ABSTRACT

The Petermann Glacier of Northern Greenland has been associated with producing large, flat, low profile and tabular icebergs observed in the north Atlantic. The glacier is speculated to have produced a rock loaded, neutrally buoyant iceberg, which was encountered by the CCGS Louis S. St-Laurent in the Kane Basin between Ellesmere Island and Greenland on August 17, 2001 during the Canadian-German Nares Strait Geo-Cruise.

Because of its tabular shape and high stability, and low profile on the water, this type of icebergs poses a serious threat to navigation in northern waters. This research has revealed recent sightings of similar rock-loaded icebergs of a similar source as far south as the offshore petroleum producing areas of Atlantic Canada, emphasizing they pose a more significant threat than initially assumed.

Rock eval analysis of bituminous ice rafted debris (IRD) revealed Kerogen types II-III with a peak thermal maturity (T max) range between 385-450°C and a max total organic carbon content (TOC) of 1.28 mg HC/g rock. Thermal maturation combined with petrographic and rock descriptions of the IRD are compatible with mature and postmature occurrences expected along North Greenland. Silurian aged dolostone, bioclastic debris and skeletal wackestones prevailed on the iceberg and support a northern origin along the Cambrian through Devonian Arctic Platform. Source regions of the platform are located across southern Hall Land and Washington Land near the Petermann Glacier and Humboldt Glacier of NW Greenland.

The massive floating ice tongue of the Petermann Glacier is flanked by valley walls exceeding 500 m providing increased chance for supraglacial rock accumulation.

It is speculated that warm summer temperatures and a record breaking amount of precipitation, leading to unprecedented flooding and closure of the Thule airport in July 2001, may have facilitated mass wasting and possibly glacial surging which resulted in the production of the debris loaded iceberg encountered in August 2001.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Marcos Zentilli, Chris Harrison, of the GSC in Calgary and Alexander Grist Dalhousie Fission Track Lab for their scientific contributions to this study and their support throughout the production of this thesis. I would also like to acknowledge Dr. Yawooz Kettanah of Dalhousie for a crash course in sedimentary microscopy; Gordon Brown for thin sections and Keith Taylor for help with the XRD.

Thanks go to Brian Hill of National Research Council, Institute for Marine Dynamics, Newfoundland; Allan Ruffman of Geomarine associates Ltd; Humfrey Melling of Institute of Ocean Science, Sidney, BC for sharing their knowledge on the subject of geology and icebergs in Northern Canada. I would also like to extend thanks to Ingrid Peterson of Coastal Ocean Science, Bedford Institute of Oceanography Halifax, for helping me track down photos of similar icebergs and leading us to the 2002 Conception Bay observations of a rock loaded iceberg. Dr. P.Mukhopadhyay obtained my Rock-Eval Pyrolysis data in record time.

The greatest thanks goes undoubtedly to my friends for their support throughout my time at Dalhousie and my family whom without I would not be who I am today.

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Chapter 1: Introduction

1.1. General Statement

This thesis is concerned with using ice rafted debris to trace the source of a tabular, rock-covered iceberg encountered in Arctic waters between Ellesmere Island and Greenland in 2001. The study of these ice rafted debris increases our confidence that the iceberg originated in a northwest Greenland glacier. This interpretation is compatible with what is known about iceberg forming processes and ocean circulation in the Nares Strait. The possible threat that similar low-profile icebergs may pose to navigation and resource exploration are also considered here, as well as whether this occurrence reflects geological processes related to a recent warming trend in the Arctic.

Evidence from or left by glacier ice in the landscape or within the geological record provides one of the most important sources of information on environmental change. Research on global environmental change tries to understand how the components (atmosphere, ecosphere, cryosphere, hydrosphere and biosphere) interact in such a complex system (Nesje, 2000). One means of studying this system is through glacial monitoring. Polar glaciers in particular are extremely sensitive to environmental change and therefore make good indicators of past environmental changes (Nesje, 2000). Debris carried by glaciers and icebergs represent the vertical and lateral variety of rocks over which the glacier passes (Boulton, 1970). Thus the study of glacially deposited ice rafted debris and sediment within the geological record permits mapping of ancient ice sheet extents, historical glacial variations, and iceberg fluxes.

1.2. Background

On August 17, 2001 during the Canadian-German Nares Strait Geo-Cruise a low profile, neutral-buoyancy, rock-loaded iceberg was abruptly encountered by the Canadian Coast Guard icebreaker *Louis S. St-Laurent* in the Kane Basin between Ellesmere Island and Greenland, Lat. 80°07'N; 069°53'W (Zentilli and Harrison, 2002) (Fig.1.1). Reduced visibility (fog), added to a thick, dark debris cover and a low profile above water made the iceberg indiscernible to radar and very hard to distinguish visually from the dark surrounding water. The presence of icebergs in the Kane Basin is an expected occurrence, especially during warmer summer months of March though August. However, the very concentrated load of rafted indiscriminate cobbles and boulders was surprising to the experienced crew. An iceberg like this one had seldom been reported in the area.

Based on geographical location and prevailing currents, there exists only a few possible source glaciers along northern Greenland and eastern Ellesmere Island that have the potential of producing the loaded iceberg subject of this thesis.

1.3. Previous Work

Sample collection and initial observations of the rocks and the iceberg were conducted onboard the *Louis.S St. Laurent*, at which time samples where numbered and their possible sources approximated by Chris Harrison of the Geological Survey of Canada (GSC) in Calgary and Marcos Zentilli of the Department of Earth Sciences at Dalhousie University. Fossils were preliminarily prepared and identified on board ship by Jason Anderson, a Nares Geo-Cruise participant.

1.4. Scope and Purpose

This thesis investigates three possible sources for the iceberg based on 38 of the original 43 specimens collected during an organized 20-minute landing by Zentilli and Harrison (Fig 1.2). Macroscopic and microscopic examination combined with Rock-Eval Pyrolysis and X-ray diffraction analyses are used to geologically constrain the possible provenance of the rafted debris. Throughout this project the following major questions were addressed:

1) What is the geological source of the rafted debris?
2) What glacial source did the loaded iceberg originate from?

Two minor question engaged throughout the investigation include:

3) Are neutral buoyancy icebergs a new danger to navigation in the North Atlantic?
4) Is there sufficient information available to correlate this occurrence with global change and increased temperatures in the North?

1.3. Organization of the Thesis

Following the introduction of chapter 1, chapter 2 presents the methods used for the cutting of samples, thin sections preparation, Rock-Eval Pyrolysis and powder X-ray diffraction analysis. Chapter 3 details relevant characteristics of icebergs and glaciers. Chapter 4 reviews the initial observations acquired from the iceberg as well as preliminary interpretations. Chapter 5 presents the results obtained from study of the collected specimens. Chapter 6 discusses the source regions of southern Hall Land and Washington Land and concludes that the Petermann Glacier of NW Greenland is the source for the iceberg.

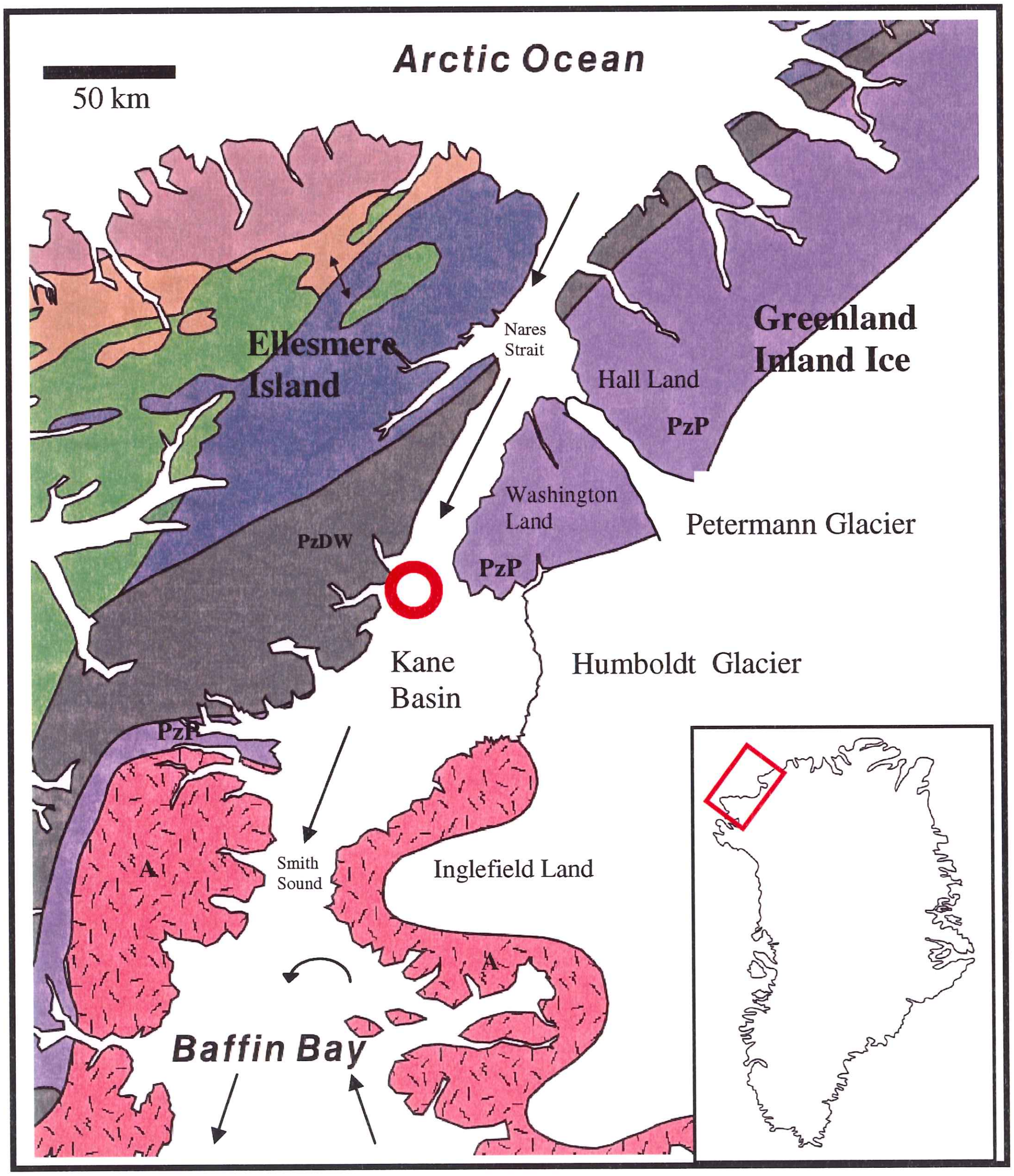


Figure 1.1. Simplified geological map of the Nares Strait area between Ellesmere Island and Greenland, showing the location of the rock-loaded iceberg. Arrows indicate approximate ocean surface current directions from various sources. Relevant geologic units include: Archean to PaleoProterozoic metasediment, granitoid intrusive, mafic dykes and sills (A), Proterozoic platform strata (Pep) and Paleozoic deep water strata (PzDW). Red Circle: Lat. 80°07.705'N; Long. 69°53.908'W. Map modified from Oakey et al. (2002, 2003).

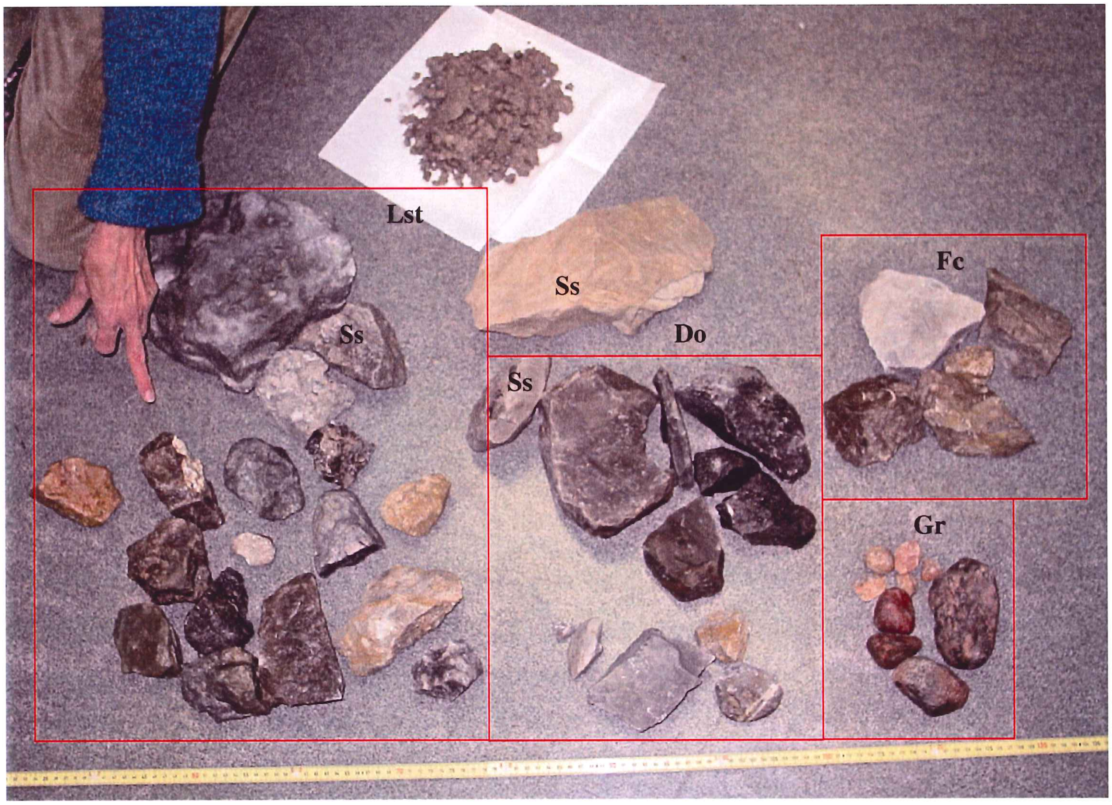


Figure 1.2. Samples retrieved from the surface of the iceberg include; five different types of rounded granites (Gr) bottom right, an assortment of limestone (Lst) left, dolostone (Do) center and fossiliferous carbonate (Fc) top right. Clastic rocks are rare among the debris: three sandstone boulders (Ss) are seen at the top of the picture. Hand belongs to Dr. Peta Mudie, GSC.

Chapter 2: Methods

2.1. Methods

Sample collection was short (20-25 min) and not systematic. The goal was to collect a wide variety of lithologies useful in pinpointing possible provenances for the IRD. For this reason bituminous and fossil bearing specimens were of particular interest and may possibly be over represented.

Thin sections and petrographic investigation were made on 12 rock specimens representative of the bulk mineralogy of the debris. Thin sections preparation was done at Dalhousie University using a standards diamond tipped rock saw to cut the samples mounting and polishing was done by Gordon Brown of Dalhousie University thin section laboratory.

Outstanding macrofossils and microfossils observed within the limestone and dolostone, already partially prepared by Jason Anderson, were further identified using paleontology texts such as Moore, Lilacker and Fisher (1952). Textures and dominant mineral assemblages present were summarized for each thin section according to the proposed limestone classification of Dunham (1962).

Three bituminous dolostones: specimens 031-25, 34, and 38 were analyzed for hydrocarbon content through P. Mukhopadhyay of Global Geoenergy Research Ltd., Halifax, N.S. Rock Eval Pyrolysis was used to determine the maturation of available hydrocarbons in the samples. Rock Eval Pyrolysis consists of a programmed temperature heating (in a pyrolysis oven) in an inert atmosphere (helium) of a small sample (~100 mg) to quantitatively and selectively determine: (1) the free hydrocarbons contained in the sample, and (2) the hydrocarbon- and oxygen- containing compounds (CO_2) that are volatilized during the cracking of the unextractable organic matter in the sample (kerogen).

The pyrolysis oven temperature is kept at 300°C for 3 min, while free hydrocarbons are volatilized and measured as the S1 peak. The amount of free hydrocarbon volatilized indicates the amount of oil or gas present in the rock. The temperature is then increased from 300°C to 550°C (at 25°C/min), where heavy hydrocarbons compounds (>C_{40}) as well as the cracking of non-volatile organic matter are measured as the S2 peak. Maximum S2 values specify maturity of kerogen and are called T_{max}, which gives an indication of the potential quantity of hydrocarbons the rock has of producing if burial and maturation continue. The CO_2 issued from kerogen cracking correlates to the S3 peak, recorded during cooling stages of pyrolysis. The Figure below in this section shows a schematic diagram of the rock eval procedure (Fig. 2.1.).

Three rocks; samples 031-30, -34 and -41, representing distinctly different lithologies present on the iceberg were analyzed in a Philips Analytical X-ray Diffraction unit in the Fission Track Research Laboratory of Dalhousie University. Rocks were first pulverized with a mortar and pestle, using ethanol as a lubricant, and then continuously scanned using a copper tube anode from 5° through 80° at a 0.025° step intervals.

Semi-quantitative peak-height analysis was used to determine percent dolomite and calcite in the rocks as well to determine if any unique mineralization were present.

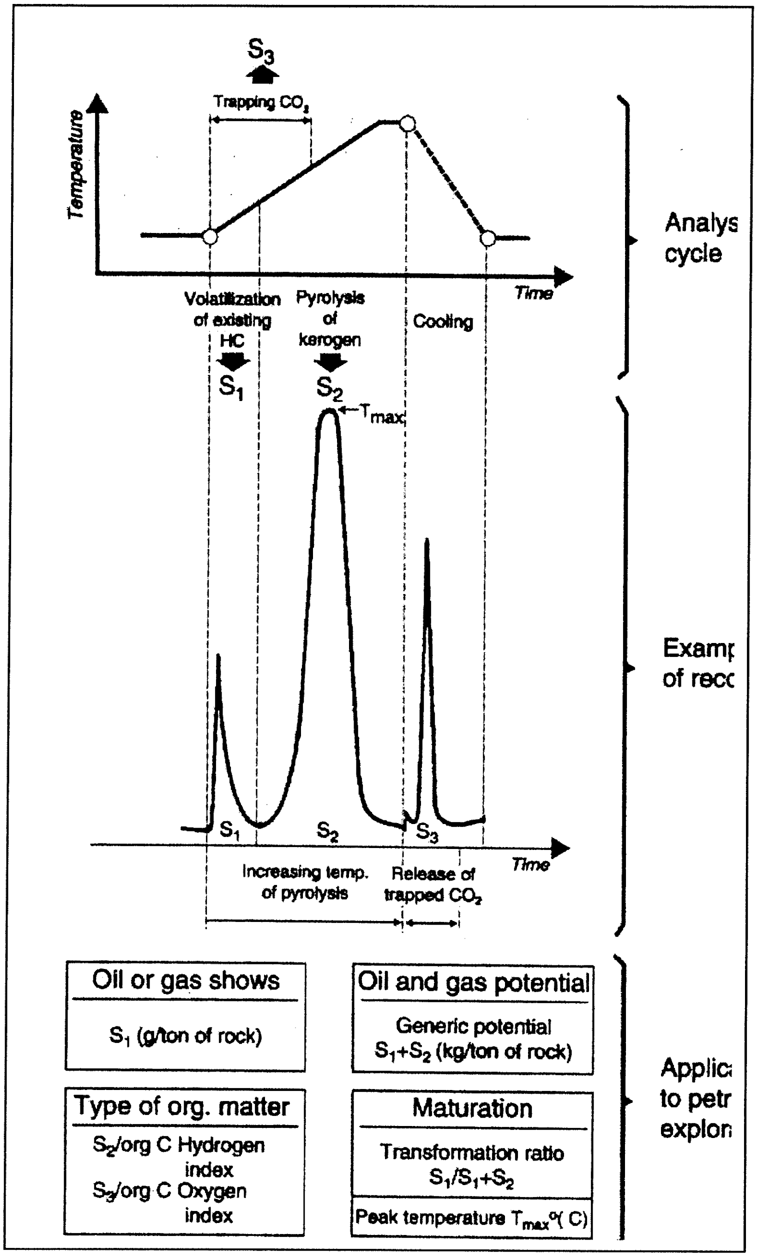


Figure 2.1. This figures schematically show the procedure and application of the Rock Eval method and the corresponding S1, S2 and S3 peak measurements. This figure is modified from the ocean drilling website http://www-odp.tamu.edu/publications/tnotes/tn30/tn30_f4.htm

Chapter 3: Icebergs, Currents, Rock Eval and Pyrite

3.1. Icebergs

Icebergs in general are irregular masses of ice that erode and fall (calve) from the front (terminus) of glaciers. Their formation and deterioration is generally random but governed predominantly by waves and tidal action (Orheim, 1987). The bulk of icebergs originating between Ellesmere Island and Greenland start off from the immense Petermann and Humboldt glaciers of NW Greenland and from tidewater glaciers on Ellesmere Island, mainly Dobbin Bay, Richardsons Bay and Rawlings Bay. The largest ice fragments from Ellesmere are derived from the Ward Hunt ice-sheet (Lat 83°N, Long 74°S), on western Ellesmere Island in the Arctic Ocean. This ice sheet is a bitter topic among climatologists as a result of cracking and sheet break-up in 2002, believed to correlate with increasing temperatures in the Arctic (Mueller and Vincent, 2003).

3.1.1. Iceberg Classification

To be consistent, ice and iceberg terms relevant to this study are described using the International Ice Patrol (IIP) simple shape classification developed by Murray (1969).

TABULAR:	An iceberg with steep sides and flat top having a length-to-height ratio greater than 5:1. Many show horizontal banding.
GROWLER:	A mass of glacial ice that has calved from a berg or the remains of a berg.
DOME:	Large smooth rounded top.
WEDGE:	An iceberg having a steep vertical side on one end and sloping on the other.
DRY-DOCK:	An iceberg that has eroded so a slot or channel is formed with twin columns.
BLOCKY:	An iceberg with flat top and steep vertical sides. Length to height ratio 2.5:1.

3.1.2. Glacier terminology

Glacier types referred to in this thesis are summarized below. All glaciers in the Nares Strait region are temperate glaciers, categorized on the basis of ice temperature (Weidick 1995).

OUTLET:	Flow at ice sheet margins channelized by topography.
VALLEY:	An individual glacier small in comparison to the topography; the shape of the glacier is controlled by the topography it lies in.
TIDEATER:	Terminus is grounded and resting on rock beds below sea level.
FLOATING: ICE TONGUE	Terminus is floating over length scale comparable to or large compared to the thickness. Restricted to polar glaciers. Typical examples at the Petermann Glacier of NW Greenland.
ICE SHELF:	A large region of floating ice, often roughly equidimensional in length and width. Restricted to polar glaciers. The Ross, Filchner-Ronne and Lambert Ice Shelves in Antarctica are examples.

3.2. Neutral buoyancy icebergs

The terms neutrally buoyant or rock-loaded are not official classification name for icebergs. This name is given to the iceberg on the basis that normally more then 90% of the iceberg occurs below sea level. Ice of this type is commonly referred to as growler ice however, the size and mass of this iceberg pertains to a Tabular Iceberg, not a growler. Generally speaking iceberg float with 10% of their volume exposed. An iceberg loaded with rocks (of density 2.6 to 3.0) will of course sink, and at some point its bulk density will be equivalent to that of the displaced water, thus be neutrally buoyant. It is speculated that the thin flat shape of the iceberg combined with the concentrated load of debris allows the iceberg to become depressed in the water column as deterioration progresses. Melting reduces the volume of ice, thus the volume of displaced water, allowing the iceberg to approach or achieve neutral buoyancy. The reduced profile of large icebergs such as the subject of this study increases potential collisions of ships sailing among icebergs.

Neutral buoyancy, rock-loaded icebergs of this type have previously been reported in the Prince William Sound near Valdez, Alaska. Here an empty, inbound oil tanker, the *Overseas Ohio*, collided with a debris-loaded iceberg in 1994 causing over 1 million dollars in damages to the ships hull (Tangborn, et al., 1998) (Fig. 3.1).

Icebergs of this type have been termed "Black Ice" by the Prince William Sound Operation Manager and Information Officers; Rhonda Arvidson, and Doug Schneider. These icebergs come from the Columbia Glacier approximately 20-25 km away and are simply termed black ice. It is believed the icebergs acquire their debris through basal freezing of excavated material beneath the glacier. The accumulation of rocks within the iceberg reduces the above water profile by increasing overall density. Ultimately the iceberg remains at or below the sea level reducing radar detection and increasing collision hazards in the shipping lane (R. Arvidson, pers. comm. 09/01/2004).

3.3. Ocean current in the Kane Basin

Currents in the Kane Basin are part of a complex network of currents driven mainly by circulation between the Gulf Stream and the Artic Ocean. Deep, cold Arctic currents are forced through the Fram Strait south along eastern Greenland. Flow continues around Greenland's southern tip where it converts into a north current following the coastline of west Greenland. The West Greenland Current flows north until southern currents from the Nares Strait and Kane Basin are met and a dominant southward flow along eastern Ellesmere results. Currents in the Kane Basin, Kennedy Channel and Nares Strait, are thus dominantly south and drain into Baffin Bay (Fig 1) (Melling, 2000). Approximately 30% of the Arctic total flow is channeled between Ellesmere Island and Greenland (Aagaard, 1989).

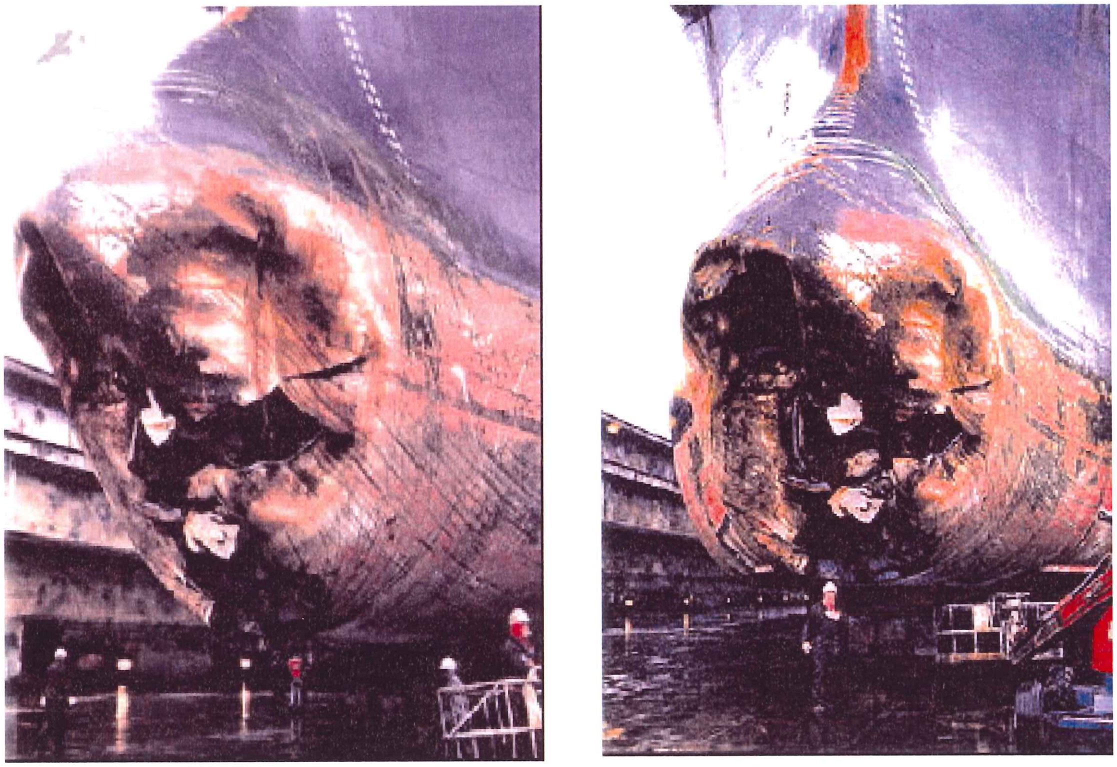


Figure 3.1. The Overseas Ohio oil tanker, struck a neutral buoyancy iceberg in the Prince William Sound near Valdez, Alaska in 1994. The bulbous bow of the ship was punched in by an estimated 4000-7500 ton iceberg, huge rocks where removed from inside the hull of the ship during repairs (Photos from Tangborn, Kane, and Tangborn., 1998).

3.4. Rock Eval Pyrolysis

Rock Eval Pyrolysis is used to determine the type, maturity and potential of hydrocarbons contained within source rocks. The organic matter can be estimated by (1) the location of HI (hydrogen index) and OI (oxygen index) on a pseudo-Van Krevelen diagram and (2) T_{max} (maximum temperature) range experienced by the rocks over time (Espitalie, 1985).

The organic matter associated with carbonate rocks is often more hydrogen-rich and thermally liable than that in fine-grained clastic rocks. As a result, more total organic carbon (TOC) in carbonate rocks may be transformed into bitumen compared with average clastic source rocks of comparable maturity (Tissot and Welte, 1978; Gehman, 1962).

Rock-Eval/TOC parameters have significance only above threshold TOC, S1 and S2 values. If TOC is less than or equal to 0.3% then all parameters have questionable significance and the experiment suggests no potential. Oxygen Index (OI), S3/TOC, has questionable significance if TOC is less than or equal to 0.5%. Both T_{max} and Production Index (PI = S1/(S1+S2)), have questionable significance if S1 and S2 values are less than or equal to about 0.2 (Gehman, 1962).

Results can be affected by minerals within the rocks. This is known as mineral matrix effects. These either retain generated compounds, lowering the S1 or S2 peaks, while increasing T_{max}, or by liberating inorganic CO_2 and increasing S3 and OI. These effects are important if TOC, S1 and S2 are low, an effect not significant where sources have TOC values greater than 5%. OI values greater than 150 mg/g TOC suggest either low TOC or a mineral matrix CO_2 contribution during pyrolysis (Tissot, and Welte, 1978).

T_{max} values between 400°C - 430°C are indicative of immature organic matter where as T_{max} values between 435°C - 450°C represent mature or oil prone zones. Higher temperature T_{max} values >(450°C) is when hydrocarbons become overmature.

In general marine organisms and algae have higher H and C content compared to land plant organisms, which have higher O to C content. HI values have a range between 100 - 600 mg/g TOC and OI from 0 -150 mg/g TOC (Baskin, 1997).

3.5. Framboidal pyrite

Potential mineralization of economic interest exists throughout western and northern Greenland (Dawes, 2000). Exploration companies such as Rio Tinto – Platinova have discovered that fault controlled lead-zinc-silver and lead-zinc-barium mineralization occur within the Ordovician strata of Washington Land and Daugaar-Jesen Land (Dawes, 2000). This area is a promising target for future work as many different mineralization types are locally impressive such as a massive 16.8 m thick pyrite (FeS_2) interval, which was found within the Cape Clay Formation of Washington Land (Dawes, 2000).

Framboidal pyrite (named after the French word for raspberry) are spheroidal aggregates of microcrysts of pyrite (Fig. 5.4) (e.g. Wilkin and Barnes, 1997a). Formation of framboidal pyrite is most commonly observed in anoxic environments such as in argillaceous marine and lacustrine sediments (Wilkin and Barnes, 1997a). Framboidal pyrite forms through inorganic and organic reactions where sulfur (S) and iron (Fe) react to produce pyrite (FeS_2), and has been observed to develop in degraded petroleum reservoirs (e.g. Wilson, 1998).

Chapter 4: Ice and Geology

4.1. General Statement

Observations by Zentilli, and Harrison, (2002) and Harrison and Brent (2002) of the rocks on the iceberg are included in Appendices I and II. The following text expands on these initial observations to answer the questions posed in section 1.4.

4.2. The Iceberg

The shape of the neutral buoyancy iceberg was roughly rhomboidal, measuring 90 m by 70 m with an overall flat surface and straight to steeply dipping ice faces. Height above sea level reached 18 m but was on average ca.10 m. The iceberg is speculated to have a draft of ca. 100 m below the surface (Fig. 4.1). The extra mass from the debris load holds the iceberg deeper in the water column then a normal iceberg which has 90% of its volume below and 10% of its volume above sea level. The iceberg is thus approaching a more neutrally buoyant state. It is estimated using size and shape that the iceberg is 95% to 97% submerged.

The depressed iceberg was very hard to distinguish from the dark surrounding water (Fig. 4.3). The surface of the iceberg was covered with a wide range of dark, angular, cobbles and boulders (<1mm – 12m^3) (Fig. 4.2). Visual estimates made on the surface support that 97% of the rafted debris was sedimentary in origin, consisting of mainly unfoliated, carbonate rocks. Of particular interest are the limestone samples as they are very porous and smell strongly of bitumen when struck. Bitumen is also visible filling available pore space in thin section. The remaining 3% of the debris was rounded metamorphic and igneous shield rocks which are assumed to originate from the Precambrian shield beneath the inland ice of the Greenland Icecap.

Four physical characteristics unique to this iceberg and its debris are useful in determining a source glacier:

(1) Debris were not entrained within the iceberg's body as commonly found with ice rafted debris (Fig 4.1, 4.2; 4.3).

(2) The concentrated load of debris indicates that little deterioration has occurred to the iceberg and that rolling or tilting of the iceberg in the water column has not occurred (Fig 4.1, 4.2; 4.3).

(3) Two distinctly different ice faces are present around the iceberg; one sloping face eroded and clear of debris. The other a vertical fractured face where calving from the source, or recent fracturing of the iceberg may have occurred (Fig 4.3; 4.4).

(4) Parallel undercutting caused by wave and water circulation erosion persists at and below sea level around the more eroded side of the iceberg, which are not present on the freshly fractured sized (Fig. 4.4).

4.3. The Peterman Glacier

The Peterman Glacier of northern Greenland is the northernmost source glacier in the Nares Strait area. The glacier is located at 81°N and 60°W and bordered on either side by Cambrian to Upper Silurian strata of Hall Land on its northern flank and Washington Land bordering the southern side of the glacier (Dawes, 2000). The glacier is approximately 150 km to the northeast from where the iceberg was encountered. However the Petermann Glacier is an active iceberg producing glacier and iceberg from this glacier are capable of reaching the northern Atlantic (Murray, 1969). The Petermann Glacier is also the longest outlet glacier in the northern hemisphere with a 100 km long floating ice tongue extending into Hall Basin (Fristrup, 1966; Weidick, 1995; Stewart, 2004). The glacier has a low terminus only 3-4 m above sea level, which produces characteristically low profile tabular icebergs. Annual ice production has been recorded at 0.6 km^3 (Weidick, 1995).

Robe et al. (1977) suspected the Petermann Glacier as a source for a large and flat tabular type iceberg which reached a low latitude of 50°N near the Grand Banks, Newfoundland in May 1976 and persisted for many days thereafter. It is believed that thin flat tabular icebergs similar to this occurrence and our low profile iceberg are much more stable in the water and tend to remain parallel to the sea surface (e.g. Robe, 1977).

Discharge studies of outlet glaciers acquired through satellite radar interferometry by Rignot (1997) conclude that the Petermann Glacier has the highest thinning rates of all northern glaciers and is the most sensitive to temperature variations and sea level changes. This observation is compatible with our study of this iceberg as it is suspected that exceedingly high amounts of precipitation occurring over the early summer of 2001 could have resulted in massive landslides of material onto the suspected glacier prior to calving.

Figure 4.1. Full view of the low profile rock loaded iceberg with people for scale. Rhomboidal in shape, maximum water line 90 meters along the starboard side, displaying horizontal undercutting at and below the waterline. Maximum width of the iceberg is 70 meters. Maximum elevation is 18 m, average height is ca. 10 m.

Figure 4.2. Sample collecting. Size of debris on the surface of the iceberg ranged between silt and sand material <1 mm to 12 m^3 limestone boulders (in background) some of which where oil bearing. (*telephoto A. Grist*).

Figure 4.3. Rock loaded iceberg is approached for further inspection, note dark angular IRD on the iceberg surface. Debris is not entrained within the ice (note clean blue ice below debris). A fresh, angular ice face is located on the port side whereas a sloping eroded face exists on the starboard side. Undercutting which extends around the front of the iceberg is a result of post calving erosion. (*photo A. Grist*).

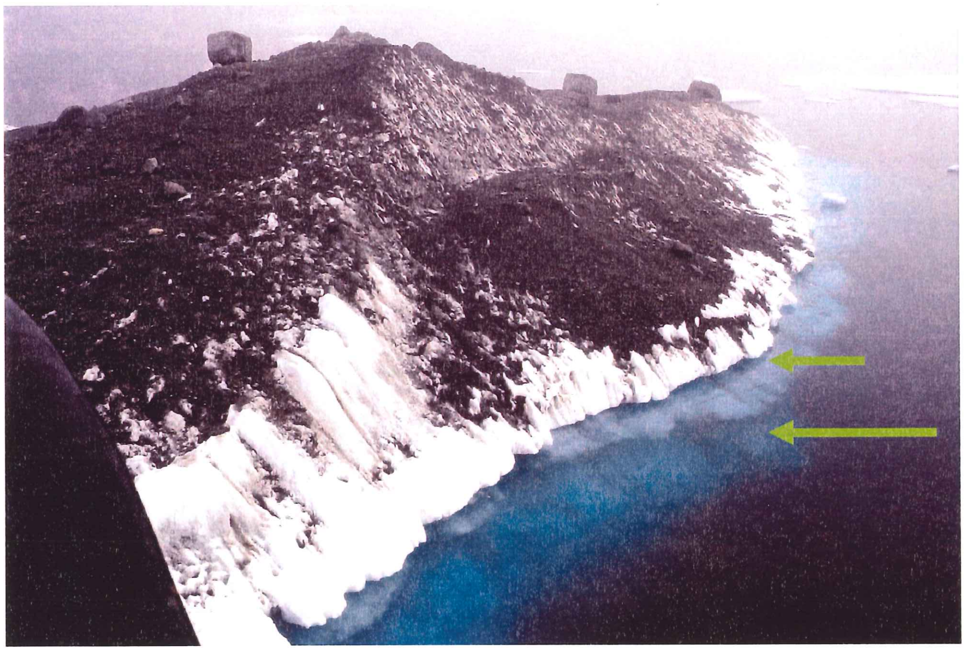


Figure 4.4. Note extensive erosion and undercutting on starboard side of the iceberg caused by tides and waves in comparison to Figure 4.3. Two incision 2-4 m is size persist around the iceberg suggesting longer exposure and previous levels at which the iceberg floated (the iceberg is sinking). Continuous melting of ice below sea level ultimate reduces above water height and detectability. Note boulder at peak for scale, 3-5 meters in height. *(photo. A. Grist)*.

4.3.1. Other Glaciers

The Humboldt Glacier is the largest iceberg-producing glacier in the northern hemisphere ablating 7.7 km^3 of ice annually into the Kane Basin (Weidick, 1995). The glacier is located between 79°N and 80°N, 70 km from the encountered iceberg. Cambrian to Lower Ordovician strata are the dominant lithologies present near the Humboldt Glacier. The glacier is flanked to the north by Daugaard-Jensen Land, a more inland portion of Washington Land (Fig 4.7). To the south the Humboldt Glacier is in contact with mainly meta-sediments of Inglefield Land (Fig 1.1).

Tabular type icebergs are characteristic of the Humboldt Glacier which has a 400 m tall and 50 km long terminus. The Humboldt Glacier is considered as the second potential source glacier for our iceberg.

The third possible source region for the iceberg is Ellesmere Island. Here three tidewater glaciers in Dobbin Bay, Richardsons Bay and Rawlings Bay are combined as one possible source. However the glaciers are smaller in comparison to the Greenland sources and apt to yield deformed shales and sandstones (e.g. Harrison, 1998-2000).

4.4. North Greenland Geology

Dawes et al. (2000) describe the geology of the extensive Arctic platform province of northern Canada and Greenland. The largest part of the ice-free area is made up of crystalline basement rocks of the crystalline (igneous and metamorphic, Archean to Proterozoic) Precambrian Shield. After a period of erosion, Proterozoic strata (e.g. Thule Group) were deposited on the stable platform, and they are only mildly deformed. In North Greenland sedimentation continued into the Palaeozoic until it was brought to a close by tectonic and metamorphic events. Folded Palaeozoic rocks are overlain by younger platform sediments deposited during basin evolution (Fig 4.5).

The Franklinian Basin is an Early Paleozoic carbonate and siliciclastic shelf succession of preserved basin fill which stretches almost 1000 km from east to west and 200 km from north to south across Greenland (Dawes et al., 2000). The basin began developing in the Proterozoic and continued until earliest Devonian in Greenland and earliest Carboniferous in Canada (Ellesmere Island). Sedimentation within the basins was brought to a close by the mid- to late- Paleozoic Ellesmerian orogeny, which is responsible for thrusting and deformation of the rocks on Ellesmere Island (Dawes et al., 2000). On Ellesmere Island, further deformation occurred in the Paleogene Eurekan Orogeny (e.g. Trettin, 1981).

These sequences of Cambrian through Silurian marine deposited platform sediments have attracted much interest from exploration and petroleum geologists. The presence of thick sections of bituminous marine shale, sandstone and mudstone have been shown to contain possibly commercial concentrations of petroleum; however their occurrence is sporadic and the locations remote (Dawes, 1975).

Organic-rich limestone, carbonate mudstone, and shale of potential source rocks mainly occur in Cambrian shelf and Silurian slope sequences along the coastline of north Greenland (Christiansen et al., 1989). The potential source rocks in these strata are dominated by oil-prone organic matter (kerogen type II-III) and extend from Ellesmere Island across Greenland from Washington Land to Peary Land.

Previous maturation studies done by Christiansen (1989) of the Geological Survey of Denmark and the Geological Survey of Greenland allowed a contoured map of maturation temperatures (T $_{max}$) to be constructed (Fig 4.6). It is known that areas south of Hall Land have maturation levels below 450°C and that carbonate content is highly variable.

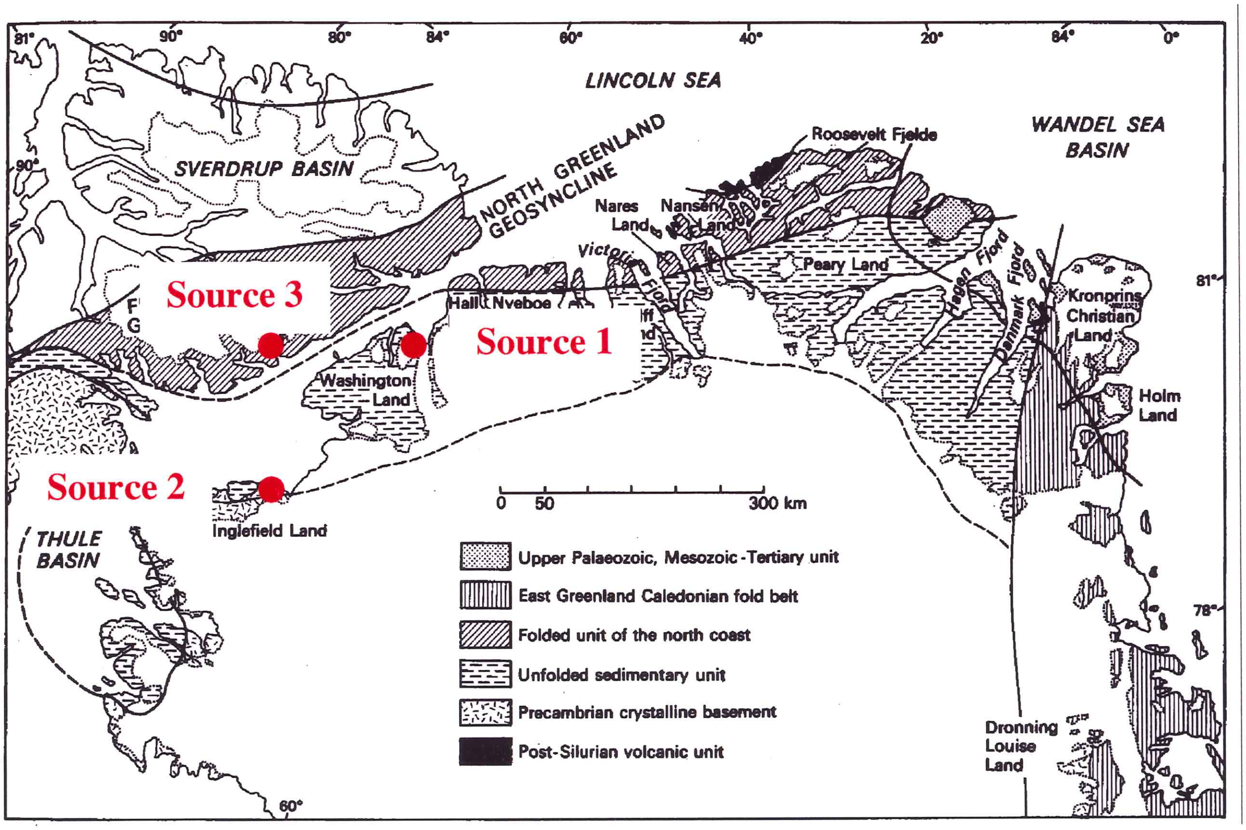


Figure 4.5. Geological regions constraining the Nares Strait and Kane Basin consist of mainly unfolded sedimentary units of the Thule Basin. Three sources for the iceberg were selected and shown in red. Area 1 is located on Washington Land. Area 2, is located where the Humboldt Glacier contacts Inglefield Land. Area 3, includes three smaller tidewater glaciers on eastern Ellesmere Island (Modified from Dawes, 1971).

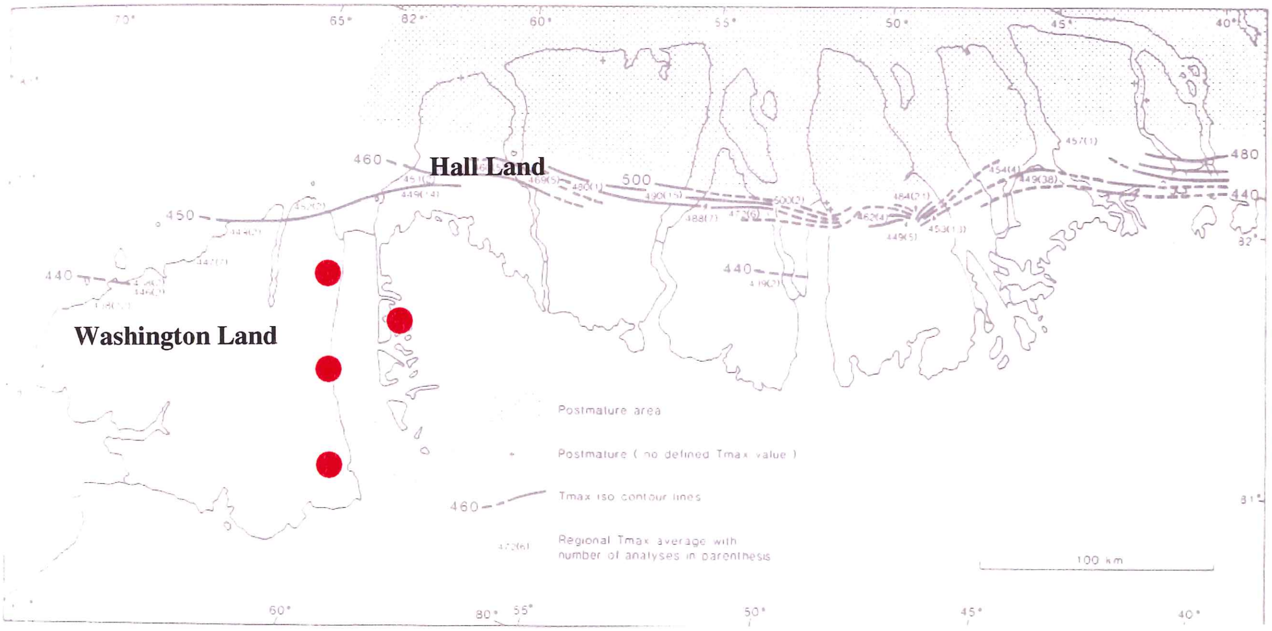


Figure 4.6. Tentative contours of averaged thermal maturation temperatures (T_{max}) from Silurian source rocks across northern Greenland. Note the head of Washington Land and southern parts of Hall Land have T_{max} less than 450°C. These areas contain rocks that are pre-mature to mature with respect to hydrocarbon production as defined by Christiansen (1989). Sample analyses from the rock loaded iceberg fall below the 450°C T_{max} placing the samples along the flanks of the Petermann Glacier (approximate locations based on T_{max} values are shown in red) (Figure modified from Christiansen, 1989).

4.4.1. Washington Land

Washington Land is a carbonate dominated section of the Franklinian Basin located between 79°N and 82°N, bordered on either side by the largest glaciers of the Greenlandic Ice cap (Weidick, 1995). The age of the strata decreases with distance from the inland ice. Lower to Middle Cambrian strata exist at the ice cap's edge in Daugaard-Jensen Land and grades through Ordovician to Silurian aged strata near the coast (Fig. 4.6).

Relevant geological groups of interest on Washington Land are listed in stratigraphical order in Figure 4.7 and pertain to those that are exposed on either side of the Petermann Glacier. These groups include Cambrian through Upper Silurian rocks of the continental platform, which consist mainly of shallow marine carbonate and limestone rocks. All stratigraphic data below are from Dawes (2000), unless otherwise indicated.

The Ryder Gletscher Group is a thick succession of shallow-water, platform interior carbonate and siliciclastic rocks, exposed close to the inland land ice on Daugaar-Jensen Land. This group contacts both the Humboldt and Petermann Glacier, two of the sources for the iceberg. Relative to the younger groups listed below, this group is expected to have the greatest amount of clastic interlaying among the carbonates and is a likely source region for the few sandstones and coarser grained shale displayed on the iceberg. The Morris Bugt Group contains similar strata with a more nodular burrowed to mottled skeletal limestone rock type. This section is also found on both sides of the Petermann Glacier. The Morris Bugt Group would contain similar rocks as the Ryder Gletscher Groups.

Washington Land and Peary Land Group, represents the youngest Silurian Strata along Greenland's coast and near the Petermann Glacier. These groups are analogous to *stromatactis*-rich carbonate build-ups, which outcrop to the north in Hall Land, Wulff Land and through to Peary Land (Stemmerik, 1997). The Silurian sequences are equivalent in age to hydrocarbon producing shales of the Franklinian Basin. Carbonate rocks from these groups have been found to contain economically amounts of hydrocarbons dispersed throughout the limestone, carbonate buildups and relict reef rocks in Ellesmere and Greenland (Dawes, 1998). However no production wells on northern Greenland are being operated. This area is still underdeveloped and further investigations need to be done along the Greenland northern coast. It is from these youngest groups however, that the bulk of the unfoliated carbonate and limestone rocks found on oure iceberg originated. The units contained within these groups are concentrated further to the north and around the mouth of the Petermann glacier (Fig. 4.7).

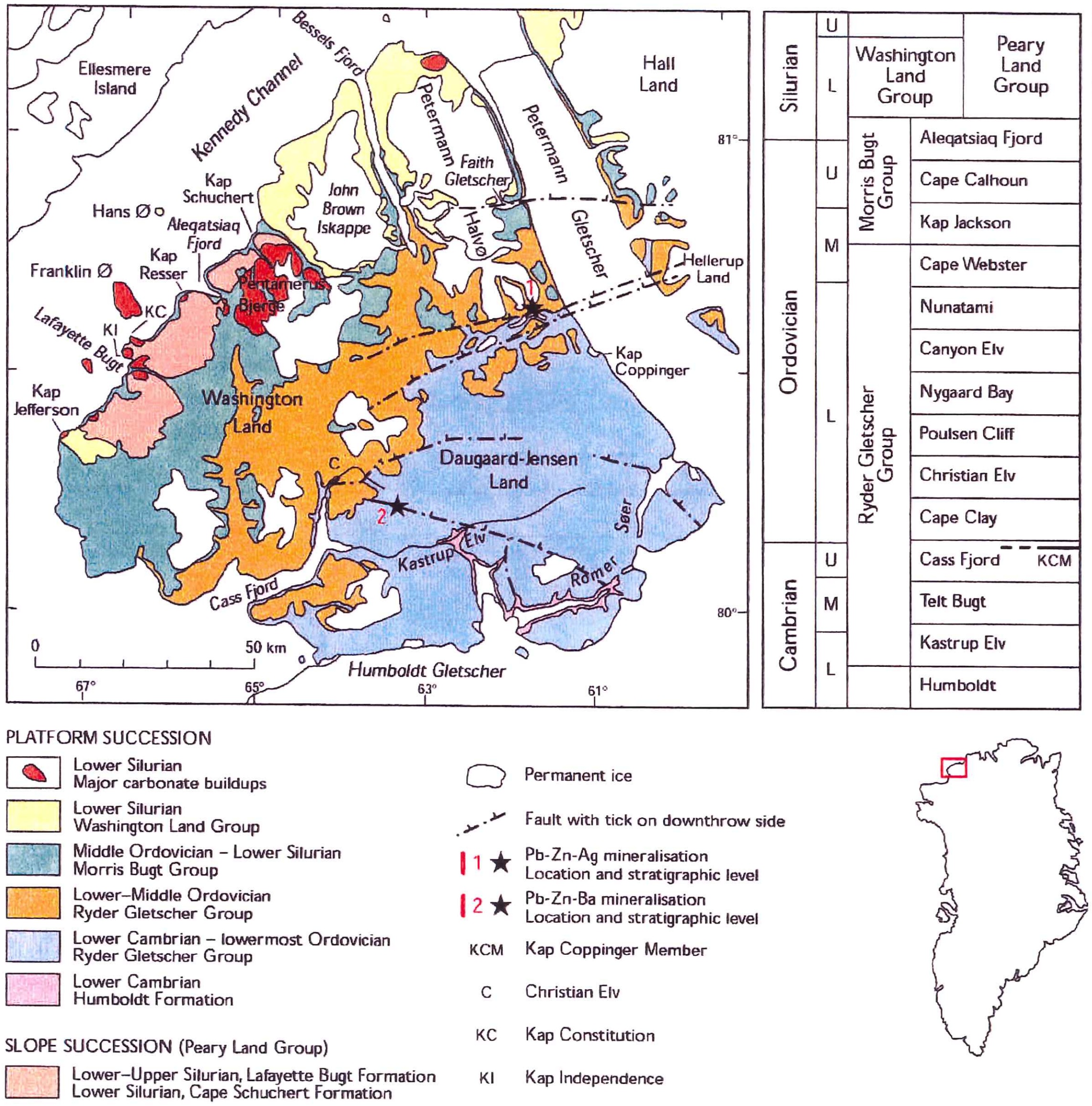


Figure 4.7. A stratigraphic summary of geological Groups and Formations present on Washington Land and southern Hall Land. Fault controlled lead-zinc mineralization are also included. Note the two faults extending on either side of the Petermann Glacier (from Dawes, 2000).

Chapter 5: Results

5.1. Ice Rafted Debris Morphology

The 38 rock specimens collected are organized into a simple table based on macroscopic and microscopic observations (Table 5.1). Following this, table 5.2 list detailed descriptions made of 12 representative specimens selected for thin section investigation (Table 5.2).

Three metamorphic / igneous specimens were investigated under the microscope and determined to be variations between gneissic granite and pink granite. Three limestone and four dolostone carbonates were also studied and represent the dominant lithologies found among the rocks collected. One specimen of quartzite was found among the debris collected in 2001.

One quartz sandstone was inspected under the microscope (Table 5.1).

Table 5.1. This table is a simplified table of the rocks investigated using a petrographic microscope and hand sample determination.

Rock type		Microscopic determination	Macroscopic determination	Total
Meta/Ign	(granite)	3	2	5
Sedimentary	(limestone)	3	13	16
	(dolostone)	4	7	11
	(siliciclastic)	1	2	3
Miscellaneous	(quartz rock)	1		1
	(quartz sand)		1	1
	(bag of pebbles)		1	1
Total		12	26	38

Table 5.2. Petrographic classification of ice rafted debris was done using Dunham (1962) limestone classification. From this list specimen 031-25, -30, and -34 were selected for maturation analysis (Rock Eval Pyrolysis). Specimens 031-25, -30, and -41 were selected for powder diffraction analysis.

Specimen	Name	Description
031-19	Granite gneiss	10 cm hand sample rounded, gneissic granite with biotite (5%) and amphibole hornblende (10%) layered with quartz and feldspar. Containing 40% quartz, 30% orthoclase, and 5% plagioclase. Accessory minerals include zircon, sphene, apatite and ilmenite (5%) (Fig. 5.7).
031-11	Granite gneiss	10 cm rounded hand sample, pink granite with biotite (5%) and amphibole hornblende (10%) with quartz and feldspar. Chloritized biotite and sericitized fledspar is visible. Mineral abundance; 40%quartz, 40% orthoclase, and 2% plagioclase. Accessory minerals include; zircon, sphene, apatite and ilmenite (3%).
031-16	Granite	5 cm hand sample, rounded red granite boulder, contains chloritized biotite, myrmekite. Mineral abundance; 35% quartz, 50% orthoclase, 10% plagioclase. Accessory minerals include; zircon, sphene, apatite and ilmenite (5%).
031-42	Biomicrite Limestone	25 cm hand sample, brown, fine-grain, angular limestone. Containing fossilized fragments of brachiopod, crinoid plates, trilobites and ostracod shell fragments (30-45%) (Fig. 5.6)
031-38	Bioclastic Wackstone	10 cm in hand sample, brown, fine-grain, angular matrix supported limestone. Containing fossilized fragments of brachiopod, crinoid plates, trilobite and ostracod shell fragments (30-45%). Contains bitumen in pore space and has a strong bituminous smell when struck with hammer (Fig. 5.5).
031-41	Biosparite	12 cm hand sample, light brown, calcite rich, containing preserved brachiopod, gastropod, trilobite and coral fragments (30-45%).
031-25	Bituminous Dolostone	15 cm in hand sample, medium-dark grey. One vertically coiled gastropod (1.5 cm) is evident as are rip-up clasts, trilobite and ostracod fragments. The matrix consists of well-formed rhombohedral dolomite crystals. Bitumen fills available pore space between dolomite and clastics grains.
031-34	Bituminous Dolostone	15 cm in hand sample, dark grey-black, fine-grained dolomite rhombs matrix with hydrocarbons filling available pore space. Framboidal pyrite microcrysts (<0.5mm) are also visible (Fig 5.2)
031-30	Dolostone	8 cm in hand sample, light grey, fine-grain. Rip-up clast and discontinuous laminae evident in hand sample. The matrix is dominantly dolomite.
031-9	Dolostone	20 cm in hand sample, interlocking fine-grained, mudstone
7551	Quartz rock	20 cm in hand sample, fractured light purple to violet quartz rock. Undeformed crystals (>1mm) with interlocking crystals boundaries.
031-43	Quartz Sandstone	25 cm in hand sample, contains well-rounded grain of quartz cemented in a fine matrix of mudstone, cross stratified layering is evident.

5.2. Rock Eval Pyrolysis

Three bituminous dolostones specimens 031-25, -30, and -34 (Fig. 5.1) were analysed for hydrocarbons. Rock eval data provided by P. Muki, Global Geoenergy Research Ltd. of Halifax, N.S. are presented in table 5.3.

The procedure for Rock Eval Pyrolysis was summarized in section 2.1. The cracking of hydrocarbon compounds and non-volatile organic matter are measured with increasing heating steps. Heavier and more resistant types of hydrocarbons are volatilized as temperature increases. S1 values recorded in table 5.3 indicate the amount of available hydrocarbons volatilized between 300-350°C in the rocks. S2 values specify the amount of hydrocarbons volatilized between 350 and 550°C. The peak temperatures (T_{max}) recorded from the S2 peak represents the thermal maturity of kerogen in the rock. Kerogen is the organic substance that forms when pressure and temperature from the earth (diagenesis) alters organic material into various liquid and gaseous hydrocarbons. T_{max} values below 450°C are considered pre-mature to mature. The S1 and S2 peaks are used to calculate the thermal maturity (T_{max}) of the rock indicating the potential quantity the rock has of producing hydrocarbons if burial and maturation had continued.

Bitumen within the dolostones is heterogenius and provided only speculative results for two of the samples. Low S1 and S2 values for samples 031-25 and -30 generate weakly creditable T_{max} data as the S1 and S2 values are below 1 mgHC/g rock. Sample 031-34 however, generated creditable data (values above 1) (Table 5.3).

Kerogen types for the three bituminous rocks plotted on Figure. 5.2. are within the oil and gas prone zone. This zone consists of kerogen types II-III indicating that hydrocarbons are derived from marine organic matter, not terrestrial plants.

Plotting the data on a pseudo van Krevelen diagram compares the Hydrogen Index (hydrogen amount) to the Oxygen Iindex (oxygen amount) present in the rock (Fig. 5.3a).

Hydrogen Index values for the samples are 59 mg HC/g TOC, 136 mg HC/g TOC and 291 mg HC/g TOC. Oxygen Index values are 19 mg HC/g TOC, 109 mg HC/g TOC and 12 mg HC/g TOC. Low Oxygen Index values and high hydrogen index values are indicative of marine environments. This is consistent with what is known of the marine platform strata exposed in northern Greenland. Also, plants evolved during the Devonian, and the rocks in the area are pre-Devonian. This analysis is compared with thermal maturities contoured across Washington Land and Hall Land of northern Greenland by Christiansen (1989) (Fig. 4.6). Corresponding data from the same area contoured in Figure 4.6 is displayed on a van Krevelen diagram in Figure. 5.3b. The data plotted here varied between kerogen type II and III , which coincide with Washington Land on Figure. 5.3b are analogues to samples 031-34 and -25 of the rocks investigated from the iceberg.

Dawes et al. (2000) indicates that the drastic increases in thermal maturity from south to north across northern Greenland leaves only a few areas to find trapped hydrocarbons; in general hydrocarbons in the area have been significantly heated and are mature to postmature to the north of Washington Land (Christiansen, 1989). The three type of kerogen are described by Type I is from algal sources and it is very rich in hydrogen, low in oxygen and contains lipids. It generates oil and is present in oil shales. Type II is liptinic and is made from algal detritus, phytoplankton and zooplankton. It has aliphatic compounds and more hydrogen than carbon. It can generate oil or gas. Type III is humic and has more carbon than hydrogen, and is rich in aromatic compounds. Type I and Type

II are usually found in marine environment and Type III is found in continental environments. That is why there is the generalization that marine produces oil and continental produces gas (Forsman, and Hunt, 1958).

Table 5.3. ROCK EVAL PYROLYSIS, report by Global Geoenergy Research, Halifax, N.S. (Mukhopadhyay, 2004).

GGRL/HGS No.	Sample Id.	Sample Type	Leco TOC	S1	S2	S3	Tmax (°C)		HI	OI	S2/S3	S1/TOC	PI	Notes	
														Checks	Pyrogram
04-2342-079136	MZ-031-25	ground rock	0.27	0.09	0.16	0.05	447	*	59	19	3	33	0.36	c	n
04-2342-079137	MZ-031-30	ground rock	0.11	0.20	0.15	0.12	387	*	136	109	1	182	0.57		n
04-2342-079138	MZ-031-34	ground rock	1.28	1.81	3.72	0.16	445		291	12	23	141	0.33		n

Tmax = °C
* =Tmax data not reliable due to poor S2 peak
TOC = weight percent organic carbon in rock
HI = hydrogen index = S2 x 100 / TOC
OI = oxygen index = S3 x 100 / TOC

S1, S2 = mg hydrocarbons per gram of rock
S3 = mg carbon dioxide per gram of rock
S1/TOC = normalized oil content = S1 x 100 / TOC
PI = production index = S1 / (S1+S2)
c = analysis checked and confirmed
n=normal

Figure 5.1. Dark, fine-grained, bituminous dolostone (90% dolomite, 3-5% calcite, 2% quartz, 3-5 % hydrocarbons, by volume). Discontinuous layering and dark, fine grained rip-up clasts are visible throughout. The rocks have visible pore space and a strong bituminous odour when struck with a hammer. In thin section framboidal pyrite microcrysts are visible.

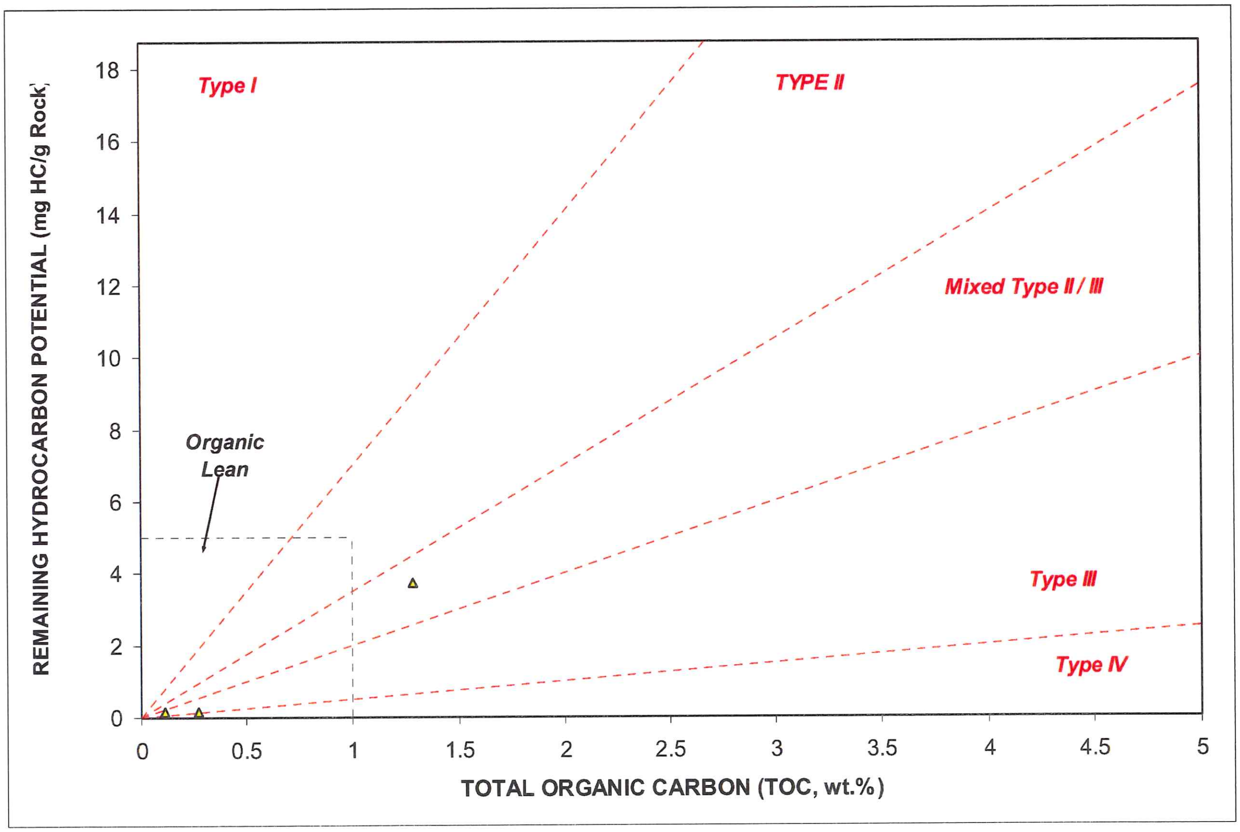


Figure 5.2. Kerogen types for three bituminous rocks used for Rock Eval Pyrolysis. All three rocks plot within the oil and gas prone zone. Kerogen types II-III indicate that hydrocarbons are derived from marine organic matter not terrestrial plants.

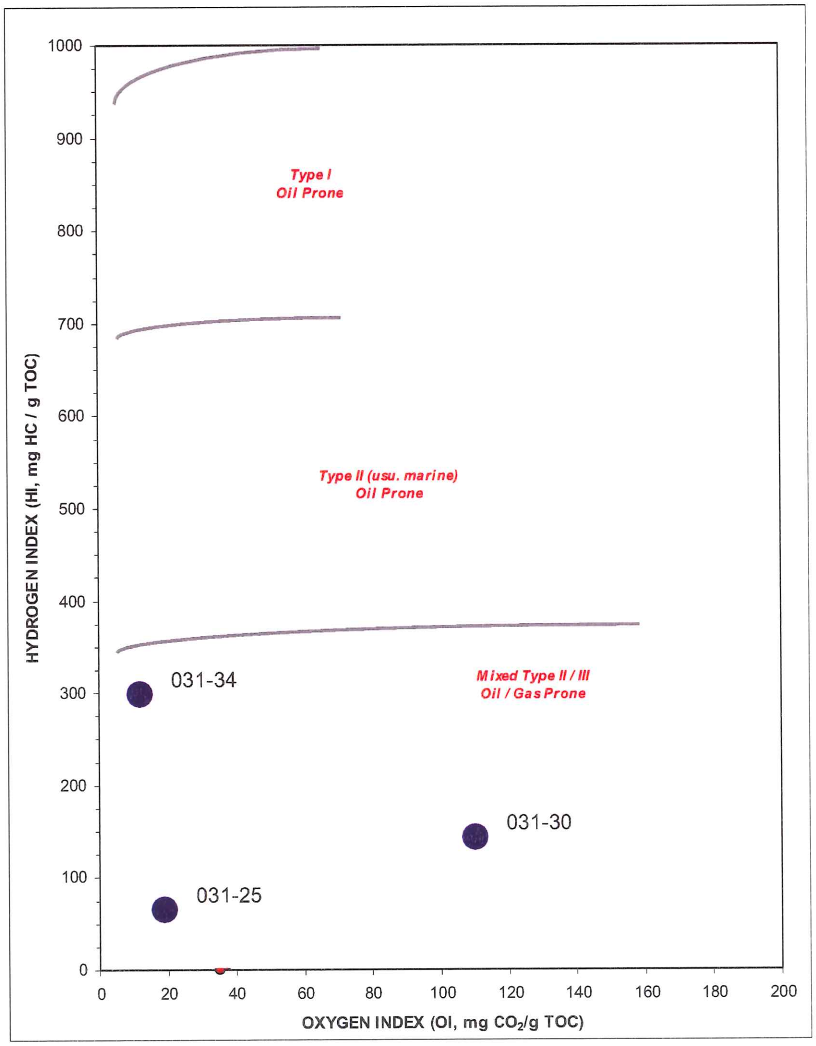


Figure 5.3a. Plot of Hydrogen Index versus Oxygen Index. Labeled, blue, values are the three bituminous rocks from the iceberg. Note all rocks plot in the oil /gas prone area. This is a modified van Krevelen diagram.

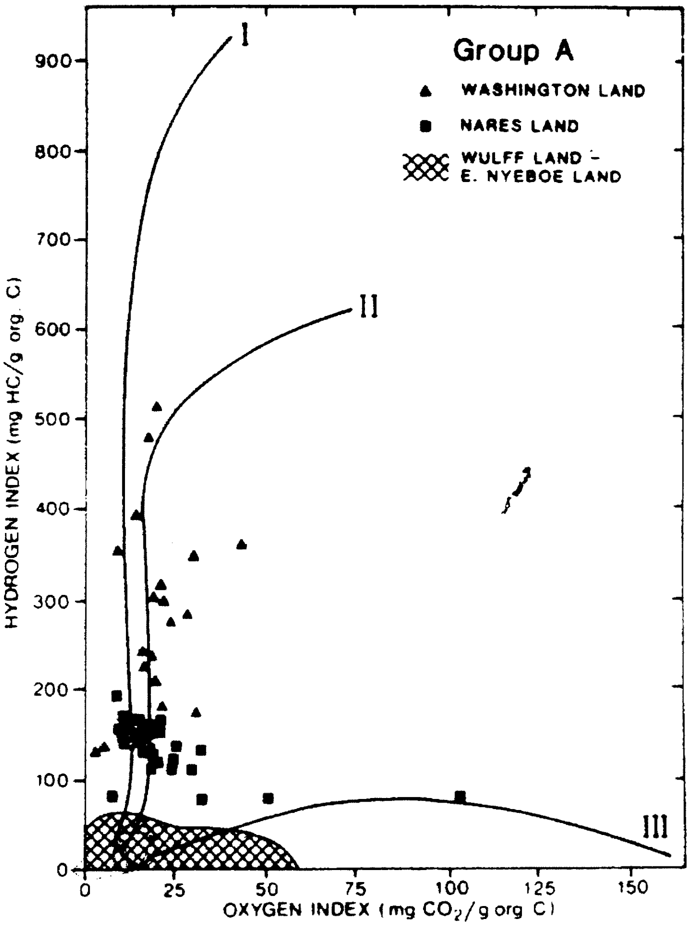


Figure 5.3b. A van Krevelen diagram of Washington Land and Nares Land HI and OI values. Bituminous rocks of the iceberg plot within the Hatched area indicating Wulff Land type values (Christiansen, 1989).

5.2.1. Mineralization

Powdered X-ray diffraction analysis of three samples 031-25, -30 and -34 was performed to identify mineral species in the rocks. The rocks revealed a dominant dolomite and calcite mineralogy. Throughout western and north Greenland the occurences of sulfide copper, gold, lead and zinc mineralizations are associated with WNW trending faults (Dawes, 2000). Dawes (2000) mapped three of these faults which are exposed on both sides of the Petermann Glacier. Although no metallic mineralization was identified by XRD, small aggregated sulphide spherules are visible in polished thin section. The aggregates formed as a result of sulphide diagenesis with bacterial intervention (sulphide reducing bacteria) within the pore space of dolostones (specimen 031-34) (Fig. 5.4).

5.2.2. Metamorphic / Igneous rocks

A total of five rounded to sub-rounded granite clasts where collected from the iceberg (Fig. 1.2). Specimens 031-11 and -19 display gneissic textures defined by compositional layering of dark amphibole hornblende with biotite (Fig. 5.5).

5.3. Fossils

Specimens 031-25, -29 and -40 contain cemented gastropods 1.5 cm in length (Fig. 5.6 & 5.7). Specimen 031-5 contains a hemispheroidal tabular coral fragment (Fig. 5.8). Specimens 031-38, -42 are sub-angular, burrow-mottled rocks which contain fossilized coral, gastropod and shelly fragments indicative of shallow reef environments (Fig. 5.9a and 5.9b). These two specimens are mineralogically and texturally representative of the bulk limestone carbonate present on the iceberg; see full description in Table 5.2.

5.4. Powder X-Ray Diffraction

X-ray diffraction of specimen 031-30, a light grey rock containing rip-up clasts; specimen 031-41; a light brown, fossiliferous rock, and specimen 031-34; a grey to black, porous, bituminous, rock, confirmed speculations that all dark grey bituminous rocks are completely dolomitized and that lighter limestones are predominantly a mix of calcite and dolomite (Fig. 5.10 a, b & c).

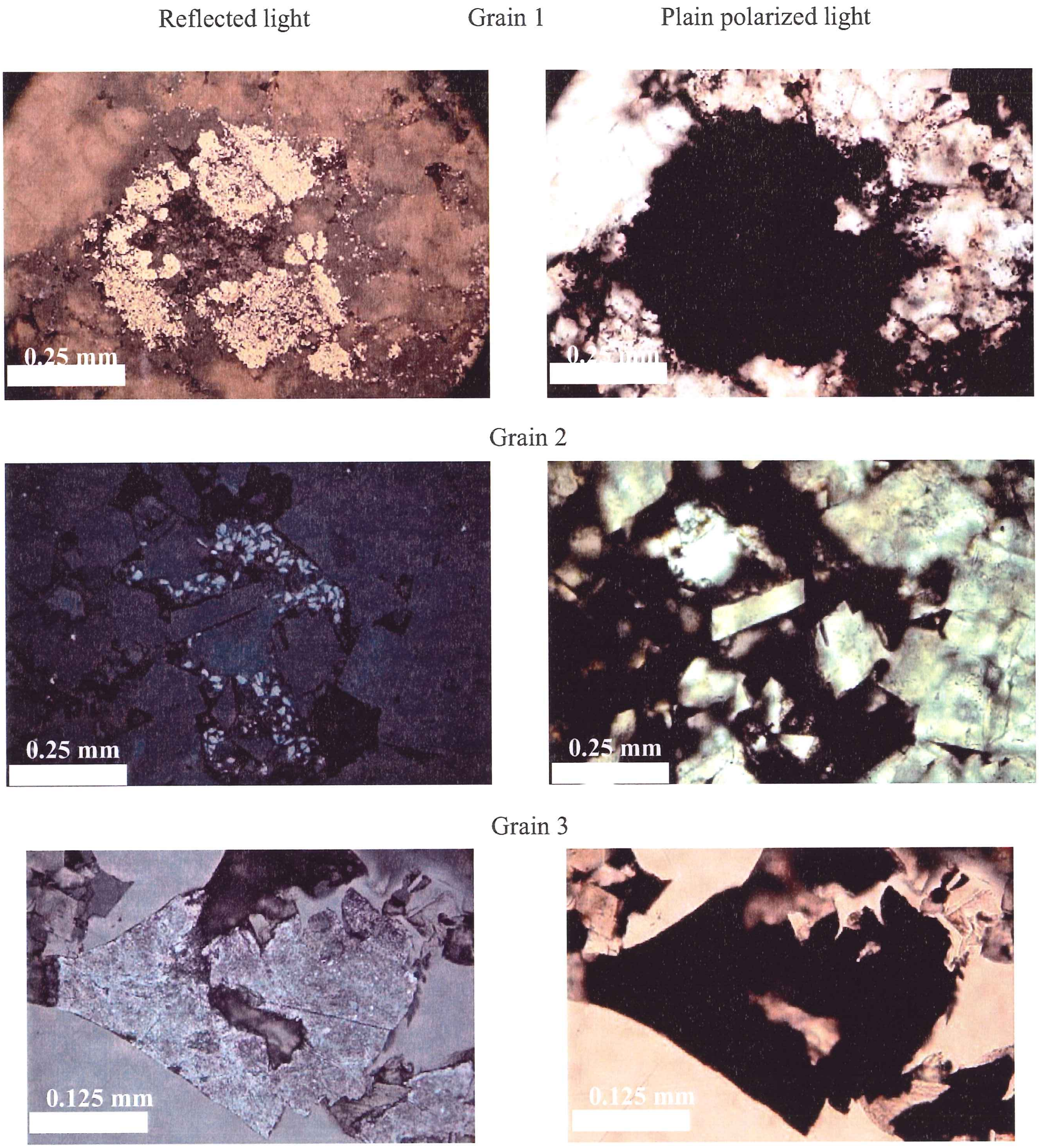


Figure. 5.4. Photomicrographs of framboidal sulfides (pyrite) found within bitumen-filled pores of sample 031-34. The spherical shapes are due to sulphide diagenesis within the dolostone.

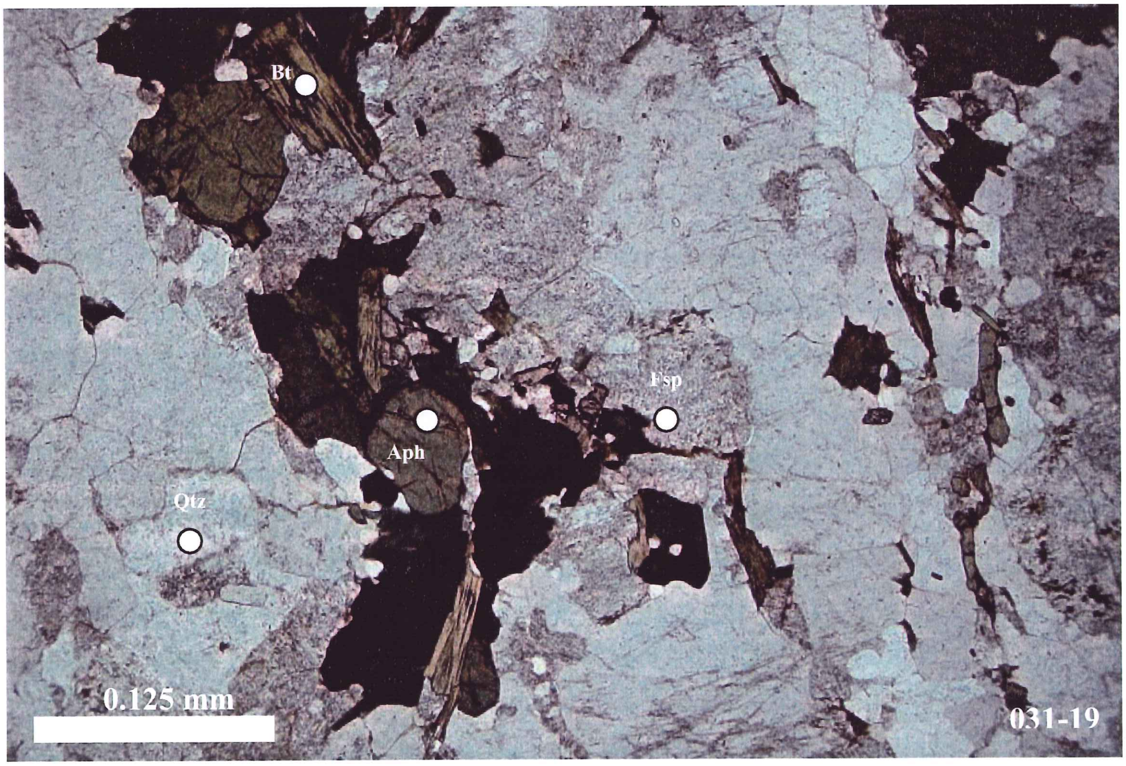


Figure 5.5. Lightly deformed, gneissic granite containing darker-green amphibole (Aph) minerals and biotite (Bt). Bulk mineralogy is 50% K-feldspar (Fsp), 50% quartz (Qtz), and 10% plagioclase, accessories minerals present include; zircon, sphene, apatite and ilmenite. Myrmekite exsolution and undulose extinction is present in quartz and feldspar crystals (field of view; 10 mm across).

Figure 5.6. Preserved Archaeogastropods within mottled dolostone. Identified as species *Maclurites*. These fossils are excellent Ordovician guide fossil, occurring below the Silurian (Moore, Lalicker and Fischer., 1952). The Family Maclurites have low conispiral whorls, and sinistral shells; their origin is common in the upper Thumb Mountain Formation (Troedsson Cliff Fm of Greenland), which is an Upper Ordovician formation (Harrison and Brent, 2002).

Figure 5.7. Preserved Archaeogastropods within mottled dolostone. Identified as species *Maclurites*. These fossils are excellent Ordovician guide fossils, occurring below the Silurian ((Moore, Lalicker and Fischer., 1952). The Family Maclurites have low conispiral whorls, and sinistral shells; their origin is common in the upper Thumb Mountain Formation (Troedsson Cliff Fm of Greenland), which is an Upper Ordovician formation (Harrison and Brent, 2002).

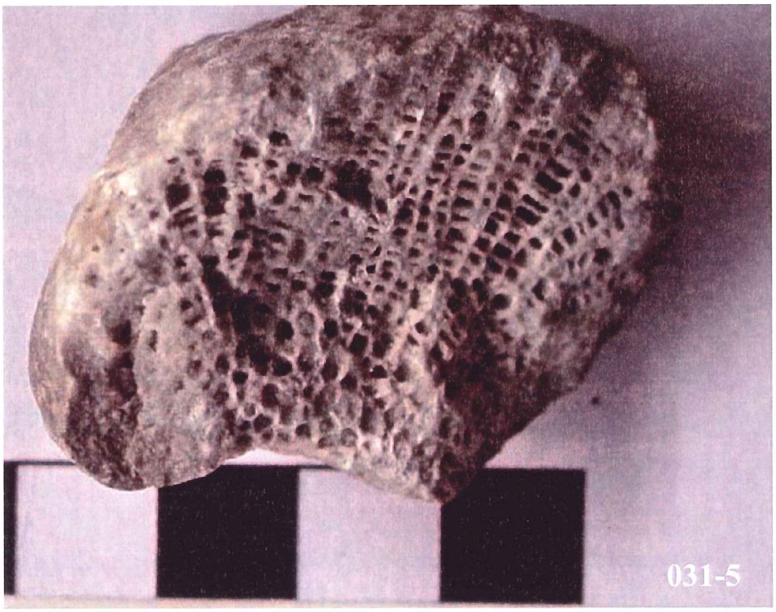


Figure 5.8. Hemispheroidal Tabular coral fragment possibly *Lichenaria*, a representative of Ordovician reef and shallow shelf environments. The Tabular coral are extinct colonial anthozoans confined to Paleozoic rock (Moore, Lalicker and Fischer., 1952). In colonies of most genera, close packing of individuals gives them a polygonal transverse section, but some exhibit relatively large tubes of subcircular sections, separated by small polygonal tubes or by irregular colonial structures

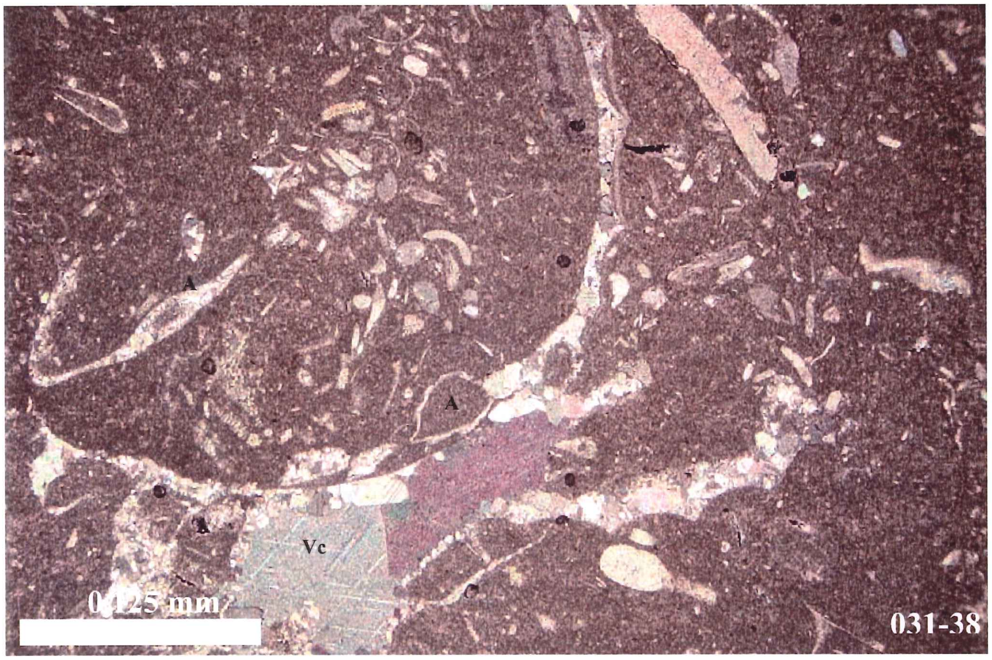


Figure. 5.9a. Light brown, matrix-supported bioclastic wackestone. Fossil pelecypods (?) shells (A) are infilled with vuggy calcite (Vc).

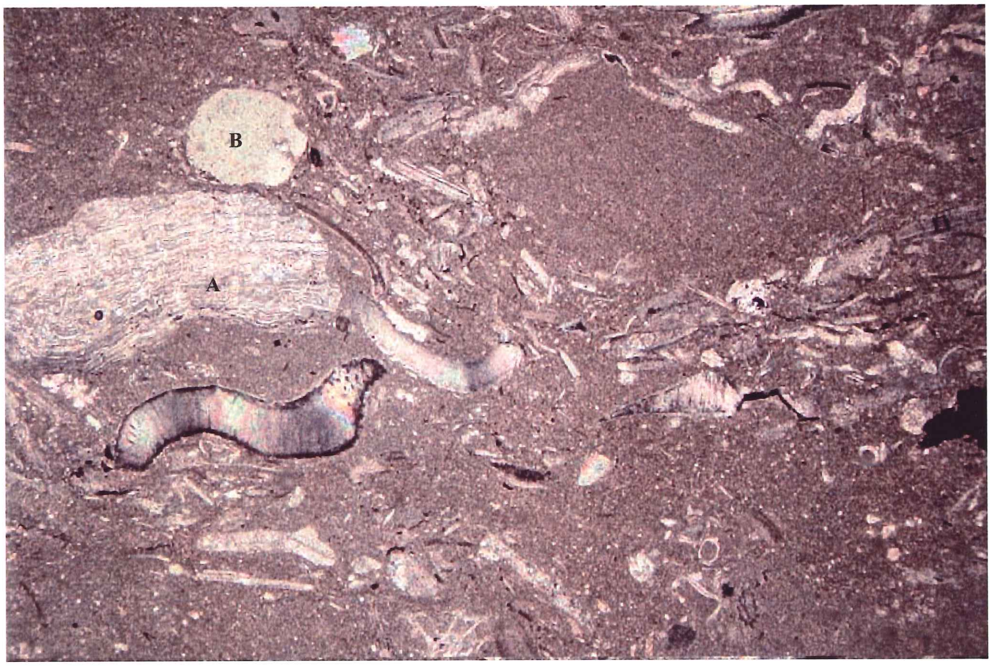
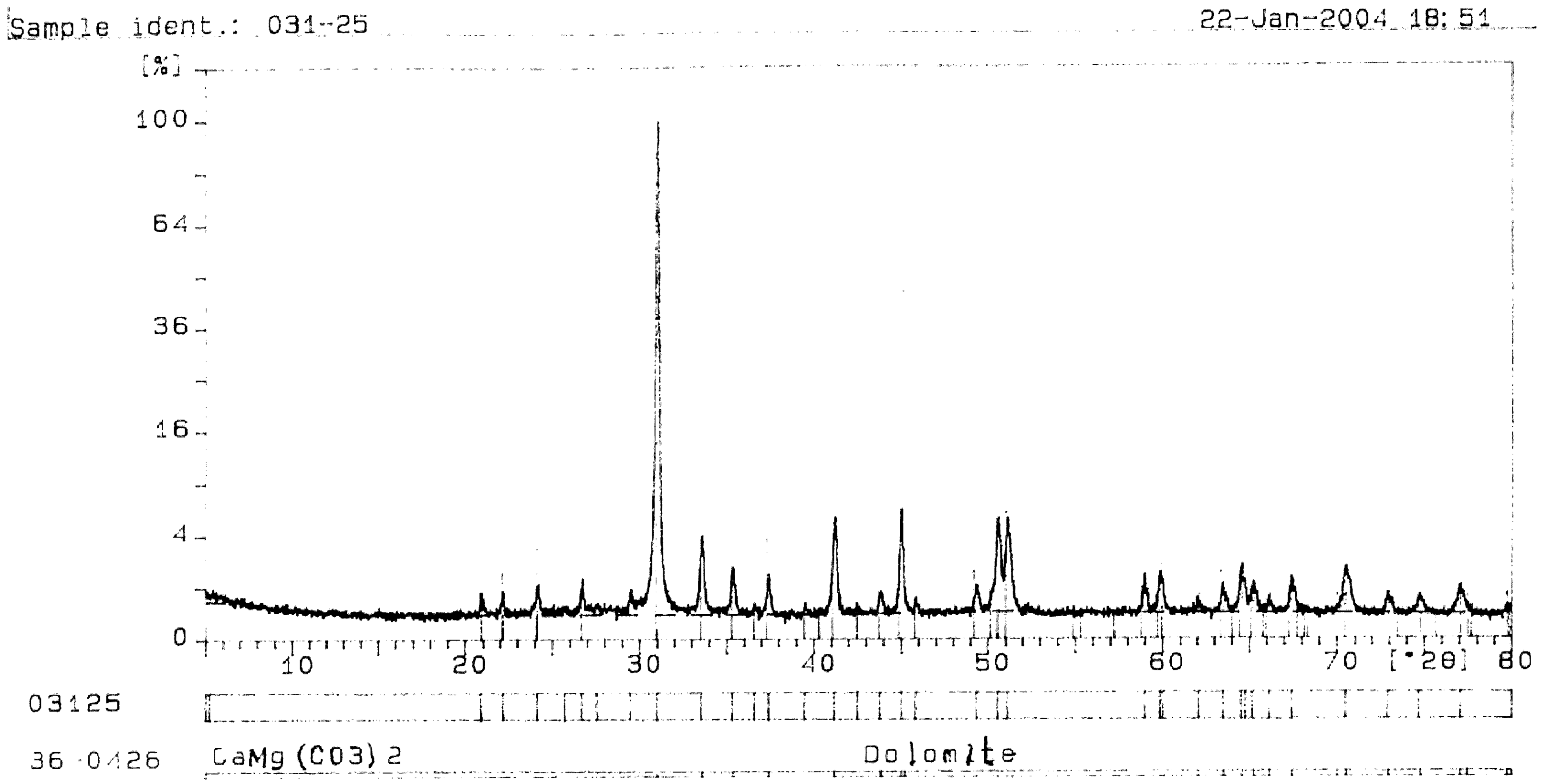
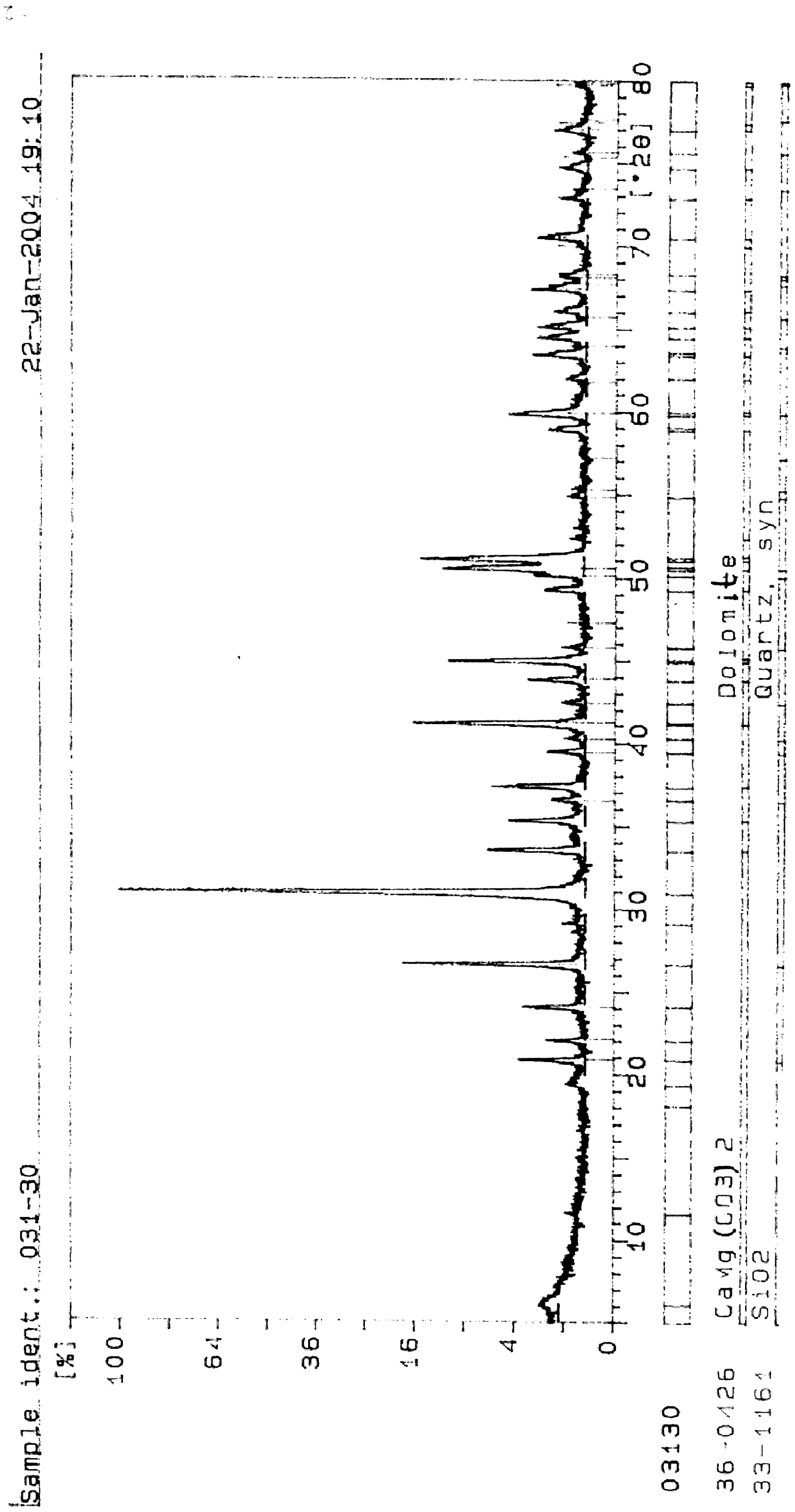


Figure 5.9b. Fine-grained, cemented Biomicritic Limestone. Calcite replaces burrows; brachiopod grains (A), crinoid plates (B), trilobite (C) and burrows (D).

Figure 5.10 a, b & c
X-ray diffraction graph display outputs from powder diffraction analysis of specimens 031-25, -30, -41. Mineralogy of bituminous rocks is mainly dolomite (031-25 and 031-30). Mineralogy of limestones is more calcite rich (031-41). All samples contain quartz as background noise.


Sample ident.: 031-25
22-Jan-2004 18:51
[%]
100
64
36
16
4
0
10
20
30
40
50
60
70
[°2θ]
80
03125
36-0426
CaMg(CO3)2
Dolomite


Sample ident.: 031-30
22-Jan-2004 19:10
[%]
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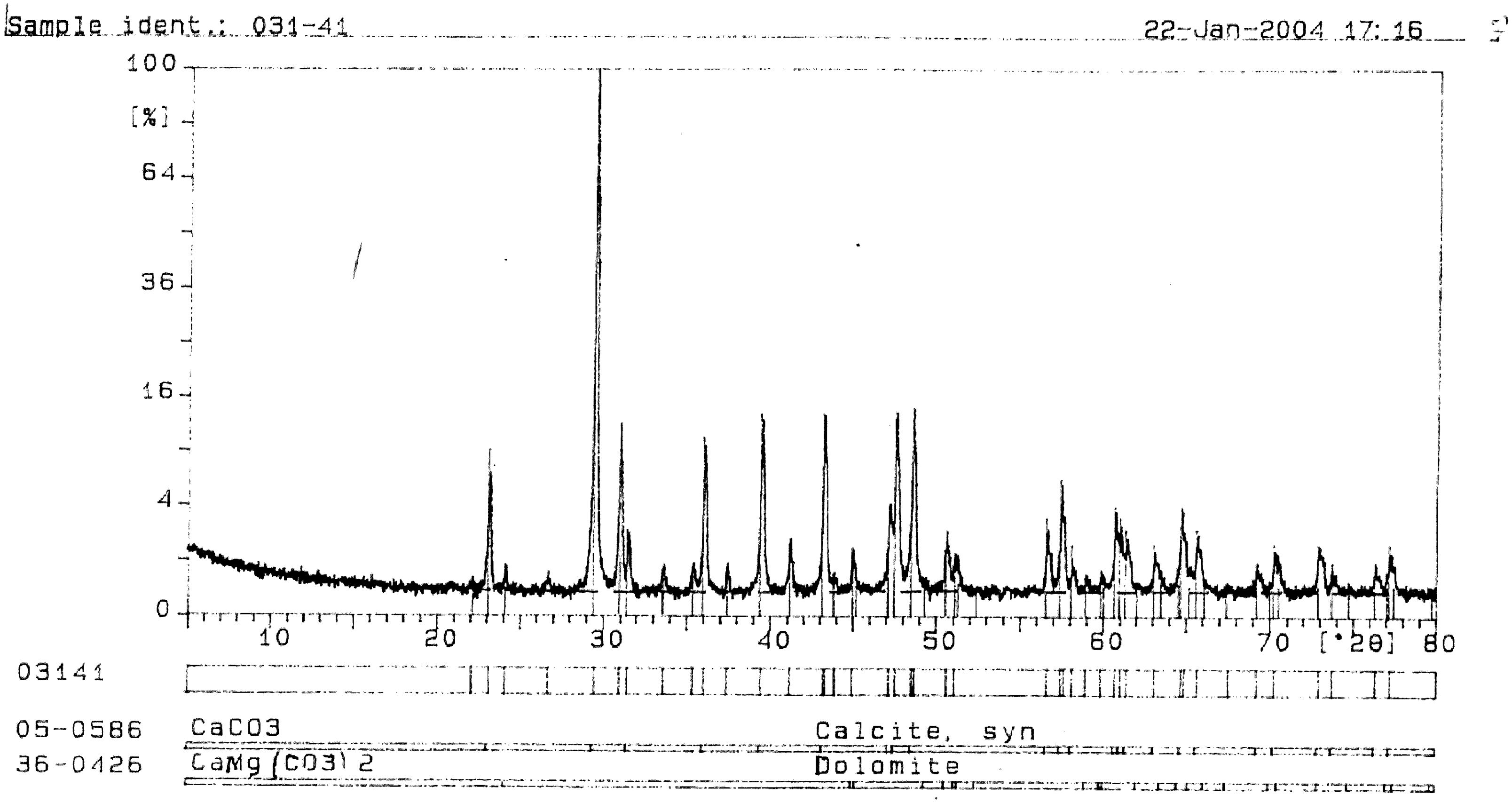
36
16
4
0
10
20
30
40
50
60
70
80
[°2θ]
03130
36-0426
CaMg(CO3)2
Dolomite
33-1161
SiO2
Quartz, syn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22-Jan-2004 17:16
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[%]
64
36
16
4
0
10
20
30
40
50
60
70
[°2θ]
80
03141
05-0586
CaCO3
Calcite, syn
36-0426
CaMg(CO3)2
Dolomite

Chapter 6: Discussion

6.1. Discussion

The 38 rock specimens retrieved from the iceberg display structures typical of platform shelf, shallow marine and basin environments of the Arctic platform region. The morphological aspects displayed by the rocks also suggest they were derived supraglacially from flanking valley walls and were not modified by subsequent abrasion.

The substantial presence of irregular shaped fossiliferous dolostone and limestone and sedimentary clasts among the debris indicate mainly carbonate reef type, shelf and platform sources. The unfoliated nature of these specimens suggests an undeformed source region.

In the study area, unfoliated Cambrian through Silurian, shallow marine platform type strata occur mainly within portions of the Franklinian Basin of NW Greenland (Escher and Watt, 1976). Bitumen occurrences of kerogen types II-III are common within carbonate shale successions of the basin and have been shown by Christiansen (1989) to originate from stromatactic-rich marine material.

Rock Eval Pyrolysis data acquired from three bituminous specimens indicate that the thermal maturity and kerogen types present in the rocks from the iceberg are derived from marine organic matter and correlate with values expected of Washington Land and Hall Land geology. Framboidal pyrite (probably low-temperature, diagenetic) within the bituminous dolostone support a Washington Land or Hall Land derivation, as fault controlled mineralization of diagenetic pyrite intervals and lead-zinc-silver is shown by Dawes et al. (2000) to exist on both flanks of the Petermann Glacier.

Fossil occurrences are extensive throughout the platform region where both macrofossils *Maclurites* and *Lichenaria* identified in this study within the ice rafted rocks are known to occur in northern Greenland (Kerr, 1967).

The metamorphic and igneous rocks are speculated to have originated from the crystalline Precambrian shield beneath the Greenland Icecap were glacio fluvial transportation could account for their worn, rounded appearance. Poly-deformed and poly-metamorphic rocks outcrop along the Inglefield mobile belt to the south of the Humboldt Glacier. However, the occurrence of metamorphic rocks on the iceberg is rare, supporting a source from an area where undeformed sedimentary rocks predominate.

Physical characteristics of the iceberg support that the steep angular side of the iceberg referred to as the port face (relative to the ship's position in Figure 4.1) is a fractured face from either: 1) where the iceberg calved from the parent glacier or 2) has had a large block broken off. The starboard side (relative to ship, Figure 4.1) displays a sloping exposed surface and erosional undercutting suggesting that this was the terminus of the glacier. A horizontal incision 5 m below sea level indicates that the iceberg after calving has acquired a lower profile deeper in the water column (i.e. sank), however the iceberg has not been free floating long enough to develop undercutting along the fractured surface at the current sea level. The absolutely horizontal underwater incision as well as the large number of free-standing rafted rocks lying on the ice surface are evidence that iceberg rolling has not occurred.

These observations point to a glacier capable of producing thin, tabular, low profile icebergs, easily calved from a terminus such that rolling does not occur and which spend very little time in a bay or fiord.

Basal melt rates for the Petermann Glacier have been shown in recent studies by Rignot (1998), and Stewart (2004), to be higher than any other northern Greenland outlet glacier. High apparent thinning rates are believed to produce thin tabular icebergs, which have a reduced chance of grounding and rolling. Robe et al. (1977) documented a large flat tabular iceberg near the Grand Banks of Newfoundland, and they interpreted it to have originated in the Petermann Glacier; they speculated it was associated with climate change (Broecker, 1994; Rignot et al. 1997; Stewart et al. 2004).

Before the field component of the Nares Strait expedition of 2001, relatively high and sustained temperatures occurred at the Thule Airbase (ca. 76°32'N; 68°50'W). A record amount of rain was recorded over two weeks in July 2001 leading to unprecedented flooding, the destruction of culverts and bridges at the Thule airbase, and the closure of the airport for several days (M.Zentilli pers.comm. 2003). Extreme thawing of permafrost areas were also encountered during work on the northwest Greenland coastal region during August, 2001 (M.Zentilli pers.comm. 2003). This record precipitation may well be a cause for the production of the rock loaded iceberg: increased temperatures and precipitation may have facilitated mass wasting (slumps, landslides) from the steep U-valley walls of the Peterman glacier. It is possible that relative warming may have caused glacial surging thus accelerating calving (however this hypothesis has not been confirmed). Surging might also promote relatively gentle calving of tabular icebergs from the glacier.

During the course of this research it has come to our attention that as recently as 2002, large tabular icebergs supporting a significant rock debris load have been noticed by scientists in Conception Bay, Newfoundland. The icebergs were not as low profile as the subject of this study, but had noticeable amounts of surface debris. A sample of the ice rafted debris was collected from a broken piece of the large tabular iceberg (late May 2002) by the ship's captain, Tony King. The rock sample was sent to C-Core at Memorial University of Newfoundland, St. John's, where scientists suggested the rocks had probably originated in northwest Greenland (Ingrid Peterson, Coastal Ocean Science, OSD, BIO, personal communication to M.Zentilli, March 17, 2004).

6.2. Conclusions

The main conclusions of this thesis are:

1) Kerogen types and organic maturation values obtained for bituminous rocks from the studied iceberg coincide with those known from Cambrian through Silurian carbonate rocks of southern Hall Land and Washington Land of northwest Greenland, geology dissected by the very large Petermann Glacier.
2) The floating ice tongue of the Peterman Glacier is the most probable source glacier for the rock-covered iceberg.
3) Circumstantial evidence allows speculation that warmer temperature and precipitation prevailing before the encounter with the rock-covereed iceberg facilitated mass wasting and debris from the steep U-valley flanks, and accumulation on the ice surface of the Petermann Glacier.
4) The low profile attained by these rock-loaded icebergs and their persistence to southern latitudes such as offshore Newfoundland and the North Atlantic points to the fact that these low-profile ice masses pose a real threat to navigation and

exploitation of offshore resources, deserving the development of better techniques for their detection.

6.3. Future work

As the occurrence of low profile rock loaded icebergs are more clearly understood it is the author's conviction that similar occurrences such as that reported off Conception Bay, Newfoundland will become known. This thesis shows that the Petermann Glacier was the likely source for the rock loaded iceberg of 2001. Following this work it would be interesting to acquire reliable satellite images of the Petermann Glacier and surrounding areas for the summer months of May through August of 2001 as well as from the previous two years. Annual images would permit visual confirmation of rock loaded iceberg production and aid in identifying the processes involved with debris accumulation. The bathymetry of the Petermann Fiord should be investigated since its sill may limit the thickness and degree of rock loading of generated icebergs able to exit to the Kane Basin.

Since radar is not very effective in detecting these low profile icebergs, detection methods involving side directed sonar will need to be developed for routine navigation in northern waters. Remote sensing images of moving tabular icebergs may be able to detect varying degrees of rock cover and assess their degree of buoyancy and navigational hazard.

Chapter 7: References

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Sample descriptions by Harrison, J.C., Zentilli, M. and Brent, T.A

031-1 Mixed unconsolidated sand and mud collected from iceberg surface

031-2 Sample has angular surfaces. Laminated and wavy laminated lime mudstone, medium light grey weathering, and dolomitic mudstone, pale yellowish grey weathering. Slightly wavy laminations. Bituminous smell when struck with the hammer. Incidence on iceberg: common. Provenance: Upper Ordovician or Lower Silurian; i.e. lower Allen Bay Formation of Arctic Islands or Aleqatisiaq Fjord Formation(?) of NW Greenland. Possible oil source rock

031-3 Collected piece is ellipsoidal subrounded with small angular surfaces. Weakly cemented lime grainstone containing angular centimetre-scale fragments of lime mudstone; pale greyish orange weathering. Individual limestone grains are rounded and vary from vitreous white to greyish yellow to (rarely) black. Possible, minor, vitreous white quartz grains, well rounded. Rock effervesces vigorously in 10% Hcl. Incidence: anomalous. Provenance: unknown

031-4 Subangular fragment of chain coral. Incidence: anomalous. Provenance: Upper Ordovician Arctic-Red River or Bighornia-Therodontia assemblages

031-5 Subrounded hemispheroidal fragment: "cabbage head" bryozoan. Incidence: anomalous. Provenence: Upper Ordovician Arctic-Red River or Bighornia-Therodontia assemblages

031-6 Subangular sample. White weathering orthoquartzite, compositionally very mature, probably silica cemented. Incidence: anomalous. Provenance: Lower Cambrian Dallas Bugt Formation, or mid-Proterozoic Thule Group

031-7 Angular fragment. Mottled pale yellowish grey weathering dolomitic mudstone with discontinuous laminae and thin beds of light grey weathering lime mudstone. Moderately burrow mottled. Not bituminous. Incidence: common and representative. Provenance: Middle Ordovician Bay Fiord Formation (Cape Webster Formation of North Greenland); possibly Cape Storm Formation (mid-Silurian, Ludlow) or Goose Fiord Formation (mid-Silurian to Lower Devonian; Ludlow to Lochkovian)

031-8 Angular fragment, 10 to 12 cm. Laminated. Light to medium brownish grey weathering, finely crystalline dolostone, distinctly bituminous, parting surfaces parallel to compositional laminae. Incidence: common and representative. Provenance:Upper Ordovician or Lower Silurian; i.e. lower Allen Bay Formation of Arctic Islands or Aleqatisiaq Fjord Formation(?) of NW Greenland. Possible oil source rock (see also 031-2)

031-9 Subrounded and angular weathered surfaces, 15 cm. Light and very light brownish grey weathering, finely crystalline dolostone. Indistinct compositional banding. Strongly bituminous. Incidence: common and representative. Provenance:Upper Ordovician or Lower Silurian; i.e. lower Allen Bay Formation of Arctic Islands or Aleqatisiaq Fjord Formation(?) of NW Greenland. Possible oil source rock (see also 031-2,031-8).

031-10 Subrounded weathered surfaces with angular fracture planes exposing fresh material. Yellowish grey and light olive grey weathering dolomitic mudrock. Weak parallel parting but no obvious compositional layering. Provenance: Middle Ordovician Bay Fiord Formation (Cape Webster Formation of North Greenland); possibly Cape Storm Formation (mid-Silurian, Ludlow) or Goose Fiord Formation (mid-Silurian to Lower Devonian; Ludlow to Lochkovian). See also 031-7

031-11 Subrounded cobble, 6 cm. Pink weathering gneissic granite with potash feldspars to 2 mm, 15 to 20% vitreous white quartz, 10% biotite and greenish amphibole. Incidence: anomalous. Provenance: fluvial gravel ultimately derived from Precambrian shield

031-12 Well rounded large pebble, 4 cm. Coarsely crystalline red weathering granite. Potash feldspars to 1 cm. Quartz aggregates to 6-8 mm. Minor biotite and black amphibole. Incidence: anomalous. Provenance: fluvial gravel ultimately derived from Precambrian shield.

031-13 Small angular pebble. Pale reddish orange lime grainstone. Incidence: uncommon, not anomalous. Provenance: unknown
031-14 Well rounded pebble, 2 cm. Mottled grey weathering and greyish orange weathering lime mudstone. Incidence: uncommon, not anomalaous. Provenance: Lower Paleozoic

031-15 Flat pebble, rounded and weathered, 1.5 cm, with an angular fresh surface. Pale reddish orange weathering lime mudstone with moderate grey mottles. Incidence: uncommon, not anomalaous. Provenance: Lower Paleozoic

031-16 Subangular pebble, 3 cm. Red weathering gneissic granite, medium crystalline. Pink and red potash feldspars to 3 mm, 15-20% vitreous white quartz, 10-12%, biotite and greenish amphibole. Incidence: anomalous. Provenance: Precambrian shield, no obvious fluvial cycle

031-17 Rounded pebble, 1 cm. Mottled pale grey weathering dolomitic mudrock and pale greyish orange weathering dolomitic mudrock. Incidence; moderately common. Provenance: Middle Ordovician Bay Fiord Formation (Cape Webster Formation of North Greenland); possibly Cape Storm Formation (mid-Silurian, Ludlow) or Goose Fiord Formation (mid-Silurian to Lower Devonian; Ludlow to Lochkovian). See also 031-7, 031-10

031-18 not examined

031-19 Well rounded cobble, 10 cm. Biotite cordierite(?) orthogneiss. Incidence: anomalous. Provenance: fluvial gravel ultimately derived from Precambrian shield.

031-20 Angular fragment, 10 cm, hammered from larger angular block. Pale yellowish brown and brownish grey weathering mottled limestone with chalky white chert nodules. Incidence: burrow-mottled limestone is very common, chert nodules are anomalous. Provenance: upper part of Thumb Mountain Formation (or Troedssen Cliff Fm of North Greenland), Upper Ordovician

031-21 Angular fragment hammered from larger block. Burrow-mottled limestone, pale yellowish brown and brownish grey mottles. Incidenece: very common. Provenance: Upper Ordovician Thumb Mountain Formation (or Troedssen Cliff Fm of North Greenland) or Lower Silurian Allen bay Formation (Aleqatsiaq Fjord Fm of NW Greenland).

031-22 Subrounded pebble, 4 cm. Nodular limestone: brownish grey weathering skeletal lime mudstone nodules in a sparse recessive matrix of pale yellowish brown weathering lime mudstone. Nodular fabric is produced by in-sediment burrowing. Recognizable brachiopod valves and trilobite fragments. Cross-cutting and bifurcating calcispar vein (8 mm wide). Incidence: common. Provenance: Irene Bay Formation (Cape Calhoun Formation of N Greenland), Upper Ordovician

031-23, 24 two pieces hammered from common original angular block. Voarsely crysalline very pale yellowish orange weathering lime grainstone with cavernous lenticular voids containing boxworks of yellowish orange weathered earthy calcite(?). Incidenece: anomalous. Provenance: unknown, lithological similarity to 031-3

031-25 Subangular, 15 cm. Intensely burrow-mottled medium light grey and medium dark grey lime mudstone. Distinctly bituminous. 3-5% white calcispar as replacement of brachiopod valves and unidentifiable skeletal fragments. Vertically coiled gastropod (one). Incidence: common. Provenance: lower Allen Bay Formation (Aleqatsiaq Fjord Fm of Greenland), Upper Ordovician

031-26 Subangular fragment hammered from large piece. Medium dark grey weathering lime mudstone, possible calcispar replacement of skeletal fragments (10%). Modestly bituminous smell when struck.

Incidence: common. Provenance: lower Allen Bay Formation (Aleqatsiaq Fjord Fm of Greenland), Upper Ordovician

031-27 Small angular piece hammered from larger block. Intensely burrow-mottled light grey skeletal wackestone and nodular medium grey weathering lime mudstone. Tiny trilobite fragments Incidence: common. Provenance: Irene Bay Formation (Cape Calhoun Formation of N Greenland), Upper Ordovician (see also 031-22).

031-28 Irregular angular fragment hammered from larger piece. Fine and indistinctly flat laminated, very pale yellowish brown dolostone. Notable sets of wavy subparallel grooved surfaces (styolites?) arranged perpendicular to compositional layering. Bedding-parallel parting surfaces, bounded by styolites, feature smooth dish-shaped concave lenses of residual pyrobitumen(?); (one of these dish-shaped features is interpreted as the cast of an unornamented armoured placoderm carapace fragment - Jason Anderson, UofT). Incidence: rock type common, features anomalous. Provenance: Restricted marine carbonates, Lower Ordovician to Lower Devonian

031-29 Subangular fragment. Pale yellowish grey weathering, finely crystalline dolostone. Indistinctly flat laminated. Styolitic grooved fractures perpendicular to layering. Good flat-coiled macluritids on one surface. Disc-shaped impression of possible placoderm carapace, including dimpled ornamentation. Incidence: rock type common, features anomalous. Provenance: Maclurites sp is common in the upper Thumb Mountain Formation (Troedsson Cliff Fm of Greenland) Upper Ordovician.

031-30 Subangular piece. Pale grey and very pale grey weathering, wavy and discontinuously laminated microcrystalline dolostone with very pale grey rip-up clast layers and stratified breccia layers. Incidence: uncommon, not anomalous. Provenance: Lower Paleozoic

031-31 Clast-supported lime mudstone breccia. Medium pale grey lime mudstone angular clasts in a medium dark grey lime mudstone matrix. Incidence: uncommon, not anomalous. Provenance: Lower Paleozoic, as for 031-30

031-32 Subrounded piece, 10cm, hammered from larger cobble. Very pale rey weathering dolostone with discontinuous partings of dark yellowish brown weathering pyrobitumen. Light grey dolostone without bitumen also occurs in "clasts" forming laminated pseudobreccia layers. Incidence: uncommon, not anomalous. Provenance: Lower Paleozoic, as for 031-30, 031-31

031-33 Subangular fragment, 10 cm, hammered from larger piece. Pale grey weathering lime mudstone containing angular breccia clasts of very pale yellowish brown weathering dolostone. Not bituminous. Incidence: uncommon, not anomalous. Provenance: Lower Paleozoic, as for 031-30, 031-31, 031-32

031-34, 031-35 Two fragments broken from common large piece. Moderate yellowish brown and brownish grey weathering finely crystalline dolostone, indistinctly laminated and profoundly bituminous. Incidence: relatively common, not usually this dark. Provenance: Upper Ordovician or Lower Silurian; i.e. lower Allen Bay Formation of Arctic Islands or Aleqatisiaq Fjord Formation(?) of NW Greenland. Possible oil source rock (see also 031-2)

031-36 Pale reddish orange weathering lime grainstone. Tiny cavities on weathering surfaces; also several centimetre-scale cavernous voids. Incidence: anomalous. Provenance: Unknown, possibly same as for 031-13?

031-37, 031-38 Angular (031-37) and subrounded (031-38) pieces. 031-37 was likely hammered from a larger block. Moderate yellowish brown weathering skeletal wackestone with fissile discontinuous partings of pale greenish grey weathering skeletal lime wackestone. Skeletal material includes crinoid ossicles and trilobite fragments. Incidence: very common. Provenance:
Irene Bay Formation (Cape Calhoun Formation of N Greenland), Upper Ordovician (see also 031-22, 27).

031-39 Angular fragment hammered from a larger block. Pale yellowish brown weathering skeletal lime grainstone. Brachiopod valves to 2 cm replaced by white calcispar. Negative zinc test on honey brown calcispar. Distinctly petroliferous odour when struck with the hammer. Incidence: fossils rarely observed; rock type is common. Provenance: Upper Ordovician or Lower Silurian; i.e. lower Allen Bay Formation of Arctic Islands or Aleqatisiaq Fjord Formation(?) of NW Greenland.

031-40 Intensely burrow mottled moderate yellowish orange lime grainstone with nodules of moderate brownish grey limestone. Collected for Maclurites sp. Common crinoid ossicles Incidence: very common rock type Provenance: Maclurites sp is common in the upper Thumb Mountain Formation (Troedsson Cliff Fm of Greenland) Upper Ordovician.

031-41 Moderate yellowish brown weathering skeletal lime grainstone. Good brachiopods, some identifiable. Incidence: common rock type, fossils are unusual. Provenance: probably Silurian platform carbonate formation

031-42 Large angular block, 25 cm. Moderate yellowish brown weathering skeletal wackestone with fissile discontinuous partings of pale greenish grey weathering skeletal lime wackestone. Skeletal material includes crinoid ossicles and trilobite fragments. Incidence: very common. Provenance: Irene Bay Formation (Cape Calhoun Formation of N Greenland), Upper Ordovician (see also 031-22, 27, 37, 38).

031-43 Large angular block, 25 cm. Tabular cross-stratified calcispar-cemented quartz arenite in 10 cm-thick bed with downlap of stratification onto a bed of orthoquartzite. Overlain by very pale yellowish orange weathering dolomitic mudstone (2+ cm thick). Incidence: anomalous. Provenance: Thule Group (mid-proterozoic), Lower Cabrian Dallas Bugt Formation, or possibly Cape Storm Formation or equivalent mid-Silurian (Ludlow) shelf carbonate of NW Greenland

Associated rocks with similar provenance (arranged from most common to least common):

031-20,21,27,40 Burrow-mottled limestone. 031-28,29 Styolitic dolostone with Macluritids: Thumb Mountain Formation (Troedsson Cliff Fm of Greenland) Upper Ordovician, one with Maclurites sp. Incidence: most common

031-2,8,9, 25,26,34,35 Variably bituminous shelf carbonate. Upper Ordovician or Lower Silurian; i.e. lower Allen Bay Formation of Arctic Islands or Aleqatisiaq Fjord Formation(?) of NW Greenland; Incidence: very common

031-22, 27, 37, 38, 42 Nodular burrow mottled skeletal limestone. Irene Bay Formation (Cape Calhoun Formation of N Greenland), Upper Ordovician. Incidence: very common

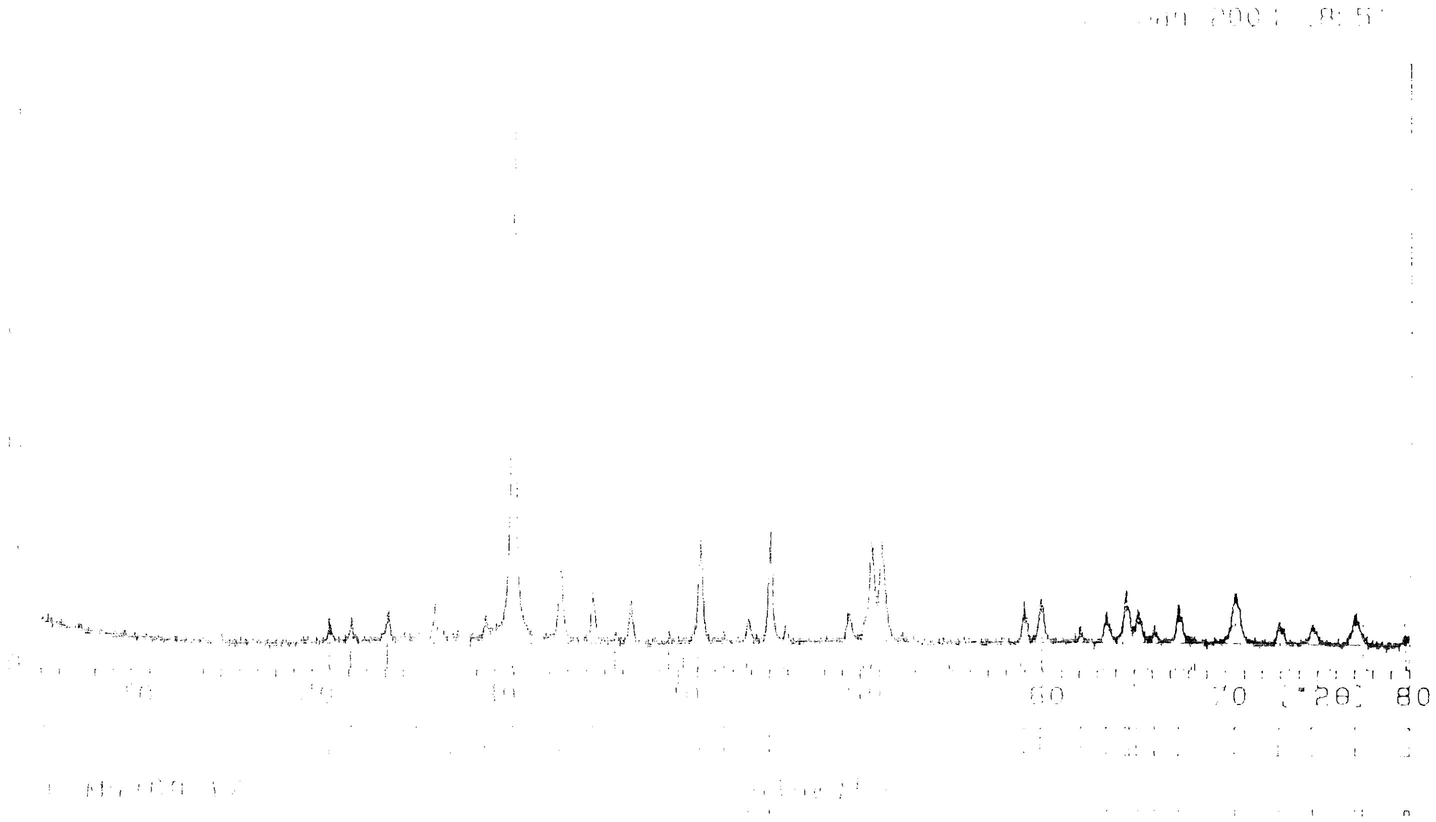
031-7,10,17 Wavy laminated carbonate mudstone. Provenance: Middle Ordovician Bay Fiord Formation (Cape Webster Formation of North Greenland); possibly Cape Storm Formation (mid-Silurian, Ludlow) or Goose Fiord Formation (mid-Silurian to Lower Devonian; Ludlow to Lochkovian). Incidence: common

031-30 to 33 Carbonate intraclast breccia. Provenance unknown. Incidence: uncommon, not anomalous

031-13 to 15, 031-18,36 Reddish orange weathering lime grainstone. 031-3,23,24 Yellowish orange lime grainstone, weakly cemented. Provenance unknown. Incidence: anomalous

031-6,43 Orthoquartzite interbedded with dolomitic mudrock. Mid-Proterozoic Thule Group, Lower Cambrian Dallas Bugt Formation or Cape Storm Formation and equivalent mid-Silurian of Greenland. Anomalous

031-11,12,16,19: Precambrian shield samples(Lower Proterozoic or Archean), some showing evidence of fluvial or glaciofluvial rounding. Incidence: all highly anomalous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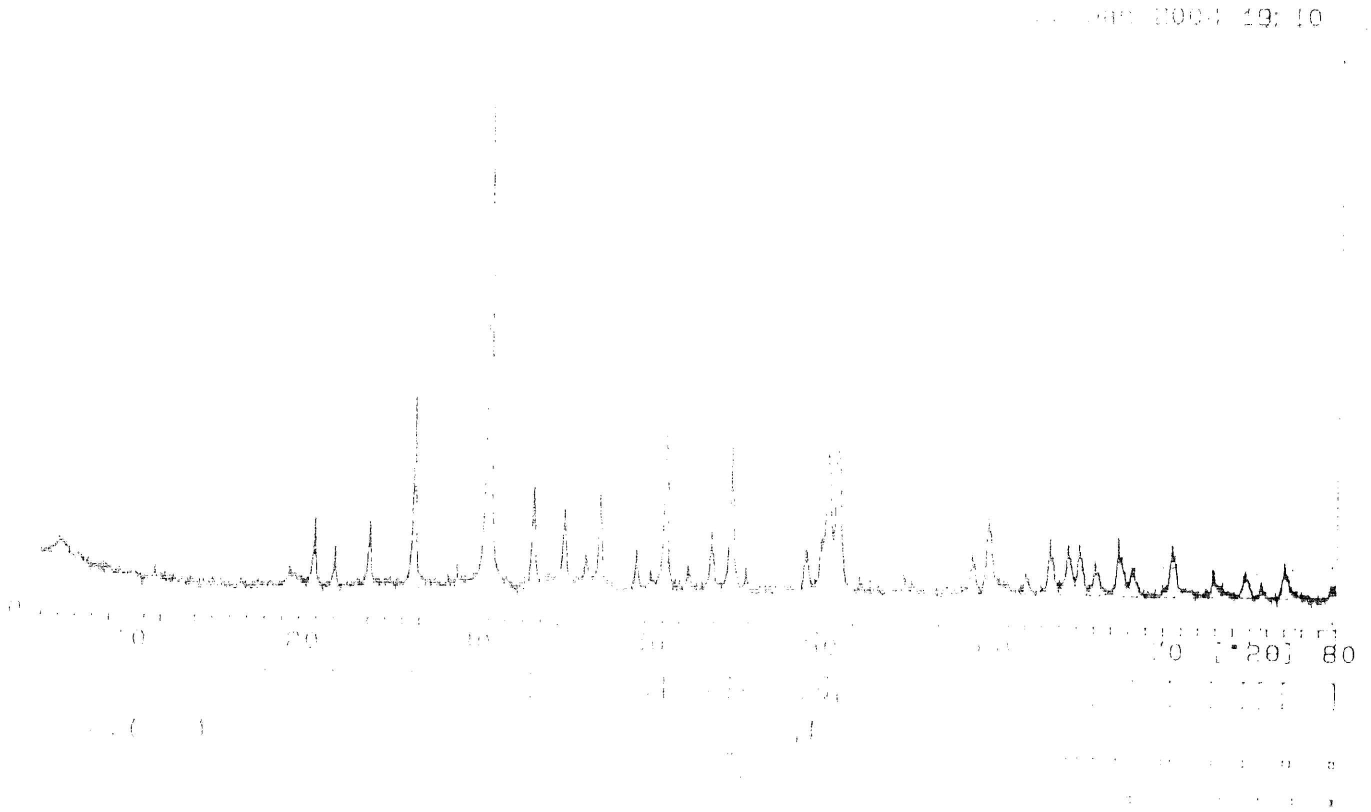
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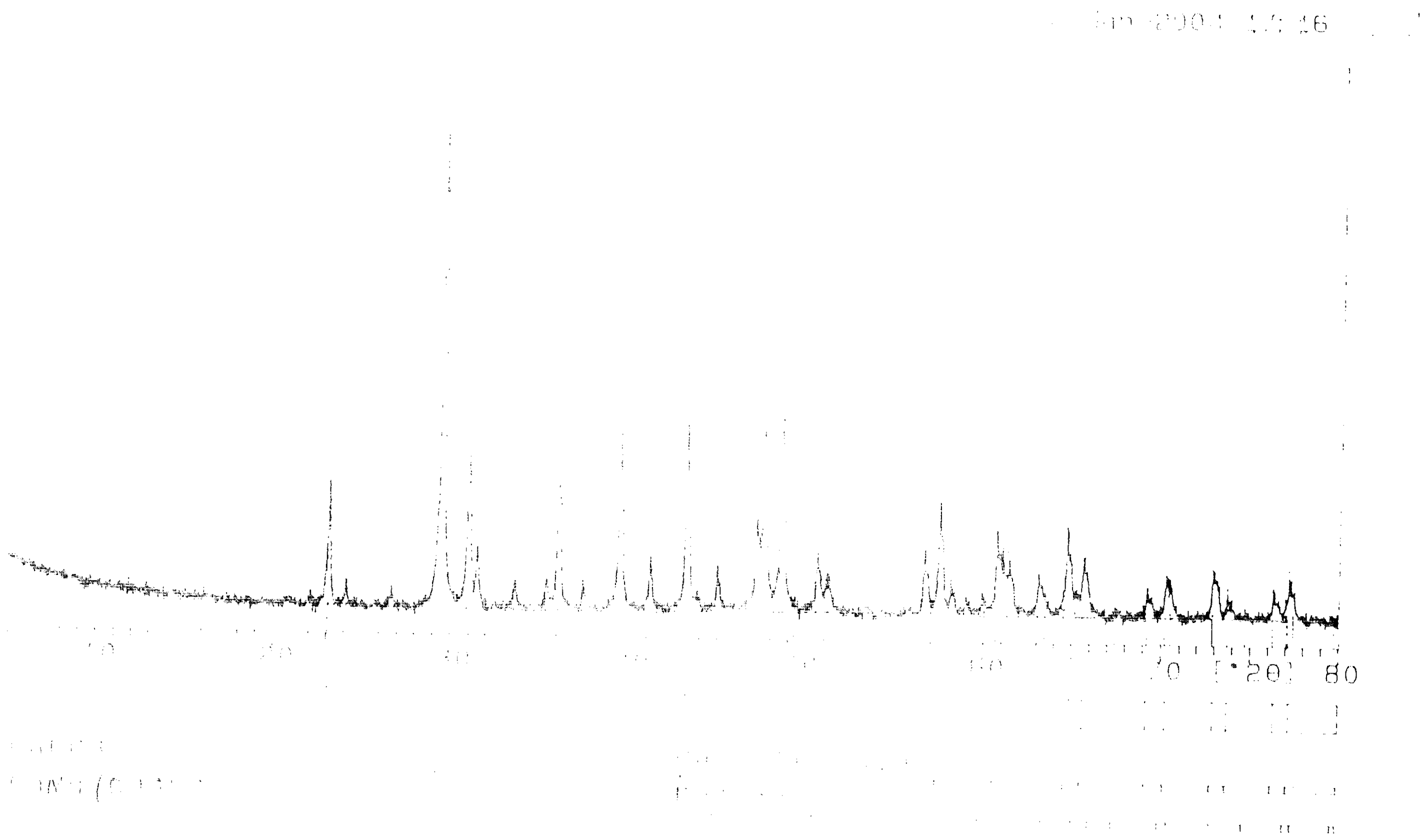
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