bases and are separated by calcisiltite (GBC-1; Fig. 2.5A) or thin shale partings (GBC-2). Graded units typically have planar lamination and local hummocky cross-stratification. *Zoophycos* is present in the poorly fossiliferous calcisiltites between graded grainstones (GBC-1; Fig. 2.5C), but is absent in all other rocks. Lower Great Bear Cape rocks are not present at North Caledonia Bay (Fig. 2.3).

The middle Great Bear Cape is red-stained, locally cherty floatstone (GBC-3) with interbedded red siliciclastic mudstone. The floatstone contains colonial corals (GBC-3); most are rugose corals with one documented colonial tabulate. Bioclasts are large fusulinid foraminifera (GBC-3; Fig. 2.5F), pelmatozoan ossicles, fragmented bryozoans, and spiriferid brachiopods. Iron-rich lithoclasts composed chiefly of quartz silt, and fusulinids (GBC-3; Fig. 2.4E) are also present. The lithic fragments have overall composition similar to the matrix in which they are found. Under cathode luminescence (CL), calcisponge spicules, which are distinguished from siliceous spicules by the lack of a central canal, are present in the neomorphic spar of fusulinid-bearing units (GBC-3).

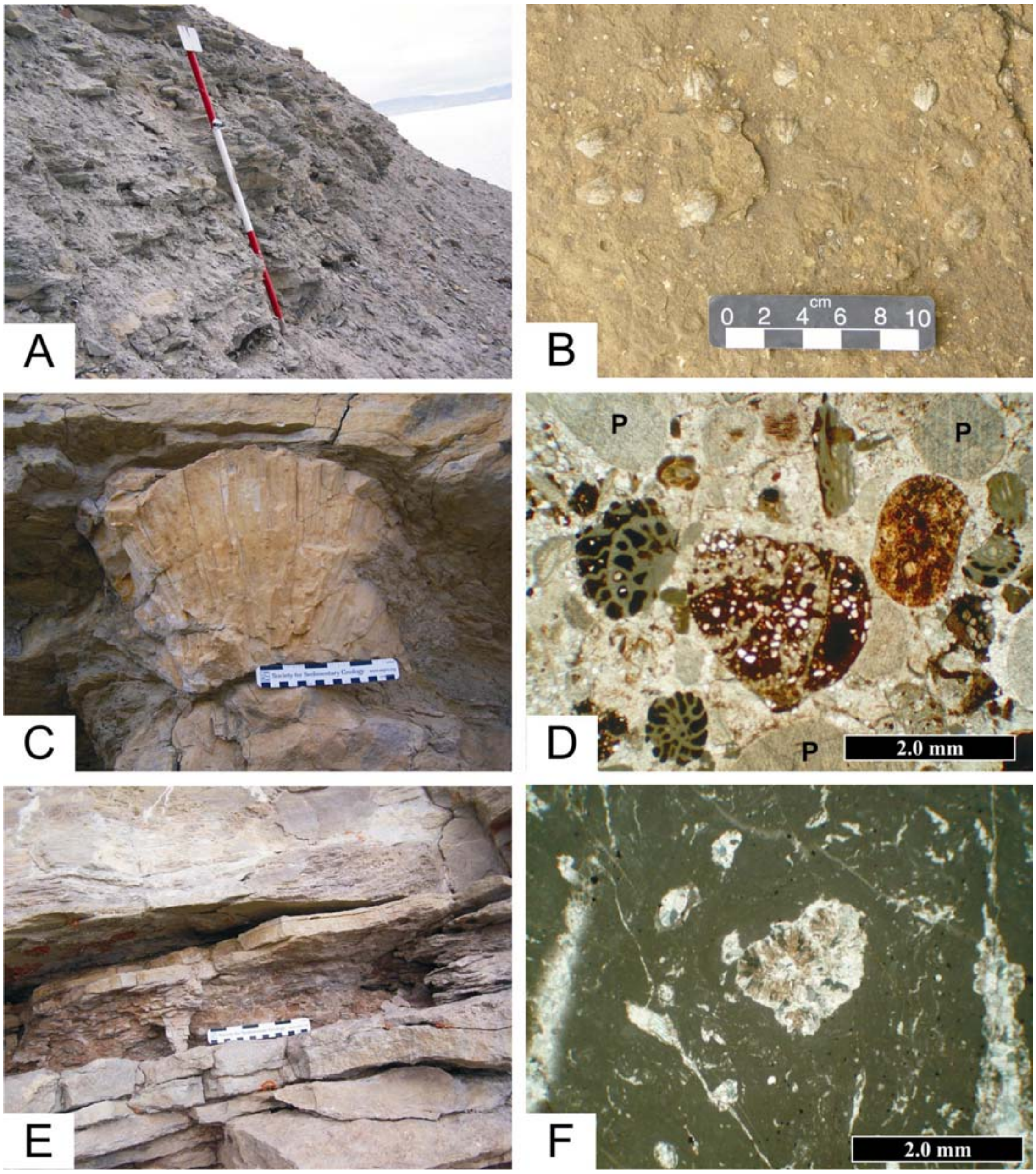

Figure 2.4: Lithologies and fossils present in Raanes and Great Bear Cape formations. A) Poorly consolidated mudstones of the Raanes. Jacob staff for scale is 1.5 m (Greely Fiord). B) Floatstone typical of mid-ramp with large spiriferid brachiopods and pelmatozoans (East Cape South). C) Large colonial rugose coral typical of Great Bear Cape. Scale bar is 15 cm (South Hamilton Penninsula). D) Photomicrograph of fusulinid intraclast floatstone with iron oxide cement and pelmatozoan ossicles (North Caledonia Bay). E) Red paleosol interbedded with inner-ramp facies rocks. Scale bar is 15 cm (South Hamilton Penninsula). F) Photomicrograph of calcrete from the top of the Great Bear Cape. Sample is micrite with some spar filled fractures and Microcodium *(Greely Fiord).*

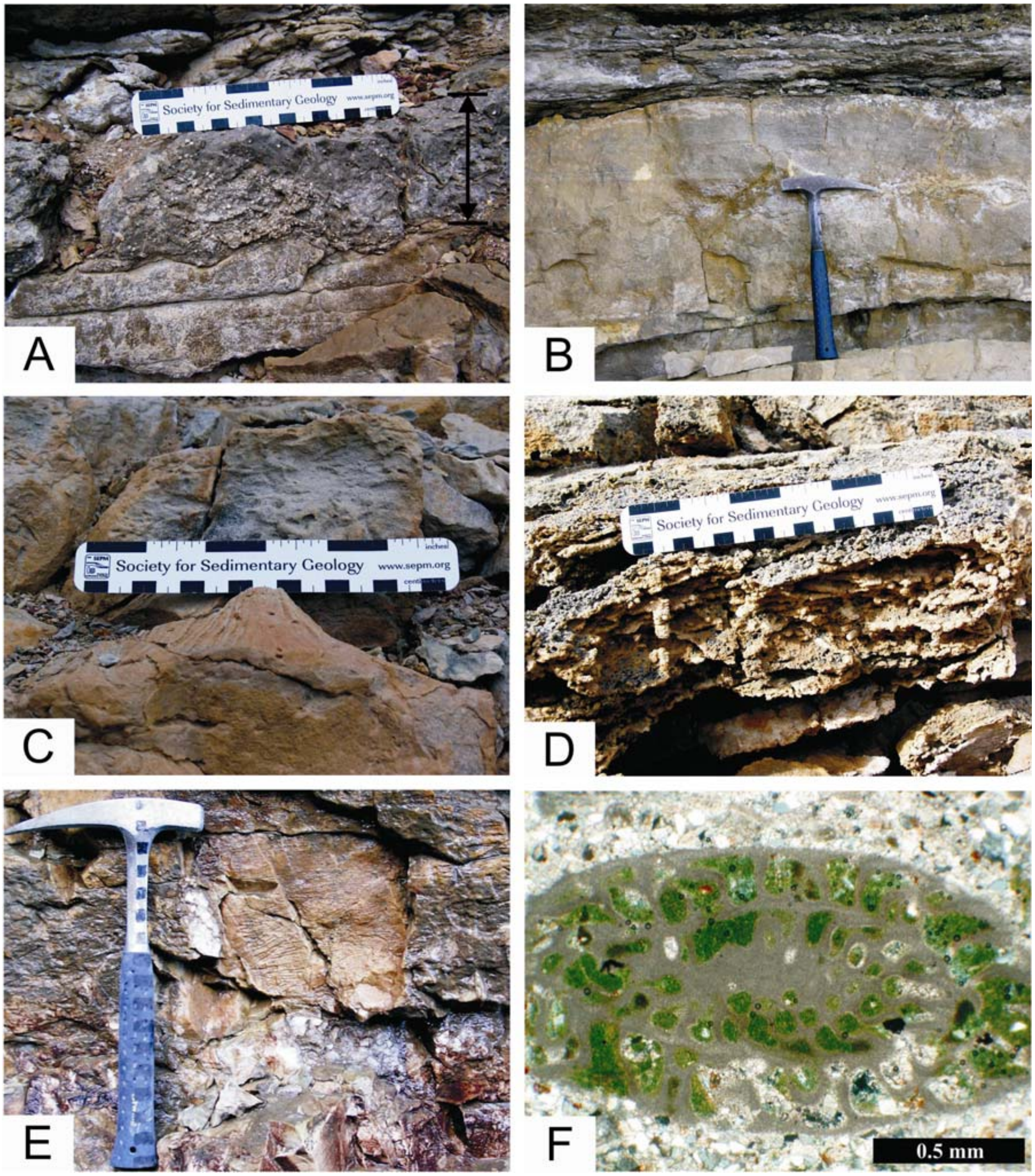

Figure 2.5: Sedimentary features present in the Raanes and Great Bear Cape formations. A) Graded tempestites with abundant pelmatozoan fragments becoming less abundant upwards. Base of bed is scoured into underlying calcisiltite (Greely Fiord). B) Hummocky cross stratification in pelmatozoan-rich grainstone (East Cape South). C) Zoophycos trace fossil in calcisiltite of Great Bear Cape (North Hamilton Penninsula). D) Thalassinoides bioturbation in recrystallized bioclastic grainstone at top of Great Bear Cape, just below the basin-wide unconformity (South Hamilton Penninsula). E) Crossbedded bioclastic grainstone (Greely Fiord). F) Glauconite filling intraskeletal porosity of a large fusulinid foraminifera (Greely Fiord).

Confirmation that these are calcisponges was made by comparing the CL pattern of these neomorphosed spicules to the CL pattern of non-neomorphosed calcisponge spicules recognized in underlying warm-water units. Middle Great Bear Cape bedding is scoured and graded, but these beds are amalgamated and lack intervening calcisiltite or shale; exceptions are locally interbedded red mudstones with columnar structure (Fig. 2.4E). Planar crossbedding is locally present in the limestone, as are *Skolithos* ichnofossils. Red staining of the limestone is caused by iron oxide filling intraskeletal porosity of fusulinids, bryozoans, and pelmatozoans, as well as in borings and rounded lithic fragments. Glauconite has a habit similar to the iron oxide, and these components locally grade into each other in the pores of a single fossil. These red-stained rocks are present at all sections except East Cape River and East Cape South (Fig. 2.3).

Rocks of the upper Great Bear Cape are more variable in composition, comprising coral–fusulinid floatstone (GBC-4), bioclastic grainstone (GBC-5), neomorphosed limestone (GBC-6; GBC-7), and calcrete (GBC-8). Coral–fusulinid floatstone (GBC-4) contains large syringoporid and rugose colonial corals in a matrix of fusulinids and pelmatozoans, and is interbedded with fusulinid-bearing calcisiltite. Fossils in bioclastic grainstone are highly fragmented pelmatozoans and bryozoans (GBC-5). Iron oxide and glauconite are present only in the intraskeletal porosity, but not in great enough abundance to pervasively stain the rocks. Quartz sandstone is interbedded within this unit. Neomorphosed crystalline limestone is locally present at the top of Great Bear Cape sections and is planar crossbedded (GBC-6) or pervasively bioturbated with *Thalassinoides* (GBC-7; Fig. 2.5D). Relict bryozoan fragments and pelmatozoan ossicles are rare in these rocks due to neomorphism. Calcrete is locally present at the unconformable contact with the overlying Sabine Bay formation. It is micritic with spar-filled fractures, *Microcodium*, and micrite-coated grains (GBC-8).

Table 2.1—Lithofacies of Raanes and Great Bear Cape Formations

Facies	Description	Interpreted Environment
RF-1: Mudstone	Poorly indurated, poorly fossiliferous, green-weathering siliciclastic mud.	Outer Ramp; deep-cool water.
RF-2: Argillaceous Wackestone	More resistant layers interbedded with RF-1. Poorly fossiliferous. Fossils = small pelmatozoans, small brachiopods, large cystoporate bryozoans, and siliceous sponge spicules. Quartz silt. *Zoophycos*.	Outer Ramp; cool water; normal marine salinity
GBC-1: Pelmatozoan Grainstone and Calcisiltite	Graded bedding with base of beds scoured into underlying calcisiltite. Grainstone has small pelmatozoan plates, brachiopods and brachiopod fragments, bryozoan fragments, and recrystallized sponges. Calcisiltite is poorly fossiliferous with large productid brachiopods and large solitary rugose corals. Abundant silt and fine-sand-size quartz. *Zoophycos* ichnofacies.	Mid-ramp; cool water; storm dominated; normal marine salinity.
GBC-2: Coral–Pelmatozoan Grainstone–Floatstone	Highly fossiliferous with pelmatozoans, spiriferid brachiopods, fragmented fenestrate and branching bryozoans, large colonial rugose corals, small solitary rugose corals. Common glauconite. Hummocky cross stratification. Thin shale partings between tempestites. Larger fossils (corals and spiriferid brachiopods) more common at bases of beds (fining upward).	Mid-ramp; subtropical, storm dominated, normal marine salinity.
GBC-3: Fusulinid–Intraclast–Pelmatozoan Floatstone	Red-stained limestone. Fusulinids, pelmatozoans, bryozoans, spiriferid brachiopods, calcisponge spicules, colonial rugose corals (smaller than in GBC-2), and colonial tabulate corals (less common than colonial rugose). Iron oxide cement, iron-cemented fusulinid intraclasts, and glauconite cements are present. Planar cross bedding. Rare *Skolithos*. Interbedded with red columnar siliciclastic mudstone.	Inner ramp; shallow, subtropical, normal marine salinity, within photic zone, low sedimentation rate.
GBC-4: Coral–Fusulinid Pelmatozoan Floatstone and Calcisiltite	Large syringoporid and rugose colonial corals with fusulinid–pelmatozoan grainstone matrix and fusulinid-bearing calcisiltite.	Inner ramp; subtropical, normal marine salinity, within photic zone.
GBC-5 Bryozoan–Pelmatozoan Grainstone and Sandstone	Interbedded biofragmental grainstone and sandstone. Skeletal grains include pelmatozoan and bryozoan fragments. Glauconite also present.	Inner ramp; shallow-cool water, normal marine salinity.
GBC-6: Planar cross-bedded Pelmatozoan Grainstone	Neomorphosed. Pelmatozoan and bryozoan fragments. Syntaxial cement overgrowths. Planar crossbedded.	Inner ramp; shallow-cool water, normal marine salinity.
GBC-7: Neomorphosed limestone	Neomorphosed limestone. Sand–size quartz grains. Thoroughly bioturbated with *Thalassinoides*.	Inner ramp; cool water, high nutrients in sediments
GBC-8: Calcrete	Micrite and micrite-coated quartz grains, spar-filled fractures, *Microcodium*.	Semiarid terrestrial environment

ENVIRONMENTAL AND SEDIMENTOLOGICAL INTERPRETATION

Depositional Processes—Deposition of the Raanes and Great Bear Cape formations is interpreted to have occurred on a storm (tempestite)-dominated ramp.

Tempestites of the Great Bear Cap have graded bedding and local hummocky cross stratification, are scoured into underlying rock units, and locally have shaly partings or calcisiltite between them (GBC-1; GBC-2; GBC-3), similar to “proximal storm layers” described by Aigner (1985). Thicknesses of individual storm beds range from ~ 5 to ~ 15 cm (Fig. 2.5A). Thin shales between event beds (GBC-2; ECS; Fig. 2.3) decrease in abundance and thickness upward in stratigraphic sections and are replaced in more proximal sections by calcisiltites (GBC-1; Greely Fiord; North Hamilton Penninsula; Fig. 2.3). Shale partings are green and poorly consolidated, similar to the thick accumulations of shale in the Raanes (RF-1). The disarticulated and fragmented nature of fossils such as pelmatozoans and bryozoans, and the presence of lithic fragments interpreted as intraclasts (Fig. 2.4D; GBC-3), indicate periodic high energy, followed by relative quiescence.

The sedimentary features can be used to make depositional divisions with respect to ramp position (cf. Burchette and Wright, 1993). The outer ramp is dominated by siliciclastic mudstone and interbedded limestone of the Raanes (RF-1; RF-2). The environment would have been below storm wave base and thus minimally affected by storm processes, allowing fine-grained siliciclastic material to settle out of suspension after large storms up-ramp. Graded bedding is uncommon and hummocky cross stratification is absent, further indicating that storm deposition did not affect the outer ramp. The mid-ramp is dominated by tempestites that have local hummocky cross stratification, and are separated by shaly partings or calcisiltite that would have been deposited during the waining energy of storms or during times of fair weather. Such mid-ramp rocks were deposited between fair-weather wave base and storm wave base. The inner ramp is characterized by amalgamated tempestites, crossbedded units, or neomorphosed limestone at the unconformable top surface of the Great Bear Cape. The shallow-water nature of these rocks is shown by their stratigraphic proximity to the exposure surface at the top of the Great Bear Cape that is marked by local calcrete (GBC-8). Red mudstones interbedded with red-stained rocks of the Great Bear Cape (GBC-3) are interpreted to be paleosols and the columnar structures interpreted as soil peds (Retallack, 2001), further supporting the interpretation of shallow-water deposition. Evidence of deposition between storm events in the inner ramp is destroyed, inasmuch as these units are amalgamated storm layers. The presence of iron-cemented lithoclasts (Fig. 2.4D) and borings in these rocks suggest the probable formation of hardgrounds during depositional quiescence, which were subsequently ripped up and redeposited during storm events.

Biota—The Raanes and Great Bear Cape, which are stratigraphically transitional between underlying warm-water rocks and overlying cool-water rocks, can be compared to modern-day transitional environments to gain a greater understanding of the conditions under which deposition occurred. Modern carbonates accumulating in subtropical zones with water temperatures transitional between tropical and temperate are influenced by environmental factors other than temperature, such as nutrients, light, and terrestrial input (Carannante et al., 1988; Halfar et al., 2006). Biotic assemblages are predominantly heterozoan with the addition of scattered, non-reef forming zooxanthellate corals, large photosymbiont-bearing foraminifera, coralline algae, and poorly calcified green algae (Carannante et al., 1988; Betzler et al., 1997; James et al., 1999; Halfar et al., 2000; Lukasik et al., 2000; Halfar et al., 2004; Halfar et al., 2006). The mixed photozoan-heterozoan assemblage present in the Raanes and Great Bear Cape is similar to such subtropical assemblages observed in modern and Cenozoic subtropical environments.

Fossils in the Great Bear Cape Formation have been subject to some post-depositional transport and represent a mixed assemblage of autochthonous and allochthonous grains. This is most evident with the fusulinids, which are present in cross-bedded units and in intraclasts. Such transported grains, however, do not significantly deter environmental interpretation because they were likely redistributed only locally during storms. All fusulinids occur in inner ramp settings, and none are present in the outer ramp, which suggests redeposition of these grains near the environment in which they lived.

Large Benthic Foraminifera—Large fusulinids of the Paleozoic are thought to have housed photosymbionts (Ross, 1974; 1977), thereby making it possible to compare them to modern large photosymbiont-bearing foraminifera. Betzler et al. (1997) suggest that large benthic foraminifera, which have calcite shells, are the most important constituent in identifying Neogene subtropical carbonates because they are preserved where other subtropical components that were originally composed of aragonite are not. Large benthic foraminifera are known from many modern and Cenozoic subtropical carbonates deposited at subtropical latitudes (Carannante et al., 1988; Betzler et al., 1997; James et al., 1999; Halfar et al., 2006). Large benthic foraminifera are indicators of well-lit waters, and can extend into slightly cooler waters than aragonitic photozoan components, such as calcareous green algae and colonial corals (Betzler et al., 1997).

Corals—Large, non-reef-forming zooxanthellate colonial corals live in modern subtropical settings. Although the presence of photosymbionts in large colonial corals of the Paleozoic, particularly the rugosans, is controversial (Coates and Jackson, 1987; Wood, 1999), the overall similarity of the fossil assemblage herein to that of the modern subtropical environment, and the abundance of colonial corals in underlying rocks and their absence in overlying rocks, suggests a transitional environment similar to modern subtropical settings. This is further supported by the presence of colonial tabulate corals, which are believed to have had photosymbionts (Coates and Jackson, 1987). In modern environments, colonial corals have an 11^{o}C temperature minimum, with reefs forming only at temperatures above ~ 18^{o}C (Veron, 1995). The large size of corals, like those of the Great Bear Cape, may be due to rapid calcification allowed by the presence of photosymbionts, or could be an adaptation to scarce food supplies (Wood, 1999). Modern hermatypic corals are also best adapted to nutrient-poor environments and become less abundant with increasing trophic resources (Hallock and Schlager, 1986).

Calcareous Algae and Palaeoaplysinids—Other photozoan constituents in modern subtropical carbonates are calcareous green algae, particularly *Halimeda* (Betzler et al., 1997; James et al., 1999). Paleozoic calcareous algae such as phylloid algae, originally composed of aragonite and high-magnesium calcite, and dasycladaceans and palaeoaplysinids, originally aragonitic (Wray, 1977; Beauchamp, 1994; Wahlman, 2002), are abundant in underlying warm-water units (Beauchamp, 1994; Beauchamp and Desrochers, 1997; Reid et al., 2007) but are rare in the Great Bear Cape assemblage. Calcareous algae are present in the Great Bear Cape formation only in the very shallow and micritic rocks at the Mt. James section, which overlies dolomitic lacustrine rocks (Scott, 1991) and may represent a uniquely warm-water environment. The scarcity of green algae in the Raanes and Great Bear Cape is a departure from the typical subtropical assemblage found in modern environments.

CONTROLLING FACTORS

Based on the biotic components typical of modern subtropical environments, the controlling factors of this ancient subtropical system can be inferred. Such factors are light, temperature, carbonate saturation, nutrients, oxygen, and terrestrial input. The interplay and relation of the factors can be complex, where a change in one factor does not occur independently of change in the others.

Light—Organisms dependent on photosynthesis make up a photozoan association, whereas non-photosynthetic organisms make up a heterozoan association (James, 1997). Therefore, lack of light may be the cause of the restricted photozoan association of the Great Bear Cape Formation, but the presence of fusulinids, colonial tabulate corals, and calcareous green algae confirms an illuminated sedimentary environment. In the modern ocean, large photosymbiont-bearing foraminifera are sensitive to light penetration (Hallock, 2001), and by implication large, photosymbiont-bearing fusulinids (Ross, 1977) would also have been sensitive in the same way. Lack of light, therefore, cannot be the cause of the restricted biota observed in the Raanes and Great Bear Cape.

Temperature—Decreased diversity of photozoan components of the Raanes and Great Bear Cape can be explained best by cool seawater temperatures. Lack of green algae might be explained by warmer temperature thresholds of modern calcareous green algae compared to the other subtropical components. Modern *Halimeda* is more sensitive to lowered temperature than are many modern large foraminifera and zooxanthellate corals (Betzler et al., 1997). *Halimeda* is restricted to warm-water environments and the warmest of subtropical environments (approximately 14.5^{o}C; Betzler et al., 1997), whereas non-reef-forming zooxanthellate corals may survive to temperatures as low as 11^{o}C (Veron, 1995). Paucity of algae in the ancient subtropical carbonates of this study may be due to temperatures below ~ 14^{o}C, although, palaeoaplysinids, which are rare in the Great Bear Cape, yet abundant in underlying Carboniferous rocks of Sverdrup Basin, are interpreted to have occurred in cooler-water settings than other contemporary algae (Wahlman, 2002). Furthermore, dasycladacean algae, which are mostly restricted to modern warm-water environments, with a few extending into the subtropical realm (Wray, 1977), are present in the Great Bear Cape at the Mt. James section. The presence of these algae suggests local environments may not have been stressed by cool-water conditions during deposition of the Raanes and Great Bear Cape.

Further information about water temperature can be gained through an understanding of the carbonate saturation of seawater, which decreases with lower seawater temperature (Morse and Mackenzie, 1990). Previous work has shown that aragonite may not be preserved beyond the marine realm due to early dissolution (Cherns and Wright, 2000; Wright et al., 2003) especially in cool-water environments (Brachert and Dullo, 2000; Smith and Nelson, 2003), despite sea water being saturated with respect to this mineral (James et al., 2005). Lack of aragonite in the Great Bear Cape may be additionally explained by the fact that most calcareous algae, and other aragonitic components, are preserved by the formation of early micrite envelopes, a process not observed in modern environments below temperatures of ~ 20^{o}C (Betzler et al., 1997). Furthermore, modern *Halimeda* from subtropical environments are poorly calcified to non-calcified, and although they may live in such an environment, they do not contribute to the surrounding sediment (James et al., 1999). The only rocks containing calcareous algae in the Great Bear Cape are also the only inner-ramp rocks that contain micrite at Mt. James. Therefore, it is probable that these rocks more closely reflect the original biotic composition due to early preservation of aragonitic components. The general absence of calcareous green algae in the ancient subtropical environment is interpreted to be the result of weak calcification and taphonomic loss, and as such the absence of these components from the rock record does not contradict the interpretation that the Raanes and Great Bear Cape rocks represent an ancient subropical system. Preservation of fusulinids, which are calcitic, further suggests that the absence of other warm to subtropical components is because of early aragonite loss (Betzler et al., 1997) due to early dissolution as observed in the modern environment (James et al., 2005). Lack of abiotic precipitates, such as synsedimentary marine cements and ooids, also supports the notion that these rocks were deposited at a time of lowered carbonate saturation due to cooler water temperatures.

Terrigenous Input, Sedimentation Rates, and Salinity—The input of terrigenous sediment can inhibit production of photozoan components and lead to a fossil assemblage similar to that found in cool-water by decreasing light penetration and disrupting suspension-feeding organisms (Hallock, 2001; Halfar et al., 2006). Rocks of the Raanes and Great Bear Cape contain siliciclastic material, indicating terrigenous input (RF-2; GBC-1), which would have affected the living biota. Colonial corals are present, however, suggesting that this stress was not significant (Hallock, 2001). According to Hallock (2001), terrigenous mud and accompanying nutrients have a greater destructive range on modern coral development than do coarser sediments. In modern environments colonial corals are not greatly affected by coarse siliciclastic sediments that are only periodically introduced during storm events (Halfar et al., 2006). Therefore, storm-derived siliciclastic sand in the Great Bear Cape would probably not have been a significant stress on the large colonial corals. Furthermore, the abundance of corals, pelmatozoans, and fusulinids argues against any significant salinity stresses due to dilution by fresh-water runoff, which may accompany the input of terrigenous material.

Further information about terrigenous input and accumulation rates of the Raanes and Great Bear Cape can be gleaned from the presence of green marine clays and iron oxides. Textural similarity between glauconite and iron oxides in the Great Bear Cape, and gradation between glauconite and iron oxide in single fusulinid tests, suggests that these minerals are genetically related. Hydrated ferric oxides are a known alteration product of green marine clays in the marine environment when placed in contact with oxidizing waters, and this process is particularly rapid in subtropical environments (Odin and Fullagar, 1988). Green marine clay, such as glauconite, typically reflects slow sedimentation and low-energy conditions, which are commonly found at flooding surfaces, far from paleoshorelines, or at hardgrounds (Odin and Matter, 1981; Kelly and Webb, 1999). Iron for these minerals can be sourced from lateritic soils introduced by fluvial input (Odin and Matter, 1981; Thamban and Rao, 2000). In this study, glauconite is found in the regressive shallow-water Great Bear Cape rather than in deeper-water units. Glauconite was likely able to develop due to periods of slow sediment accumulation rates and low energy between storm events as indicated by the shaly partings between tempestites. Iron was probably sourced from contemporaneous iron-rich soils (GBC-3) such as those found interbedded with red-stained, shallow-water units

(GBC-3) of the Great Bear Cape and above the calcrete at Greely Fiord. Such iron could come from wind blown soil, or from terrestrial material introduced to the marine realm during periodic storms. Quartz silt and sand in the Great Bear Cape (GBC-1; GBC-5) indicates that there was some terrestrial input. Coastal setup associated with storms raises water level at the shore (Aigner, 1985) and any return flow could likely be the source of periodic terrigenous input. Furthermore, storm activity introduces terrestrial material to the marine environment by increasing runoff (Halfar et al., 2006). Iron-cemented intraclasts are likely clasts of hardgrounds that formed at times of low energy and slow sedimentation, but were subsequently ripped up and slightly reworked by high-energy storms. Hardgrounds with iron oxides and glauconite are found in recent carbonates due to slow accumulation rates and extended exposure to sea water, which is common in cool-water environments (Odin and Matter, 1981; Nelson and James, 2000). Iron-filled borings are also present in Great Bear Cape rocks associated with these intraclasts, which further supports a marine hardground precursor to the intraclasts (Nelson and James, 2000).

Nutrients—Increased nutrients, rather than decreased temperature, can lead to the development of a heterozoan association (Hallock and Schlager, 1986; James, 1997; Lukasik et al., 2000). The glauconite and associated ferric oxides may indicate elevated nutrients in the form of iron (GBC-2; GBC-3; GBC-5); however, glauconite typically forms in a “semi-confined micro-environment” that is different from the surrounding sea water (Odin and Matter, 1981). Furthermore, iron from oxides derived from terrestrial soils would need to become biologically available to be considered a nutrient. The presence of iron-bearing minerals, therefore, does not necessarily confirm high iron (nutrients) in sea water. Infaunal bioturbation, which is also an indication of increased trophic resources in sediments, is present in the Great Bear Cape as *Zoophycos* (GBC-1), and as such is evidence of increased nutrients in the Sverdrup Basin. Nutrient input is often tied to other parameters, such as temperature and salinity. Whereas upwelling increases nutrients, yet decrease temperature, runoff increases nutrients, but decreases salinity, and evaporation concentrates both nutrients and salinity (Hallock and Schlager, 1986). Furthermore, lowered temperature decreases an organism's metabolic rate and nutrient requirements, potentially leading to a relative increase in nutrients (Hallock et al., 1991; Brasier, 1995). The presence of corals, pelmatozoans, and fusulinids argues against any salinity stresses. Cooling with accompanied eutrophication might explain the increase in nutrients (Hallock and Schlager, 1986), but the increase of non-photosynthetic filter feeders in the Great Bear Cape compared to older rocks suggests a true increase in nutrients. Lack of ooids and synsedimentary cements, which are dependent on carbonate saturation, and thus temperature, suggests that excess nutrients were not a more significant stress than decreased temperature.

Summary of Climatic Setting and Sedimentology—Depositional features, combined with paleogeographic reconstructions, allows refinement of oceanographic settings for the Sverdrup Basin during deposition of the Raanes and Great Bear Cape formations. It is probable that sea-water temperatures similar to those at modern subtropical latitudes were present during the transitional period between warm-water and cool-water carbonate deposition. Accepting that modern environments could be broadly representative of the past, the overall mixed photozoan–heterozoan association of the rocks, the localized occurrence of green algae, and the absence of micritic envelopes and abiotic precipitates argues against consistent temperatures greater than 20°C. It is possible, however, that summer temperatures were greater than 20°C, as demonstrated by the presence of colonial corals and fusulinids. These constituents, as well as calcareous green algae, also imply that water temperatures would not have been less than ~ 14°C for extended periods of time (Betzler et al., 1997). It is thus probable that there was temperature seasonality similar to modern subtropical environments where summer temperatures facilitated the presence of warm-water components, but winter temperatures would be prohibitive of all warm-water components.

Other attributes that are common but do not alone define modern subtropical to temperate environments are also present in the Great Bear Cape; specifically the recurring storm deposits and calcrete. Whereas large storms are present in the form of large cyclonic depressions (hurricanes and cyclones) in the tropics, the mid-latitudes, where subtropical sediments are common, are locales of recurring annual winter storms and attendant sediment reworking. Likewise even though calcrete is present in the tropics it is particularly evident in the semiarid, mid-latitude belts (Esteban and Klappa, 1983).

SEQUENCE STRATIGRAPHY

Deposition of the Raanes and the Great Bear Cape formations in the Sverdrup Basin occurred during a second-order rise and fall of sea level, respectively (Sequence 4; Fig. 2.1; Beauchamp and Henderson, 1994). In the Raanes of the Fosheim–Hamilton sub-basin, however, relative sea-level changes were tectonically controlled. No true maximum flooding surface showing abrupt increase in water depth, more basinal deposits, or evidence of condensed sections, such as hardgrounds or layers rich in pyrite or phosphate (Loutit et al. 1988), are present. Previously, a thin siltstone unit at the contact of the Raanes and Great Bear Cape was regarded as the maximum flooding surface (Beauchamp and Henderson, 1994); however, in this study there is no evidence of a siltstone significantly different from the thick shaly mudstone of Raanes (RF-1) at the contact. Furthermore, there is an increase in the frequency and thickness of limestone units (RF-2) at the top of the Raanes suggesting that shallowing began well before the contact between the Raanes and the Great Bear Cape. Therefore the maximum flooding surface in the Fosheim–Hamilton sub-basin is probably lower in the section, where exposure is poor. Shallowing is shown by a decrease in siliciclastic mudstone (RF-1) and an increase in limestone (RF-2).

The Raanes comprises a succession of meter-scale siliciclastic mudstone packages (RF-1) each of which is a parasequence that grades upward from siliciclastic mudstone to limestone (RF-2). The top of each parasequnce is sharp and overlain abruptly by siliciclastic mudstone of the next package. These parasequences could have been a response to tectonic pulses during rifting that accompanied deposition of the Raanes (cf. Scott, 1991; Beauchamp and Henderson, 1994), and are herein interpreted as such, because they are not stratigraphically uniform (Fig. 2.3).

The shallowing nature of the Great Bear Cape is demonstrated by an increased proportion of richly fossiliferous limestone, crossbedded units (GBC-3; GBC-6), paleosols (GBC-3), and local calcrete towards the top of the formation (GBC-8). Paleosols interbedded with rocks of the mid–Great Bear Cape indicate brief periods of exposure during deposition. Basin-wide exposure at the top of Great Bear Cape is inferred from calcrete at even the most basinal section (East Cape River).

Lithofacies Tthrough Time—Raanes and Great Bear Cape lithofacies change upward from deposition of heterozoan-dominated sediments (RF-1, RF-2), to mixed photozoan-heterozoan carbonates, and finally, a return to a heterozoan association (Fig. 2.3; Fig. 2.6). This progression is observed at all localities except the most inboard section (North Caledonia Bay; Fig. 2.3), which contains only subtropical carbonates, and the most basinal section (East Cape River; Fig. 2.3), which was pervasively dolomitized, destroying all biotic components. Furthermore, dolomite at East Cape River is fine grained and contains fine-grained siliciclastic material, with no relict fabrics that suggest warm-water components were ever present. These rocks also lack evidence suggesting that they were similar to other lithofacies of the Great Bear Cape observed in this study. The interpreted temperature progression was due to shallowing in the semirestricted Fosheim–Hamilton sub-basin, which may have been temperature stratified. Because of this confinement and possible temperature stratification, global-scale climatic changes driven by eustasy can not be recognized in these rocks.

Middle Sakmarian to Early Artinskian (Raanes to Early Great Bear Cape)—Sediments during this time have both cool and subtropical assemblages (Fig. 2.3; Fig. 2.6A). The outer ramp is characterized by siliciclastic mudstone (RF-1) and interbedded wackestone (RF-2) with cool-water fossil assemblages representing deposition in cool, deep water (East Cape River; Fig. 2.3). Biota in the mid-ramp (lower Great Bear Cape) is heterozoan (GBC-1; Greely Fiord; North Hamilton Peninsula; Fig. 2.3), with the exception of some sections that have large colonial corals but lacks the fusulinids of more inboard sections (GBC-2; South Hamilton Peninsula; East Cape South; Fig. 2.3). Inner-ramp facies from North Caledonia Bay contain abundant fusulinids and colonial corals. (GBC-3; GBC-4; Fig. 2.3).

Middle Artinskian (Lower to Mid–Great Bear Cape)—Shallowing occurred during this time, as demonstrated by the interpreted presence of shallow-water, inner-ramp rocks that are interbedded with red paleosols overlying mid-ramp rocks. Red-stained limestone facies restricted to near the basin margin (North Caledonia Bay) during the mid Sakmarian to Early Artinskian is located in more outboard sections (mid-basin) during Middle Artinskian due to the relative fall in sea level (GBC-3; GBC-3; Figs. 2.3, 2.6B; Greely Fiord; North Hamilton Peninsula; South Hamilton Peninsula). Red-stained limestone is interbedded with red paleosols, indicating brief intervals of exposure, possibly related to higher-order sea-level changes overprinted on overall shallowing. The most inboard areas (North Caledonia Bay) may have been exposed during this time of lowered sea level. This is the final occurrence of mixed photozoan–heterozoan facies, inasmuch as all sediments deposited after this time show no warm-water characteristics.

Late Artinskian to Early Kungurian (Upper Great Bear Cape)—Deposition was entirely characterized by heterozoan carbonates in all facies and by implication at all depths (Figs. 2.3, 2.6C). This is especially important in the inner-ramp setting, where, despite shallow-water conditions, there are no photozoan components (GBC-6; GBC-7). These attributes indicate that environmental change during the Early Permian eventually resulted in the accumulation of heterozoan carbonates at all depths. Local calcrete (GBC-8; Greely Fiord; East Cape River) and other signs of exposure, such as micrite-coated grains at the top of the Great Bear Cape, confirm exposure of the basin at this time (Fig. 2.6D).

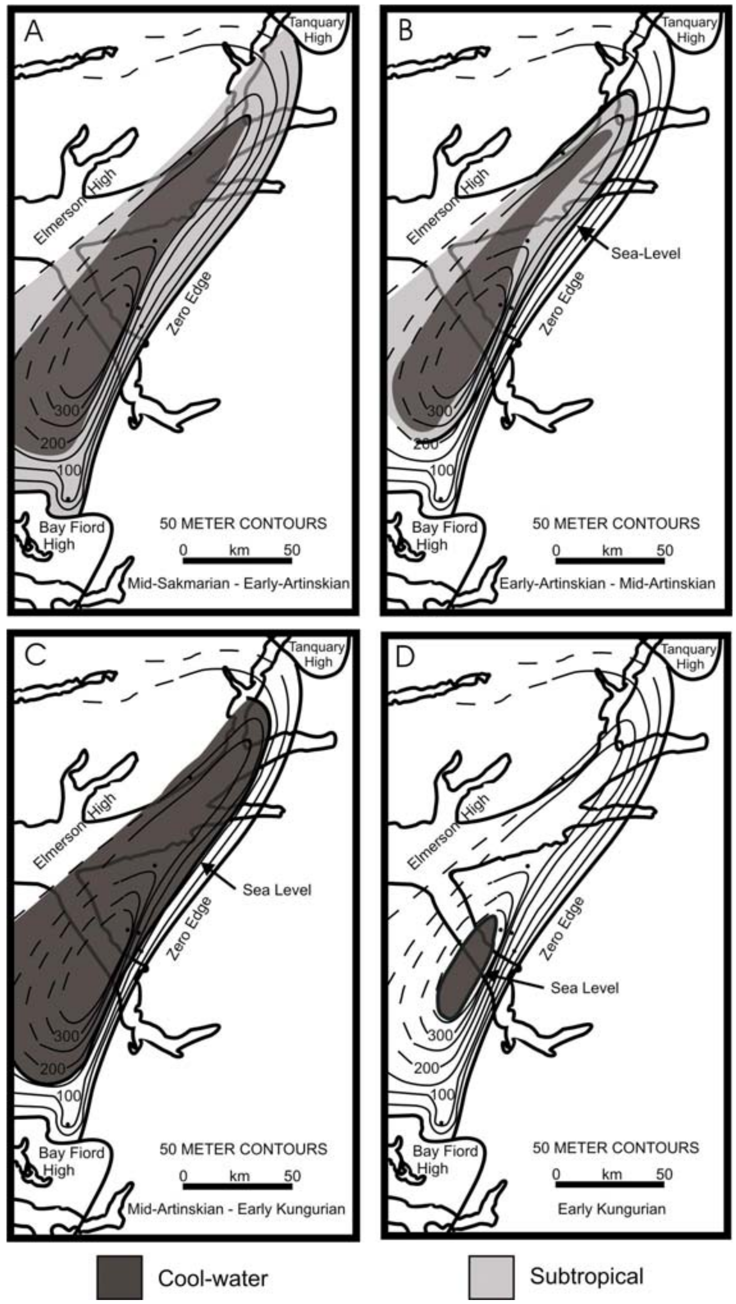

Figure 2.6: Paleobathymetry map of study area with interpreted changes in sea level and sea-water temperature through time. A) Sakmarian to Early-Artinskian. Cool-water in mid- and outer-basin. Subtropical conditions near the basin margin. B) Early-Artinskian to Mid-Artinskian. Time of third-order sea-level fall. Cool-water conditions persist in outer-basin. Mid-basin has subtropical conditions in areas that were previously cool-water. Basin margin is exposed, and sedimentation ceases before oceanographic cooling effects shallow waters. C) Mid-Artinskian to Early-Kungurian. No evidence of subtropical conditions remain. Cool-water deposits occur at all depths. D) Early-Kungurian. Lowered sea level exposing all sections studied.

SUBTROPICAL CARBONATES AND THE ROCK RECORD

Recognizing carbonate environments throughout the geologic record comes with the caveat of evolutionary change. If it can be assumed that fossilized organisms of the past, such as fusulinids, colonial rugose and tabulate corals, and phylloid algae, had the same life habits as similar modern organisms, such as large benthic foraminifera, colonial scleractinid corals, and calcareous algae, then it is possible to distinguish subtropical carbonates in the geologic record. Large benthic foraminifera are particularly important to in this regard because their lowest temperature threshold marks the limit of subtropical conditions and their calcite test makes them more likely to be preserved than aragonitic algae (Betzler et al., 1997). Fusulinids are comparable to modern large foraminifers because they are believed to have housed photosymbionts (Ross, 1977), a trait that Paleozoic colonial corals may not have possessed (Wood, 1999).

Identification of Paleozoic subtropical carbonates is based on the presence of fusulinids in a stratigraphic succession that is otherwise heterozoan in nature (Fig. 2.7). Furthermore, the ability to delineate such carbonates confidently is therefore restricted to the late Paleozoic and the Late Triassic to Holocene, which are times when large benthic foraminifera lived in shallow-marine environments (Ross, 1974). For rocks deposited during periods when these key organisms were not present, particularly the early to middle Paleozoic, it is currently not clear how to identify the subtropical carbonate depositional realm, because there is currently no recognized link to the modern environment.

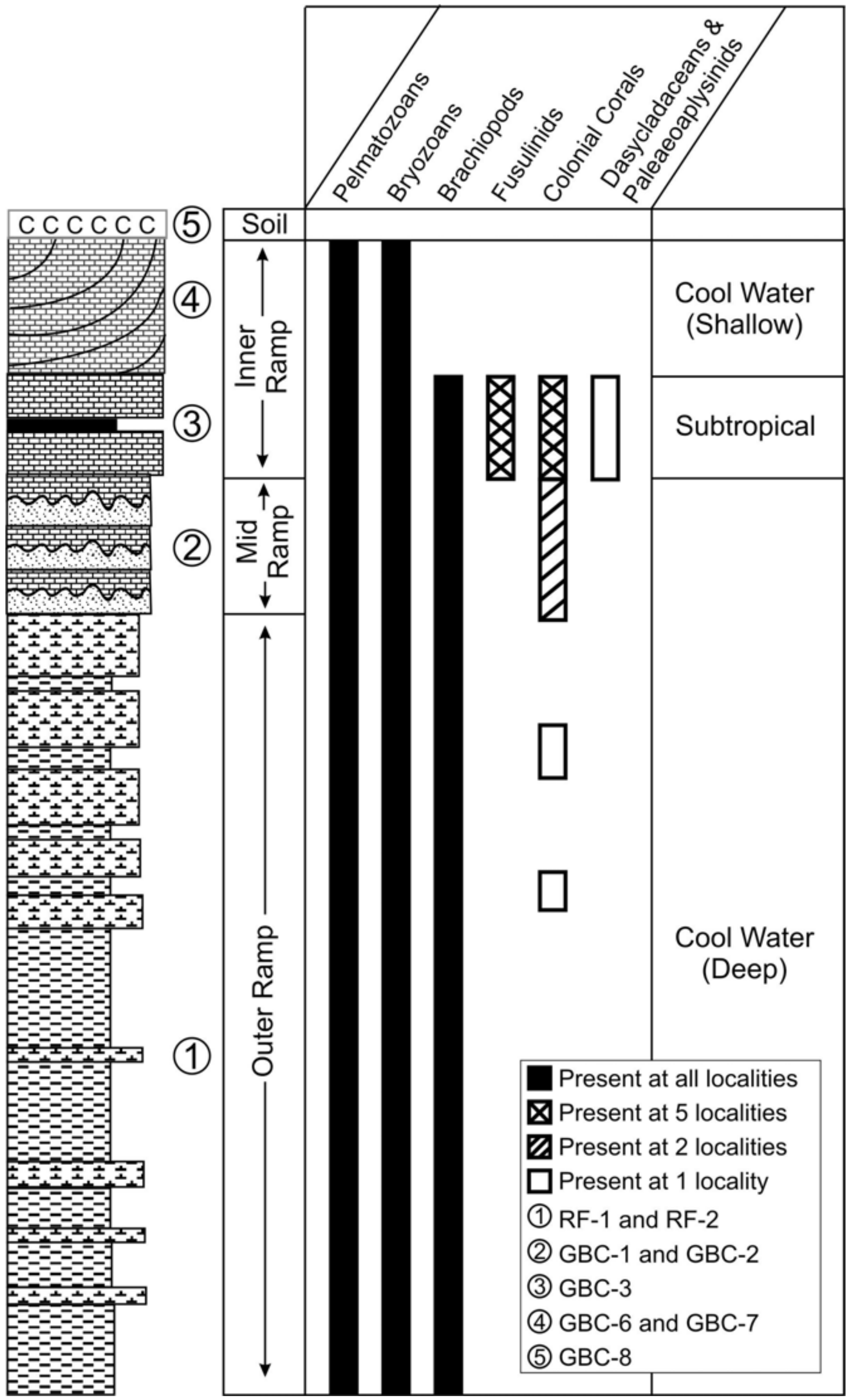

Figure 2.7: Summary chart and idealized stratigraphic section showing the distribution of important fossils in the Raanes and Great Bear Cape formation. Heterozoan components are present throughout the succession, whereas fusulinids are restricted to shallow-water, subtropical carbonates. The stratigraphic restriction of fusulinids to subtropical carbonates, as well as their widespread occurrence in the basin, makes them the best indicator of subtropical carbonates.

CONCLUSIONS

1. The Raanes and Great Bear Cape formations accumulated during a time of prolonged sea-level fall and ocean cooling. They contain the last evidence of what was a persistent warm-water biota during the preceding Carboniferous and early Permian. The succession is, however, not one of unidirectional cooling. Lower Raanes Formation and lower Great Bear Cape sediments are deep-water and cool-water. The middle Great Bear Cape is neritic but subtropical, whereas upper Great Bear Cape is similarly neritic but cool-water. This sediment mosaic illustrates the complexity to be expected at the boundary between major carbonate depositional realms.
2. Criteria for recognizing subtropical carbonates of the Cenozoic as first proposed by Betzler et al. (1997) can be extended into the ancient rock record. Late Paleozoic subtropical neiritic carbonates can be recognized primarily by the presence of large fusulinids in an otherwise shallow-water heterozoan assemblage. Other warm-water components such as colonial corals can also be present but are equivocal evidence for subtropical conditions.

ACKNOWLEDGMENTS

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CHAPTER 3:

MARINE ROOTS FOR METEORIC CEMENTS: NEOMORPHISM AND NEW INSIGHT INTO THE ORIGINS OF EPITAXIAL CEMENTS*

ABSTRACT

Diagenetic fabrics of subtropical rocks in the Early Permian (Artinskian-Kungurian) Great Bare Cape Formation consist of calcite cements, iron oxide and glauconite, and silica. Calcite cements are manifest as isopachous rinds lining intraskeletal pore space and coating the outsides of grains, as well as optically continuous epitaxial cements around pelmatozoan fragments. Two stages of epitaxial cement are recognized with an early, inclusion-rich stage, and a later, more volumetric clear stage. The relict fabric, and cathode-luminescence patterns of the early stage of the optically continuous cements are similar to the isopachous rinds seen elsewhere in the Great Bear Cape, and similar marine origins are interpreted for both. These calcite cements clearly predate, or have inclusions of, iron-oxide and glauconite, which are of marine origin. Furthermore the early calcite cements have a patchy-dull luminescent pattern similar to that of the bioclasts around which they are precipitated, indicating that they were present prior to neomorphism. Based on these observations, the isopachous cements, and early stage of optically continuous cement around pelmatozoans are of marine origins. Neomorphism of both pelmatozoan grains and the surrounding cement stabilized these two phases into a single crystal of calcite. This single crystal then acted as a seed on which later epitaxial cements grew. These later stages are interpreted as meteoric in origin as they

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*From Bensing et al. (submitted).

predate pressure-solution features and silicification, and by implication, significant burial. Based on this study, early epitaxial cements, interpreted as marine, may not have originally precipitated epitaxially, but are likely a product of neomorphism. This neomorphic origin may help explain the non-uniqueness of environments in which epitaxial cements are believed to form. Furthermore, if epitaxial cements during times of aragonite seas originated as isopachous, high magnesian calcite, these cements would be expected in such an environment, and do not suggest that they are the product of 'calcite sea-like' diagenesis.

INTRODUCTION

Original constituents of carbonates, as well as the waters with which they come in contact, are the main controls on the diagenetic fabrics present, and as such the diagenetic processes of warm-water carbonates, deposited in waters saturated with respect to aragonite, differ greatly from those affecting calcite-rich cool-water carbonates (Nelson et al., 1988; James and Bone, 1989). It has recently been suggested that cool-water carbonates of aragonite-sea times have diagenetic characteristics similar to warm-water rocks of calcite-sea times with an abundance of epitaxial overgrowths on echinoderms being the common link (Knoerich and Mutti, 2006).

With both heterozoan (cool-water) and photozoan (warm-water) characteristics, rocks of the Great Bear Cape Formation of the Sverdrup Basin are an example of ancient subtropical carbonates (Bensing et al., in press), and, as such, can provide important information about the long-term diagenesis of 'transitional' carbonates not yet documented. The purpose of this paper is to document the diagenetic characteristics of subtropical carbonates that include intraskeletal isopachous rinds, epitaxial cements around pelmatozoan fragments, pore-filling iron oxide and glauconite, and microcrystalline silica replacement of biofragments.

GEOLOGIC SETTING

Rocks of this study are from subtropical inner-ramp deposits of the early Permian (Artinskian – Kungurian) Great Bear Cape Formation of the Sverdrup Basin. The Sverdrup Basin is a 1200 km-long and 400 km-wide rift basin now located in the Canadian Arctic Archipelago that contains up to 12 km of lower-Carboniferous to mid-Tertiary terrigenous clastic, carbonate, evaporite, and siliceous sedimentary rocks. The biotic assemblage of Late Paleozoic rocks reflects a cooling-upward trend in sea-water temperature with warm-water limestones from Carboniferous to early-Permian (Sakmarian) and cool-water limestones and cherts from early Permian to late Permian (Beauchamp et al., 1989a; Beauchamp, 1994; Beauchamp and Desrochers, 1997; Gates et al., 2004). Warm-water Carboniferous to early-Permian rocks also contain significant synsedimentary marine cements that were originally composed of high-Mg calcite and aragonite (Davies, 1977; Davies and Nassichuk, 1990).

The Great Bear Cape Formation is a shallowing-upward succession that ranges in thickness from a few meters to 300 meters (Beauchamp and Henderson, 1994). This formation is a transitional unit bridging tropical rocks below and nontropical rocks above, and is considered to represent a subtropical depositional system (Bensing et al., in press). Rocks are composed of a dominantly heterozoan assemblage, dominated by pelmatozoans, bryozoans, and brachiopods, with the addition of some photozoan elements such as colonial rugose coral and large fusulinids. The top surface of the Great

Bear Cape is an unconformity with well-developed calcrete (Beauchamp and Henderson, 1994; Bensing et al., in press). Overlying rocks are part of the deltaic Sabine Bay Formation, and locally, the Esayoo Volcanics. Deposition of these sediments occurred at a paleogeographic position of approximately 35^{o}N (Ogg and Steiner, 1991; Golonka et al., 1994) during passive subsidence of the basin.

METHODS

This study is based on petrographic observations of 72 samples collected from six stratigraphic sections of the Great Bear Cape Formation. In addition to standard petrographic procedures, the samples were analyzed further by cathode luminescence (CL) to understand better the overall character and timing of cementation. Selected samples were also etched in mild acid and stained with Alizirin red-S to differentiate between dolomite and calcite, and to identify any potential dolomite inclusions in cements (Dickson, 1965).

DIAGENETIC FEATURES

Isopachous cement rinds—Thin rinds of isopachous calcite cement (up to 0.1mm in thickness) line the intraskelatal pores of fusulinid foraminifera and bryozoans (Fig. 3.1A). These cements are fibrous to blocky and are always nucleated directly on the skeletal surface. Such cements are most common in intraskeletal pore spaces, but are also present around the outside of grains. Glauconite, iron oxide, and late stage epitaxial calcite cement are in contact with the isopachous cements in the intraskeletal pores. The isopachous cements have a dull and patchy luminescence pattern that is the same as the biofragments upon which they were precipitated (Fig. 3.1B).

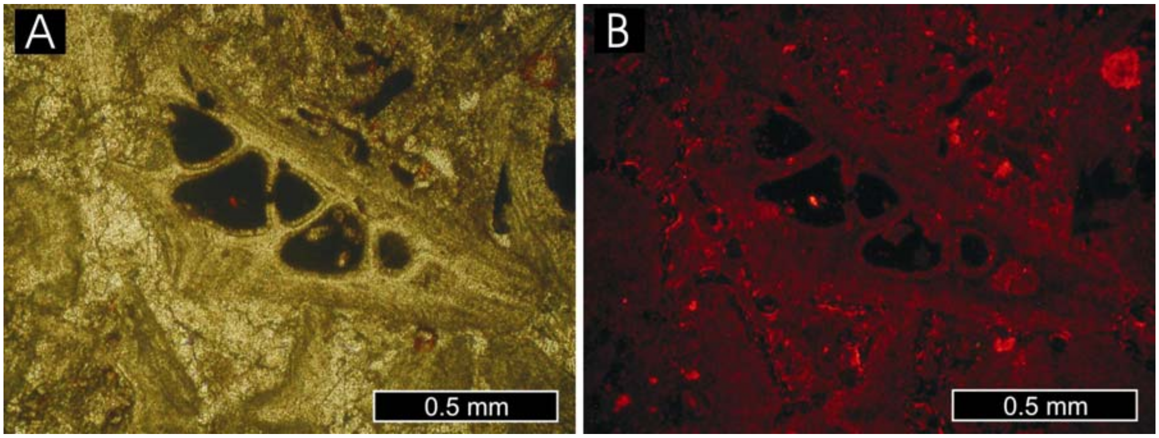

Figure 3.1: (A) Thin and fibrous isopachous cement precipitated in intraskeletal pores of a bryozoan fragment. Dark material in the center of the pore spaces is iron oxide. (B) Cathode luminescence image of the same isopachous cements showing the dull and somewhat patchy luminescence pattern of the cements, which is the same as the biofragment on which it is precipitated.

Optically continuous and epitaxial cements—The most volumetrically important cements in the Great Bear Cape are single crystals encasing, and in optical continuity with, pelmatozoan fragments. These cements are only present around pelmatozoans. Under transmitted light these cements have two distinguishable phases (Fig. 3.2A). The first phase (EC-1), in direct contact with the pelmatozoan, is inclusion-rich and stained by iron oxide, similar to the iron-oxide staining present within pelmatozoan stoma. Typical thickness of this stage of cement is 0.1 mm. Pyramidal terminations are present locally, and although now a single crystal in optical continuity, relict fibrous textures are present locally. This early stage of cement is also isopachous around the pelmatozoan fragments. Acid-etched thin sections viewed under reflected light, and staining with Alizirin red-S reveal no dolomitic inclusions in these cements. Under CL, this cement exhibits patchy, dull luminescence that is similar to the luminescence pattern of pelmatozoan skeletons themselves (Fig. 3.2B; Fig. 3.2C).

The second phase of the optically continuous cement is epitaxial (EC-2), inclusion free, and lacks staining by iron oxide (Fig. 3.2A). This stage of epitaxial cement is volumetrically more significant than EC-1, and is locally poikilotopic, filling the same intraskeletal pores as isopachous cements. Under CL, EC-2 is dominantly non-luminescent with occasional thin, brightly luminescent bands (Fig. 3.2B).

Iron oxide and Glauconite—Iron-oxide is present in sufficient abundance to pervasively stain the rocks red (Bensing et al., in press). Both iron oxide and glauconite infill the intraskeletal porosity of biofragments, and there is a lateral gradation between the two in single skeletal grains (Figs. 3.3A, 3.3B, 3.3C). The iron-rich infill of intraskeletal pores is either in direct contact with the biofragment or is preceded by a thin isopachous rim of calcite around the pore space. In addition to filling skeletal pores, iron oxide, but not glauconite, also cements fusulinid intraclasts (Fig. 3.3C), fills microborings, and is present as inclusions in early-stage pelmatozoan cement (Fig. 3.2A).

Silica—Replacement of calcareous biogragments by microcrystalline (polycrystalline) quartz and botryoidal arrays of chalcedony is common. Replacement by microcrystalline silica typically preserves original structure of the replaced material (Fig. 3.2F), whereas the botryoids are fabric destructive. Silicification of a biofragment ranges from local to total replacement, and affects pelmatozoans, bryozoans, and brachiopods. Non-skeletal replacement is restricted to epitaxial overgrowths; however, these are only silicified where the pelmatozoan has also been replaced, and although it is not restricted to any single stage of overgrowths, it most commonly replaces EC-1.

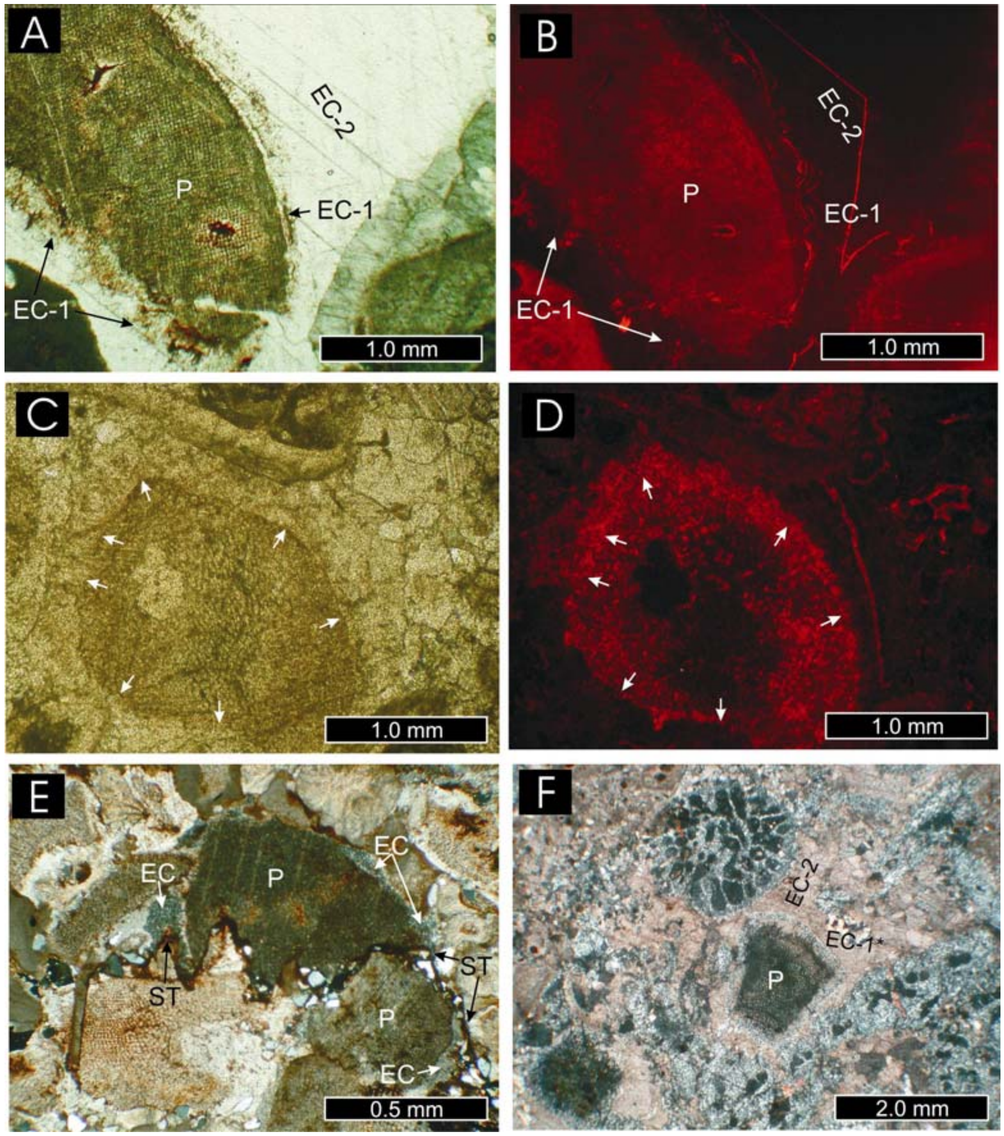

Figure 3.2: Photomicrographs showing important features of epitaxial cements in the Great Bear Cape Formation. (A) Photomicrograph taken under plan- polarized light showing the early, inclusion-rich cements (EC-1) and later clear cements (EC-2). Note generally isopachous nature of EC-1 and relict fibrous texture. (B) Cathode-luminescence image of same area as in (A). EC-1 has a dull, non-uniform luminescence pattern, whereas EC-2 is mostly non-luminescent. A few brightly luminescent bands separate the two stages of cement. (C) Plane-polarized light photomicrograph of pelmatozoan fragment with cement. (D) Cathode-luminescence photomicrograph of same pelmatozoan as C with arrows pointing to the margin of the pelmatozoan. Note that luminescence pattern of the early stage of overgrowth is very patchy and indistinguishable from the pelmatozoan around which it is precipitated. (E) Photomicrograph of pelmatozoan overgrowths (EC) cut by a stylolite (ST). (F) Photomicrograph of silicified biofragments of the Great Bear Cape Formation. Also note that EC-1 has also been silicified.*

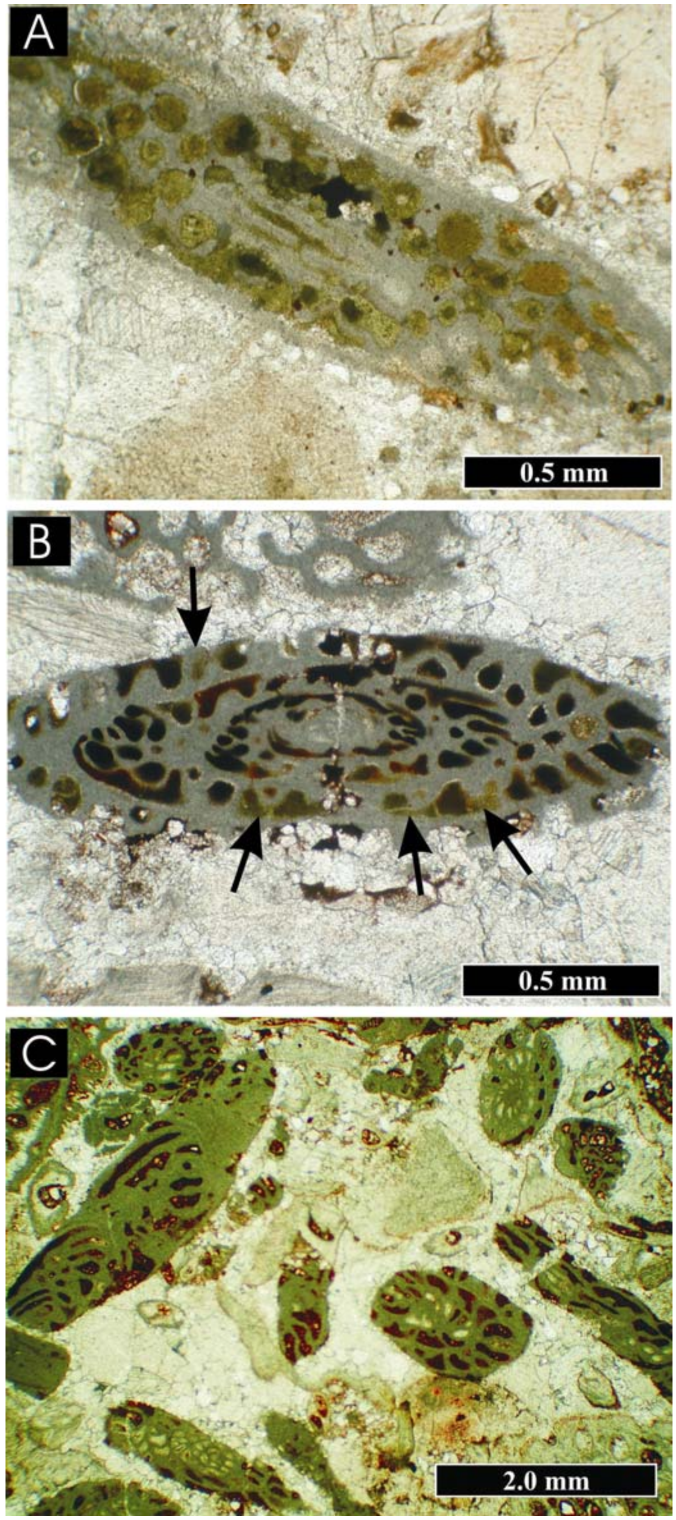

Figure 3.3: Photomicrographs showing the textural similarities of glauconite and iron oxide. (A) Fusulinid with intraskeletal pores filled with glauconite. (B) Fusulinid with with both iron oxide and glauconite in the pore spaces. Arrows point to pores filled with green glauconite. (C) Iron oxide-filled fusulinids, which have been broken and rounded.

Compaction Features—Compaction of the Great Bear Cape is manifest as thin, clay-rich dissolution seams, stylolites, and tangential grain contacts. Dissolution seams and stylolites cross-cut biofragments as well as epitaxial cements (Fig. 3.2E).

PARAGENESIS

Based upon contacts and cross-cutting relationships it is possible to determine a paragenetic sequence with several stages of cementation for the Great Bear Cape Formation (Fig. 3.4).

Isopachous rinds are always in direct contact with the skeletal grain, and are thus the earliest stage of cement. The presence of inclusions in these cements and a dull, patchy luminescence pattern similar to that of biofragments such as pelmatozoans and bryozoans (Fig. 3.1b), suggests that these cement phases were neomorphosed from a high magnesian calcite (HMC) precursor at the same time as mineral stabilization of the skeletal grain, and thus predates neomorphism.

Textural similarity of iron oxide and glauconite in the Great Bear Cape and gradational relationships of these two minerals suggests shared origins (Fig. 3.3). Glauconite, which can be oxidized to hematite when exposed to oxygenated waters (Odin and Fullagar, 1988), is a likely precursor of the iron oxide in the Great Bear Cape. Both of these iron rich minerals may be present in the same pore spaces as isopachous cements (Fig. 3.1A; Fig. 3.3A). Where both are present, however, the isopachous cement always separates the iron minerals from the skeletal grain. Thus, the iron oxide and glauconite clearly post-date isopachous calcite cement. Iron-oxide inclusions in early-stage pelmatozoan overgrowths (EC-1; Fig. 3.2A) suggest that these two phases are co-genetic, with the iron oxide being introduced to the system as the overgrowth precipitated.

Pelmatozoan stomata are filled with iron oxide that must have been introduced into the skeletal pores prior to complete entombment by epitaxial overgrowths.

Early-stage pelmatozoan overgrowths (EC-1) are similar to the isopachous cements in that they are inclusion-rich, first-generation cements precipitated in direct contact with skeletal fragments. This overgrowth stage has a dull and patchy luminescence pattern similar to the pelmatozoans, and has abundant inclusions, thus suggesting that these cements have also been neomorphosed from HMC (Fig. 3.2B; Fig. 3.2C). Whereas the isopachous rims in intraskeletal porosity clearly predate iron oxide, the first stage of overgrowths is coeval with the iron minerals, which stain the early-stage calcite overgrowths as well as filling the stoma of pelmatozoans, and, therefore, EC-1 likely post-dates the isopachous cements. Pressure solution seams and stylolites truncate EC-1 (Fig. 3.2E), confirming precipitation prior to significant burial.

Late-stage (EC-2) epitaxial overgrowths post-date the inclusion-rich EC-1, iron oxides, and isopachous cements. These cements do not have the abundant iron-oxide inclusions of EC-1 indicating that the later-stage overgrowths post-date iron oxide formation. Where the late-stage overgrowths are poikilotopic and are present in the intraskeletal pores they clearly post-date isopachous cements. These cements also lack inclusions, and therefore likely precipitated as low magnesian calcite (LMC), and as such were not neomorphosed.

Precipitation of silica is the latest-stage cement. Silica most commonly replaces skeletal fragments; however, it can also replace syntaxial overgrowths (Fig. 3.2F). Although replacement of syntaxial overgrowths by silica is most common in EC-1, it is not restricted to this phase of overgrowths. Because silicification overprints the latest stage of calcite cements it is clear that this is the final stage of diagenetic cementation in the Great Bear Cape Formation.

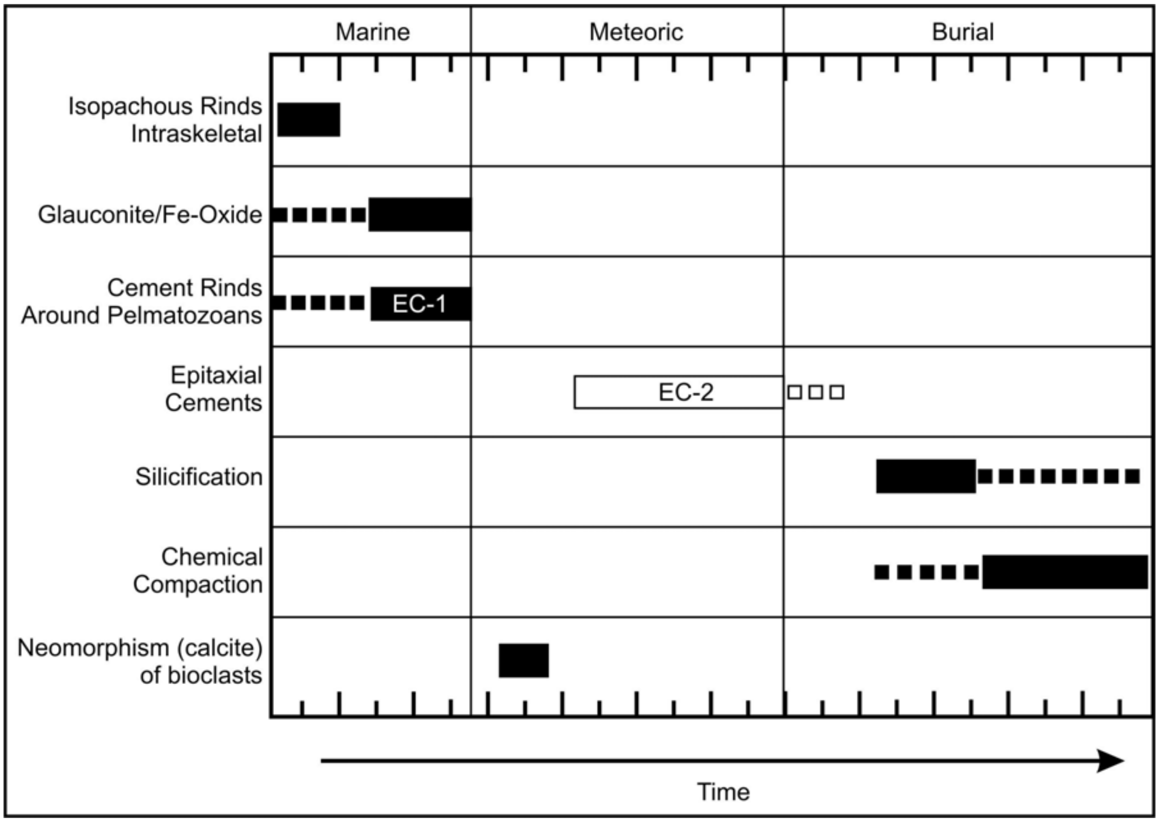

Figure 3.4: Chart summarizing the relative timing of the diagenetic features of the Great Bear Cape Formation.

SOURCE OF CEMENTS AND ENVIRONMENT

In cool-water environments, where sea water is generally less saturated with respect to carbonate minerals compared to warmer-water environments, the source and timing of cements found in the carbonates are still being explored. Tradition holds that cool-water carbonates have a low diagenetic potential, largely due to an original mineralogy dominate by LMC and lacking aragonite (Nelson et al., 1988; James and Bone, 1989; Nicolaides, 1995). Furthermore, the cool waters of the marine environment are less saturated with respect to calcium carbonate making it a less likely constructive diagenetic realm than warm-water environments, wherein synsedimentary marine cements are a hallmark (Davies, 1977; Davies and Nassichuk, 1990). The Great Bear Cape Formation, however, was deposited in subtropical conditions and has characteristics of warm-and cool-water carbonates (Bensing et al., in press), and therefore the diagenetic features also show characteristics of both realms.

Marine Diagenesis—Alteration of sediments comprising the Great Bear Cape began on the sea floor. Glauconite is an authigenic marine clay (Odin and Matter, 1981) and can thus be used as a benchmark by which to constrain marine diagenesis. From characteristics of the cements, their relationship to glauconite, and their relationship to other diagenetic features, it is apparent that glauconite, iron oxide, isopachous cements, and early pelmatozoan overgrowths (EC-1), were all products of the marine diagenetic environment.

The cogenetic relationship of glauconite and iron oxide (Fig. 3.3) indicates that iron oxide in the Great Bear Cape Formation originated in the marine environment by the oxidation of glauconite. Rounded intraclasts cemented by iron oxide are evidence of marine reworking of sediments after precipitation of the iron oxides (Fig. 3.3C). Glauconite and iron oxide have been reported from hardgrounds in Tertiary cool-water limestones (Nelson and James 2000), and because the Great Bear Cape is dominated by tempestites (Bensing et al., in press), iron-cemented intraclasts are interpreted as remnants of marine hardgrounds broken and reworked during storms.

The isopachous cements have many characteristics consistent with having been precipitated in the marine environment including their isopachous fibrous texture, and their always present as first-generation cement (Jernigan and Walker, 1989; Tucker and

Wright, 2004). Where these cements are in the same pore space as glauconite and iron oxide, the isopachous calcite always predates later precipitates (Fig. 3.1A; Fig. 3.3A), and by this reasoning they should be marine cements. Lastly, the dull, patchy CL pattern of the isopachous rinds, which is the same as the skeletal fragments on which they are precipitated, indicates that the cements and the skeletal fragments both underwent mineralogical stabilization under the same conditions, thus providing further evidence of the early nature of the isopachous cements.

The first stage of pelmatozoan overgrowths (EC-1) is also believed to have precipitated in the marine environment. The similar characteristics of EC-1 with the isopachous cements in intraskeletal porosity suggest similar origins. Because features of overgrowths precipitated in different diagenetic environments may have very similar characteristics, it is necessary to analyze closely the cross-cutting relationship of these types of cements with diagenetic features with more straightforward origins. The inclusion-rich nature of these cements is consistent with having been precipitated in the marine environment (Meyers, 1974; Jernigan and Walker, 1989), but may also represent precipitation in a freshwater–seawater mixing zone (Meyers and Lohmann, 1978). By implication of their coeval relationship with iron oxide, the early stage of overgrowths (EC-1) was precipitated in the marine environment (Fig. 3.2A).

The $CaCO_3$ required for epitaxial cements can be derived from dissolution of sediments at unconformities, release of carbonate from silica (chert) replacement, carbonate from pressure dissolution, extraformational sources, or sea water (Meyers, 1978; Knoerich and Mutti, 2006). For EC-1, all of the above can be discounted, except sea water. EC-1 clearly predates pressure dissolution (Fig. 3.2E) and silicification (Fig.

3.2F) and thus, the release of $CaCO_3$ during these processes cannot account for the overgrowths. The blotchy luminescence pattern of EC-1 is indicative of precipitation prior to neomorphism, a process that can occur in the presence of marine, meteoric, or burial fluids (Hendry et al., 1995; Kyser et al., 1998; Dickson, 2001). Early overgrowths (EC-1) predate burial, as shown by their relationship with stylolites, and thus could only have been neomorphosed in the meteoric or marine environment. As it is unlikely for cement to be both precipitated and neomorphosed in the meteoric environment, the cements were likely present prior to entering the meteoric environment, and would likely have originated in the marine environment.

Substrate selectivity of the overgrowths, by precipitating only around pelmatozoans, suggests that these cements were derived from waters with low levels of oversaturation (Meyers and Lohmann, 1978). This has been previously interpreted as an indication of precipitation in a mixing-zone environment; however, it could also represent precipitation from cool sea water (Meyers and Lohmann, 1978) which were the very conditions present in the Great Bear Cape (Bensing et al., in press). Furthermore, dull luminescence of carbonates, activated by Mn^{2+}, is indicative of reducing porewaters and has been suggested to support mixing-zone origins of substrate selective overgrowths by Meyers and Lohmann (1978). The iron oxides that are also present in the dull, patchy luminescent overgrowths of the Great Bear Cape, however, indicate alteration in an oxidizing environment. Thus the Mn^{2+} required for activation of the luminescence is interpreted to have been derived from later neomorphism, rather than precipitation in an anoxic (mixing-zone) environment.

Meteoric (Phreatic) Cements—Late-stage epitaxial cements (EP-2) are interpreted to have been precipitated in the fresh-water phreatic environment. Calcrete and karstification at the top of the Great Bear Cape mark a basin-wide unconformity, and clear epitaxial cements are commonly precipitated in phreatic lenses associated with unconformities, with carbonate sourced from dissolution of intraformational strata (Meyers, 1974). Non-luminescence of cements is attributed to a relative lack of Mn^{2+} with respect to Fe^{2+}, and overgrowths precipitated from meteorically dissolved limestones would not be a sufficient Mn source for luminescence (Meyers, 1974). Furthermore, intrastratal iron in the Great Bear Cape could be made available for diagenetic cements, which would also lead to nonluminescent phreatic cements.

Burial Cements—Silicification of carbonate grains likely occurred in burial environments; however, the exact origins of silicification cannot be resolved. The source of silica for the precipitation of chert could have come from a number of likely sources in the Great Bear Cape. Siliceous sponge spicules are first preserved in the Sverdrup Basin in the Raanes and Great Bear Cape formations, and redistribution of silica from these spicules could be a silica source. Secondly, the Great Bear Cape formation is locally overlain by the Esayoo volcanics, yet another likely source for diagenetic chert. Lastly, Cenozoic volcanic dykes cross-cut the Great Bear Cape at several localities and may have introduced exogenous silica into the system.

NEOMORPHISM OF OPTICALLY CONTINUOUS CEMENTS

The processes by which the two stages of cements encase pelmatozoans in the Great Bear Cape Formation were precipitated and neomorphosed requires further scrutiny, as the relict features of EC-1 suggest it was originally composed of numerous isopachous and columnar crystals. Neomorphism of this early cement is critical as it would align the isopachous cements with the pelmatozoan optically, as well as provide the single-crystal seed on which the later epitaxial cement (EC-2) could precipitate. As discussed above, the first stage of the pelmatozoan cements were marine in origin, and were present at the time of neomorphism of the pelmatozoan skeletons. Pelmatozoans, prior to neomorphism, are known to be originally composed of aligned polycrystalline aggregates (Towe, 1967; Dickson, 2001). During the neomorphism of polycrystalline pelmatozoans, the isopachous cements would have also been neomorphosed and incorporated into a single crystal with the pelmatozoan. Consolidation of polycrystalline calcite material into a single crystal is not unknown in geology, as epitaxial overgrowths can neomorphose adjacent micrite to be included in the single crystal overgrowth (Bathurst, 1971). It has been shown that cements that are present in pelmatozoan pores prior to neomorphism can be involved in the mineral transformation, thus destroying evidence of the pre-existing pore space (Dickson, 2001). Dickson (2001) further documents that numerous small crystals grew on pelmatozoans with their long axes in optical orientation with the skeletal grain. It stands to reason, therefore, that the isopachous cements on the outside of the pelmatozoans in the Great Bear Cape could have been many discrete, aligned crystals that were stabilized into a single crystal during neomorphism. After this neomorphism, the single crystal of the combined pelmatozoan and isopachous cements could seed the growth of the epitaxial cements (EC-2) in the meteoric environment (Fig. 3.5).

IMPLICATIONS FOR EPITAXIAL CEMENTS THROUGH TIME

Knoerich and Mutti (2006) described similarities in the diagenesis, particularly shallow-water epitaxial overgrowths, of cool water rocks during aragonite-sea times with those of warm water rocks from times of calcite seas. Furthermore, the review of Knoerich and Mutti (2006) is based upon nontropical epitaxial overgrowths from the late-Paleogene, with no reported overgrowths from the aragonite-sea time spanning the Carboniferous to Jurassic. The subtropical cements of the Great Bear Cape, which were deposited in non-tropical waters during a time of aragonite seas, can be used to understand better the relationship between sea-water chemistry and sea-water temperature, and their effect on diagenesis. Although at first thought the pelmatozoan-related cements of the Great Bear Cape might support the stipulation of Knoerich and Mutti (2006), the origin of the marine cements must be understood. The first stage of cements precipitated on pelmatozoans were not originally epitaxial, but were HMC isopachous rims. Such cements are representative of the marine diagenetic environment for aragonite sea times, and do not suggest an unusual calcite-sea-like origin for the pelmatozoan overgrowths during a time of aragonite seas.

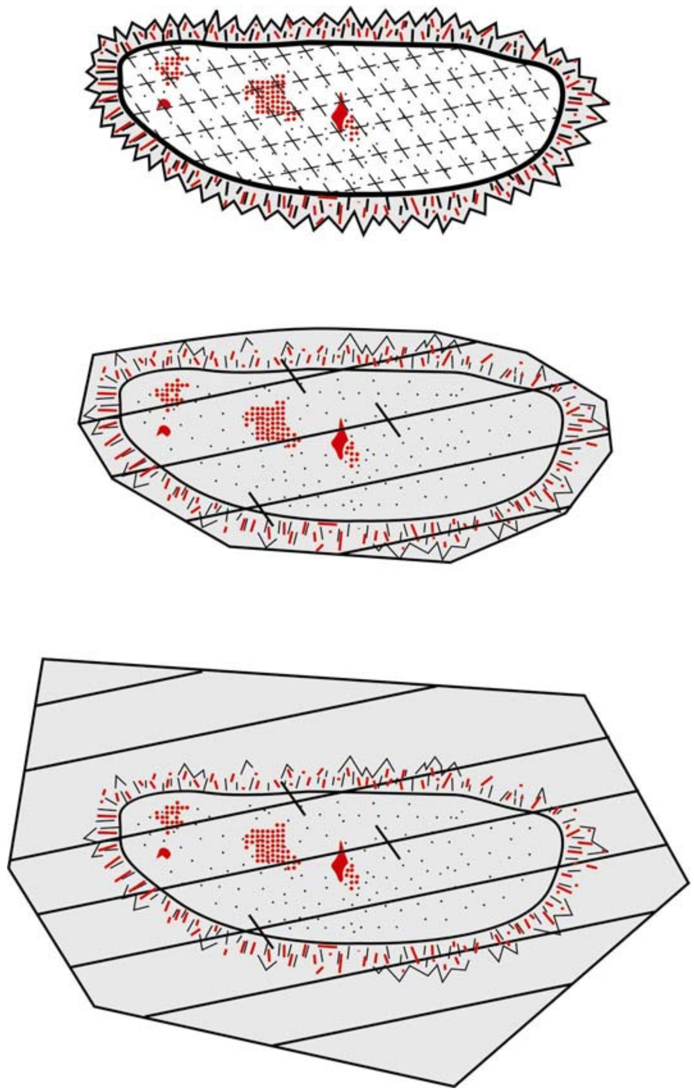

Figure 3.5: Sketch drawing of proposed progression of cements grown around pelmatozoan. Stage one shows aligned aggregate of crystals in pelmatozoan and numerous isopachous HMC crystals surrounding pelmatozoan. Stage 2 is after neomorphism when pelmatozoan and isopachous cements have been neomorphosed into a single crystal. Stage 3 shows epitaxial cement (EC-2) growth around pelmatozoan and earlier cement (EC-1).

CONCLUSIONS

1) Cementation of the subtropical rocks of the Great Bear Cape began in the marine environment and continued through the meteoric and burial realms. Importantly, pelmatozoan cements were precipitated in the

marine environment, but did not originate as epitaxial overgrowths. Pre-existing isopachous cements around the pelmatozoans were neomorphosed into a single crystal during contemporaneous neomorphism of the skeletons and marine cements and provided the base on which later epitaxial cements could grow.

2) True epitaxial cements of the Great Bear Cape were formed in the meteoric realm. Earlier marine cements precipitated around pelmatozoans were originally isopachous HMC, which is consistent with cements expected during aragonite sea times, rather than having 'calcite sea-like' characteristics.

ACKNOWLEDGEMENTS

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CHAPTER 4:

OVERALL CONCLUSIONS AND SUMMARY

The Raanes and Great Bear Cape formations are interpreted as a subtropical depositional system at a time of climatic transition with tropical carbonates below, and temperate carbonates above. Changes in sea level ('shallowing upward') overprinted on sea-water cooling produced a complex series of deep-cool, shallow-subtropical, and shallow-cool carbonate facies in the stratigraphy. In addition to describing the complexity to be expected at such transitional carbonates, this study shows that the modern criteria for identifying subtropical carbonates can be applied for those times when large benthic foraminifera lived in shallow marine environments (Fig 4.1).

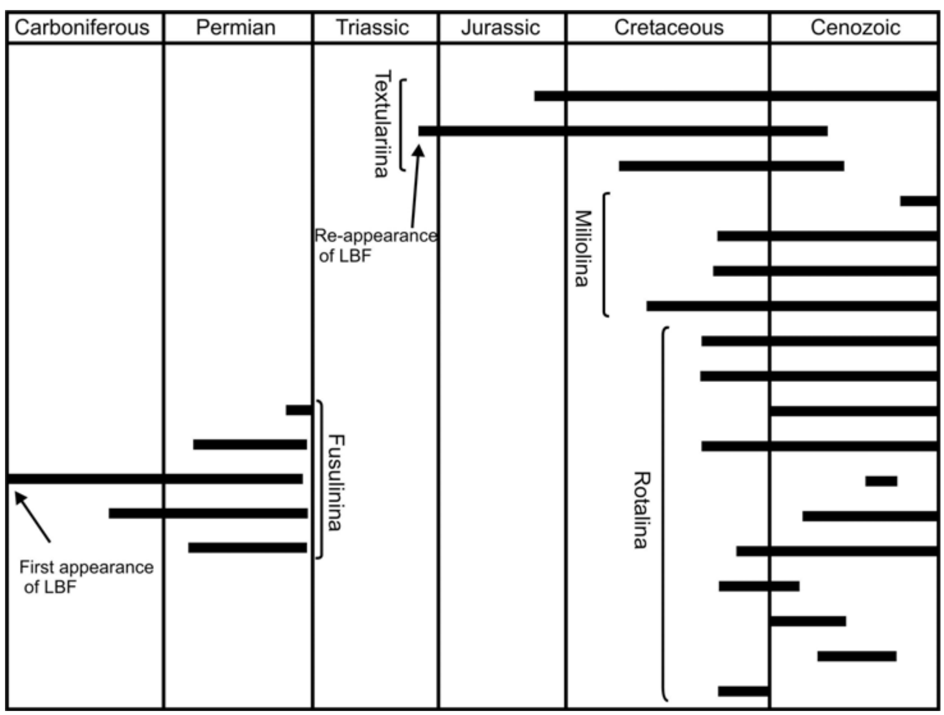

Figure 4.1: Times throughout Earth's history in which photosymbiont-bearing, large benthic forams (LBF) lived in shallow seas; representing times in which subtropical carbonate assemblages could be identified based on modern equivalents. After Ross, 1974.

In addition to describing and interpreting the environmental and sedimentological controls on subtropical deposition, this work provides insight into the diagenesis of such rocks. Although the bioclasts of these rocks have mixed photozoan and heterozoan characteristics, the diagenetic fabrics have limited marine cements and are diagenetically heterozoan. The marine cements that are present are thin, isopachous cements, with no indication of pervasive marine cementation. Although not volumetrically impressive, the thin isopachous cements around pelmatozoans, which were subsequently neomorphosed into a single epitaxial cement crystal, are important because they show that the single-crystal habit of early, marine cements can be a product of neomorphism. Furthermore, because the marine phase of these cements was originally precipitated as HMC rinds, as expected for tropical aragonite seas, it suggests that early epitaxial cements are a product of neither tropical calcite seas nor cool water aragonite-seas, but are the result of neomorphism and meteoric diagenesis. The mere presence of these cements, therefore, does not have a greater paleo-oceanographic implication.

This work on epitaxial cements is significant in terms beyond paleo-oceanography in that the presence of such cements has been attributed to numerous diagenetic environments. The process by which polycrystalline marine cements are converted into a single, optically-continuous crystal, and later seed meteoric epitaxial cements may provide an explanation for the non-uniqueness of settings in which these single-crystal cements can form. The evidence here suggests that marine ‘epitaxial’ cements are in part a product of neomorphism, rather than being an originally marine fabric. It is therefore possible that early-stage epitaxial cements in other units that are believed to have been precipitated from sea water may have originated as polycrystalline, isopachous precipitates.

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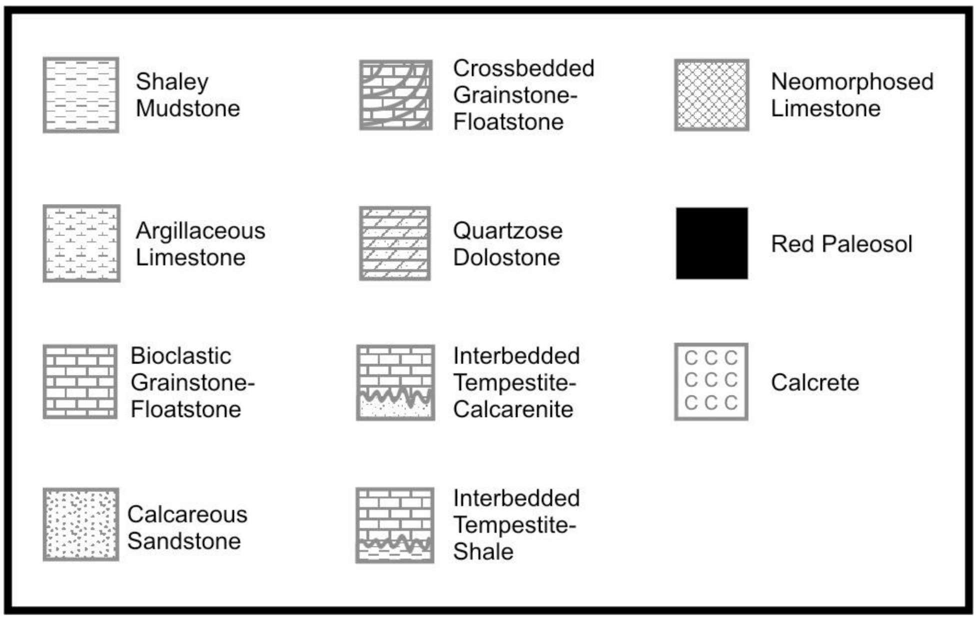
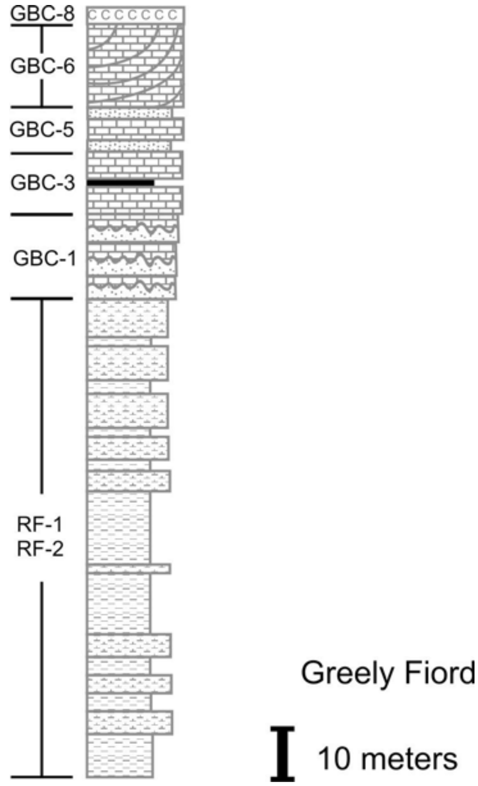
APPENDIX A:

STRATIGRAPHIC SECTIONS

LEGEND:



Facies descriptions given in Table 2.1
Map of stratigraphic column locations given in Fig. 2.2


GBC-8
GBC-6
GBC-5
GBC-3
GBC-1
RF-1
RF-2
Greely Fiord
10 meters

GREELY FIORD

Location: **$80^o44'$ N** **$80^o15'30''$ W**

0m-100.25m: Raanes Formation. Alternating beds of slope forming green weathering mudstone and thin limestone (wackestones)

0m-9.2m: Covered Raanes Formation. Green slope formed from weathering of poorly-consolidated siliciclastic mudstone of Raanes.

9.2m-14.8m: Brown-weathering limestone (wackestone) with brachiopod and solitary rugose coral fossils. Sample GF-1 collected at 11m.

14.8m-19.05m: Covered slope. Inferred mudstone.

19.05m-20.7m: Pelmatozoan-bryozoan wackestone. Large, broken fragments of fenestrate bryozoans. Small diameter pelmatozoan columnals (approx. 0.5 cm long). Pebble sized lithic fragments. Sample GF-2 collected at 19.05m.

20.7m-24.7m: thin-bedded, slope forming argillaceous mudstone.

24.7m-26.15m: Wackestone/argillaceous limestone. Fragments of brachiopods, pelmatozoans and bryozoans (fenestrate and branching). GF-4 collected at 26.15m.

26.15m-44.65m: Argillaceous mudstone. Generally covered with few out crops at 29.55m-30.35 and 38.35m-44.65m. Outcrops have thin-diameter, 2cm long pelmatozoan columnals, robust branching bryozoans, and fenestrate bryozoan fragments. Very thin bedding is present and outcrops are generally poorly consolidated with some possible lime-concretions. GF-5 at 29.55m. GF-6 at 38.5m.

44.65m-45.00m: Resistant wackestone outcrop with bryozoan and pelmatozoan fragments. Possibly some small brachiopod fragments. GF-7 at 44.7m.

45.00m-61.19m: Covered mudstone slope.

61.19m-68.6m: Thick-bedded, silty limestone (wackestone) with large, solitary rugose corals, bryozoans, and pelmatozoans. GF-8 collected at 61.33m. Large, cement-filled productid brachiopods present at 63m (GF-9). GF-10 collected at 67.1m.

68.6m-70.2m: Argillaceous mudstone/siltstone

70.2m-71m: Resistant wackestone with large productid brachiopods and fenestrate bryozoans. Vertical burrows present. GF-12 collected at 70.2m.

71m-73m: Silty limestone bed GF-13 collected at 73m.

73m-76.5m: Wackestone. Big brachiopods (productid) at 75.25m. Whole sponge, solitary rugose coral, and *Zoophycos* at 75.6m. GF-14 collected at 73.1m. GF-15 collected at 75.25m.

76.5m-77.4m: Argillaceous musdstone/siltstone

77.4m-78.1m: Wackestone with large whole sponge (-3cm diameter) at 78m. GF-16 collected at 77.7m.

78.1m-79.6m: Argillaceous mudstone/siltstone.

79.1m-82m: Silty limestone (wackestone) with abundant brachiopods.

82m-100.2m: Alternating beds of argillaceous mudstone/siltstone (recessive) and more resistant limestone; same as previously described. Measurements as follows:

82-86.6 – recessive (GF-18 sampled at 84 m).
86.6-87.1 – limestone (GF-19 at 87m).
87-87.8 – recessive
87.8 – 89.5 - limestone (GF-20 at 88.9m).
89.5 – 90.0 - recessive
90.0-91 - limestone (GF-21 at 91m). Abundant *Zoophycos* on top of bed (91m).
91-91.4 - recessive
91.4-92.55 - limestone
92.55-93 - recessive
93-93.7 - limestone
93.7-94 - recessive
94-94.8 – limestone
94.8-95.4 – recessive
95.4-96.1 – limestone
96.1-96.8m – recessive
96.8-99.6m – limestone (GF-22 at 98.6).
99.6-100.25 recessive – Last occurrence of siliciclastic argillaceous beds

Great Bear Cape

100.25m-117.66m: Alternating beds of poorly-fossiliferous quartzose (sandy-silty) limestone, and fossiliferous wackestone. Limestone beds, with rare low angle cross bedding at the tops of beds, are scoured into sandy beds. Sandy beds are planar to slightly wavy laminated. *Zoophycos* and less common *Planolites* are present on tops of sandy beds. Frequency of sandy beds decreases upwards. Fossils in wackestones are dominated by small pelmatozoans with less common spiriferid brachiopods and bryozoans. Large productid brachiopods and solitary rugose corals are present in sandy units.

102.35m – pelmatozoan rich limestone. (GF-24)

103.45m – sandy unit with faint-cross bedding. (GF-25)

104.5m – brachiopod and pelmatozoan limestone. (GF-26)

105.25m – brachiopods in sandy bed. (GF-27)

106.1m – sandy unit with few pelmatozoans. (GF-28)

106.8m – wackestone with large bryozoans (fenestrate and branching) brachiopods and pelmatozoans also present. (GF-29)

108.4m – sandy unit. (GF-30)

109.9 – numerous brachiopods in limestone (GF-31)

111.4m – large productid brachiopod in sandy bed (GF-32)

112m – large solitary rugose coral in sandy bed. (GF-33)

112.3m – abundant pelmatozoans and spiriferid brachiopods in limestone. (GF-34; GF-35)

113.6m – sandy unit with few pelmatozoans (GF-36). Large solitary corals also present.

113.65m – base of limestone bed scoured into underlying sandy unit (GF-37)

115.35m – sandy unit (GF-38)

115.35m – contact of pelmatozoan-rich limestone with underlying sand (GF-39)

116.6m – cement filled brachiopod in pelmatozoan-rich wackestone (GF-40)

117.6m-127.9m: Red stained limestones.

117.6m-121.26m – red stained, cross bedded wackestone-grainstone with thin interbedding of sand-silt. Similar to underlying units, except red-stained, more obvious cross bedding, and lack of bioturbation. Large brachiopods and bryozoans in grainstone at 121.1 (GF-42 at 117.6m, GF-43 at 118.8m, GF-44 at 119.1m GF-45 at 120.23m, GF-46 at 121.1)

121.26m-121.63m – white, flat-bedded sand-silt stone. (GF-47 at 121.26m)

121.63m-123.4m – Large fenestrate bryozoans and brachiopods present in well-cemented grainstone. First occurrence of fusulinids, although very rare.

123.4m-124.4m – Red stained sandstone. Planar laminated. Few fusulinids present. (GF-48 at 123.4m)

124.4m-124.6m – thin outcrop of well cemented grainstone. Large fenestrate bryozoans and spiriferid brachiopods. Abundant fusulinids. (GF-50)

124.6m-124.62m – Thin red paleosol (red mudstone)

124.62m-127.9m – Interbedded sandstones and limestones with bryozoans, fusulinids, and brachiopods. Poor exposure. (GF-51 at 127.15m) 127.9m: red stained unit with red to yellow chert. Abundant pelmatozoans with small bryozoan and brachiopod fragments (GF-52)

127.9m-142.4m: Interbedded limestone and sandstones. Variably silicified. No longer red stained.

127.9m-130.9m – Sandy bed with brachiopod fragments and glauconite. Some silicification. (GF-53 at 129.4m)

130.9 – 131.4m – Packstone with brachiopods and bryozoans. Minor pelmatozoans. Fining upward tempestites. Minor glauconite and variable silicification (GF-54 at 130.9m)
131.4m-131.6m – Sandy bed with glauconite and minor red pigment (GF-55)

131.6m-133.5m – Silicified limestone with long bryozoans, large brachiopods and small pelmatozoans. (GF-56 at 131.6, GF-57 at 133.4)

133.5m-134.7m – sandstone (GF-58 at 134.7)

134.7m-137.6m – Grainstone with abundant fine grained fossil fragments (pelmatozoans, brachiopods, and bryozoans; GF-59 at 137.6)

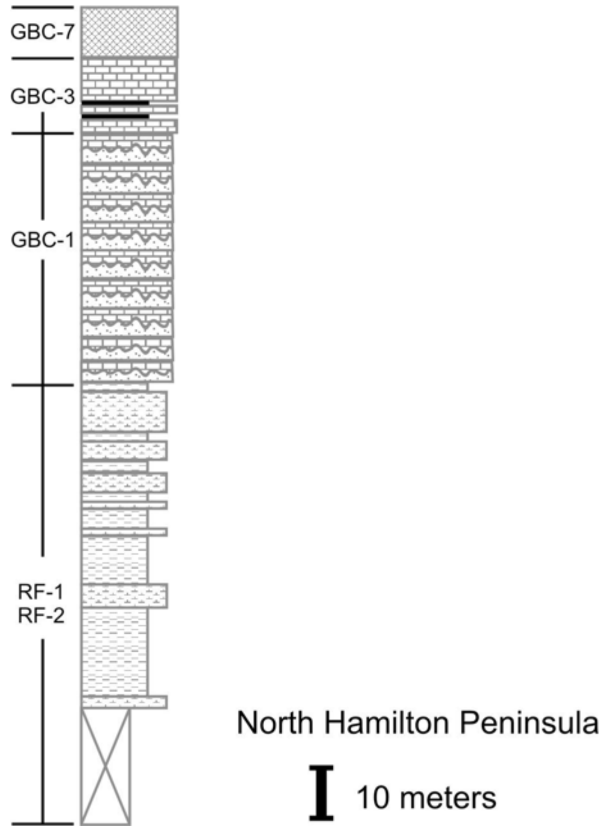
137.6m-137.9m. – Red stained sandstone

137.9m-139.6m. – Pelmatozoan rich, crystalline limestone with few bryozoans and glauconite (GF-60 at 137.9, GF-61 at 139.6)

139.6m-159.15m – Massive, crystalline limestone with abundant low amplitude sylolites. Faint, high angle crossbedding present. Fossils not readily identifiable in field. (GF-62 at 143.4; GF-63 at 145.3m; GF-64 at 147.4; GF-65 at 150.9; GF-66 at 155.3; GF-67 at 158.6; GF-68 at 159.15)

159.15m-159.25m – Calcrete (GF-69)

Red paleosol above calcrete (GF-70)


GBC-7
GBC-3
GBC-1
RF-1
RF-2
North Hamilton Peninsula
10 meters

NORTH HAMILTON PENNINSULA

Location: 80°21’30” N 81°16” W

0m-94.87m: Raanes Formation. Alternating beds of poorly consolidated siliciclastic mudstone and more resistant fossiliferous wackestone. Raanes Formation is poorly exposed, requiring lateral shifts in order to measure complete section.

> 0m-27m – Covered Raanes Formation. Begin measuring from unconformable contact with Nansen formation, which is folded
>
> 27m-27.8m – Silty-wackestone with abundant small bryozoan fragments, small pelmatozoan, and brachiopod fragments. (NHP-30R at 27.8)
>
> 27.8m-48.9m – Covered Raanes Formation/siliciclastic mudstone
>
> 48.9m-50m – Wackestone with pelmatozoans, brachiopod fragments, and large cystoporate bryozoans (NHP-31R at 48.9)
>
> 50m-60m – Cover/siliciclastic mudstone
>
> 60m-60.3m – Wackestone. Brachiopods and pelmatozoans. Large cystoporate bryozoans and solitary rugose coral. (NHP-32R at 60.3)
>
> 60.3m-66.2m – cover/siliciclastic mudstone
>
> 66.2m-67.5m – Large, whole brachiopods, intact pelmatozoan stems and somewhat intact bryozoan fragments. Fossils generally less broken up than below. Mudstone less common than limestones from this point. (NHP-33R at 66.5)
>
> 67.5m-68.6m – Poorly consolidated siliciclastic mudstone.
>
> 68.6m-69.9m – Wackestone, same as previous (NHP-34R)
>
> 69.9m-70.5m – Siliciclastic mudstone
>
> 70.5m-72m – Poorly exposed wackestone
>
> 72m-72.8m – Siliciclastic mudstone
>
> 72.8m-73.6m – Large pelmatozoan and bryozoans. Whole brachiopods. Very abundant fossils at 73.4m, mostly pelmatozoans and brachiopods (NHP-35R at 73.4)
>
> 73.6m-74.1m – siliciclastic mudstone

74.1m-75m – wackestone same as previous (NHP-36R at 75)

75m-75.2m – mudstone
75.2m-76m – wackestone (NHP-37R at 76)

76m-76.12m – mudstone

76.12m-77.22m – wackestone (NHP-38R at 76.55)

77.22m-77.62 – mudstone

77.62m-78.62m – wackestone (NHP-1 at 78.42)

78.62m-79.07m – mudstone

79.07m-79.76m – wackestone. (NHP-2 at 79.76m)

79.76m-81.32m – silty limestone

81.32m-82.1m – mudstone

82.1m-94.87m – poorly fossiliferous, silty to sandy-limestone (NHP-3 at 83.77; NHP-4 at 86.27; NHP-5 at 87.07)

Great Bear Cape 94.87m-145.86m: Great Bear Cape Formation. Dominated by Non- to poorly-fossiliferous sandy limestone interbedded with sandy wackestones with small and fragmented fossil fragments.

94.87m-96.37m – Silty limestone with large productid brachiopods and zoophychus trace fossils (NHP-6 at 95.62m)

96.37m-98.87m – Silty limestone. Platy weathering pattern. Zoophychus trace fossils are abundant and large. Rare/small bryozoan fragments. (NHP-7 at 98.87)

98.87m-101.62m – Poorly fossiliferous, silty limestone. large productid brachiopod collected at 100.7 (NHP-8; NHP-9 at 101.62)

101.62m-103.17m – More abundant fossils than previous units. Brachiopods (productid and spirifer), abundant pelmatozoans, and minor branching bryozoans.

103.17m-105.97m – Pelmatozoan and brachiopod rich wackestone in contact with poorly fossiliferous sandy limestone. Other fossils in wackestone include sponge, large, solitary rugose corals and possibly some bryozoans (NHP-11 collected at 104.5m)

105.97m-106.24m – Sandy limestone (NHP-12 at 105.97)

106.24m-108.21m – Wackestone with sponge, solitary coral, brachiopod, bryozoans and pelmatozoans. (NHP-12 at 106.24)

108.21m-118.57m – Poorly to nonfossiliferous sandy limestone with lisegang banding and some glauconite. (NHP-15 at 110; NHP-16 at 114; NHP-18 at 118.5)

118.57m-138.47m – Variably sandy wackestone with pelmatozoans, brachiopods and bryozoans. Minor silicification of biofragments. Fairly large fenestrate bryozoans and brachiopods at 129m-131m. Lisegang banding very abundant. Some dissolution of biotic grains = moldic porosity (NHP-19 at 129.27; NHP-20 at 131.77; NHP-21 at 132.47; NHP-22 at 134.97; NHP-23 at 135; NHP-24 at 138.47)

138.47m-143.97m – Poorly fossiliferous, sandy limestone (NHP-25 at 143.97)

143.97m-145.86m – Pelmatozoan-rich floatstone. Beds have clearly scoured bottoms. Nodular chert is abundant and laterally extensive. Thin bed of highly-fossiliferous grainstone of fragmented fossils (pelmatozoans, brachiopods, and bryozoans) at 145.86. (NHP-26 at 144.97; NHP-27 at 145.86)

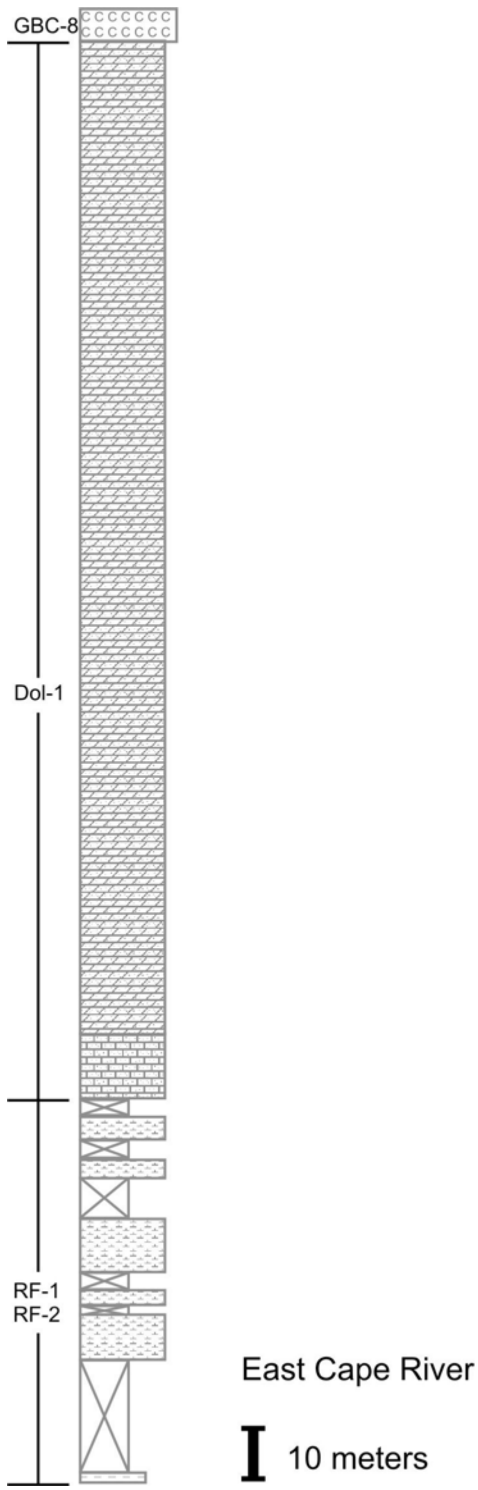
145.86m-155.94m: Great Bear Cape Formation. Red stained, highly fossiliferous grainstones-packstones. Fusulinids abundant, with large spiriferid brachiopods, and large fenestrate bryozoans. Large colonial corals present (rare). Interbedded with limestones are thin, red mudstones (paleosols)

145.86m-146.47m – Fusulinid grainstone/packstone. Also present are abundant fenestrate bryozoans and spirifer brachiopods. One large colonial (tabulate) coral present. (NHP-28 at 146.47; NHP-29 at 145.37)

146.47m-147.3m – Red mudstone/paleosol. Fusulinids just below.

147.3m-155.94m – Red stained grainstone/packstone. Abundant fusulinids, large spiriferid brachiopods, and large fenestrate bryozoans. Pressure dissolution common. Some silicified fossil fragments (particularly brachiopods) as well as nodular chert. (NHP-40 at 147.3; NHP-41 at 148.47; NHP-42 at 150.77; NHP-43 at 151.14; NHP-44 at 153.39; NHP-45 at 155.94)

155.95m-169.22m: Massive, crystalline limestone. No-fossils present. Somewhat crumbly. (NHP-48 at 159.22; NHP-49 at 161.22; NHP-50 at 169.22)



*Dol-1 = pervasively dolomitized and undifferentiated Great Bear Cape

EAST CAPE RIVER

Location: 80°06’ N 81°48’ W

Raanes Formation

0m-28m – Covered Raanes Formation. Large colonial corals and possible paleosol at contact with Tanquery Formation. (ECR-11 – Greenish clay at contact; ECR-12 – top of Tanquery Formation and colonial coral)

28m-38m – Very fine sand to silty limestone with low-angle trough cross-bedding and abundant vertical to subhorizontal burrows. Biota includes solitary rugose coral, spirifer brachiopods, pelmatozoan columnals, branching bryozoans, and minor bivalves. Partial silicification of bioclasts. Some bioclasts also leached. Possible moldic porosity of fusulinids.

38m-40m – Cover

40m-41m – Outcrop; same

41m-43m – Cover

43m-49m – Discontinuous outcrop; same

49m-55m – Outcrop similar as below. Few scattered fusulinids. Black nodules, possibly P, or Mn on bedding surfaces. Fossils same as above, but less obvious sedimentary structures.

55m-62.5m – Cover

62.5m-63.5m – Outcrop; same

63.5m-70.5m – Cover

70.5m-72m – Outcrop; same

72m-76.5m – Cover to base of cliff.

76.5-86.5m – Outcrop similar to below. Less sedimentary structures/intensely bioturbated. Fossils same as below, but more fragmented and broken. ~4cm thick alterations of green siliciclastic mudstone

86.5m-116m – Regularly bedded alterations of green siliciclastic mudstone and limestone. Limestones are less fossiliferous. Most fossils are now moldic porosity. Some vugs filled with chert nodules. (ECR-6)

Great Bear Cape

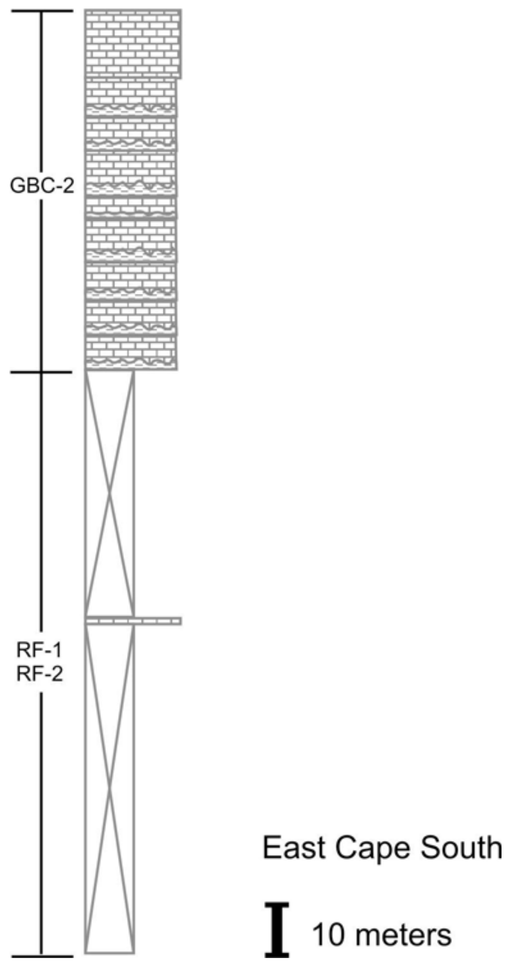
116m-191m – Thick resistant beds of silty dolostone. Non-fossiliferous. Few planolites burrows, but nothing else. (ECR-7 at 137; ECR-8 at 168)

191m-213m – Similar dolostone, but more cherty and a few molds of dissolved fossils. Possibly brachiopods. Solitary rugose corals present. (ECR-9 and ECR-10 at 213m)

213m-253m – Similar dolostone, however very unstable cliff face to dyke. Inaccessible.

-Samples collected at top of cliff (accessed by helicopter)

T-ECR-1 Grainstone above dyke
T-ECR-2 Calcrete
T-ECR-3 Calcrete
T-ECR-4 White calcrete, laminated, semi-nodular, poorly indurated.
T-ECR-5 Grainstone between dyke and calcrete
T-ECR-6 Laminated calcrete
T-ECR-7 Top GBC calcrete


GBC-2
RF-1
RF-2
East Cape South
10 meters

EAST CAPE SOUTH

Location: 80°03' N 81°48'30" W

Raanes Formation

0m-69m – Covered. Overlying richly fossiliferous (with abundant and diverse colonial corals) and cross-bedded Canyon Fiord Formation

69m-69.3m – Thin, flaggy outcrop. Extensively bioturbated by *Zoophycos* and *Planolites*. Poorly fossiliferous. Only a few brachiopods and pelmatozoans. (ECS-10)

69.3m-121.8m – Covered

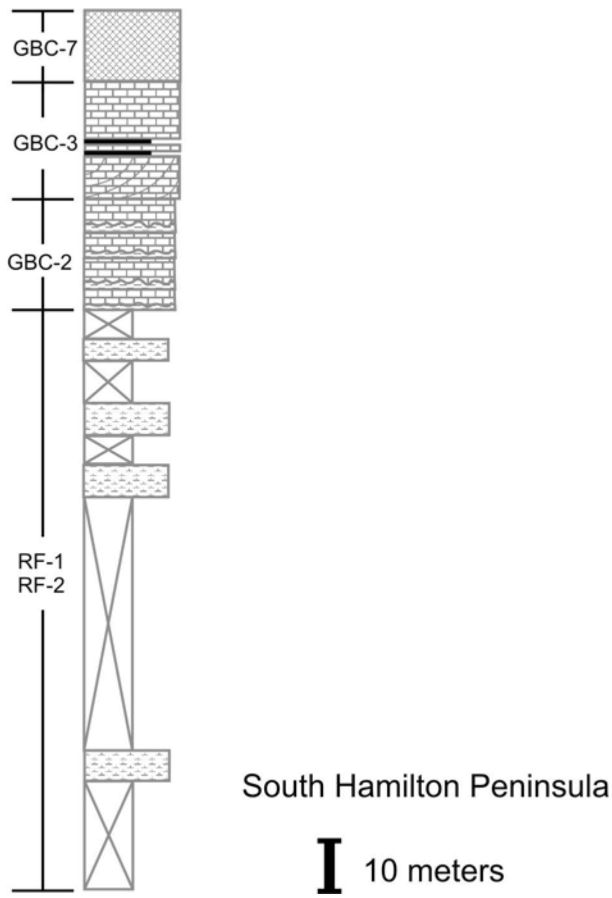
Great Bear Cape

121.8m-133.8m – Cliff forming sandy limestone. Richly fossiliferous with abundant large colonial rugose corals. Thinly laminated with trough cross bedding and scoured bed bottoms. Abundant whole, spirifer brachiopods and small pelmatozoans. Bryozoans (branching and fenestrate) are in mostly intact. Gastropods and large solitary rugose corals also present. Very sandy limestone becoming less sandy in top few meters. (ECS-11 = highly fossiliferous sample; ECS-12 = brachiopods; ECS-13 = pelmatozoan grainstone matrix; ECS-14 = colonial rugose coral)

133.8m-149.8m – Cross-laminated, resistant and sandy limestone interbedded with thin, grey, muddy limestone. Limestones beds about 20-40 cm thick. Fossils are brachiopods, bryozoans, and solitary rugose corals. Limestones have HCS and are scoured into interstitial mudstones (ECS-15, ECS-16, ECS-17, ECS-18, ECS-19)

149.8m-183.8m – Same as rocks below, but less sandy and more pelmatozoan matrix. Glauconite also present. Large fenestrate bryozoans present and spirifers very common (ECS-20)

183.8m-198.9m – Encrinites (abundant pelmatozoans) with scattered, small colonial rugose corals. Glauconite common as are large burrows. Fenestrate bryozoans very common, with wide range of sizes. (ECS-21)


GBC-7
GBC-3
GBC-2
RF-1
RF-2
South Hamilton Peninsula
10 meters

SOUTH HAMILTON PENNINSULA

Location: 80°05'30" N 81°36' W

Raanes Formation

0m-21m – Cover

21m-26.5m – Sandy limestone with abundant large productid brachiopods, solitary rugose corals, colonial rugose corals, and pelmatozoans. *Zoophycos* ichnofossils present. (SHP-29R at 21; SHP-30R = solitary coral; SHP-31R = productids; SHP-32R at 26.5; SHP-33R at 26.5)

25.5m-87.8m – Cover

87.8m-87.9m – Sandy limestone with brachiopods and pelmatozoans.

87.9m-110.3m – Cover

110.3m-113.3m – Outcrop; same

113.3m-120.5m – Cover to base of large cliff

Great Bear Cape Formation

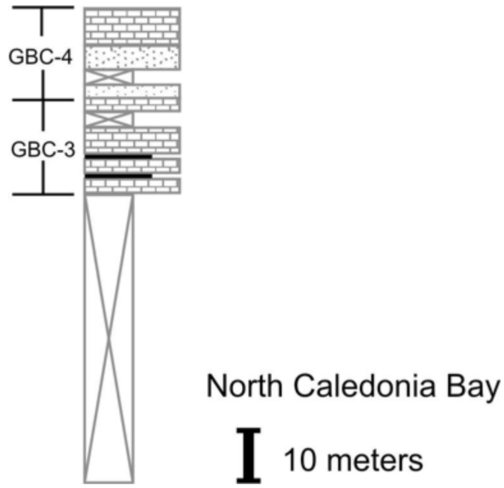
120.5m-131.5m – Fossiliferous grainstones interbedded with siliciclastic mudstone. Very large colonial rugose corals in bottom of limestone beds. Limestones have some possible HCS and are scoured into mudstones. Fossils fine grained and broken, dominated by pelmatozoans and bryozoans, with some larger fragments of brachiopods. (SHP-4 at 120.5; SHP-5 at 124.4; SHP-6 at 124.8; SHP-7 at 126)

131.5m-144.5m – Fossiliferous grainstones very sandy-silty (more so than underlying units) Fossils are very fragmented; dominated by pelmatozoans, bryozoans and brachiopods. Colonial corals much smaller than below, and somewhat broken. Solitary rugose corals also present. Fewer interbedded mudstones than below. After 132.5m whole spirifer brachiopods become very common. Possible HCS at 137.7. Glauconite at 144.5 (SHP-8 at 88.5; SHP-9 at 132.5 (coral); SHP-10 at 132.5; SHP-11 at 137; SHP-12 at 137.2; SHP-13 at 137.5; SHP-14 at 137.7; SHP-15 at 140 (coral); SHP-16 at 140.5)

144.5m-151.3m – Grainstone-packstone. Abundantly fossiliferous. Fossils not very broken. Bryozoans very abundant: fenestrate, branching, and Archimedes. Pelmatozoans present and abundant spirifer brachiopods. Colonial corals absent. (SHP-17 at 147.5)

151.3m-167.5m – Red stained grainstones. Fusulinids very abundant as well as brachiopods, pelmatozoans, and bryozoans. Fossils quite large. Some minor glauconite present. Trough cross-bedding present as well as skolithos ichnofossils. Colonial corals very rare, and small. Red mudstone/paleosol at 153m. (SHP-18 at 150.6; SHP-19 at 151.5; SHP-20 at 153.5; SHP-24 at 158; SHP-25 at 159.5; SHP-26 at 161; SHP-27 at 163; SHP-28 at 166)

167.6m-183.5m – Recrystallized limestone. No apparent fossils. Possibly some pelmatozoans. Abundant bioturbation by *Thalassinoides* and *Planolites.* (SHP-21 at 172.5; SHP-22 at 172.5; SHP-23 at 183.5)


GBC-4
GBC-3
North Caledonia Bay
10 meters

NORTH CALEDONIA BAY

Location: **80°01'30" N** **81°31' W**

Raanes Formation

0-61.5m – Covered-Raanes Formation

Great Bear Cape Formation

61.5m-72.1m – Grainstone/packstone. Minor iron oxide staining. Thin red mudstone/paleosols at 65.3 and 69.1. Bedding of units are approximately 20 cm. thick. Biota dominated by pelmatozoans (larger diameter than other sections). Large spirifer brachiopods and fusulinids common. Few fenestrate bryozoans. Some colonial rugose corals present, but are small. Rounded intraclasts present. (NCB-1 at 61.7; NCB-2 at 64; NCB-3 at 65 (coral); NCB-4 at 65; NCB-5 at 65.3; NCB-6 at 66m; NCB-7 at 66.5; NCB-8 at 68; NCB-9 at 69m; NCB-10 at 71m; NCB-11 at 72m)

72.1m-78.1m – Cover

78.1m-78.6m – Similar to underlying red outcrop. More friable. Rounded intraclasts. Iron oxide very abundant. (NCB-12 at 78.2m)

78.6m-81.6m – White sandstone. Planar laminated with laminations approximately 0.5cm thick. Non-fossiliferous. (NCB-13)

79.6m-81.9m – Very thin outcrop of red grainstone, poorly consolidated. Highly weathered. (NCB-14 at 81.6)

81.9m-87.9m – Cover

87.9m-88.7m – Grey to white sandstone, same as below.

88.7m-98.9m – White grainstone to packstone. Very abundant fusulinids and pelmatozoans form matrix. Large colonial rugose corals and tabulate corals present as well. Highly weathered and crumbly. (NCB-16 (grainstone); NCB-17 (grainstone); NCB-18 (colonial rugose); NCB-19 (colonial tabulate))