GEOLOGICAL SURVEY OF CANADA
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Seabed geologic features and processes and their relationship with fluid seeps and the benthic environment in the Northwest Passage

Blasco, K.A., Blasco, S.M., Bennett, R., MacLean, B., Rainey, W.A., and Davies, E.H.

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1. INTRODUCTION

The Geological Survey of Canada, Atlantic Division (GSCA) is working in collaboration with a consortium of international scientific parties as part of the International Polar Year project on Arctic Ocean Diversity (ArcOD) led by Dr. Rolf Gradinger at the University of Alaska Fairbanks and Dr. Andrey Gebruk at P.P. Shirshov Institute of Oceanology; and ArcticNet. The GSCA's project contribution is geological linkages to potential biologic "hotspots", areas of increased benthic activity in the Northwest Passage in the Canadian Arctic.

The study has focused on unique geologic environments throughout the Northwest Passage, including: mud volcanoes, pockmarks, oil and gas seeps, faults, slopes and ice scours. These features hold particular interest to the oil and gas industry, northern communities, environmentalists and the general public; as well as scientists, due to their association with possible greenhouse gas emissions, potential hydrocarbons at depth, geohazards, and unique ecosystems.

This report details the geologic framework and processes of these unique seabed environments with potential linkages to ecologic hotspots. Historic data, as well as data collected in the Northwest Passage up to 2007 has been used in the current report. Future work will endeavour to integrate the geological setting with the benthic environment in these areas of interest.

For additional information regarding Arctic Ocean Biodiversity Projects please visit the ArcOD website at http://www.arcodiv.org/IPY_cluster/arcod_75.html

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2. HISTORIC DATA

Exploration of the seafloor of the Northwest Passage in the Canadian Arctic generally commenced with hydrocarbon exploration and development starting in the early 1970s. Numerous survey lines of single and multichannel seismic, echosounder, and sidescan sonar as well as borehole data were collected during the oil industry's early heyday. Even from these early records, evidence of an active seafloor environment was observed. The most striking examples were the existence of possible mud volcanoes and areas of oil and gas seeping from the seafloor. These features were not unique to northern Canadian waters, evidence of seep activity and mud volcanism were found to exist in many areas of the world's oceans (e.g. Hovland and Judd, 1988).

2.1. Oil and Gas Seeps

The leakage of hydrogen sulphide, methane, and hydrocarbon fluid from the seafloor is known as cold seepage and differs from hydrothermal venting in the rate, composition and temperature of eruption. Patches of oil floating at sea surface were reported throughout the Gulf of Mexico throughout the 1900s (Hovland and Judd, 1988) and the discovery of methane seeps in the same area was made by C. Paull in the mid-1980s. The movement of gases and liquids from the seafloor into the water column is collectively referred to as *fluid flow* as defined in Judd and Hovland (2007).

2.1.1. Scott Inlet Oil Seep

During a seismic survey off the eastern coast of Baffin Island in 1976, an expansive oil slick was noted at the sea surface, appearing to be bubbling from depth (Loncarevic, 1976; Loncarevic and Falconer, 1977) (Figure 1). Subsequent surveys to this site over the next ten years verified the continued presence of the slick and attempted to investigate its origin and nature. Details about the Quaternary geology of the area can be found in Praeg et al. (2007).

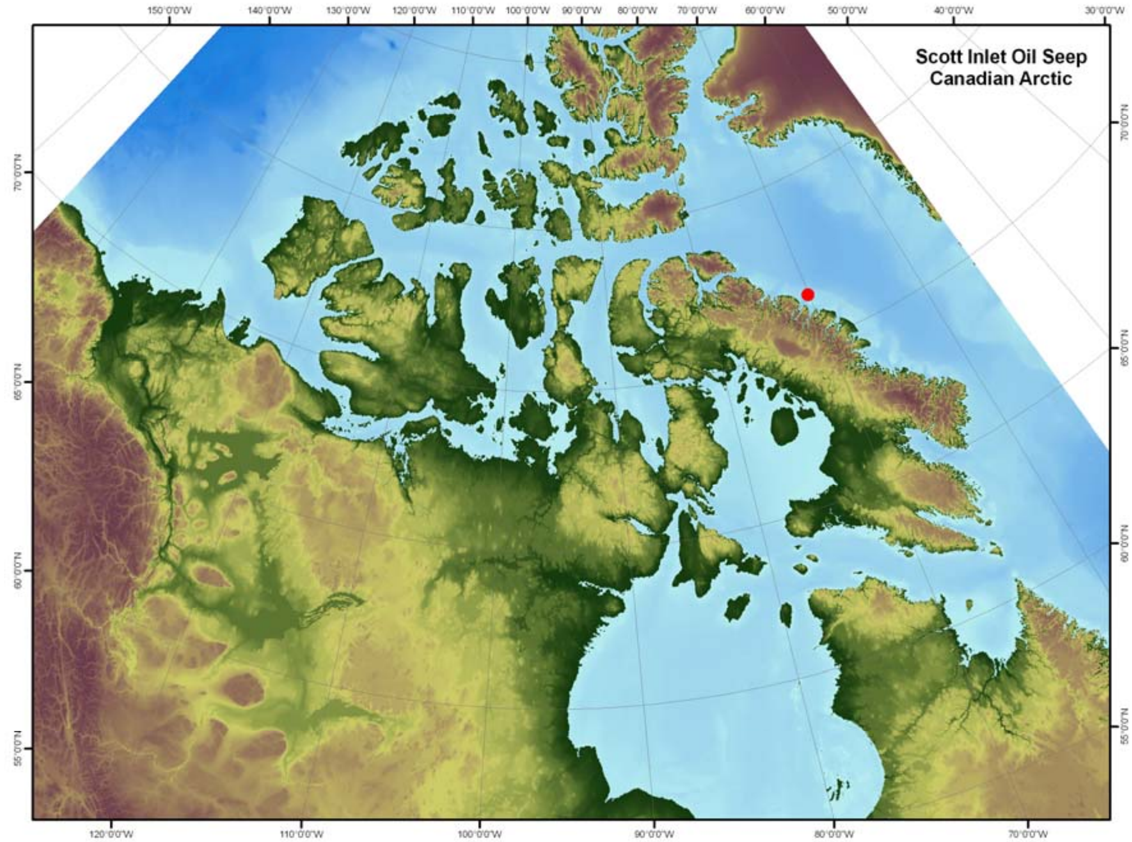

Figure 1: Location of Scott Inlet Oil Seep

2.1.1.1. Scott Inlet Seep Surveys

The oil seep surveys included the use of remote sensing techniques; collection of gravity, magnetic and high-resolution seismic data; bedrock, sediment and water column sampling; geochemical and chemical analyses; and submersible investigation including photographic and video documentation of the seabottom and water column in the area of the slick (MacLean et al., 1981; Levy and MacLean, 1981).

As summarized in MacLean et al. (1981), evidence suggested that hydrocarbons were leaking from the seafloor in the area of Scott Inlet – Buchan Gulf on the eastern coast of Baffin Island, with the primary site of seepage occurring near the south wall of the outer part of Scott Trough (Figure 2). Video footage taken from submersible dives in 1981 and 1985 aboard the Pisces IV showed a distinctive layer of white bacteria on the seafloor below the area of the oil slick (Figure 3 and Figure 4).

Pisces IV submersible dives in 1985 indicated that the site included a large circular seabed depression, possibly a pockmark, that contained surficial sediments coated in the same white bacteria observed in previous dives and later analyzed as belonging to the genus *Beggiatoa*. (Grant et al., 1986) The bacteria-coated sediments within the depression were solidified into a carbonate crust, which was trapping oil beneath it (Grant et al., 1986) (Figure 5 and Figure 6). A set of underlying fissures extending into sea bottom below the crust suggested a possible mode of transport for the oil from depth (Grant et al., 1986).

2.1.1.2. Oil Analysis

Analysis of the oil by the Geological Survey of Canada, Atlantic Oceanographic Laboratory and BP Petroleum resulted in a variety of opinions as to its composition. Discrepancies may have arisen because of the primitive methods of sampling (Fowler et al., 2005, Fowler et al., 2005a), the small amount of sample material, its biodegradation, the equipment used for the original analysis and the methods of interpretation (L. Snowdon, personal communication 2008).

Initial findings indicated it was not a typical ‘crude oil’ in that it had none of the indicative hydrocarbon compounds (L. Snowdon, personal communication 2008); its components pointed towards an essential or vegetable oil. Later sampling methods however suggested a biodegraded mature oil originating from an Upper Cretaceous marine source rock (Fowler et al., 2005, Fowler et al., 2005a and MacLean et al., 1981). Shallow borehole samples of organic-rich Upper Cretaceous strata from Home Bay are a further indication that petroleum source rocks occur on the northeast Baffin shelf (MacLean et al., 1990).

The geological and biological characteristics of the Scott seep including the abundance of micro-fauna, carbonate-bound sediments and possible pockmark association, are similar to those of oil and gas seeps in other oceans of the world (Geyer, 1981; Judd and Hovland, 2007; Hovland and Judd, 1988).

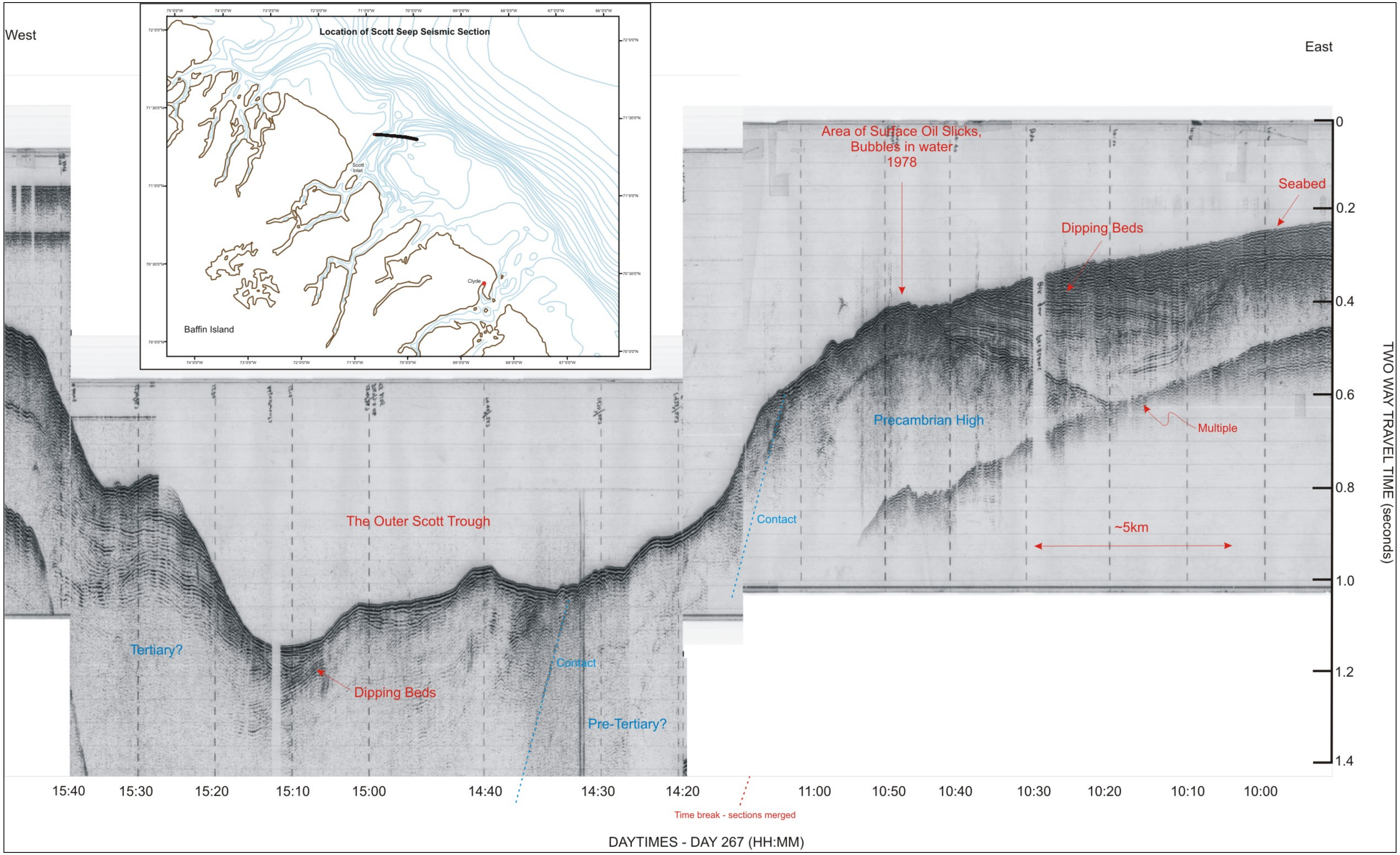

Figure 2: Seismic Section - Scott Trough (1978 airgun seismic record – Hudson 78029)

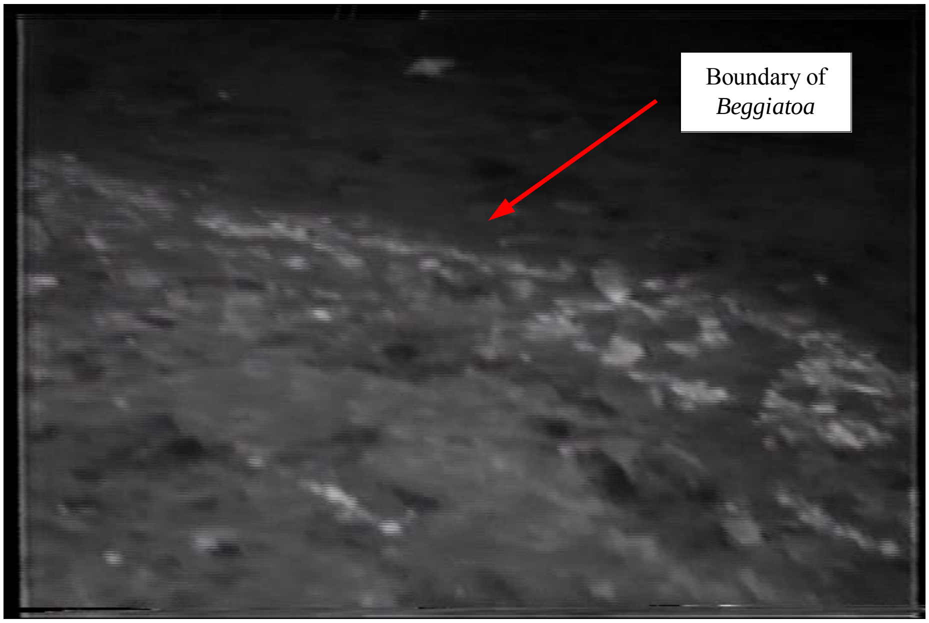

Figure 3: Scott Inlet Oil Seep - Sea bottom showing boundary of white bacterial mat as observed on Pisces IV 1981 submersible dive

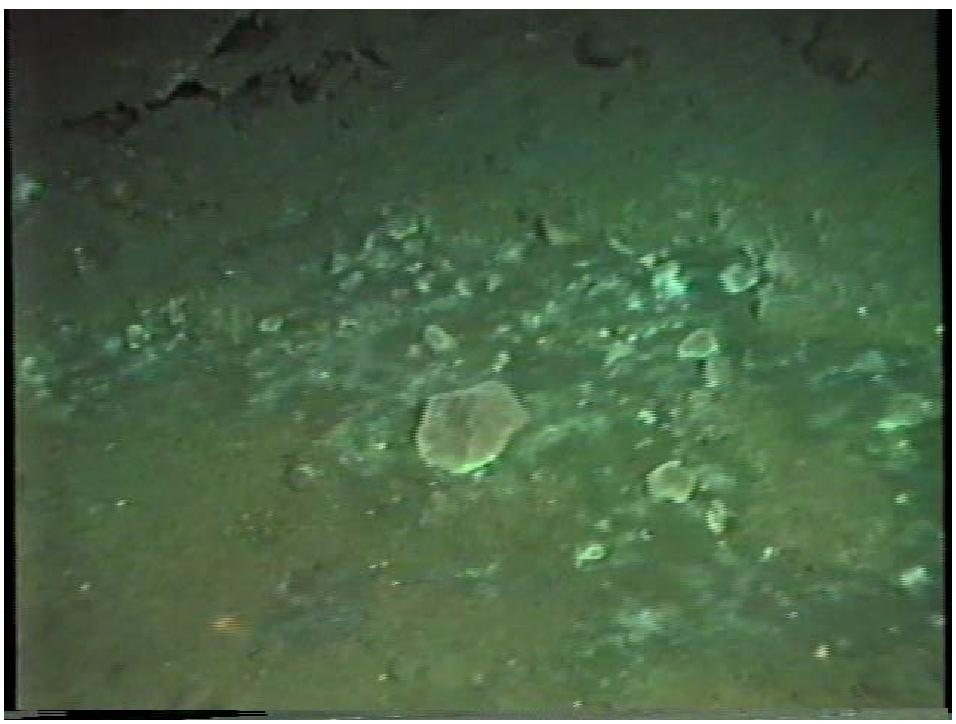

Figure 4: Scott Inlet Oil Seep - Sea bottom coated in bacteria Beggiatoa as observed on Pisces IV 1985 submersible dive

Figure 5: Scott Inlet Oil Seep – Oil-bearing carbonate crust on the sea floor (Pisces IV 1985)

Figure 6: Sample of oil-coated carbonate crust (courtesy of A. Grant)

2.1.2. Other Seep Activity

Petroleum exploration companies and scientific parties working in northern Canada in the 1970s and 1980s reported oil slicks at the sea surface offshore north-eastern Baffin Island and Bylot Island. A National Energy Board report published in 2002 summarizes the findings of a radar satellite data study which located 17 small sea surface oil slicks in Lancaster Sound (NPA Group & TREIC°Ltd, 2002) (Figure 7). In the western Arctic, the presence of naturally occurring oil in seabed sediments has been documented on the Beaufort Shelf (Pelletier, 1984) (Figure 8).

A feature resembling a seafloor mud volcano was discovered in a 1979-1980 geophysical survey off the south coast of Baffin Island in the eastern Arctic. The feature was apparent on all four survey records collected: high-resolution sub-bottom profiler, sidescan sonar, multichannel seismic, and echosounder (Woodworth-Lynas, 1983). The feature was found to be conical in shape, measuring 12m high and 600m diameter at the base, with a possible vent below the summit (Woodworth-Lynas, 1983). The mound was determined to be a potential mud volcano because of its shape; the presence of a surficial crater; its position in a seismically active region above a geological contact ideal for fluid transport, and the lack of ice scouring on its flanks compared to the highly ice-scoured surrounding seabed (Woodworth-Lynas, 1983). A subsequent submersible visit to the area in 1985 failed to locate the feature.

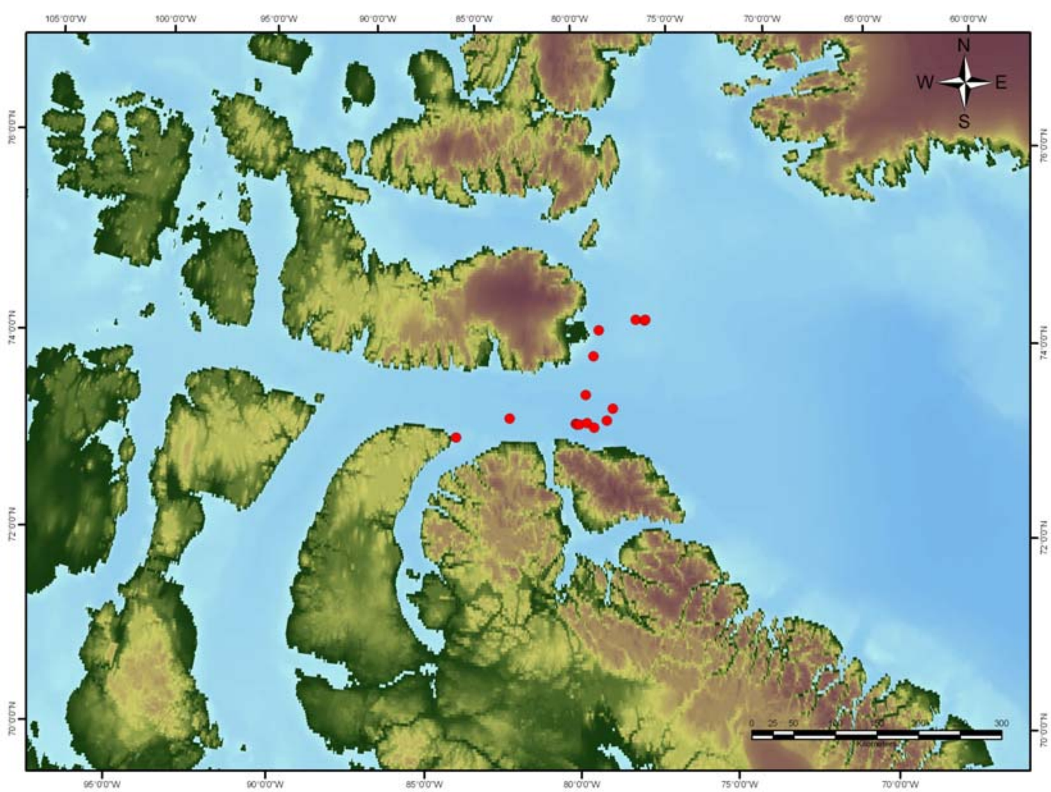

Figure 7: Location of sea surface oil slicks in Lancaster Sound as measured from radar satellite data (represented as red dots) (after NPA Group & TREIC°Ltd, 2002)

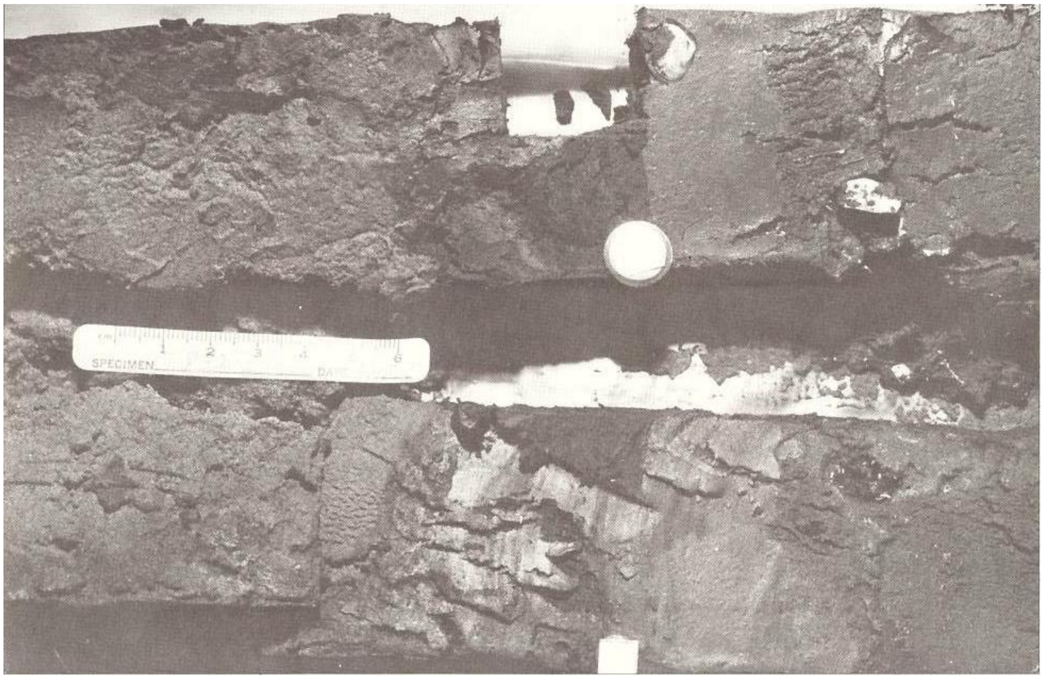

Figure 8: Natural oil occurrence in porous seabed sand, 50km northwest of Atkinson Point on the Tuktoyaktuk Peninsula (after Pelletier, 1984)

2.2. The Beaufort Shelf

2.2.1. Surficial Geology

The upper 100m of sediment defining the Beaufort Shelf represents a period of sea level rise over the last 27,000 years (Blasco et al., 1990). This 100m sequence has been divided into three major stratigraphic units: A, B, and C by O'Connor (1980) based on the interpretation of thousands of line kilometres of seismic data integrated with borehole and core logs.

The base of the 100m sequence consists of 40 metres of Unit C sands deposited by a prograding delta and glacial outwash system (Blasco et al., 1990). A high-amplitude seismic reflector distinguishes the top of Unit C and represents a period of erosion during sea level lowstand (Blasco et al., 1990).

Lying above the erosional reflector at the top of Unit C, Unit B consists of thin beds of dense sand and silt interlayered with stiff silty clays (Blasco et al., 1990). This transitional sequence between C and A varies in thickness from 0m to 10m and is associated with high-energy deposition during sea-level rise (Blasco et al., 1990). Ranging in thickness from a few centimetres to > 20m, the marine silty-clays of Unit A are primarily the result of low-energy sediment deposition by the Mackenzie River (Blasco et al., 1990).

2.2.2. Pingo-Like Features

Positive-relief seafloor mounds, or pingo-like features (PLFs) were first discovered on the Beaufort Shelf in 1969 on a cruise by the tanker S.S. Manhattan. Due to the concern about PLFs as a potential shipping hazard, the Canadian Hydrographic Service (CHS) and the GSC carried out bathymetric and geophysical survey programs throughout the 1970s targeting these features.

Prior to the year 2000, over 200 features were mapped with echosounder and later with sub-bottom profiler and sidescan sonar from the Yukon Shelf and the western edge of the Mackenzie Trough across the southern Canadian Beaufort to the Baillie Islands. Early work by Pelletier, Poley and Shearer studied some of the features in detail and examined their potential as an engineering hazard.

The term PLF was originally coined due to the similarity between the seabed features and terrestrial pingos of the nearby Tuktoyaktuk peninsula (Blasco et al., 2006). Over time it was apparent that not all of these features were likely of the same origin (Shearer and Meagher, 1980). Over 380 PLFs have been identified on the Beaufort Shelf (Campbell et al, 2008) (Figure 9); they are classified under the following five categories:

- Mud volcanoes (Section 2.3)
- Submarine-formed pingos
- Diapirs
- Relict topography

- Slump features (along ridge and margin boundaries)

The topographic relief created by these features and their potential association with seeping gases and fluids from the seabed gives them unique environmental characteristics which may influence the local biota.

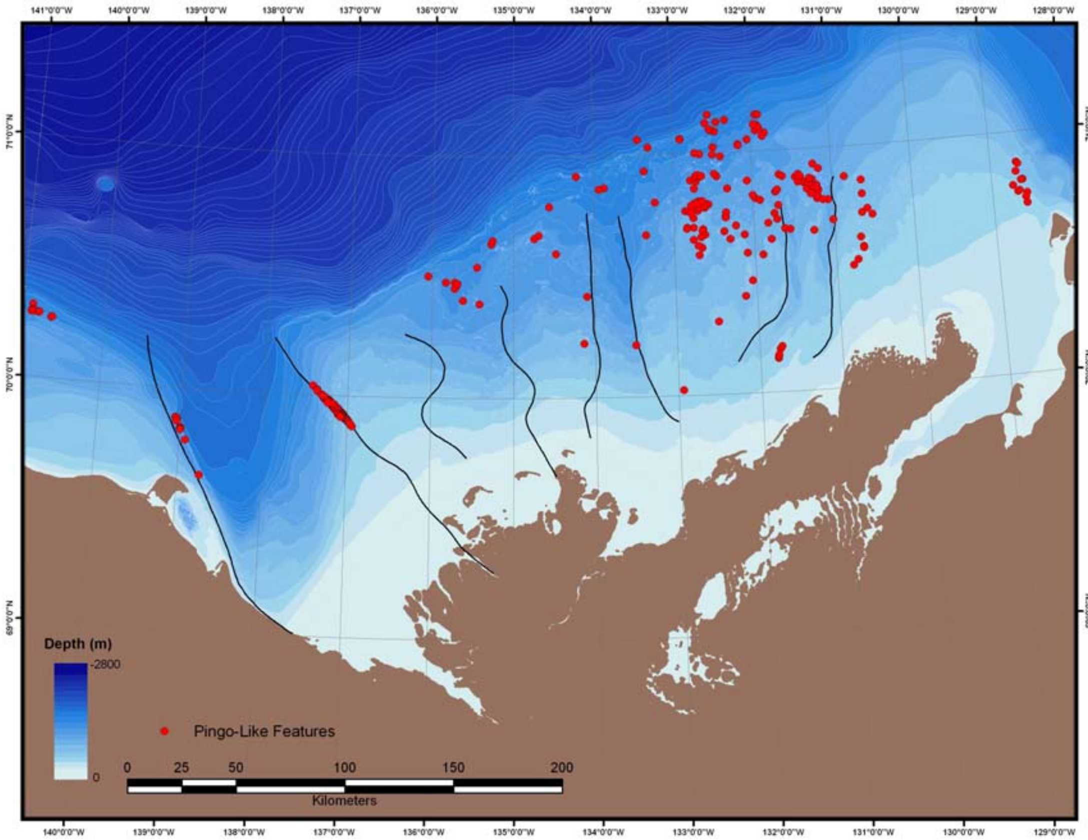

Figure 9: Distribution of Pingo-like features on the Canadian Beaufort Shelf

2.3. Mud Volcanoes

"Mud volcanoes are geological structures formed as a result of the emission of argillaceous material on the Earth's surface or the sea floor." (Dimitrov, 2002) Over 900 terrestrial and 800 offshore mud volcanoes are believed to exist globally (Dimitrov, 2002). The presence of seafloor mud volcanoes has been documented in various locations around the world including the Persian Gulf, offshore New Zealand, the Gulf of Mexico, the Caspian Sea and offshore Portugal (Judd and Hovland, 2007; Hovland and Judd, 1988).

Mud volcanism appears to be responsible for at least some of the Beaufort Sea PLFs based on their morphology, methane emission, and seismic signatures. Analysis of the age of the sediments that make up these features and the biological habitats associated with them is discussed in the following sections.

2.3.1. The Håkon Mosby Mud Volcano

The well known Håkon Mosby Mud Volcano (HMMV) is a methane-emitting feature in the Barents Sea. The HMMV has been the target of multidisciplinary scientific studies uniting researchers in the fields of both geology and biology (Vogt et al., 1999; Milkov et al., 2004). Numerous papers and studies of the geology, geophysics, biology, biochemistry, and geochemistry exist on the HMMV, some of which are mentioned above. Milkov et al. (2004) provides a good review of many of these studies prior to 2004. This offshore mud volcano was visited during a study off the platform RV Polarstern as part of the Hotspot Ecosystem Research on the Margins of European Seas (HERMES) International Polar Year project (HERMES, 2008; AWI(1), 2008).

Over 1 kilometre in diameter, the HMMV was discovered during a sidescan sonar survey (Vogt et al., 1991) on the Barents Sea margin off the Norwegian mainland. The HMMV sits at 1250 metres water depth in an area of mass wasting (Vogt et al., 1999; Mienert et al., 2003) associated with the Bjørnøyrenna slide (Vogt et al., 1999). The feature is organized into a pattern of concentric zonation from its biological communities to its morphology, directed by eruption and dissemination of mud and fluid from the crater outwards (Milkov et al., 2004).

The HMMV, located on a passive continental margin, is classified as a 'cold seep', although it measures higher temperature anomalies both in the upper sediments and bottom waters (Vogt et al., 1999). High concentrations of methane are present in the volcano's porewater sediments as well as within the water column, and shallow methane hydrate was retrieved in cores taken at the site (Vogt et al., 1999).

Although not observed on earlier expeditions to the site (Vogt et al., 1999; Milkov et al., 2004), actively venting methane with plumes reaching 600m to 900m above the seabottom has been witnessed on recent video and acoustic surveys (AWI(2), 2008; HERMES, 2008; Berndt et al., 2006; Sauter et al., 2006). Changes in the volcano morphology, also observed on recent surveys, indicate active mud flow activity (HERMES, 2008). The volcano's origins appear to be anywhere from 3km to 6km (Vogt et al., 1999; Berndt et. al., 2006) below seabed, with a mixed biogenic-thermogenic origin postulated for the escaping gas (Vogt et al., 1999). Its formation may be related to movement of fluid along a fault (Judd and Hovland, 2007).

The volcano is associated with a somewhat prolific biological community (relative to its inferred age) including methane-consuming bacteria, tubeworms and abundant benthic fish (Vogt et al, 1999). A significant portion of the flattened centre of the feature, associated with higher methane discharge, is devoid of any benthic habitats (Jerosch et al., 2007). The presence of seafloor carbonate nodules similar to those found at other seeps (e.g. Scott Seep, Gulf of Mexico, others - see Judd and Hovland, 2007) is referenced in Milkov et al. (2004).

A recent study of the microbial communities at the volcano by Niemann et al. (2006) examined the decrease in methanotrophic oxidation associated with high flow rates of mud volcano fluids, which may indicate that higher amounts of methane than previously believed, are escaping into the environment at the HMMV site. Sauter et al. (2006) proposed that coating of methane bubbles by gas hydrate is allowing the escape of more gas to the upper water column.

3. CURRENT STUDY

The GSC's IPY study in the Northwest Passage is focused on geological features and seafloor processes that may be associated with unique benthic habitats. There is particular interest in those features and areas that may be associated with oil and gas seepage or hydrocarbon occurrence, especially pockmark fields and mud volcanoes.

Beginning in 2001, geophysical mapping in the Northwest Passage aboard the CCGS Nahidik, the CCGS Sir Wilfrid Laurier and the NGCC Amundsen has focused on mapping seabed geomorphic features and iceberg scours. The geophysical surveys have included collection of sidescan sonar, sub-bottom profiler, single-channel seismic, multichannel seismic and multibeam data. Geotechnical, geological and benthic ecosystem sampling onboard the Nahidik and Sir Wilfrid Laurier, between 2003 and 2007 involved the collection of several hundred box, gravity and push cores as well as photo and video documentation of sites along the eastern Beaufort Shelf. The following sections describe features mapped as part of this study.

3.1. Barrow Strait Pockmarks

A set of northwesterly-southeasterly, linearly-trending pockmarks was observed during a 2005 Amundsen survey in Barrow Strait, Nunavut. Nine features (pockmarks?) were mapped by multibeam and sub-bottom systems in approximately 300m of water between Somerset and Devon Islands (Figure 10).

The pockmarks? were approximately 200m wide and 10-25m deep. At least one of the features appeared to be actively venting gas from the sea floor as observed on sub-bottom records (Figure 10), although the source of this reflection anomaly is still in question. Sediment from piston and box cores taken at the site showed no indication of hydrocarbons.

Seismic reflection data collected in eastern Barrow Strait in the 1980s in the vicinity of the pockmarks indicate the presence of faults and dipping strata within seafloor sedimentary rocks (MacLean et al., 1989) (Figure 11-Figure 14). The faults may provide a conduit for the migration of gases from deeper formations.

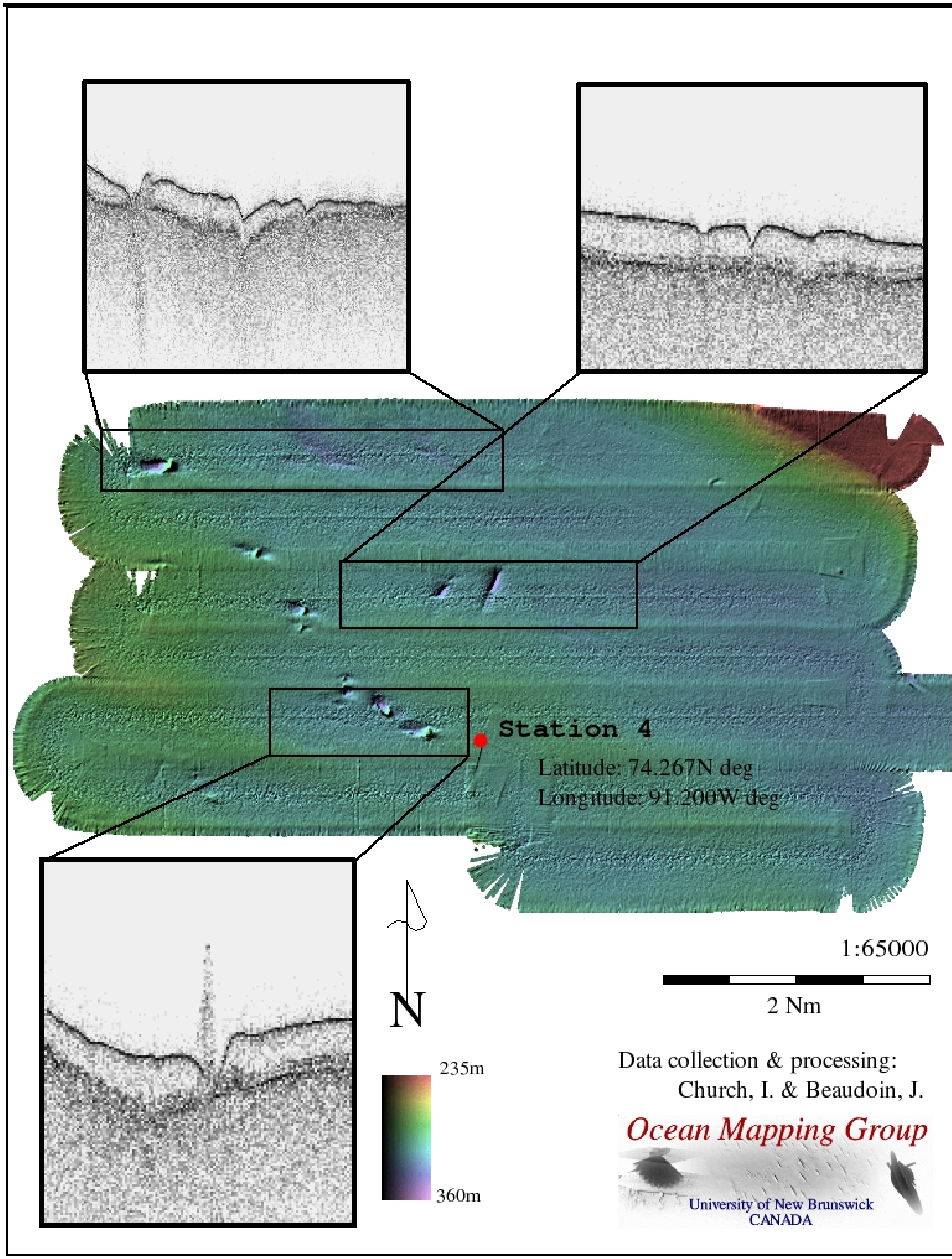

Figure 10: Multibeam and Sub-bottom images showing pockmarks and gas venting (Ocean Mapping Group, UNB, 2007)

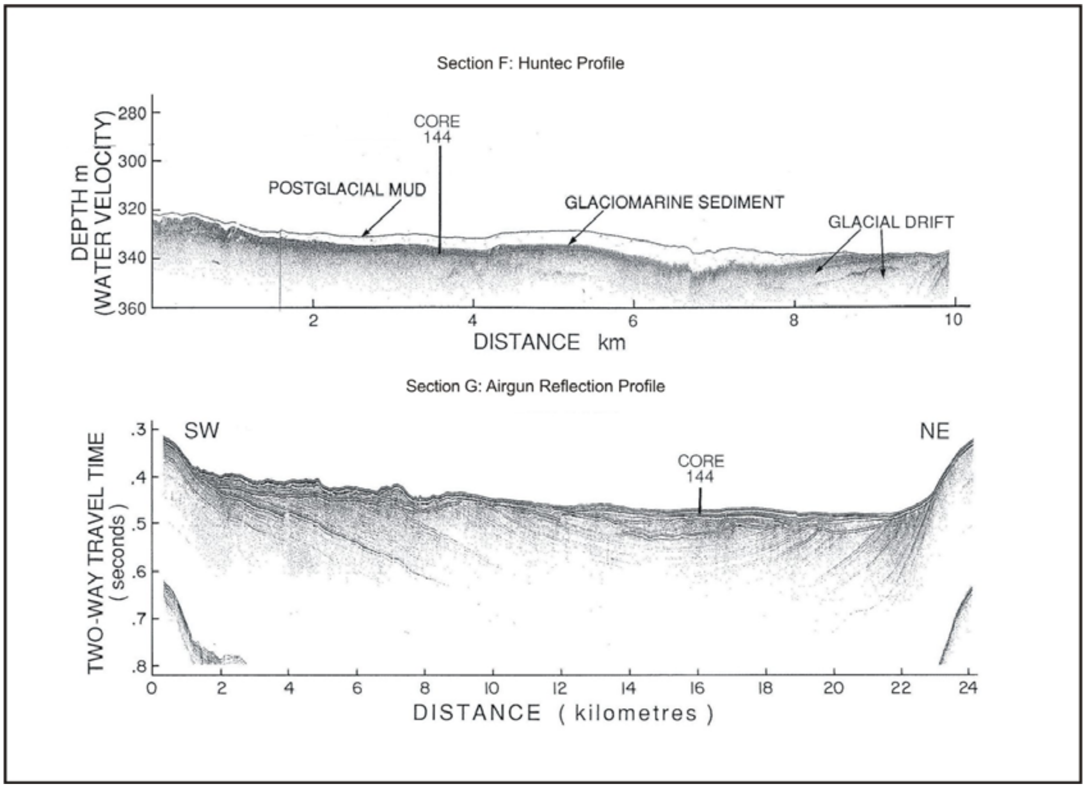

Figure 11: Seismic sections in Barrow Strait (after MacLean et al., 1989)

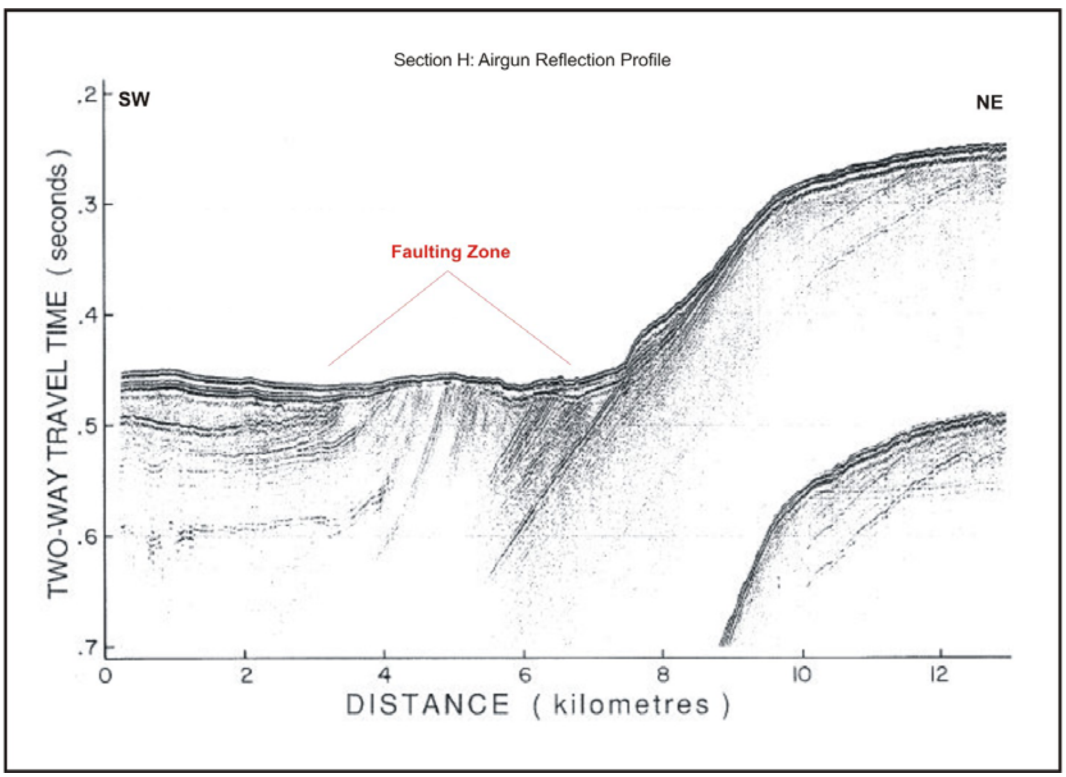

Figure 12: Seismic section in Barrow Strait (after MacLean et al., 1989)

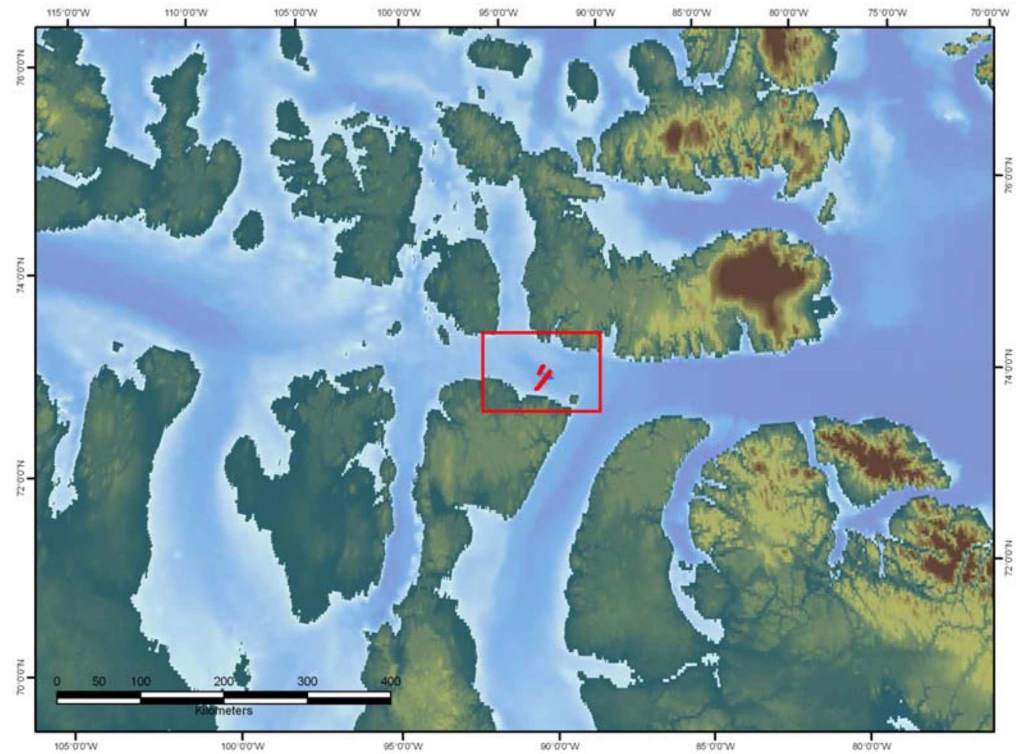

Figure 13: Regional location of Barrow Strait pockmarks with seismic section locations

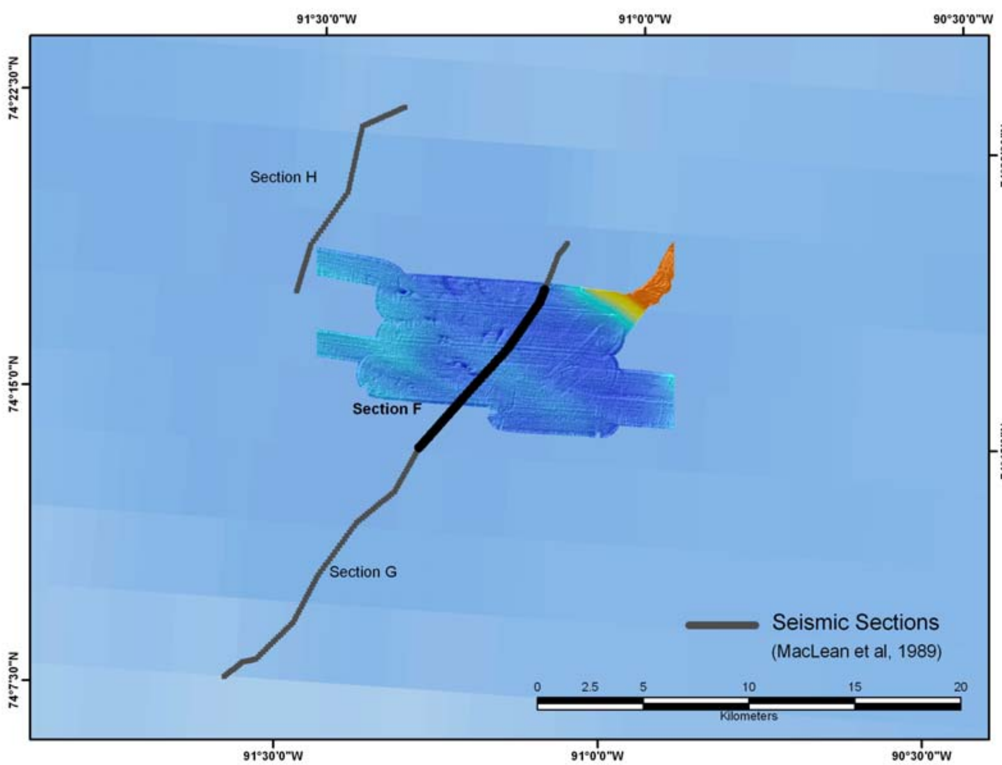

Figure 14: Barrow Strait multibeam and seismic section locations

3.2. The Eastern Beaufort Shelf

Pingo-like features are present as isolated individuals and in clusters over the eastern Beaufort Shelf. Several of these features have been surveyed and sampled including: Kopanoar mud volcano, Kaglulik PLF, "Admiral" A, B, and C, and PLF Z. Because the eastern shelf is predominantly underlain by permafrost, mud volcanoes and other gas related features are thought to form by the migration of gas and liquids through taliks in the sub-seabed. This hypothesis would explain the clustering of features in the eastern area of the Beaufort.

3.2.1. Kugmallit Bay Pockmark Field

In the shallow waters of the Beaufort north of the Tuktoyaktuk Peninsula lies an area of seabed that is undergoing high-pressure gas venting. The region contains in excess of 2000 individual pockmarks in an area slightly larger than one square kilometre (Figure 15). Within the central zone of the field, it is difficult to distinguish between individual features, as thousand of holes have merged into one large indent in the sea floor.

The area was first discovered during the 2001 Nahidik mapping program. Repetitive geophysical mapping over the area in 2001, 2004, and 2005 defining distribution of the features, sediment infill and relationships with ice berg scouring indicate episodic activity of the gas vents over the last decade (Figure 16 and Figure 17).

The individual vents are as deep as 8 to 10 metres and have widths of 5 to 10 metres at the sea floor. Water depth in the area is approximately 10 metres and is located on a gradual slope between the 5m and 10m bathymetric contours.

The presence of void spaces indicating gas in the sediment was discovered during geotechnical bottom sampling in 2003 (K. MacKillop, personal communication 2008) (Figure 18). Additional sampling revealed the presence of oil in two of the pockmarks (M. Papst, personal communication 2008). The nature of this oil is currently being ascertained through laboratory analysis at the Department of Fisheries and Oceans.

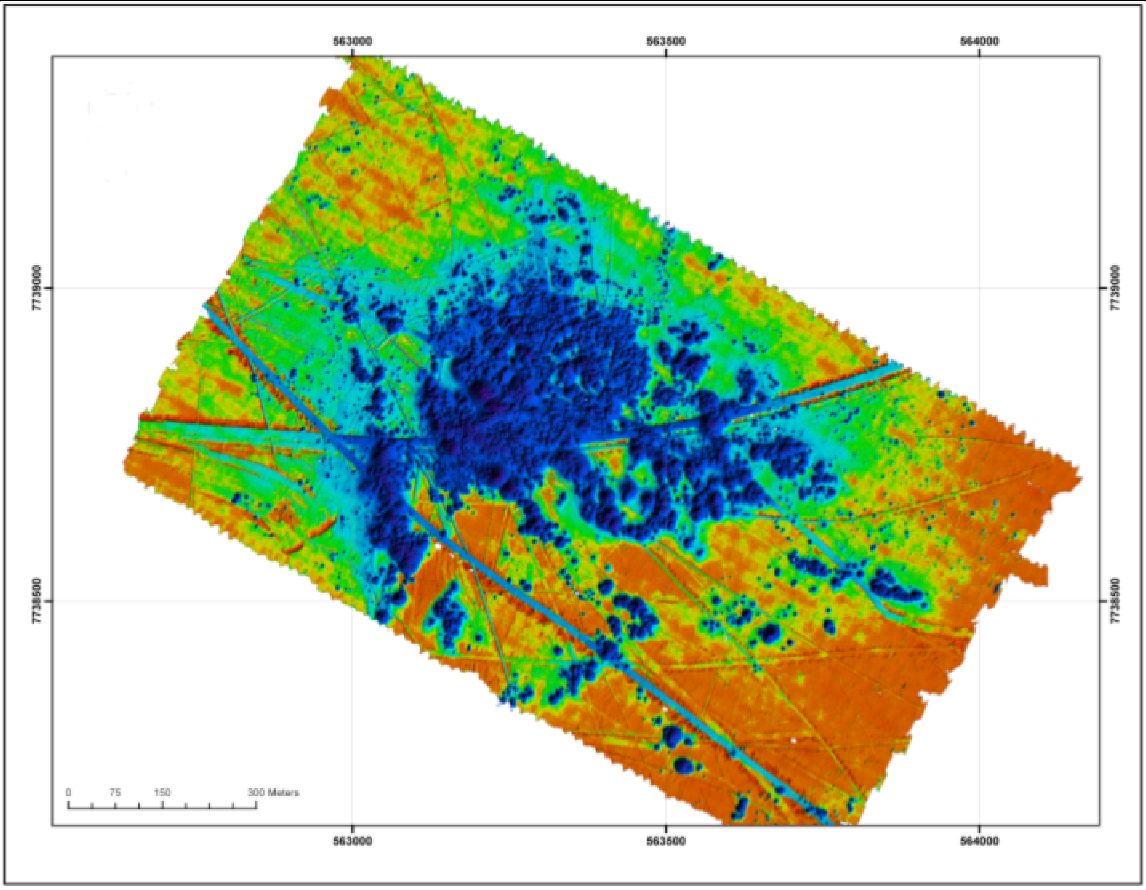

Figure 15: Kugmallit Bay pockmark field, 2005 multibeam bathymetry (WGS84, Zone 8N)

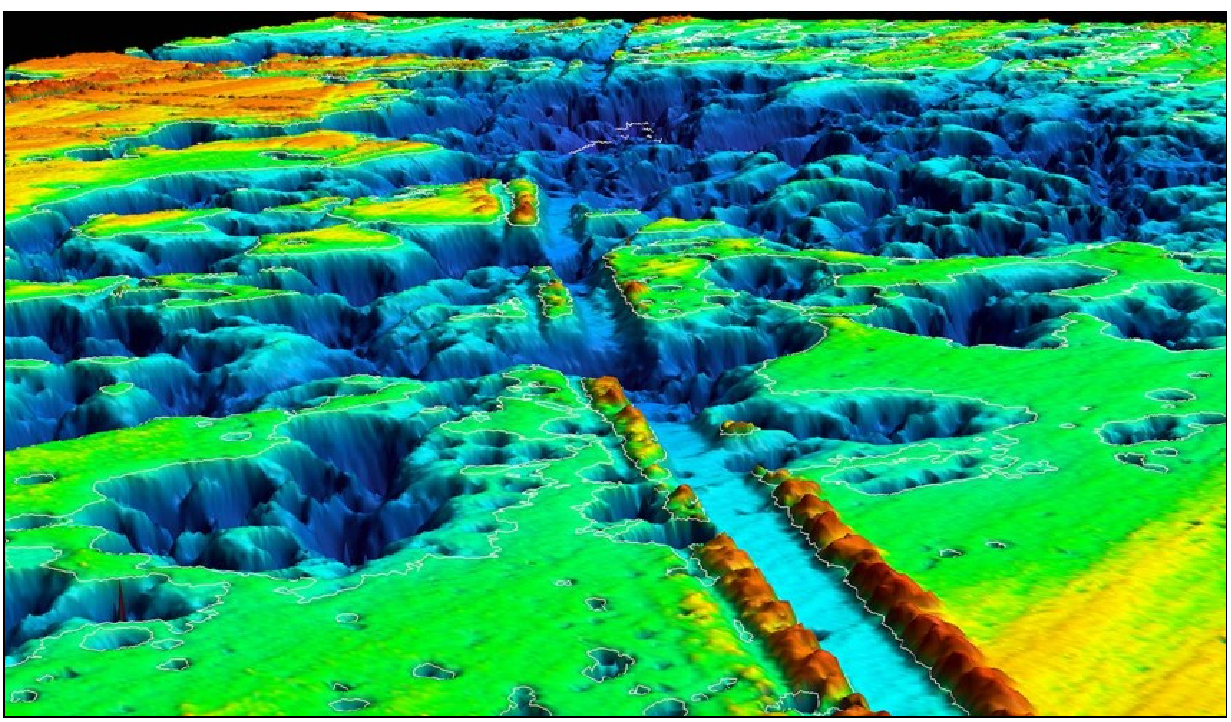

Figure 16: Seafloor view of Kugmallit Bay pockmark field showing craters with intersecting iceberg scour

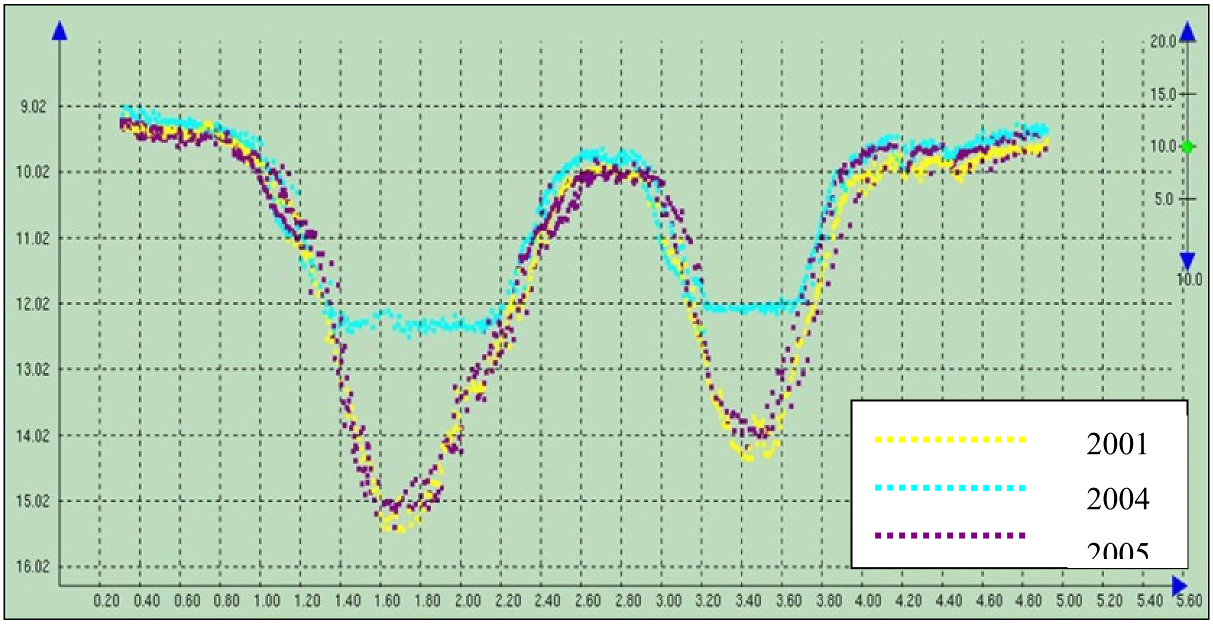

Figure 17: Cross-section of Kugmallit Bay pockmarks showing sediment infill and subsequent venting between the years 2001 and 2005

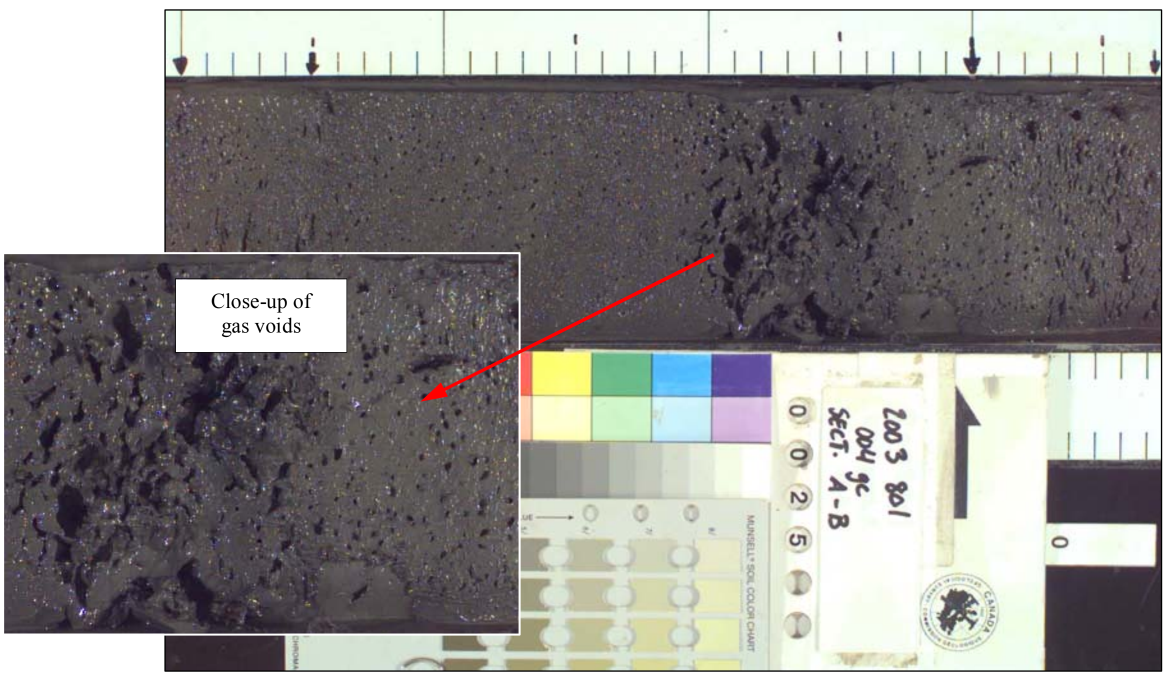

Figure 18: 2003 Push Core from Kugmallit Bay Gas Vents showing gas voids in near-surface sediment (courtesy of K. MacKillop)

3.2.2. Kopanoar Mud Volcano

The Kopanoar PLF (Figure 19) was first surveyed in the 1970s with echosounder and sidescan systems. The feature lies in the Ikit Trough in the central Beaufort and is approximately 425m in diameter and 26m in height. Water depth at its base is approximately 62m. Kopanoar is partially surrounded by a depression and evidence of slumping can be seen on one side.

Multibeam and sidescan data collected over this feature show no evident change in size or shape in the last 25 years; however, ice scouring around the base indicates that growth of this feature within the last hundred years must have dominated destruction by ice gouging processes.

Mud volcanism is suggested by the presence of actively venting gas on sub-bottom data (Figure 20) and observation of gas bubbles at the sea surface in the vicinity of the volcano. Sediment cores taken aboard the Laurier in 2003 contained high amounts of methane (Paull et al., 2007) and gas voids were present in push cores (K. MacKillop, personal communication 2008). Void spaces in sediment samples may indicate the presence of gas bubbling from depth, or may be created by melting of ice nodules, such as were found at several of the PLF sites including the Kopanoar mud volcano (Paull et al., 2007, Medioli et al., 2005). Alternately, as postulated by Paull et al. (2007), voids created by gas flow in sediments may have later been infilled with freshwater ice.

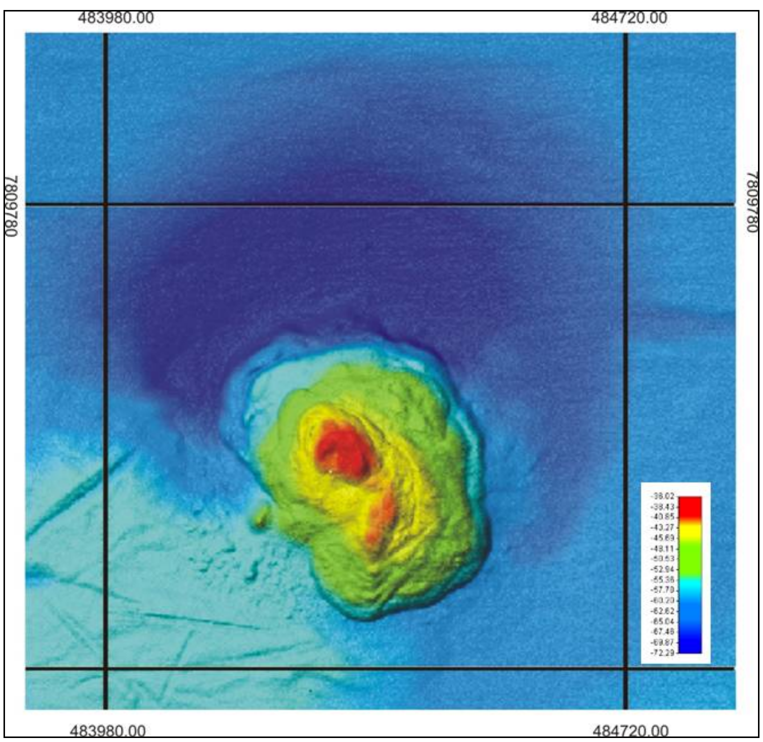

Figure 19: 2004 Multibeam bathymetry of Kopanoar Mud Volcano (WGS84, Zone 8N)

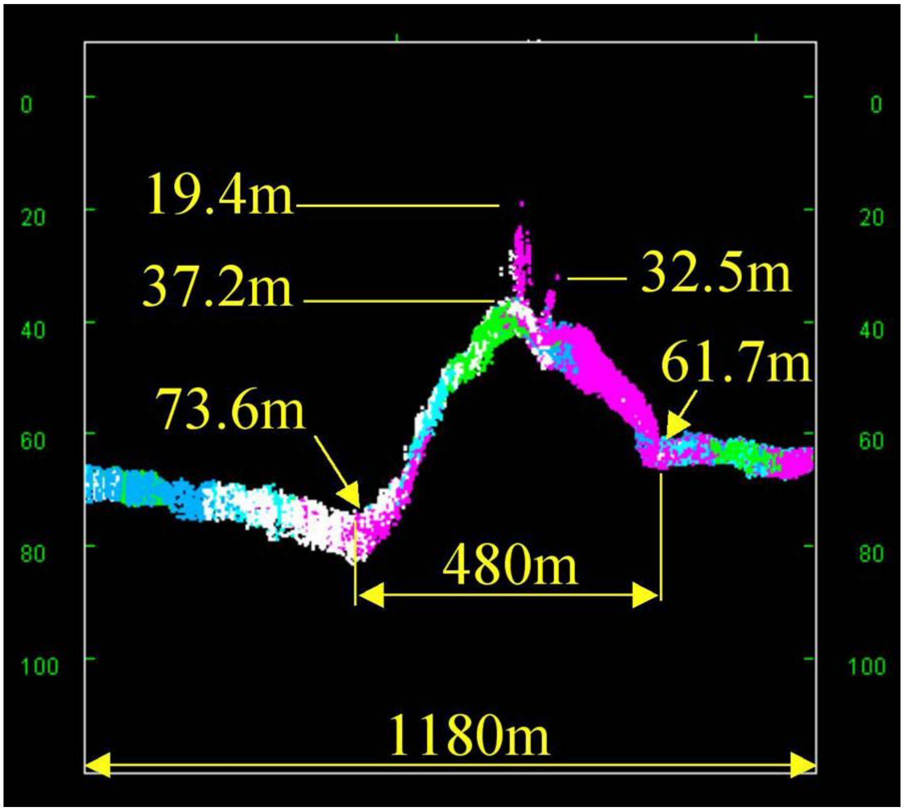

Figure 20: Sub-bottom image showing gas venting from Kopanoar Mud Volcano (2002 Mirai Cruise)

3.2.3. Kaglulik PLF

The Kaglulik PLF was first mapped and studied by Shearer and Meagher (1980) who described it as a sub-marine pingo. This elongated mound measures approximately 720 metres long by 320 metres wide and has a height of 23 metres above the sea floor. Shallow core results from Paull et al. (2007) and Medioli et al. (2005) reveal the presence of ice nodules in the PLF crest.

Kaglulik is semi-surrounded by a depression, which is filled with laminated sediments as can be seen on single-channel seismic records (Figure 21). No lakebed reflector, as is typical of terrestrial pingos, is apparent on the seismic records and the laminated sediments would suggest active growth of the feature. Results of sedimentological studies by Medioli et al. (2005) would suggest the feature was formed in a marine environment. These characteristics, along with its non-circular shape point to a non-pingo origin. (see Bennett et al., 2004 for additional Kaglulik survey details)

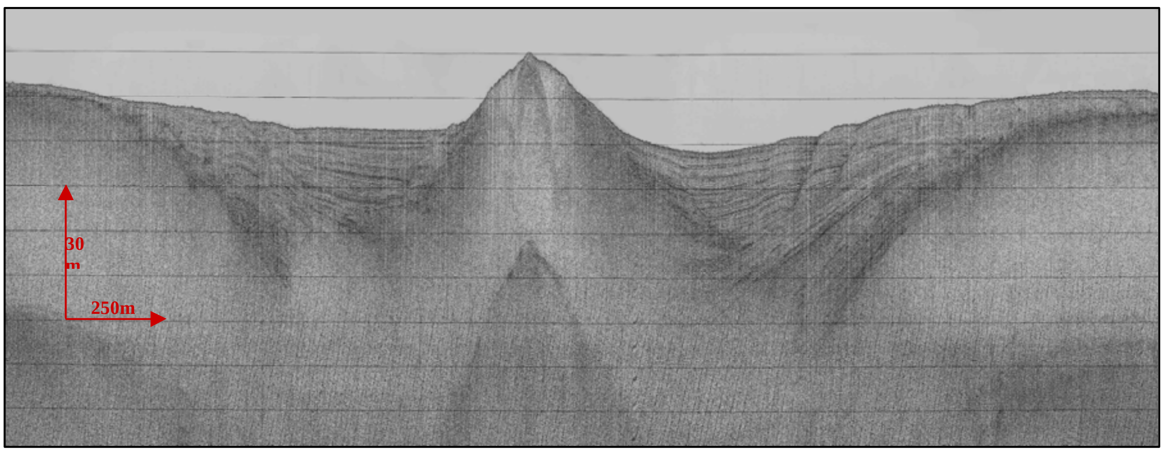

Figure 21: Single-channel seismic record of Kaglulik PLF (2003)

3.2.4. “Admiral’s Finger” Area

In the east-central Beaufort Shelf around the area known as “Admiral’s Finger” (Figure 22), a total of 15 PLF features have been mapped since 2001 using multibeam, sidescan, and single-channel seismic systems. Several of these features were initially discovered in the 1970s and 1980s.

Gas venting from the crest of the PLF feature known as Admiral B (Figure 22 and Figure 23) was observed on ROV dives in 2003 (Paull et al., 2007) and gas presence was noted at sea surface in the vicinity of the Admiral PLFs on the 2004 Nahidik cruise. Venting gas sampled aboard the Laurier in 2003 was determined to be primarily methane, containing less then 1% modern carbon (Paull et al., 2007).

North of Admiral B (Figure 22), a sequence of four PLFs known as the Z-complex, lie in a east-westerly trend (J. Shearer, personal communication 2008). The westernmost of these features was observed to be actively venting gas into the water column; analysis of this gas revealed a similar methane-rich composition (Paull et al., 2007).

A push core taken between Admirals B and C (Figure 22) contained void spaces in the near-surface fine-grained sediments (K. MacKillop, personal communication 2008) and freshwater ice nodules were present in shallow sediment cores on the crests of the features (Paull et al., 2007; Medioli et al., 2005).

In 2007, several features in the Admiral's Finger region (first discovered in the 1970s) were surveyed with multibeam sonar and shallow single-channel seismic (Figure 24-Figure 26). Sediment slumping is present along the flanks of some of the features and their location is within a bathymetric depression similar to that observed at Gary Knolls (see Section 3.3.1) (Figure 25). Single-channel seismic data over one of the features shows the acoustically-opaque crest surrounded by laminated sediments (Figure 26), a similar profile to Kaglulik and other PLFs believed to have formed by fluid flow processes.

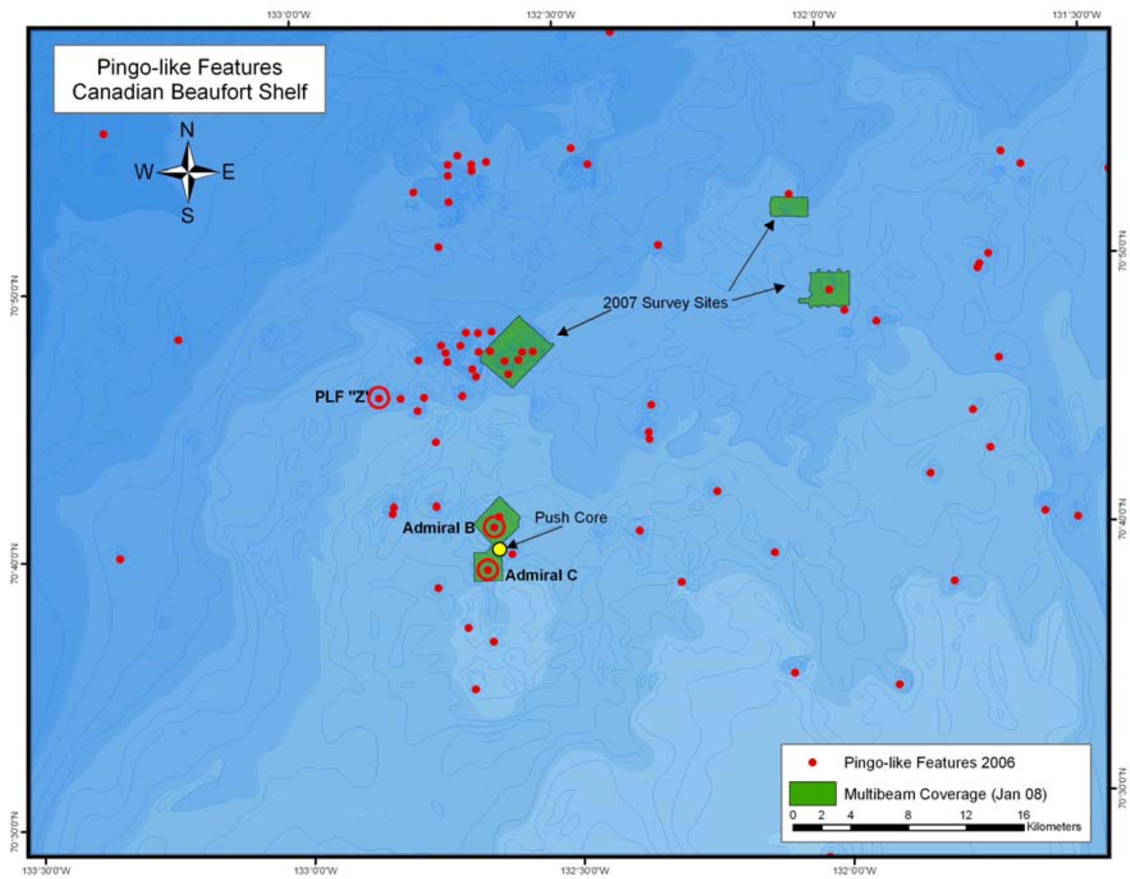

Figure 22: "Admiral's Finger" area of the eastern Beaufort Shelf

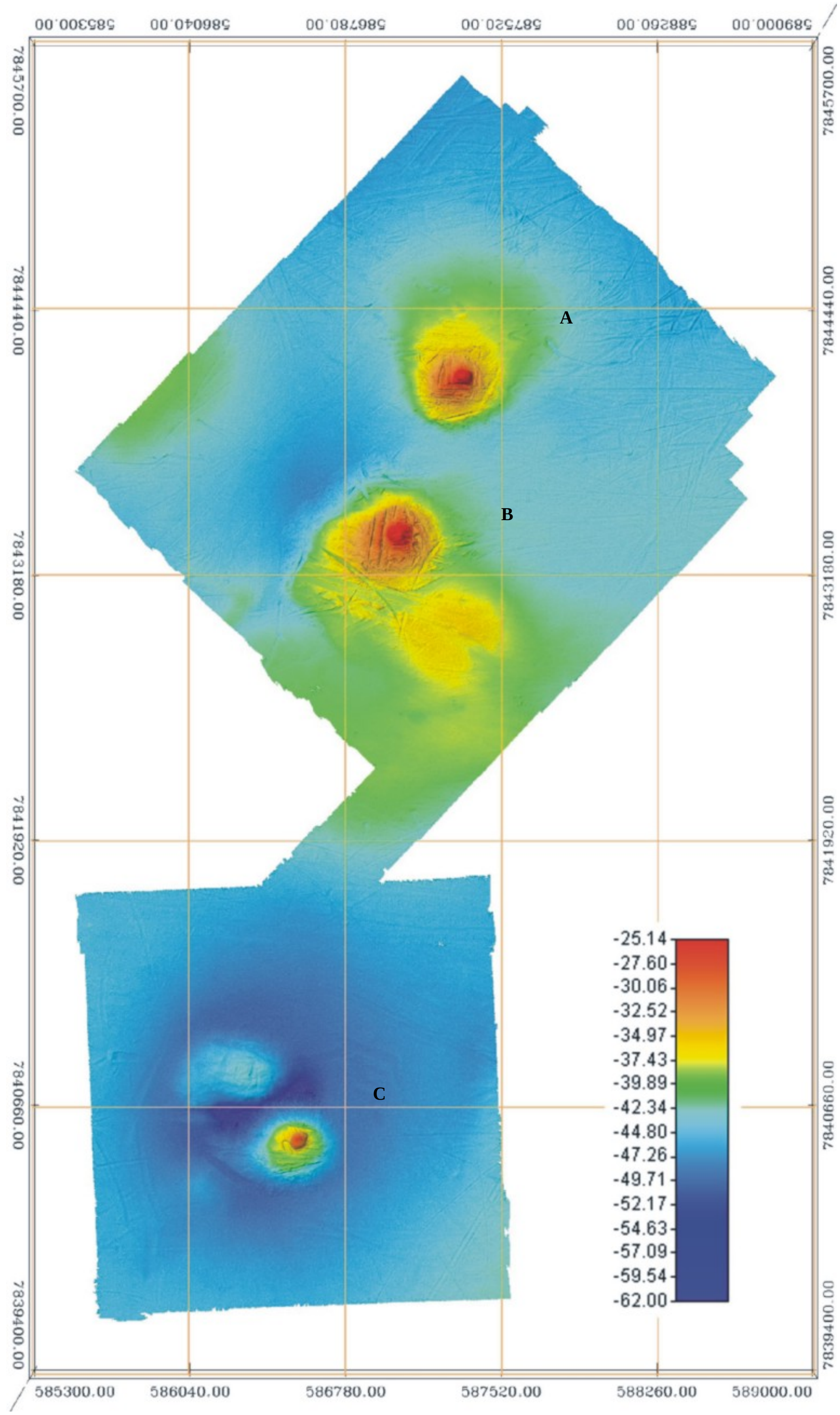

Figure 23: Multibeam bathymetry of Admiral's Finger features A, B, and C (2004) (WGS84, Zone 8N)

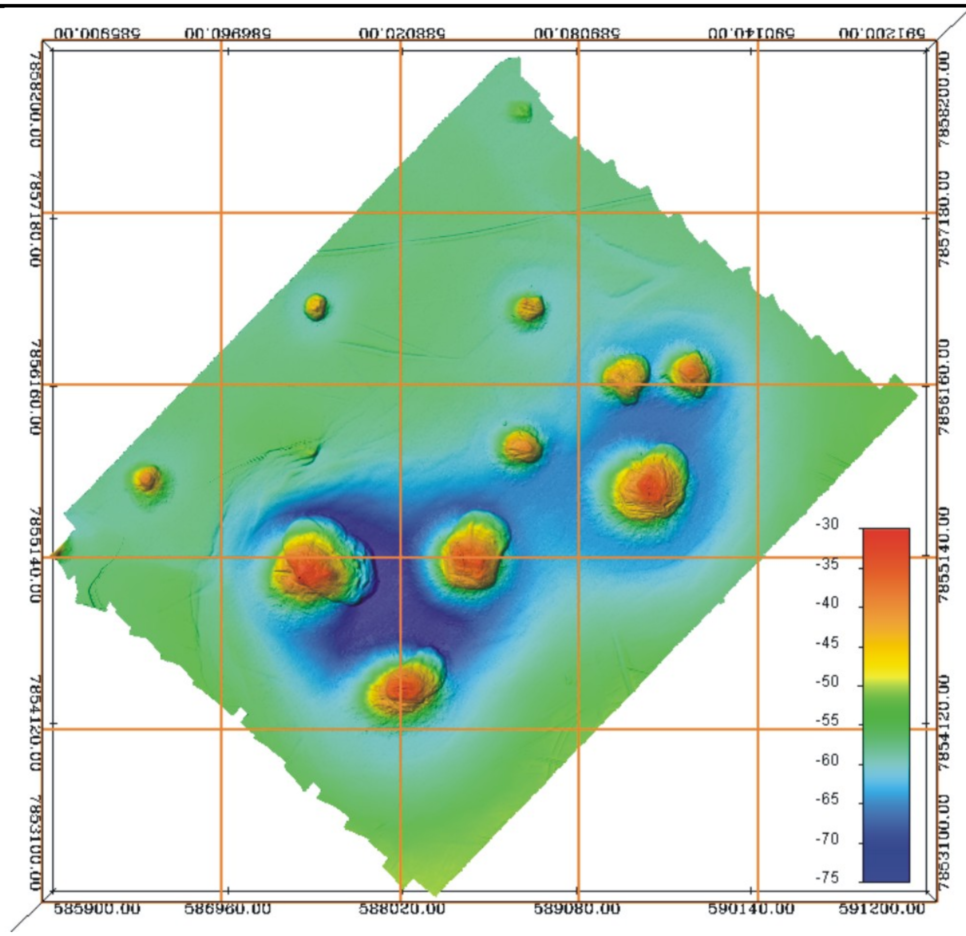

Figure 24: Multibeam bathymetry of "Admiral" PLF field (2007) (WGS84, Zone 8N)

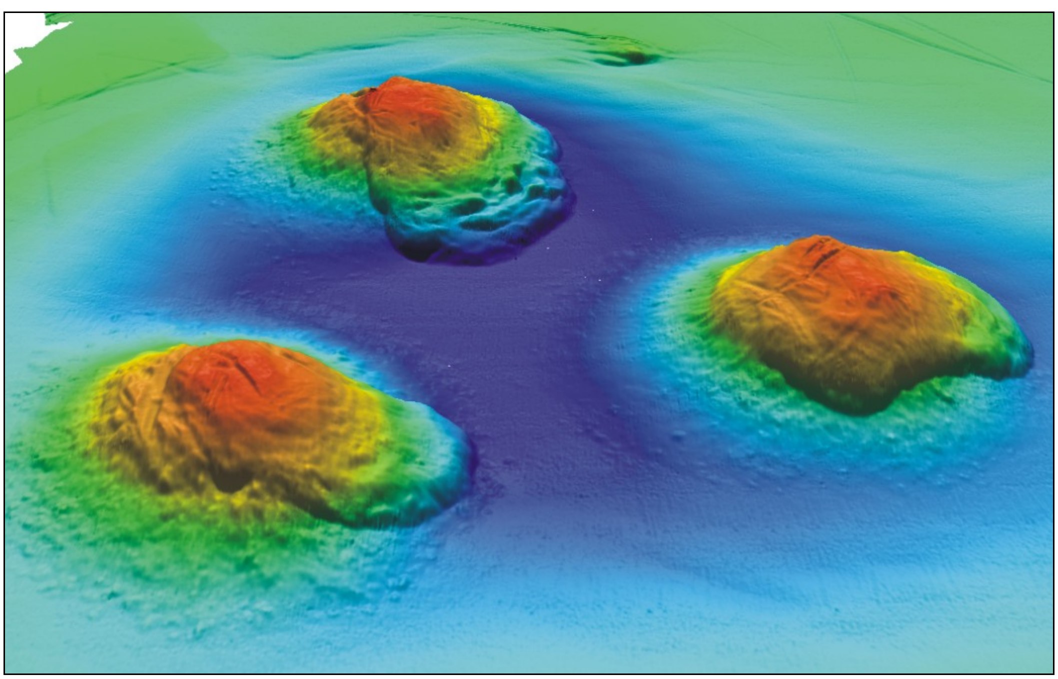

Figure 25: 3-dimensional view of "Admiral" PLFs (2007)

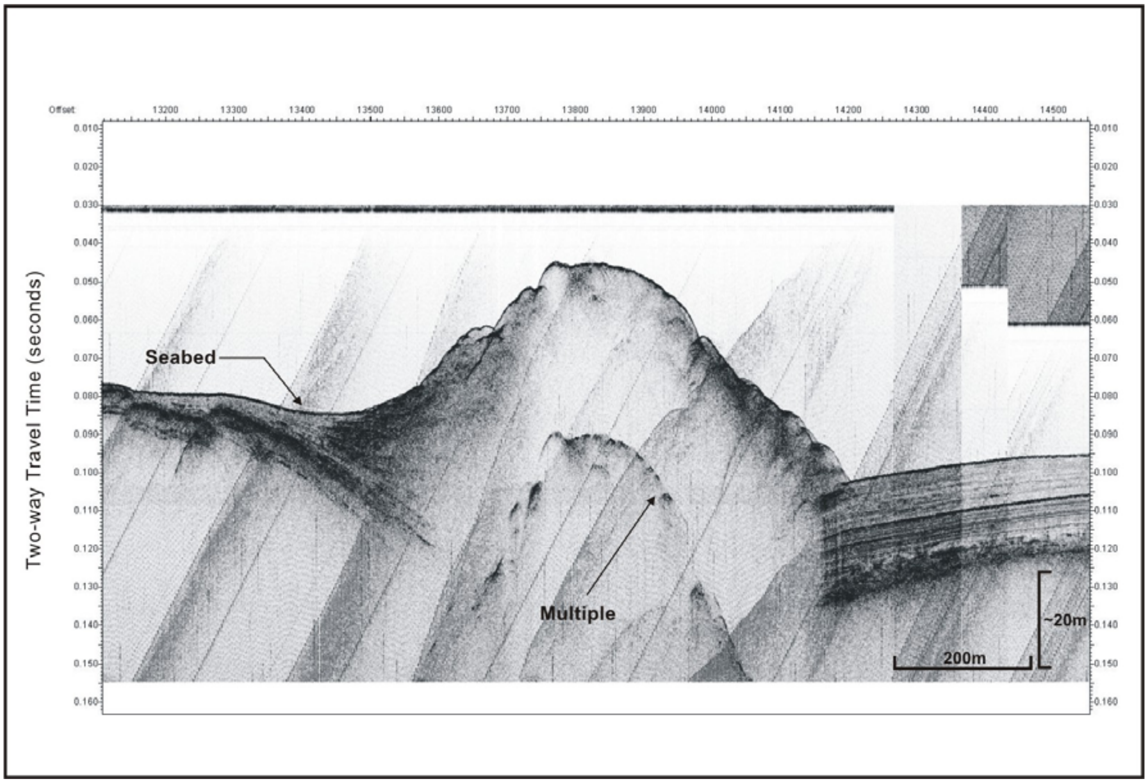

Figure 26: Single-channel seismic data over "Admiral" Area PLF (Line 10, 2007)

3.3. Mackenzie Trough

The Mackenzie Trough is a northwest-southeast linearly-trending bathymetric and paleobathymetric depression that was formed by glacial excavation along the Beaufort Shelf during the Wisconsinan (Blasco et al., 1990; Moran et al., 1989). Several areas of possible gas migration coincide with the eastern and western margins of the trough (Figure 27). The eastern margin is characterized by a field of PLFs, pockmarks, and evidence of gas venting throughout the water column. The western trough also has several PLF features which may be associated with gas, however data coverage in this area is not as extensive as on the eastern flanks of the trough.

O'Connor's 1985 model of the trough suggests the possibility of gas migration from underlying strata along the Base of Trough Unconformity; a hypothesis which would account for the seabed geological activity observed along the trough margins (Figure 28). Wellsite and seismic surveys from the 1970s and 1980s reveal the presence of shallow gas within the trough sediments and along the trough sediment boundaries (McGregor, 1992).

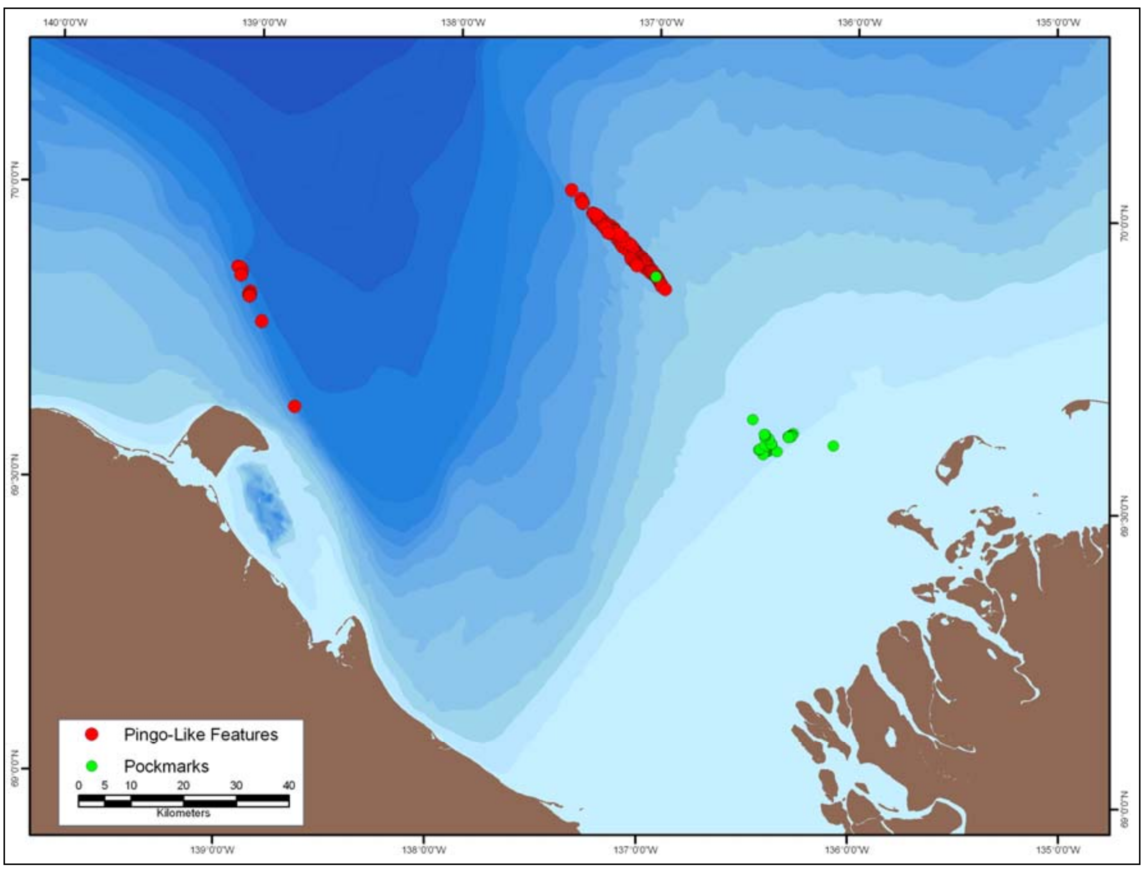

Figure 27: The Mackenzie Trough

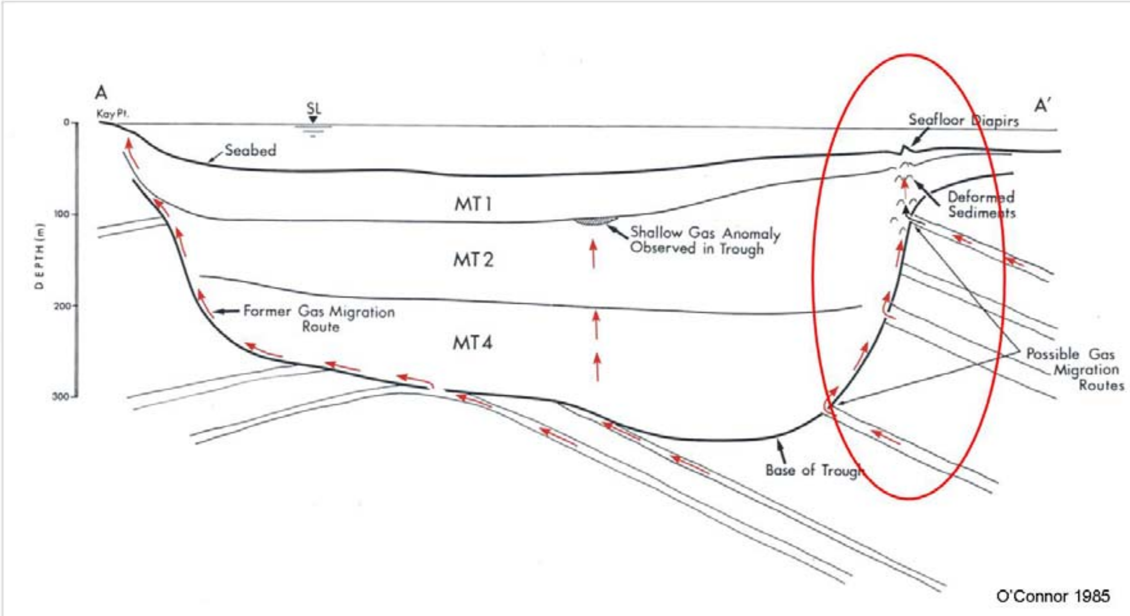

Figure 28: Model for gas migration along the Mackenzie Trough margins (after O'Connor, 1985)

3.3.1. Gary Knolls

Acoustic mapping of three PLFs along the eastern edge of the Mackenzie Trough in the 1970s led to the discovery of the Gary Knolls PLF field in 2004. Multibeam sonar, sidescan sonar and single-channel seismic systems have been used to map the site. As of the 2006 data analysis, 161 features exist within the Gary Knolls corridor (Campbell et al., 2008), a linearly-trending swath spanning approximately 26km x 2km along the eastern trough margin (Figure 29-Figure 31).

The features are circular to elongate in shape and have average diameters and heights of 95m and 9m respectively. The mud mounds lie within a bathymetric low where most evidence of ice scouring has been destroyed. The features are acoustically opaque and are surrounded by laminated sediments (Figure 32). Multichannel seismic data collected in the trough area shows evidence of gas throughout the sub-seabed, trapped along sediment boundaries (Figure 33). Based on initial analysis, fluid flow may be a mechanism of formation for the mud mounds at Gary Knolls. No evidence of active fluid expulsion from the features has been noted to date. A seabed depression resembling a pockmark is located near the southern extent of the PLF field. The feature is visible on single-channel, sidescan, and multibeam records (authors; Campbell et al., 2008) (Figure 34) and is further evidence of fluid flow in the region.

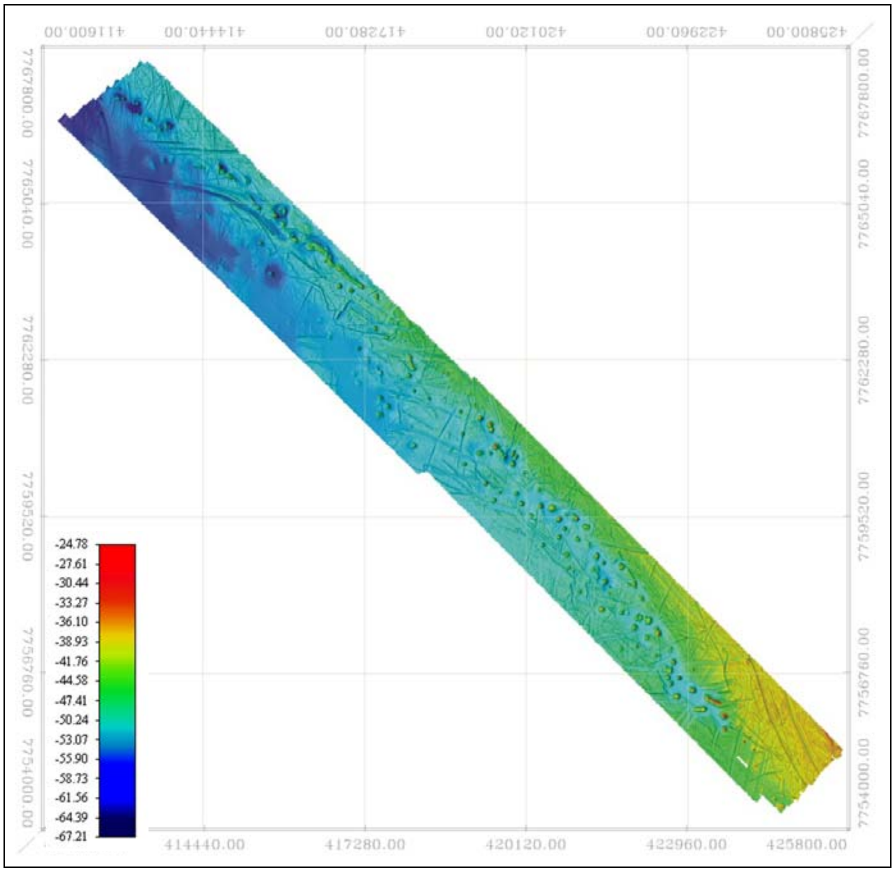

Figure 29: Gary Knolls (2005 multibeam dataset, WGS84, Zone 8N)

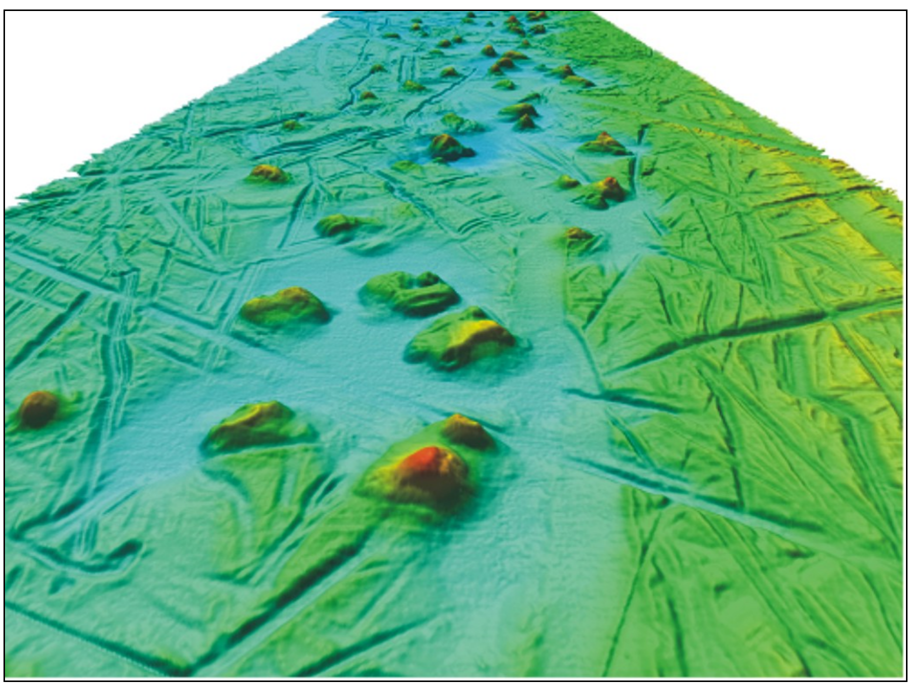

Figure 30: 3-Dimensional view of Gary Knolls

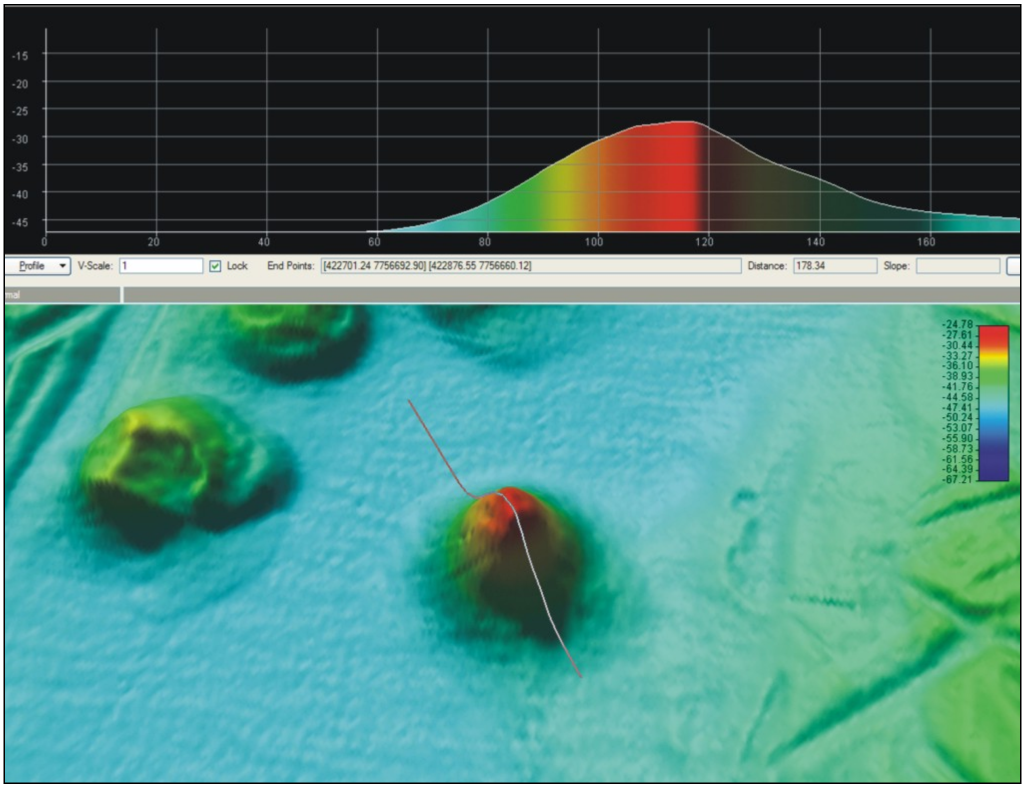

Figure 31: 3-dimensional view of Gary Knolls PLF

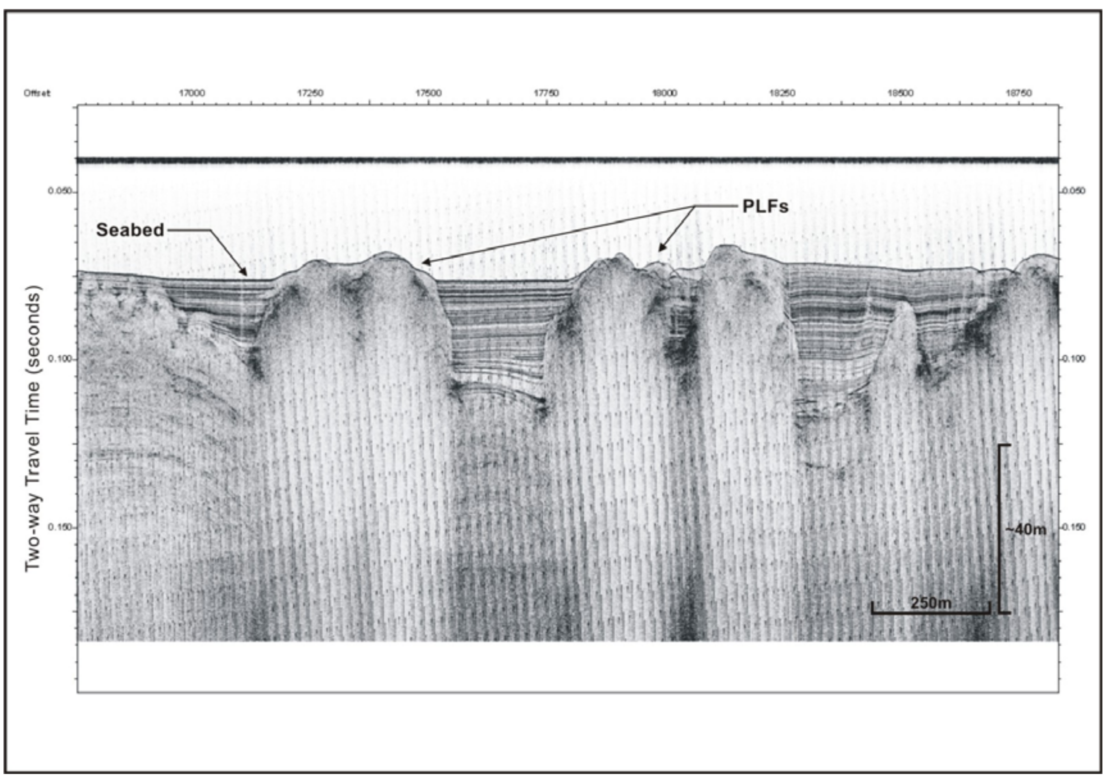

Figure 32: Gary Knolls PLFs, single-channel seismic record (Line 73, 2005)

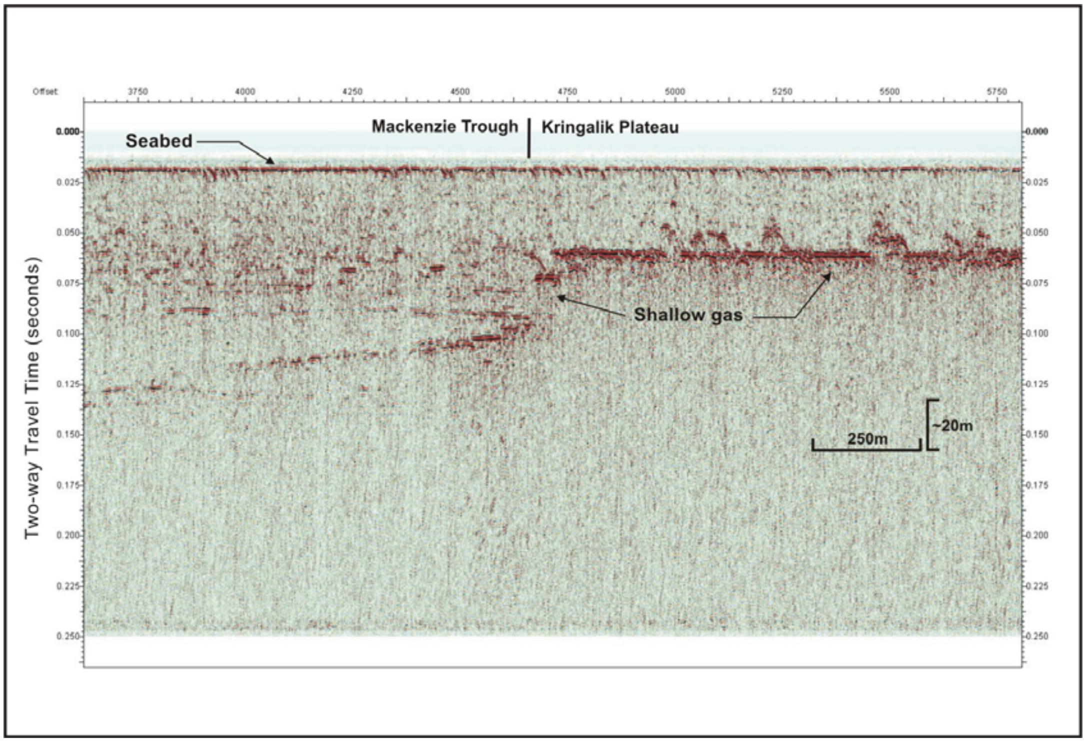

Figure 33: High-amplitude reflectors indicating shallow gas along the Mackenzie Trough boundary (Multichannel Line 70, 2005) (after Campbell et al, 2007)

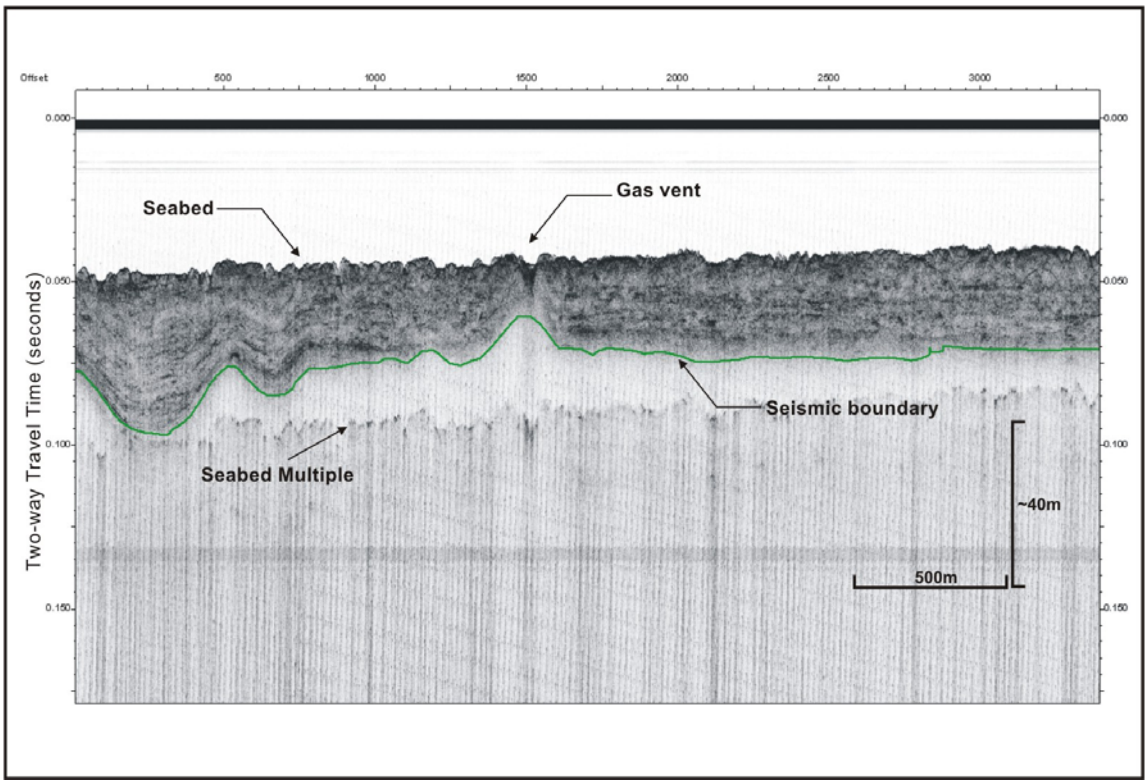

Figure 34: Gary Knolls pockmark - southern end of PLF field (Line 03, 2006 single-channel seismic)

3.3.2. Paktoa Pockmark Fields

Southeast of the Gary Knolls PLF field lies a zone containing over 100 seafloor vents, also known as pockmarks (Figure 35). These seabed depressions lie in an area coincident with gas migration along the eastern Mackenzie Trough boundary. They differ in physical character from the Gary Knolls mounds, possibly due to the region's sediment type, the composition of expelled fluid (e.g. gas versus gas and liquid), and the rate of fluid expulsion. Gas within the water column and sub-seabed is evident on single-channel seismic over the features, indicating the area is presently actively venting (Figure 36 & Figure 37).

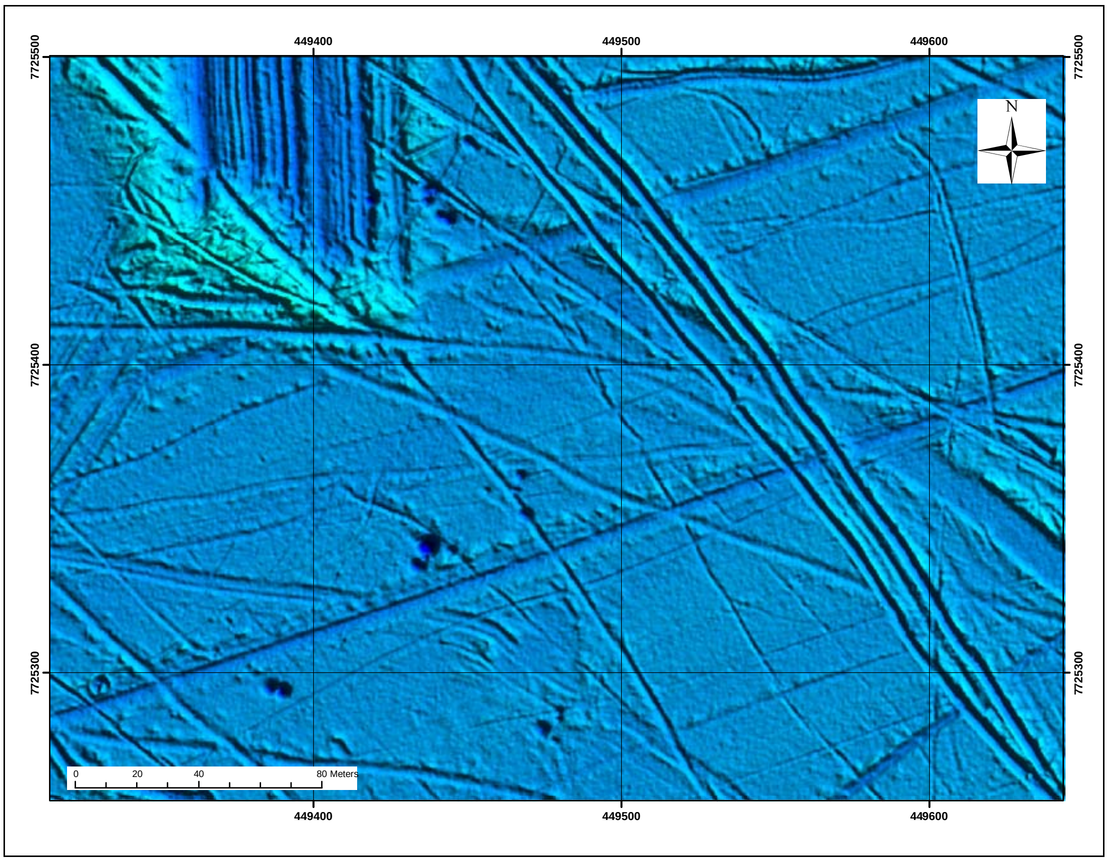

Figure 35: Paktoa Pockmarks (linear features are scour tracks) (WGS84, Zone 8N)

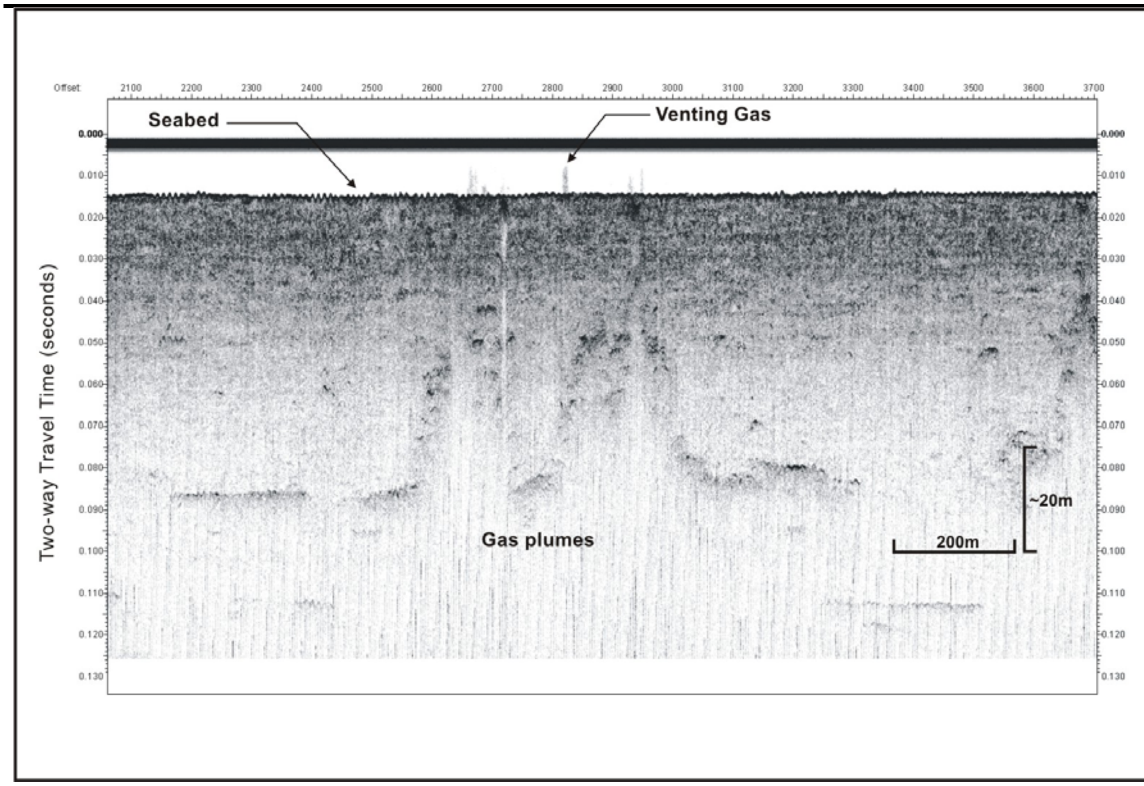

Figure 36: Single-channel seismic profile showing subseabed gas and venting at Paktoa pockmarks

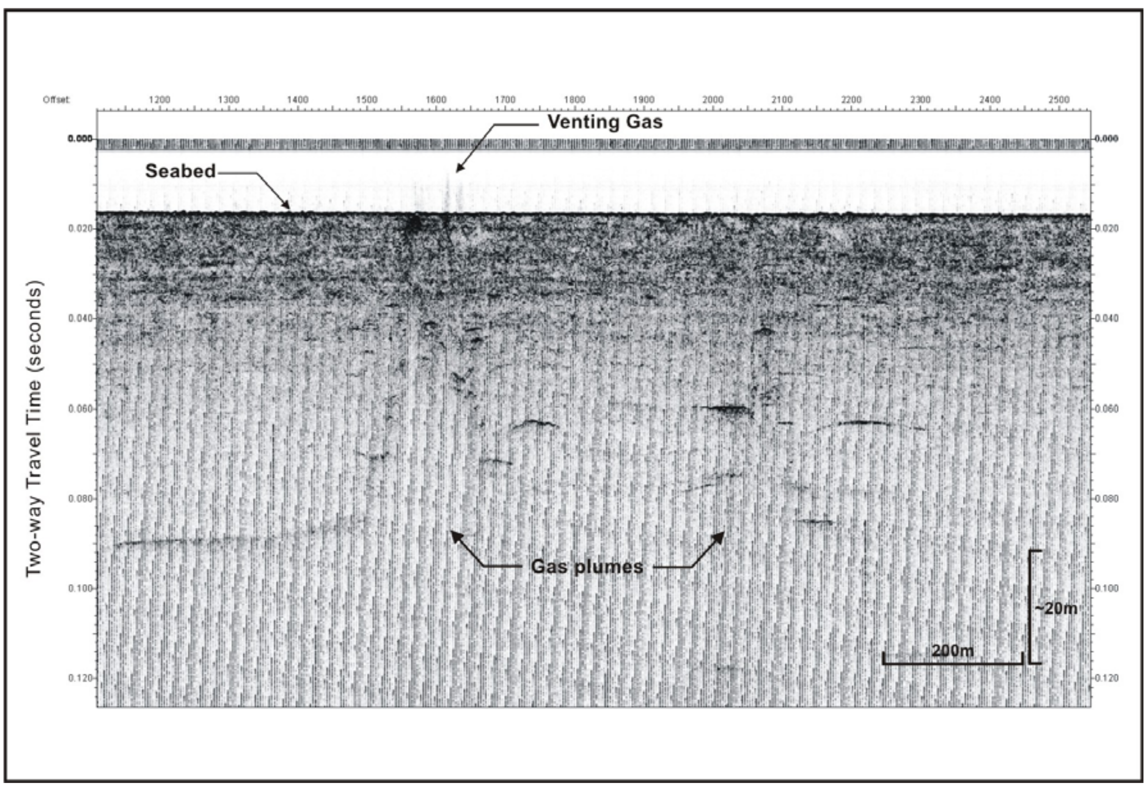

Figure 37: Single-channel seismic profile showing subseabed gas and venting at Paktoa pockmarks

3.3.3. The Western Trough and Beyond

Approximately 15 PLFs have been documented along the western edge of the Mackenzie Trough (Campbell et al., 2008). These features were first noted on airgun seismic records from the mid-1980s (McGregor, 1992). Further west, along the Yukon Shelf, 11 PLFs were mapped with sidescan in the 1970s (Shearer and Meagher, 1980) (Figure 38). The origin of these features and their possible association with seepage of gas and fluids is under investigation.

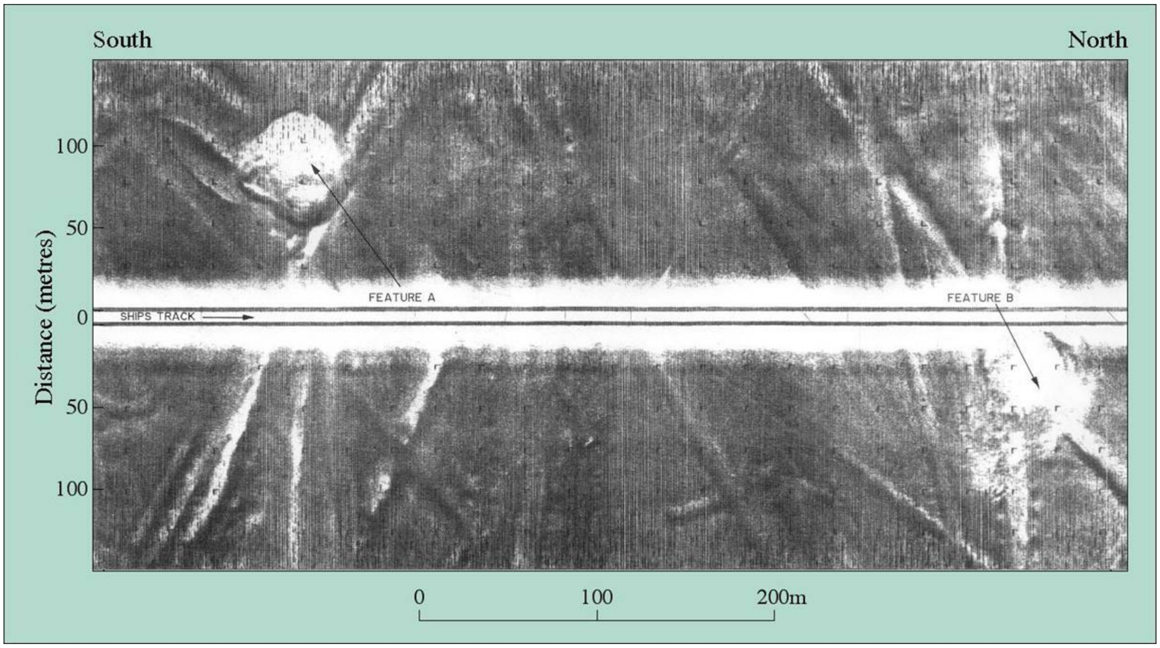

Figure 38: Sidescan Sonar image of PLFs on the Yukon Shelf (after Shearer and Meagher, 1980)

3.4. Ice Scouring

The Canadian Arctic offshore, particularly in shallow water areas such as the Beaufort Shelf, is highly susceptible to sea bottom deformation caused by ice scouring. Ice keels from sea ice pressure ridges and floating sea ice cut deep grooves into the sea floor creating hazardous environments for pipelines and other sea bottom structures and operations. Of interest to this study on benthic habitats, ice scouring processes disrupt of seafloor communities and create new geological habitats.

The GSC and its contractors (Canadian Seabed Research, J. Shearer Geological Consulting) instigated a repetitive ice scour mapping program in the Beaufort Sea beginning in 2001. This study is the continuation of an earlier program undertaken between 1986 and 1990. The objective of the program is to establish the current ice scour dynamics in the Canadian Beaufort including the rate of scouring and the shape, size and distribution of scours using sidescan, micro-profiler, and single-channel seismic records. This knowledge will be used to constrain the design of sea bottom structures. (For detailed discussion and scour statistics up to 2005 see Oickle et al., 2006 and subsequent publications.)

A selection of scour features was sampled for benthic analysis (see section 5) in order to compare the biological diversity in and outside of the scour zones.

3.5. PLFs and Other Geomorphic Features

The discussion of geomorphic features throughout the Northwest Passage has so far included PLFs (some of which are mud volcanoes), pockmarks, and other seeps; and ice scours. Other areas of interest include: sea floor slopes and associated upwellings, whale feeding areas, seafloor depressions and faults.

Depressions in the sea floor, believed to be maw marks created by feeding whales have been observed on sidescan records in several locations in the Beaufort Sea (Campbell et al., 2007; Blasco et al., 2006; Bennett et al., 2004). There is some debate as to the cause of these features, but evidence suggests that whales may be disturbing the sediment and siphoning it through their baleen to extract amphipods for feeding. The United States Geological Survey (USGS, 1996) summarizes work by Nelson documenting maw marks made by California grey whales and walruses feeding on crustaceans in the Chirikov Basin. The USGS paper estimates that at least 6 percent of the basin is disturbed by feeding whales. Judd and Hovland (2007) make reference to the Chirikov Basin features in a geometrical comparison to seabed pockmarks.

4. PALAEONTOLOGICAL CHARACTERIZATION

(summarized from Davies, 2006)

Of the 80 plus vibracores taken aboard the Sir Wilfrid Laurier in 2003 along the Beaufort Shelf, 55 were selected for detailed palaeontological analysis over features of interest including Kopanoar, Kaglulik, and Admiral's area PLFs. Three sets of samples taken over the PLF features included a control station in the outer seabed region away from the feature, a sample within the moat or depression surrounding the PLF, and a sample at the crest of the feature. This analysis (Davies, 2006) was aimed at determining the origin of the sediments composing the PLF features – lacustrine or marine.

The background cores had microfossil assemblages typical of O'Connor (1980) marine Holocene Units A and B (see Section 2.2.1) found in the upper sediment sequence of the Beaufort Shelf. The crest of the features consisted of palynomorphs typical of the glacial sediments of O'Connor (1980) Unit C, indicating that the sediments composing the top of the features probably came from depth. The palynomorphs characterizing the moat sediments were consistent with Unit A marine sediments, but had a higher organic productivity than background cores. Of particular note, was the presence of previously unobserved silicoflagellates ebridians and diatom cysts and frustiles within the moat sediments, but absent in the vents and surrounding sediments.

Results from the shallow Palaeontological analysis indicate a marine origin for the features. The features consist of Unit C sediments which were likely pushed to surface from a deposition depth of 100m or greater. The moat sediments appear to be the result of present day marine deposition, and their higher organic productivity may be related to the presence of methane or other fluids coming from depth. Overall terriginous assemblages are minimal and can be attributed to offshore transportation.

5. BIOLOGICAL ASSOCIATIONS

Seafloor geologic features associated with cold seepage activity are of particular interest to marine biologists and ecologists. From the abundance of oyster and clam beds in oil seep locales off Trinidad (Geyer, 1981) to bacterial mat coated seafloor seeps off Baffin Island (Grant et al., 1986); there is a documented relationship between unique ecosystems and subsea seepage of liquids and gases. Hovland and Judd (2007; 1988) have compiled numerous cases of increased biological activity around active methane and hydrocarbon seeps around the world.

Between 2003 and 2007, the Canadian Museum of Nature conducted benthic macrofaunal sampling of geological features on the Beaufort Shelf including the Kugmallit and Paktoa pockmarks, several valleys and canyons, Kaglulik, Kopanoar, Admiral's and Gary Knolls mud volcanoes, ice scours, upwelling zones, possible whale feeding areas, and glacial beaches. Many of these sites were also sampled for soil properties and methane content as mentioned above.

Ongoing work for this project includes analysis of the benthic habitats at seep sites and geologic features in the Beaufort Sea and other areas of the Northwest Passage; and comparison of these results to other cold-water benthic communities such as the Håkon Mosby mud volcano. The relationship between methane release and the benthic community is of particular interest. The decrease in $\delta^{13}C$ values of foraminifera associated with high methane levels has been investigated (e.g. Rathburn et al., 2000; Smith et al., 2001) and may be of interest at locations where past methane seepage is suspected, but is no longer an active process (A. Jennings, personal communication 2008).

6. CHARACTER OF SEEPS

6.1. *Active Seeps in the Northwest Passage*

After the 1976 discovery and subsequent studies of the Scott Inlet oil seep off Baffin Island, there was relatively little investigation into cold seepage in the Canadian Arctic until the last several years. The re-initiation of a seabed mapping program in the Beaufort Sea and throughout the NW Passage has led to the confirmation of several areas of active gas and fluid seepage (Table 1; Figure 39). The geological, biological, geochemical and geophysical characteristics of these unique environments are still under investigation.

Feature	Type	Latitude	Longitude
Kopanoar Mud Volcano	Gas	70°23 23.18 N	135°25 05.74 W
“Admiral’s Finger” B Mud Volcano	Gas	70°40 58.18 N	132°38 39.60 W
PLF Z	Gas	70°45.80 N	132°51.08 W
Scott Trough Hydrocarbon Seep	Oil/Gas	71°23.80 N	70°09.00 W
Paktoa (cluster 1)	Gas	69°37 50.16 N	136°18 40.97 W
Paktoa (cluster 2)	Gas	69° 36 31.8 N	136° 25 36.0 W
Kugmallit Pockmarks	Oil/Gas	69°44 54.42 N	133°21 18.17 W
Barrow Strait Pockmarks*	Gas	74°16.02 N	91°12.00 W

Table 1: Location of active oil and/or gas seeps in the Northwest Passage
*Confirmation of venting at the Barrow Strait site is pending

Note on source of data for above seep locations: Kopanoar mud volcano, Admiral B, and PLF Z locations were measured from multibeam data collected by CHS between 2001 and 2006. The Paktoa and Kugmallit locations represent the approximate centre of the pockmarks as measured from CHS multibeam data collected between 2003 and 2005. The Barrow Strait location is based on multibeam data collected onboard Amundsen in 2005 representing the centre of the pockmark field. The Scott Trough seep location is an approximate coordinate based on airgun seismic from a 1978 Hudson cruise and the area of submersible activity in 1981 and 1985; it represents a point part way between observed surface droplets and the approximate location of seabed oil. There is likely more than one specific source point in the vicinity. The age of the data, and therefore the precision issues with navigation positioning should be recognized.

Based on current analysis, the following information has so far been ascertained in regards to the nature of the seepages from Northwest Passage features:

Mud Volcanoes:

- Gas seeping from the Beaufort Shelf mud volcanoes is predominantly methane (Paull et al., 2007). The origin of this methane appears to be biogenic based on isotope analysis (Paull et al., 2007); however, thermogenic gases from petroleum and natural gas deposits in the Canadian Beaufort have anomalously high methane content which is similar to that of the mud volcanic gases. Terrestrial pockmarks on the nearby Mackenzie Delta are venting similar high-methane gas which appears to be of thermogenic origin (Bowen et al., 2008).
- There is some question as to whether the methane gas from the volcanoes is associated with decomposition of gas hydrates (Paull et al., 2007) and/or a source at depth.

- No bacterial mats, carbonates or exotic fauna were visually noted around the crests of the venting volcanoes (Paull et al., 2007) although detailed benthic analyses is ongoing.
- Age dating of the near-surface sediments indicate the volcanoes are recent features formed in a marine setting (Medioli et al., 2005; Davies, 2006; Paull et al., 2007)

The Scott Seep:

- Bacterial mats of *Beggiatoa* and carbonate crusts similar to those found in other seep locations worldwide are associated with the Scott seep site.
- The Scott seep needs further investigation to determine its linkage with hydrocarbons.

Pockmark fields:

- The Kugmallit pockmarks show evidence of recent episodic activity; analysis of the gas and oil found in at least one of the depressions is pending.
- The Barrow pockmarks appear to be actively venting gas as interpreted from sub-bottom records, although there is some question as to the validity of this interpretation at present.
- Gas venting into the water column at the Paktoa pockmark field is present on single-channel seismic records.

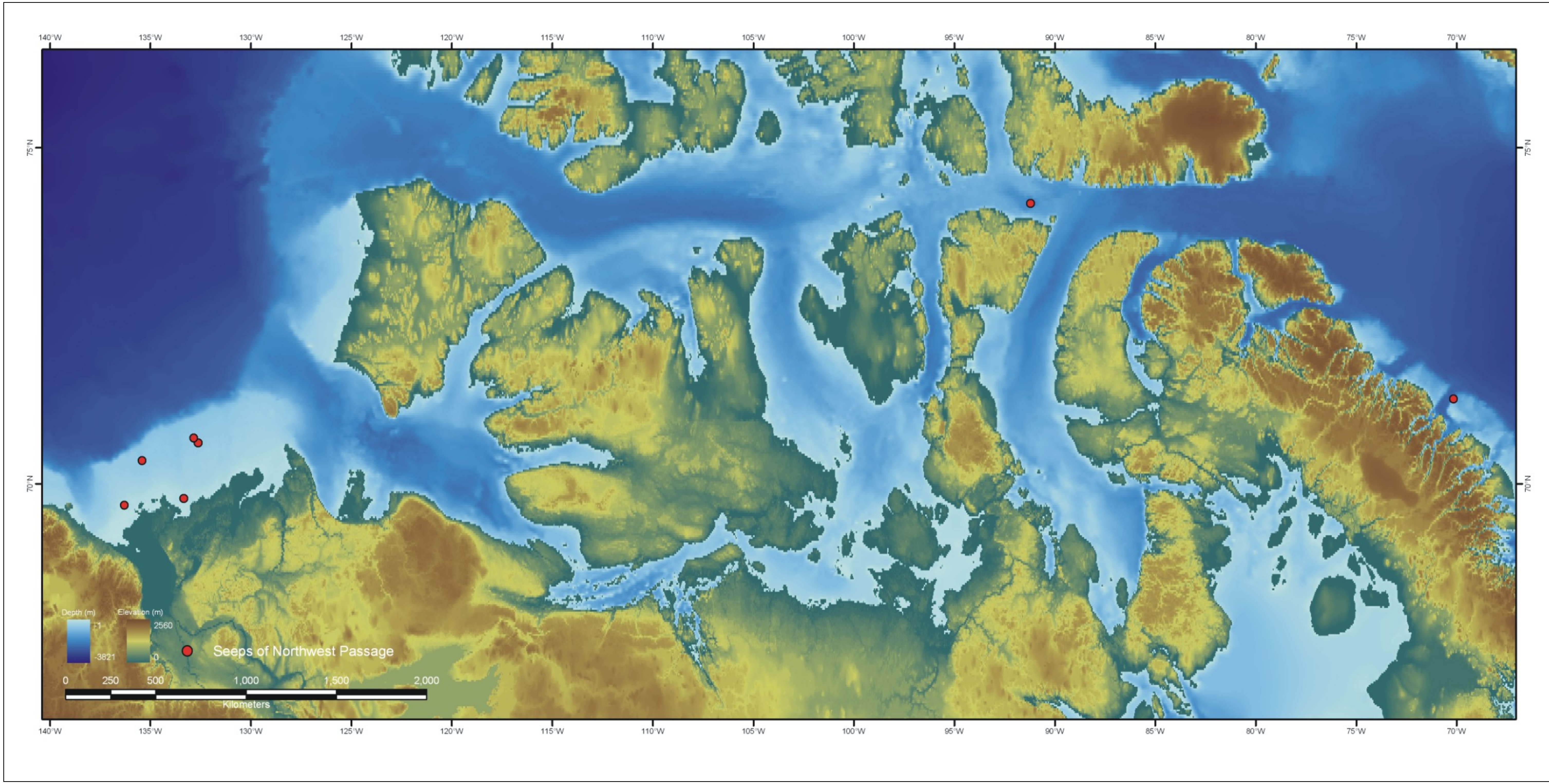

Figure 39: Active Seeps of the Northwest Passage

6.2. Potential seeps

At several of the seabed sample sites (including Kugmallit gas vents as discussed above), voids and/or oil were found in the shallow seabed sediments (Figure 40 and Figure 41) (K. MacKillop, personal communication 2008).

The chemistry and origin of the oil in five of the push and gravity core samples have not been determined as the cores were taken for geotechnical purposes (K. MacKillop, personal communication 2008). As previously mentioned, a sample of oil taken from the Kugmallit pockmarks is currently under analysis.

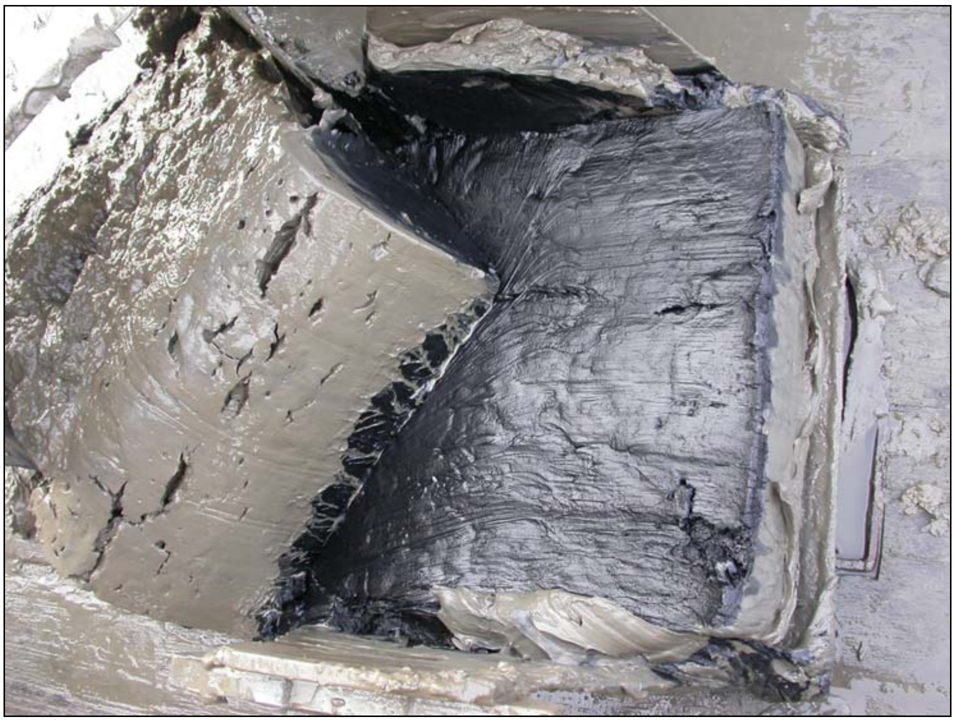

Figure 40: Oil in box core at Issungnak site (2007) (courtesy of K. MacKillop)

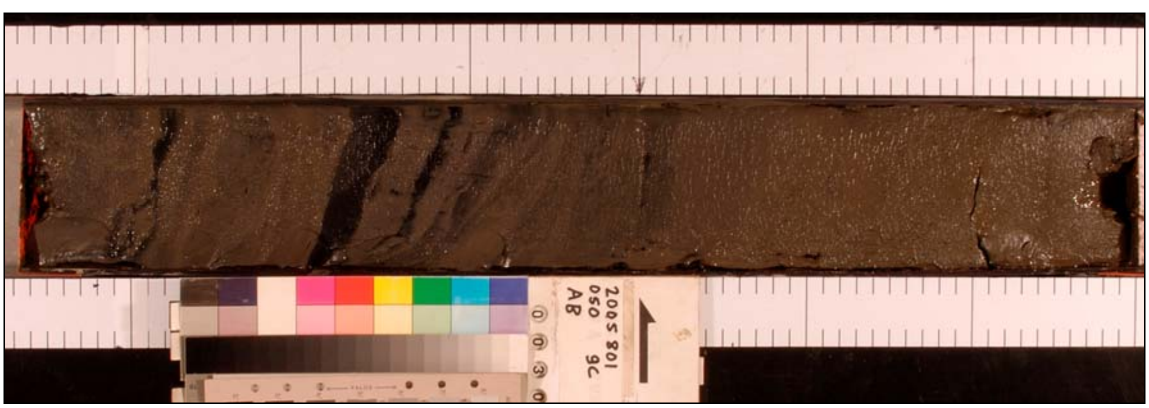

Figure 41: Oil in push core from Kugmallit Bay area (2005) (courtesy of K. MacKillop)

Sub-seabed shallow gas is present on recent seismic records from the Beaufort Shelf, particularly near the Mackenzie Trough – Kringalik Plateau physiographic boundary (see O'Connor, 1982 for further reading on physiographic regions of the Beaufort Sea). Single-channel seismic records show what appears to be gas venting into the water column in several locations along the boundary and on the Kringalik Plateau (Figure 42).

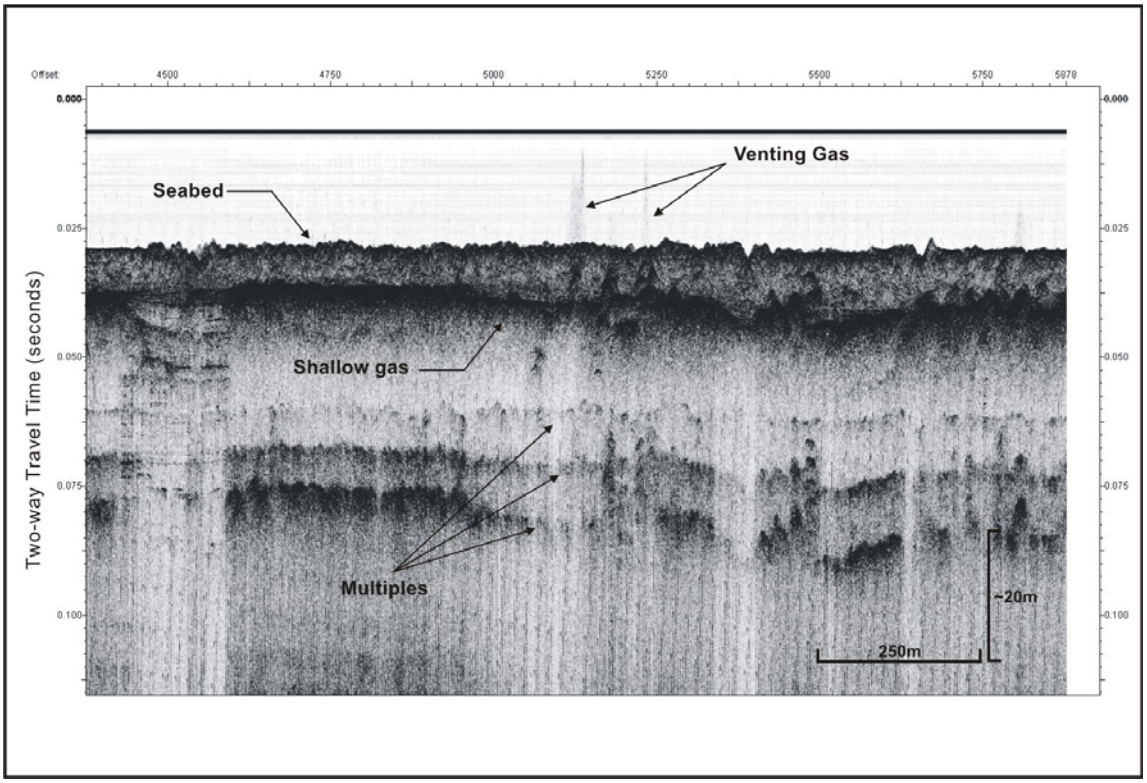

Figure 42: Single-channel seismic showing venting gas on the Kringalik Plateau (Line 20, 2006)

6.3. Terrestrial Seeps

6.3.1. Alaska's Klawasi Group

If the Tuktoyaktuk pingos are the morphological counterparts of the Beaufort Sea PLFs, then the mud volcanoes of the Klawasi group located in Alaska's Copper River Basin are dynamically-similar cousins. The trio of active terrestrial mud volcanoes including Shrub, Lower Klawasi and Upper Klawasi resemble the Beaufort seafloor volcanoes in structure and in their expulsion of mud, fluids and gases from depth.

Gas emitted from both Shrub and Upper Klawasi has carbon dioxide levels in excess of 98% (Sorey et al., 2000). High-temperature expulsion of gas and fluids, together with their chemical composition indicates a combined mantle and crustal source (Sorey et al., 2000).

The emission of CO_2, high temperature venting, and association with tectonic activity suggest that the origin of the Alaskan features is different from that of the Beaufort submarine mud volcanoes.

Figure 43: One of the Klawasi group of mud volcanoes of southern Alaska (courtesy of W. Manley, 2008)

7. Future Work and Recommendations

From 2001 to 2007, >1000 line kilometres of geophysical data and several hundred seafloor samples were collected in the Beaufort Sea and central-eastern NW Passage. These data have allowed mapping of a variety of seabed geologic features including mud volcanoes, pockmarks, and ice scours. This is an ongoing study, integrating recent datasets with those collected in the 1970s and 1980s, with many questions and hypotheses arising with each new discovery. In order to understand the seafloor dynamics, the nature of the oil and gas seeps and the geohazards affecting safe and environmentally sound exploration and development; there are several specific areas where follow-up and additional survey work is recommended.

7.1. Sample Results

The results of the Canadian Museum of Nature benthic sampling program must be integrated with the geologic information at seep sites and other features of interest. Benthic sampling should be carried out at all sites where geophysical data is available. The possible links between benthic organisms and methane flux at the seep sites should be examined.

A series of PLF sediment cores are being analyzed for sedimentology, geochemistry, and biostratigraphy (S. Dallimore, GSC Pacific). Analysis continues on the sedimentology and age of many of the 350 plus PLFs, their lacustrine versus marine origin and their association with mud volcanism. Initial palaeontological results have indicated marine origins for some of the PLFs although these results are based on shallow sampling only.

The results of M. Papst's (DFO) oil analysis for the Kugmallit Bay pockmarks is pending. In locations where oil was encountered in geotechnical sampling, it is recommended that sampling of the oil is undertaken for similar analysis.

7.2. Examination of Ecologic Hotspots

ROV and/or submersible video surveys over additional mud volcano, PLF and gas features (i.e. Gary Knolls; Paktoa, Kugmallit and Barrow pockmark sites) should be completed to ascertain the level of geological and biological activity of the seeps. Repetitive geophysical surveys over the features will help to identify yearly changes and levels of activity. Survey infill between the Paktoa pockmark clusters should be completed as well as collection of multibeam data over the western cluster. Additionally, RADARSAT and other similar datasets may be useful in identifying other seep areas in the NW Passage (C. Woodworth-Lynas, personal communication 2008).

The Scott Seep should be re-visited with multibeam and ROV, and oil samples taken for analysis as well as benthic samples for ecology and sediment properties.

Further comparison between the NW Passage mud volcanoes and others in Arctic regions (e.g. the Caspian Sea Mud Volcanoes and HMMV) is necessary. The relationship between benthic organisms and fluid seepage should be examined.

Investigation of the seep properties including: depth of origin, emission of biogenic vs. thermogenic methane, and relationship with structures at depth and/or gas hydrates is recommended. A data search for archive deep seismic records under benthic seep sites should be conducted in conjunction with the National Energy Board (NEB) to determine if the seeps are related to features at depth.

Geophysical data over the western Mackenzie Trough PLFs and the new features mapped in 2007 around "Admiral's Finger" should be examined in more detail. Additional multibeam data should be collected in the area of the western Mackenzie Trough PLFs.

In areas where venting gas is present on single-channel seismic records, the multibeam data results should be examined and if none exists, surveys over these sites should be undertaken as well as benthic, sediment, and gas sampling.

8. References

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Appendix A: Location of Geophysical Sections

The following table gives locations of seismic sections, where not already indicated in the document.

Description	Figure No.	X (centre)	Y (centre)	X_start	Y_start	X_end	Y_end	Projection
Kaglulik seismic	Figure 21	652010	7868789					Nad83z8N
Admiral mud volcano	Figure 26			586811	7854849	588197	7855372	Nad83z8N
Gary Knolls	Figure 32			413109	7766154	414519	7764774	Nad83z8N
2D section - gas	Figure 33			441879	7730296	443380	7731801	Nad83z8N
Gary pockmark	Figure 34			423758	7755644	426154	7753208	Nad83z8N
2007 gas plumes	Figure 36			443963	7723553	445515	7723107	Nad83z8N
2004 gas plumes	Figure 37			445008	7722460	444176	7723680	Nad83z8N
Kringalik gas section	Figure 42			448394	7754888	448826	7756268	Nad83z8N