GEOLOGICAL SURVEY OF CANADA
COMMISSION GEOLOGIQUE DU CANADA

Open File 3780

BASIC GEOLOGICAL AND GEOPHYSICAL INDICATIONS OF GAS HYDRATE DISTRIBUTION AND VOLUME IN CANADA

By

J.A. Majorowicz and K. Osadetz

Geological Survey of Canada (Calgary), 3303 - 33 Street N.W.
Calgary, Alberta T2L 2A7

October 1999

BASIC GEOLOGICAL AND GEOPHYSICAL INDICATIONS OF GAS HYDRATE DISTRIBUTION AND VOLUME IN CANADA

J.A. Majorowicz[1] and K. Osadetz[2]

[1] Northern Geothermal, 105 Carlson Close, Edmonton, Alberta, T6R 2J8
[2] Geological Survey of Canada: Calgary, 3303 33rd St. NW., Calgary, Alberta, T2L 2A7

ABSTRACT

Gas hydrates are inferred to occur widely in Canadian polar and continental shelf regions. Although direct indications are few and widely separated, conditions potentially favorable for gas hydrate formation and stability, especially low to moderate thermal gradients, combined with favorable geological conditions for gas generation and storage covers vast areas and indicates an immense potential for natural hydrocarbon gas in the upper 2 km of many Canadian sedimentary basins. Analysis of this potential suggests that the vast continental shelves and Arctic permafrost regions of Canada constitute one of the largest potential storehouses for gas hydrates worldwide. Gas hydrates have been detected from geophysical logs and "gas kicks" in the Mackenzie Delta-Beaufort Sea and Arctic Archipelago in the north, and Davis Strait, the Labrador Shelf, Scotian Shelf and Grand Banks of Newfoundland, along the Canadian Atlantic margin, in regions exhibiting favorable physical conditions for hydrate stability. In addition, hydrates have been indicated by bottom simulating seismic reflections (BSR) and Ocean Drilling Project (ODP) activities along the Canadian Pacific margin (Hyndman, 1992). A conservative calculation suggests 10^{10} - 10^{12} m^3 of gas hydrates in these three regions with an associated methane gas potential estimated to be in the range of 10^{12} - 10^{14} m^3. Geographically this methane potential is distributed in the following regions, 9.3×10^{12}-2.7×10^{13} m^3 in the Mackenzie Delta-Beaufort Sea, 8.3×10^{13}-2.6×10^{14} m^3 in the Arctic Archipelago, 5.4×10^{13}-1.6×10^{14} m^3 on the Atlantic Margin and 3.0×10^{12}-9.3×10^{12} m^3 on the Pacific Margin. The total amount of methane in hydrates in Canada is estimated to be 1.5- 4.6×10^{14} m^3, as compared to a conventional Canadian hydrocarbon gas potential of approximately 2.68×10^{13} m^3. This implies that gas hydrates represent a possible future assurance of North American energy supply. In most Canadian settings, gas hydrates are stable, both currently and for the foreseeable future, even when potential destabilizing factors such as sea level changes, global warming and post-glacial isostatic rebound are considered. The most sensitive regions to potential destabilizing factors occur in the shallower portions of the Beaufort Sea and inter-island waterways in the Arctic Archipelago, where some naturally-induced gas release from hydrates may be possible.

INTRODUCTION

Immense amounts of natural gas, composed mainly of methane, can occur as gas hydrates. Gas hydrates may form under marine conditions where pressure is great, sea bottom temperature is low and the geothermal gradient is low to moderate (e.g. Westbrook, et al., 1994; Carson et al., 1995). They may also form in circumpolar regions where surface temperature is very low, permafrost is present, and the geothermal gradient is low to moderate. In such settings natural hydrocarbon gas consisting largely of methane may be "trapped" in ice-like crystalline structures called "gas hydrates" or "clathrates" (Katz et al., 1959; Davidson et al.,1978; Makogon, 1982; Kvenvolden, 1988a, b). Such structures occur within sediments under specific temperature and pressure conditions that define the hydrate stability zone. Hydrate structures store natural gas very efficiently. On a volume per volume basis, the mass of methane stored in hydrate structures is approximately 150-189 times greater than that present in an equal volume of free gas under standard conditions.

Several occurrences of hydrates have been interpreted from geophysical logs in the Beaufort-Mackenzie, Arctic Islands and Canadian Atlantic Margin (Bily and Dick, 1974, D&S Petrophysical Consultants, 1983; Hardy and Associates (1978) Ltd., 1984; Thurber Consultants, 1986, 1988; Judge et al., 1994, Dallimore et al.,1998). Most of these hydrate indications occur between a depth of 0.2 km and the maximum methane hydrate stability depth inferred from regional pressure and temperature conditions. The gas hydrate maximum stability depth is up to 1.4 km in the Mackenzie Delta-Beaufort Sea and up to 1.8 km in the Arctic Archipelago (Majorowicz and Judge, 1992; Judge et al., 1994). Hydrates have also been inferred from geophysical well log data on the Atlantic Margin, specifically on the Labrador Shelf (Taylor et al, 1979) and in the northeast Grand Banks of Newfoundland (Judge et al, 1990). Studies of bottom-simulating seismic reflectors (BSRs) (Hyndman and Davis, 1992; Hyndman and Spence, 1992; MacKay, et al., 1994; Hyndman, 1996) indicate the presence of hydrates on the Pacific margin, specifically offshore of Vancouver Island.

The interpretation of hydrate occurrence from geophysical well logs is ambiguous due to the difficulty of distinguishing between a gas zone and hydrate zone. It is, therefore, important to determine the pressure and temperature stability zone for hydrates in the sedimentary succession in order to distinguish hydrate occurrence from conventional gas responses on wireline geophysical logs. For example, analysis of corrected temperature data and thermal conductivity structure in the Mackenzie Delta-Beaufort Sea region defined a base for the methane hydrate stability zone that indicated that a number of previously inferred gas hydrate occurrences were in fact probably conventional gas accumulations, since they occurred below the calculated maximum depth for methane hydrate stability (Majorowicz et al., 1995). In many cases, hydrate occurrences have been interpreted at depths 400 m to 1100 m, well below the deepest methane stability limit as inferred from pressure and temperature data.

Several petrophysical characteristics of free gas, hydrate and ice are similar. This makes the analysis of hydrate stability a necessary condition for the correct interpretation of geophysical data and hydrate identification (Collett et al., 1988; Collett, 1993). This study re-evaluates geophysical log data from 30 wells in the western Beaufort Sea region. This work indicates that many previously inferred gas hydrate occurrences are actually free gas accumulations occurring below the lower methane hydrate zone. Similar revised interpretations have been made in Northern Alaska (Collett, 1997).

Gas hydrates composed of heavier gases can persist at depths below the base of methane hydrate stability. Complex gas compositions have been used to explain observed difference in gas hydrate occurrence and the base of hydrate stability as interpreted from geophysical logs (Judge and Majorowicz, 1992; Judge et al., 1994). However, gas chemistry from eleven wells in the western Beaufort Sea indicates a predominance of Type I, or methane, hydrates. Most previously assumed gas hydrate occurrences at depths below predicted Type I gas hydrate stability are reinterpreted as free gas occurrences. Currently, hydrate zones are commonly interpreted from the geophysical data from a single well. The correlation of geophysical characteristics of hydrate zones that consider multiple well sections should result in better and more consistent interpretations.

The difficulties and uncertainties in the interpretation of geophysical data affects the assessment of gas hydrate volume. This reconnaissance study is also dependent upon data availability, particularly with respect to well data since well density and data reliability varies greatly among regions. The Mackenzie Delta-Beaufort Sea region and Canadian Arctic Archipelago have more wells and permafrost studies compared to other frontier regions of Canada. These regions have the best data set for identifying hydrate occurrences and determining hydrate stability zones. In contrast, the Atlantic and Pacific oceanic margins have few wells that are widely separated across vast areas. This renders the estimation of hydrate potential in these two regions both more difficult and uncertain. These differences in data and resulting inferences and descriptions of hydrate potential, as a function of geographic region, also affects our estimates of the amount of gas stored in hydrates. Therefore, we cite the probable range of hydrate volume and associated methane, as opposed to single values. Still, we employ a single and similar approach to the estimation in all regions. This provides comparable assessments of both total volume of gas hydrate and gas potential in all Canadian frontier regions considered by this study.

GAS HYDRATE STABILITY CONDITIONS

Gas hydrate stability depends on many factors (Davidson et al., 1978, Kvenvolden, 1988a, b; Makogon, 1982; Collett, 1993; 1997). Among these factors, temperature, pressure and gas composition are the most important (ibid.). Most gas hydrate studies assume hydrostatic conditions characterize the subsurface pore pressures. Commonly a hydrostatic gradient of 9.795 kPa/m is assumed. Pore pressure gradients greater than hydrostatic extend the potential gas hydrate stability field to greater depths. In this study, hydrostatic gradients were assumed. Such a consideration can be made even though overpressured zones are known to occur in some of the sedimentary basins studied, because overpressure zones are commonly present at depths much greater than the expected depth of gas hydrate occurrence. For example gas hydrates usually form at depths less than 1000 m, whereas overpressured zones, like those in the Scotian Shelf and Grand Banks regions occur at depths greater than 3000 m.

Gas composition affects the gas hydrate stability. Methane hydrate forms Type I hydrate structures, while methane plus a few percent of ethane or propane can result in Type II hydrate structures. Hydrate structure is also sensitive to temperature and pressure (Sloan, 1990). Dissociation temperature increases in the presence of CO_2. Conversely, dissociation temperature decreases with increasing pore water salinity. Yet, almost all gas hydrate samples from deep drilling projects, such as Deep Sea Drill Project (DSDP) and Ocean Drilling Project (ODP) cores, have been methane hydrates with pore water salinities similar to sea-water (Kvenvolden and Kastner, 1990).

Canadian data also suggests that methane hydrates predominate. In the Mackenzie Delta-Beaufort Sea region gas samples and mud log gas chromatography data from petroleum wells indicate that gases from the upper 1500 m are almost entirely methane. Weaver and Stewart (1982) reported gas compositions of 99.5% methane. Bily and Dick (1974) reported 99.19% to 99.53% methane from two wells drilled on Richards Island in the Mackenzie Delta. Additional gas compositions from cuttings gas analysis from the upper 2 km in Mackenzie Delta-Beaufort wells shows a predominance of methane with some traces of C_2 and insignificant amounts of C_3 and C_4 gases (L. Snowdon, pers. comm., and industrial analyses in Kiggavik A-43, Adgo J-27, Niglintgak H-30, and Kumak E-58 well history files). Cuttings gas composition varies with increasing depth. At several thousand metres depth cuttings gases are "wetter". Data from the Alaskan North Slope also suggests that methane hydrates predominate in Arctic regions. A gas hydrate zone test recovered a gas sample that was 93% methane and 7% nitrogen gas.

Based on the above observations, we assume that gas hydrates with Type I structure are predominant and other structural types are rare. Therefore, all calculations shown in this paper were based on Type I (methane) gas hydrate stability (Collett, 1993). The hydrate stability curve as a function of temperature and pressure is given by:

$$P = e^{(14.7170 - 1886.79/T)}$$

from 248 K to 273 K and,

$$P = e^{(38.9803 - 8533.80/T)}$$

from 272 K to 298 K,

where P is formation pressure, in kPA, and T is temperature in, K.

In instances where propane and heavier gases are clathrated in hydrate structures we note that the base of the hydrate stability zone would be deeper than suggested by this study. For example, the base of hydrate stability for a gas hydrate with a composition of 96.5% methane and 3.5% propane can occur 300 m lower than that of methane hydrate (Lewin & Associates, 1983). Therefore, our assumption that all hydrates are methane hydrates will result in a smaller or conservative estimate of hydrate volume.

Onshore Locations: Methane hydrates form onshore in circumpolar regions, where significant permafrost thickness is present (Heginbottom and Vincent, 1986; Judge 1986; Taylor, 1991). In Canada sufficient permafrost occurs in both the Arctic Archipelago and Mackenzie Delta-Beaufort Sea region to allow onshore hydrates to form. Thick permafrost, often greater than 200 m, and low thermal gradients, often less than 30 mK/m, provide physical conditions very favorable for hydrate formation onshore. The Mackenzie Delta area is characterized by low thermal gradients, generally less than 30 mK/m, thick onshore and offshore permafrost, and low temperatures at the base of the permafrost layer, typically -1° C (Majorowicz et al., 1995).

In the Arctic Archipelago thick permafrost occurs onshore of coastal regions. The coastal areas of the archipelago are regions where there have been "recent" changes from marine to terrestrial environments, as a result of rising Holocene sea levels. This environmental transition affects both permafrost and hydrate formation. Geothermal gradients throughout the Arctic Archipelago exhibit a large variation, between 15 mK/m and 45 mK/m (Majorowicz and Embry, 1998). Conditions are excellent for the formation of hydrates in this region, as the recent emergence of the islands, or portions thereof, now exposes larger areas to very low surface temperatures, often between -15 C and -20 C. This ensures that upward migrating gases will be clathrated in hydrate structures. For example, data from the Hecla J-60 well (Figure 1) indicates the base of hydrate stability at less than 1.8 km +/- 100 m. The uncertainty results in this estimate is due to uncertainties in the temperature profile obtained from individual bottom hole temperatures from geophysical logging "runs" and drill stem tests. In addition various temperature-depth models result from uncertainties in the thermal conductivity profile. These variations allow a sensitivity analysis of possible temperature profiles, consistent with uncertainties in thermal data and the thermal conductivity structure of the succession penetrated by the well.

Marine Environments: Gas hydrates occur in offshore sedimentary reservoirs as a result of high hydrostatic pressure from the overlying seawater column, low sea bottom temperatures, and moderate to low thermal gradients. Under such conditions gas migrating upward can be trapped as hydrates in the region between 300 metres water depth and the edge of the continental shelf. In the offshore gas hydrate thickness depends strongly on the geothermal gradient, as illustrated (Figure 2a - 2c). For example, assume a 1000 metre water depth, a sea bottom temperature of zero degrees C, and geothermal gradients between 25 mK/m - 35 mK/m. Figure 2 illustrates how the thickness of the methane hydrate stability zone increases from less than 1.3 km to approximately 1.6 km when the thermal gradient decreases from 45 mK/m to 25 mK/m. In Canadian oceanic environments comparatively higher thermal gradients, perhaps approaching 40 mK/m are expected for the Pacific Margin, while lower thermal gradients, in the neighborhood of

30 mK/m, are typical of the Atlantic Margin. The observed average thermal gradient for the Atlantic Margin is approximately 32 mK/m. In the inter-island channels of the Arctic Archipelago thermal gradients vary between 25 mK/m and 45 mK/m. In this last region thermal gradient variations strongly influence the depth of the base of hydrate stability.

Water depth is another important factor affecting the thickness of the hydrate stability zone. The thickness and depth of the base of the methane hydrate zone increases with increasing water depth (Figure 3). Potential thickness of the hydrate-prone zone for a given water depth depends also on both thermal gradient and sea bottom temperature (Figure 4). Where the thermal gradient is stable, the thickness of the hydrate stability zone depends on water depth and sea bottom temperature (Figure 5). Therefore it is expected that the hydrate zone will be thicker in Arctic seas, with lower sea bottom temperatures, compared to other settings with similar water columns and thermal gradients. A difference of four degrees celcius at the sea bottom between inter-island Arctic waterways and open oceanic settings. In the inter-island Arctic waterways sea bottom temperatures are typically -1 degree C while in oceanic settings sea bottom temperatures are typically +3 degrees C. This makes a significant difference in both the thickness of the hydrate stability zone and the areas below which hydrate stability occurs. For a given sea bottom temperature, the thickness of the methane hydrate zone depends strongly on pressure and temperature (Figure 6). The above relationships and considerations allow mapping of methane hydrate stability as a function of water depth, sea bottom temperature, and thermal gradient.

CALCULATION OF HYDRATE VOLUMES AND ASSOCIATED RESOURCES

DETECTION AND THICKNESS OF GAS HYDRATES

Direct indications of gas hydrate occurrence are few in Canadian sedimentary basins (Davidson et al., 1978; Judge et al., 1990; Judge et al., 1994; Yuan et al., 1996; Spence et al., 1996.). Generally, gas hydrates are detected or inferred to be present from well data and seismic records. Therefore, the most important basis of this evaluation of gas hydrate potential is the inference, rather than the direct indication, of gas hydrate occurrences.

Drilling through permafrost and potential gas hydrate zones is done with chilled mud to avoid the potential hazard associated with the explosive phase change from solid hydrate to gas that can cause a well to "blowout". The attempt to avoid “blowouts” enhances drilling safety, but obscures gas hydrate detection. Mud gasification provides a means for the detection of gas from hydrates in petroleum wells. Likewise, well tests, both drill stem and production, can also indicate the presence of gas hydrates, either by the recovery of gas, or by pressure buildup in the suspected hydrate zone. Examples of mud gasification are known from the Ivik - Mallik area of the Mackenzie Delta-Beaufort Sea area, in Canada, and from the Kuparuk field, west of Prudhoe Bay, in Alaska. Large gas hydrate occurrences has been reported in Siberia in the Messoyakha field (Makogon, 1988). Two Imperial Oil petroleum exploration wells in the northern Mackenzie Delta encountered hydrate-bearing sands 99 m and 24 m thick at depths between 820 m-1103 m and 978 m-1020 m, respectively (Davidson et al., 1978). Well tests of suspected gas hydrate occurrences in two wells on Richards Island in the Mackenzie Delta recovered a predominantly methane gas (99.19 to 99.53%) (Bily and Dick, 1974). Gas hydrates have also been found in samples recovered from Deep Sea Drilling Project and Ocean Drilling Program wells (Kvenvolden and Kastner, 1990).

Geophysical logs provide additional tools for the detection of hydrates. However, the acoustic and resistivity properties of hydrates and ice in permafrost regions is similar. For this reason geophysical logs are most effective in sub-permafrost and deep marine settings. Dual induction laterologs and sonic logs are the main tools used to detect hydrates in wells. High resistivity from the induction log and high velocities from the sonic log are the primary characteristics of a response from hydrate bearing zones. In Canada, hydrates have been detected or inferred, from the interpretation of geophysical logs in the upper 1500 m of wells drilled in the Mackenzie Delta-Beaufort Sea, the Arctic Archipelago, and the Atlantic Margin. On the Atlantic Margin, hydrates have been indicated from wells in Davis Strait, the Labrador Shelf, the Scotian Shelf and the Grand Banks of Newfoundland.

In the Mackenzie Delta-Beaufort Sea area, hydrates were detected in 52 of 146 wells using geophysical logs (D&S Petrophysical Consultants, 1983; Thurber Consultants 1986; 1988; Smith and Judge, 1993; 1995). In this region hydrates are present both onshore and offshore in porous formations of the Kugmalit, Mackenzie Bay, and Iperk sequences (Figure 7). In the Mackenzie Delta-Beaufort Sea region the frequency of gas hydrate occurrence is higher in the offshore area where 35 of 55 wells were interpreted to contain hydrates. In the Arctic Archipelago, gas hydrates were interpreted to be present in 93 of 148 wells drilled in the Sverdrup Basin (Figure 7; Hardy Associates (1978) Ltd., 1984). On the Atlantic Margin, gas hydrates were detected in 26 of 48 wells examined from Davis Strait, the Labrador Shelf, the Scotian Shelf, and the Grand Banks of Newfoundland (Figure 7; Thurber Consultants Ltd., 1985). ODP wells offshore Baffin Island and southern Greenland did not find gas hydrates (Judge et al., 1990). Strong evidence for gas hydrates on the Pacific Margin comes from analysis of bottom simulating reflections (BSR) on reflection seismic lines across the northern Cascadia continental slope (Yuan et al., 1996). Analysis of the seismic velocities in this region permitted the volume of hydrates per square metre of seafloor to be estimated as high as 7 m^3/m^2 (ibid). In offshore areas of the continental slope hydrate concentrations tend to increase with depth, reaching a maximum of up to 35%. The same study on the Pacific Margin suggested that hydrates may occupy up to 20-30% of the pore space available above the BSR.

The histograms in Figure 8 indicate the thickness of gas hydrate zones detected in each of, the Mackenzie Delta-Beaufort Sea (Figure 8a), the Arctic Archipelago (Figure 8b) and the Atlantic Margin (Figure 8c), respectively. The average gas hydrate thicknesses for each of the three regions are, 82 m, 65 m and 79 m, respectively. Based on the results of ODP site 889, the thickness of concentrated methane hydrate, where hydrate occupies 10-20% of the available pore space, is restricted to approximately 110 m on the Pacific Margin (Figure 12; Yuan et al., 1996). These estimates of hydrate thickness were used to estimate the resource potential of each region.

AREAS OF POTENTIAL HYDRATE STABILITY

Few data points over vast areas leads us to calculate areas and thickness of potential hydrate stability, and to combine these estimates with the direct and indirect indications of gas hydrate occurrence, to constrain the volume of gas hydrates and the potential hydrocarbon resource in each of the four geological provinces examined for this study. Our analysis of the gas hydrate stability conditions in marine and permafrost settings is based on:

- an assumption of Type I (methane) hydrate structure,
- temperatures at the base of the marine water column and permafrost layers,
- analysis of the geothermal gradient field, as well as,
- hydrostatic pressure profiles.

Map analysis of these variables allows identification of potential gas hydrate stability regions as a function of pressure and temperature.

The inferred area of gas hydrate stability in the Mackenzie Delta-Beaufort Sea area is estimated to be approximately 124,727 km^2 (Figure 9a-9c) where the hydrate stability zone is between 0.2 km and 1.4 km thick (Figure 10). The inferred area of the potential Type I (methane) gas hydrate stability zone varies considerably as a function of depth and location. The inferred stability zone is drastically reduced in size at depths greater than 1 km (Figure 9c). In permafrost regions the thickness of the inferred stability zone is consistently between 200 m-500 m thick (Figure 10), depending on thermal gradient and pressure. The permafrost layer itself varies in thickness between 100 m and 900 metres. Thus, the inferred hydrate layer in the Mackenzie Delta-Beaufort Sea area tends to occur at greater depths; between 700 m and 1400 m. Throughout the region, the effective average thickness of the gas hydrates inferred from well data is approximately 82 m (Figure 8a).

In the Arctic Archipelago the occurrence of the inferred Type I gas hydrate stability zone occurs inland onshore (Figure 11) and offshore in the deep inter-island channels (Figure 12). Low surface temperatures and a very thick permafrost layer in areas of moderate geothermal gradient (25-35 mK/m) results in a hydrate stability zone that is between 200 m and 2 km thick. Most of the inferred Type I hydrate stability zone below the onshore permafrost layer is between 200 m and 600 m thick. In the deep inter-island channels, low sea bottom temperatures moderate thermal gradients (25-35 mK/m) and high water column pressures result in inferred hydrate stability zone with thicknesses that are less than 1200 m (Figure 12). In the narrow zone between the emergent islands and the deep inter-island channels hydrates are either absent or unstable due to the reduction of pressure accompanying post-glacial coastal emergence (Figure 12). In such settings, the decomposition of unstable hydrates can discharge methane directly to the environment. In the Arctic Archipelago the total inferred area of the hydrate stability zone is estimated to be 766,500 km^2 (Figures 11 and 12) with a mean indicated thickness of 65 m (Figure 8b).

In the offshore areas of the Atlantic and Pacific margins, conditions favorable for the stability of methane hydrates occur over large areas of the continental margin at water depths between 300 m and 2 km (Figures 13, 14). On the Atlantic Margin moderate thermal gradients (~30 mK/m), low sea bottom temperature (-1.8 degrees C - +3 degrees C), and thick water columns contribute to vast regions of potential hydrate stability offshore (Figure 13). The area of inferred methane hydrate stability on the Atlantic Margin is estimated to be 402,000 km^2, while the inferred mean thickness of hydrates of approximately 79 m (Figure 8c; Hyndman, et al., 1994.).

On the Pacific Margin geothermal gradients are generally slightly higher (~35-40 mK/m) than on the Atlantic margin (Hyndman et al., 1992; 1993; Wang et al., 1993). Combined with generally shallower water depths in geologically favorable settings this restricts the region of inferred hydrate stability to a narrow offshore zone (Figure 14). The inferred area of hydrate stability in the Pacific offshore is approximately 29,500 km^2 and the average thickness of hydrates with concentrations in the range of 10-35%, is approximately 110 m (Table 1, Hyndman, 1997).

ESTIMATES OF HYDRATE VOLUME AND METHANE RESOURCES

Well log data of inferred hydrate occurrences from the Arctic regions and Atlantic Margin, and the analysis of BSRs and oceanic drilling program data from the Pacific Margin provide expected hydrate thicknesses (Figure 8) that can combined with the estimated areas of potential Type I gas hydrate stability (Figures 9-14) to provide preliminary estimates of hydrate volumes in the four study regions. The estimates made here assume hydrate concentrations of 20-30% of the available pore volume, following previous studies of offshore hydrates (Yuan, et al., 1994; Yuan et al., 1996). Using simple geological models, we suggest that the porosity in the inferred zone of hydrate stability is between 10-20%. The assumption of pure methane hydrate and hydrostatic pore pressures results in a conservative estimate of potential hydrate volumes.

Higher hydrate volumes than those calculated here would be expected if reservoir pressures are hydrostatic, or if Type II gas hydrate structures are present as a result of the presence of C_2H_6, C_3H_8, CO_2, or H_2S. Conversely, higher than assumed pore water salinity would decrease the thickness of the inferred hydrate layer and reduce estimates of hydrate potential. The description of natural variations in these parameters and their impact on hydrate resources estimates provides opportunities for future research and refinement.

The estimated potential hydrate volumes (m^3) and the estimated potential volume of methane in gas hydrates for each of the four regions studied are given in Table 1. We infer the total hydrate volume in Canadian sedimentary basins to be in the range of 9.4×10^{11} m^3 - 2.9×10^{12} m^3. This suggests an immense inferred potential natural hydrocarbon gas volume. Assuming that 1 m^3 of hydrate releases approximately 160 m^3 of methane (Lewin & Associates, 1983), the amount of methane stored in inferred gas hydrates, we estimate that the natural hydrocarbon gas potential of Canadian hydrates may be in the range of 1.5×10^{14} m^3 - 4.6×10^{14}

m^3. This potential is distributed, 9.3 X 10^{12}-2.7 X 10^{13} m^3 in the Mackenzie Delta-Beaufort Sea, 8.3 X 10^{13}-2.6 X 10^{14} m^3 in the Arctic Archipelago, 5.4 X 10^{13}-1.6 X 10^{14} m^3 on the Atlantic Margin and 3.0 X 10^{12}-9.3 X 10^{12} m^3 on the Pacific Margin (Table 1).

DISCUSSION

The large methane resource, as well as other possible gases, inferred to reside in gas hydrates has the potential to make significant impacts both as an energy resource and as a potential source of natural greenhouse gases. The gas potential of Canadian hydrates, inferred above to be in the range of 1.5 X 10^{14} m^3 - 4.6 X 10^{14} m^3, merits comparison to conventional Canadian hydrocarbon gas resources (Reinson et al., 1993; Osadetz, 1997). Current estimate of Canadian conventional natural gas resources is approximately 2.68 X 10^{13} m^3 gas in-place (Osadetz, 1997). The size of the inferred Canadian gas hydrate resource is illustrated by noting that the conventional raw in-place gas potential of Canada is approximately 150 times current annual production (ibid.), while the in-place gas hydrate resource is in the neighborhood of ten times the conventional natural gas resource. The inferred hydrocarbon gas resource of gas hydrates represents a major potential energy resource for North America.

The very large volume of hydrates inferred can also be compared against previous global estimates of gas hydrate volume (Kvenvolden, 1988b). Current estimates of gas hydrate in oceanic settings varies between 10^{15} m^3 and 10^{18} m^3 (Trofimuk et al., 1977; McIver, 1981; Dobrynin et al., 1981). In continental settings the estimates of hydrate volume are between 10^{13} m^3 and 10^{16} m^3 (Trofimuk et al., 1977; Dobrynin et al., 1981; McIver, 1981; Meyer, 1981). Kvenvolden (1988b) prefers a global estimate of 10^{16} m^3. This estimate is approximately the equivalent of 104 Gt of carbon. It greatly exceeds many other carbon reservoirs on Earth, such as the carbon reservoir in the atmosphere, which is approximately 3.6 Gt (ibid.).

Great as this inferred potential is, several factors are expected to delay the development of gas hydrates as a component of Canadian energy supply. In addition to the technical challenges and costs associated with production, there is competition from conventional and coal-bed methane resources in the Western Canada Sedimentary Basin where transmission infrastructure exists. The construction of transmission infrastructure into frontier regions is expected to focus on the development of established and potential conventional resources prior to the development of gas hydrates.

Canadian methane resources in gas hydrates merit further study. Especially since gas hydrates might be secondary targets geographically associated with conventional resources. Decisions to develop conventional resources would drastically alter the economics of gas hydrate resources. The production history of the Russian Messoyakha gas hydrate field shows that gas can be produced from hydrates, specifically where the reservoir contains a combination of free gas and associated gas hydrates (Makogon, 1981; Collett, 1993). The production of gas from a conventional gas reservoir below a hydrate zone has the potential for a controlled and progressive destabilization of the gas hydrate by reservoir pressure reduction accompanying free gas production. This, in turn, recharges the conventional reservoir from the decomposing gas hydrate. Not uncommonly, gas hydrates overlie, or even seal, conventional hydrocarbon gas pools. Preliminary analysis indicates that similar situations may exist in the MacKenzie Delta-Beaufort Sea region (Figure 15). In this region, most gas hydrate occurrences are associated with major conventional hydrocarbon fields. These relationships recommend such regions for more detailed study of the relationship between free gases and gas hydrates.

The potential impact of gas hydrates on global climate has been considered (Kvenvolden, 1988b; Judge and Majorowicz, 1992). Despite the vast inferred potential resource of gas hydrates, only a fraction would be released into the atmosphere as a result of global temperature increase. Judge and Majorowicz (1992) demonstrated that deeply buried gas hydrates under thick permafrost would take millennia to destabilize as a result of surface temperature increase. Calculations (e.g. Lachenbruch, 1994) show that where hydrates occur below a 600 m thick ice-free permafrost layer, as in parts of the Mackenzie Delta-Beaufort Sea region, a purely conductive warming by 10 degrees C, as might accompany marine transgression, would destabilize the permafrost layer over about a thousand years. Where the permafrost layer contains free ice, a similar warming would take several thousands of years because of the latent heat required to melt the ice (Figure 16).

Simple conductive calculations of temperature change with depth due to surface warming led Nisbet (1990) to hypothesize that the destabilization of gas hydrates and resultant methane release could have established either a positive feedback process following the last Ice Age, or a potential contribution to future global warming. However, it is now widely acknowledged that most onshore and offshore hydrates reach significant gas saturation only at depths approaching one kilometre (Judge and Majorowicz, 1992, Yuan et al, 1996). This restricts the potential for a positive feedback because of the long time interval for diffusive thermal variations. Pressure changes provide a potentially faster mechanism for destabilizing gas hydrates. Pressure variations accompanying changes in sea level and water column thickness, like those accompanying post-glacial isostatic uplift, are a potential destabilizing mechanism. The coastal regions of the Arctic Archipelago are one of the most vulnerable places for such effects. While gas hydrates are likely to remain stable in the deep inter-island waterways, the emergence of islands decreases water column thickness in the shallower parts of these channels, possibly destabilizing gas hydrates.

Ice cap melting would provide another pressure reduction mechanism. Speculatively, the melting of continental ice sheets also reduces pressure. However, the melting of large ice volumes result in relative sea level rise counteracting, to some degree, the impact of melting. Increased water column thickness accompanying coastal transgression increase the stability of the thickest deep marine gas hydrates rather than destablizing them. Therefore we infer that the influence of past, present and future global temperature variations on hydrate stability is small, both because of the thermal inertia of permafrost regions and because of the increased stability of marine hydrates below increased water columns. Arctic coastal regions are the most sensitive to such changes, and some gas release might be expected in those areas. In general, however, most

Canadian gas hydrate accumulations will remain stable and slow, on the time-span of millennia, to respond to climate change.

REFERENCES

Bily, C. and J.W.L. Dick, 1974: Naturally occurring gas hydrates in the Mackenzie Delta, N.W.T. Bulletin of Canadian Petroleum Geology, v. 22, p. 340-352.

Carson, B., Westbrook, G.K., R.J. Musgrave, and others, 1995: Proceedings of the Ocean Drilling Program, Scientific Results, 146 (part 2), College Station, TX (Ocean Drilling Program).

Collett, T.S., 1993: Natural gas hydrates of the Prudhoe Bay and Kuparuk area, North Slope, Alaska. American Association of Petroleum Geologists, Bulletin, v. 5, p.793-812.

Collett, T.S., 1997: Gas hydrate resources of northern Alaska. Bulletin of Canadian Petroleum Geology, v. 43, p. 317-338.

Collett, T.S., K.J. Bird, K. A. Kvenvolden and L.B. Magoon, 1988: Geologic implications relative to gas hydrates within the north slope of Alaska. United States Geological Survey, Open File Report 88- 389, 150 p.

Dallimore, S.R., T. Uchida, and T.S. Collett, 1998: JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well: Overview of Science Program.

Davidson, D. W., M. K. El-Defrawy, M.O. Fuglem and A.S. Judge, 1978: Natural gas hydrates in northern Canada. in: *Proceedings of the Third International Conference on Permafrost*, v. 1, p. 937-943.

Dobrynin, V. M. Yu., P. Korotajev and D. V. Plyuschev, 1981: Gas hydrates: A possible energy resource. in: R.F., Meyer and J.C. Olson eds., *Long Term Energy Resources*. Pitman, Boston, v. 1, p. 727-729.

D&S Petrophysical Consultants, 1983: A study of well logs in the Mackenzie Delta/Beaufort Sea to outline permafrost and gas hydrate occurrence. Earth Physics Branch - Energy Mines and Resources Canada, Open File 83-10.

Hardy and Associates (1978) Ltd., 1984: A study of well logs in the Northwest Territories and Yukon to outline permafrost thickness and gas hydrate occurrence. Earth Physics Branch-Energy Mines and Resources Canada, Open File 84-8.

Heginbottom, J. A., and J-S. Vincent, 1986: Correlation of Quaternary deposits and events around the margin of the Beaufort Sea. Geological Survey of Canada, Open File Report 1237.

Hyndman, R.D., 1992: "Ice" beneath the deep sea: studies of methane hydrate layers beneath the continental slope off Vancouver Island, Geoscience Canada, v. 19, p. 21-26.

Hyndman, R.D., 1996: A review of geoscience studies on the LITHOPROBE corridor across the Vancouver Island continental margin, Candian Journal of Earth Science, v. 32, p. 1777-1802.

Hyndman, R.D., 1997: Quantitative estimates of deep sea gas hydrate and underlying free gas, EOS, v.78, p. 340.

Hyndman, R. D., and E. E. Davis, 1992: A mechanism for the formation of methane hydrate and seafloor bottom-simulating reflectors by vertical fluid flow. Journal of Geophysical Research, v. 97, B5, p. 7025-7041.

Hyndman, R.D., J.P. Foucher, M. Yamano and A. Fisher, 1992: Deep sea bottom-simulating-reflectors: calibration of the base of the stability field as used for heat flow estimates, Earth Planet. Sci. Lett., 109, 289-301.

Hyndman, R. D. and G. D. Spence, 1992: A seismic study of methane hydrate marine bottom simulating reflectors. Journal of Geophysical Research, v.97, B 5, p.6683-6698.

Hyndman, R.D., G.D. Spence, T. Yuan, and E.E. Davis, 1994: Regional geophysics an structural framework of the Vancouver Island margin accretionary prims; in, Proceedings of the Ocean Drilling Program, Initial Reports, 146, College Station, TX, p. 399-419.

Hyndman, R.D., K. Wang, T. Yuan, and G.D. Spence, 1993: Tectonic sediment thickening, fluid expulsion, and the thermal regime of subduction zone accretionary prisms: The Cascadia margin off Vancouver Island, Journal of Geophysical Research, v. 98, p. 21,865-21,876.

Judge, A. S., 1986: Permafrost distribution and the Quaternary history of the Mackenzie-Beaufort Region: A geothermal perspective; in, Heginbottom, J. A., and J-S. Vincent eds., Correlation of Quaternary deposits and events around the margin of the Beaufort-Sea. Geological Survey of Canada, Open File Report 1237, p. 41-45.

Judge, A. S., I. G. Jones and C. F. M. Lewis, 1990: Gas hydrates; in: M. J. Keen & G. L. Williams ed., *Geology of the Continental margin of eastern Canada*, Geological Survey of Canada, Geology of Canada, no. 2, p. 771-774.

Judge, A. S. and J. A. Majorowicz, 1992: Geothermal conditions for gas hydrate stability in the Beaufort-Mackenzie area -- the global change aspect. Paleogeography Paleoclimatology and Paleoecology, Global & Planetary Change Section, v.98, p. 251-263.

Judge, A.S., S.L. Smith and J. A. Majorowicz, 1994: The current distribution and thermal stability of natural gas hydrates in the Canadian Polar margin; in, *Proceedings of the IVth International Offshore and Polar Engineering Conference*. Osaka, The International Society of Offshore Polar Engineering, v. V I, p. 307-314.

Katz, D.L., D. Cornell, R. Kobayashi, F. H. Potteman, J.A. Vary, J. R, Elenbas, and C.F. Weinaug, 1959: *Handbook of Natural Gas Engineering*, McGraw-Hill, New York. 802 p.

Kvenvolden, K.A., 1988a: Methane hydrates and global climate. Global Biochemical Cycle, v.2, no. 3, p. 221-229.

Kvenvolden, K.A., 1988b: Methane hydrate -- A major reservoir of carbon in the shallow geosphere? Chemical Geology, v. 71, p. 41-51.

Kvenvolden, K.A. and M. Kastner, 1990: Gas hydrate of the Peruvian outer continental margin, in, Suess & von Heune, eds., *Ocean Drilling Program Scientific Results*, v. 112, p. 517-526.

Lachenbruch, A.H., 1994: Permafrost, the active layer, and changing climate. United States Geological Survey, Open File Report 94-694, 43 p.

Lewin & Associates, 1983: Handbook of Gas Hydrate Properties and Occurrence. United States Geological Survey Report, DE-AC 21-82-MC19239.

MacKay, M.E., R.D. Jarrard, G.K. Westbrook and R.D. Hyndman, 1994: Origin of bottom-simulating reflectors: Geophysical evidence from the Cascadia accretionary prism, Geology, v. 22, p. 459-462.

Makogon, Yu. F., 1981: *Hydrates of natural gas*. Tulsa, Oklahoma, PennWell Publishing, 237 p.

Makogon, Yu. F., 1982: Perspectives for the development of gas hydrate deposits; in, *Gas Hydrates & Permafrost*. Proceedings of the IVth Canadian Permafrost Conference, p. 299-304.

Makogon, Yu. F., 1988: Natural gas hydrates - the state of study in the U.S.S.R. and perspective for its use. Third Chemical Congress of North America, Toronto, Ont. June 5-10 1988, 18 p.

Majorowicz, J. A., 1998: A constraint to the methane gas hydrate stability from the analysis of thermal data in the Arctic Archipelago; in, A. G. Lewkowicz and M. Allard eds., *Proceedings of the VIIth International Permafrost Conference*. Yellowknife, 23-27 June 1998. Nordicana, Universite Laval, Centre d'etudes nordiques, no. 57, p. 703-710.

Majorowicz, J. A. and A. F. Embry, 1998: Present heat flow and paleo-geothermal regime in the Canadian Arctic margin: analysis of industrial thermal data and coalification gradients. Tectonophysics, v.291, p. 141-159.

Majorowicz, J. A., A. M. Jessop and A. S.Judge , 1995: Geothermal field; in, J. Dixon ed. *Geological Atlas of the Beaufort-Mackenzie*. Geological Survey of Canada, Miscellaneous Report 59, p. 33-37.

McIver, R. D., 1981: Gas hydrates; in, R.F., Meyer and J.C. Olson eds., *Long Term Energy Resources*. Pitman, Boston, v. 1, p. 713-726.

Meyer, R.F., 1981: Speculations on oil and gas resources in small fields and unconventional deposits; in, R.F. Meyer and J. C. Olson eds., *Long Term Energy Resources*. Pitman, Boston, v. 1, p. 49-72.

Nisbet, E. G., 1990, The end of the ice age, Canadian Journal of Earth Sciences, v. 27, 148-157.

Osadetz, K. G. 1997: Natural hydrocarbon gases in Canada: the resource base; in, *Petrochemical '97: Transformation, Growth and Future Direction*. Proceedings of the Canadian Energy Research Institute International Petrochemical Conference, June 1-3, 1997, Kananaskis Village, Alberta, 24 p.

Reinson, G. E., P. J. Lee, J. E. Barclay, T. D. J. Bird, and K. G. Osadetz, 1993: Western Canada basin conventional gas resource estimated at 232 Tcf. Oil and Gas Journal, October 25, 1993, p. 92-95.

Sloan, E. D., 1990: *Clathrate hydrates of natural gases*, Marcel Dekker, New York, 641p.

Smith, S. L. and A. S. Judge, 1993: Gas hydrate database for Canadian Arctic and selected East Coast wells, Geological Survey Canada, Open File Report 2746, 120 p.

Smith, S.L. and A.S. Judge, 1995: Estimate of methane hydrate volumes in the Beaufort Mackenzie region, Northwest Territories; in, *Current Research 1995, Part B,* Geological Survey of Canada, p. 81-88.

Spence, G.D., T.A. Minshull, and C. Fink, 1996. Seismic studies of methane gas hydrate offshore Vancouver Island, in, Proceedings of the Ocean Drilling Program, Scientific Results, 146 (part 2), College Station, TX, 163-174.

Taylor, A. E., 1991: Marine transgression, shoreline emergence: evidence in seabed and terrestrial ground temperatures of changing relative sea levels Arctic Canada. Journal of Geophysical Research, v. 96, p. 6893-6909.

Taylor, A. E., R. J. Wetmiller and A.S. Judge, 1979: Two risks to drilling and production off the east coast of Canada -- earthquakes and gas hydrates; in, W. Denver (ed.) *Symposium on Research in the Labrador Coastal and Offshore Region.* Memorial University of Newfoundland, St. Johns, p. 91-105.

Thurber Consultants, 1986: Study of well logs in the Mackenzie Delta/Beaufort Sea area and Arctic Islands to outline permafrost thickness and/or gas hydrate occurrence: an update of wells, Department of Supply and Services, Canada, File 15SQ.23235-5-1145, 19p.

Thurber Consultants., 1988: Update of well log studies Mackenzie Delta/ Beaufort Sea area, Arctic Islands and Offshore East Coast, v. 1, Arctic Canada. Department of Supply and Services, Canada File 69SZ.23233-7-0925, 19 p.

Trofimuk, A. A., N. V. Cherskiy and V.P. Tsarev, 1977: The role of continental glaciation and hydrate formation on petroleum occurrences; in, R. F. Meyer ed., *Future Supply of Nature Made Petroleum and Gas*, Pergamon, New York, 919-926.

Wang, K., R.D. Hyndman, and E.E. Davis, 1993: Thermal effects of sediment thickening and fluid expulsion in accretionary prisms: Model and parameter analysis, Journal of Geophysical Research, v. 98, p. 9,975-9,984.

Weaver, J. S. and J. M. Stewart, 1982: In-situ hydrates under the Beaufort Sea Shelf; in, M. H. French (ed.), *Roger J. E. Brown Memorial Volume.* Proceedings of the Fourth Canadian Permafrost Conference, 1981, National Research Council of Canada, p. 312-319.

Westbrook, G.K., B. Carson, R.J. Musgrave, et al., Proc. of the ODP, Initial Reports, 146 (part 1), College Station, TX (Ocean Drilling Program), 1994.

Yuan, T., R. D. Hyndman, G. D. Spence and B. Desmons, 1996. Seismic velocity increase and deep-sea gas hydrate concentration above a bottom simulating reflector on the northern Cascadia continental slope. Journal of Geophysical Research, v. 101, B6, p. 13,655-13,671.

Yuan, T., G.D. Spence, and R.D. Hyndman, 1994: Seismic velocities and inferred porosities in the accretionary wedge sediments at the Cascadia margin, Journal of Geophysical Research, v. 99, p. 4,413-4,427.

FIGURE CAPTIONS

Figure 1. a) Example of the determination of the depth interval of methane gas hydrate stability from an Arctic well, Panarctic Hecla J-60, in the Melville Island area, N.W.T. The gas hydrate stability curve and the temperature profiles intersect in the depth interval highlighted by the arrows. The base of ice bearing permafrost is shown by the dashed horizontal line, as inferred from geophysical logs. The temperature at the base of the ice bearing permafrost layer is -1 degree C. The base of hydrate stability zone occurs at the point of intersection of the methane hydrate stability (phase change) curve and the temperature profile. The methane hydrate stability field is to the left of the phase boundary curve and the free gas stability field is to the right. b) Examples of different depth-temperature zones in which gas hydrates are stable onshore in a permafrost region and offshore on a continental margin (in part after Collett, 1997)

Figure 2. Example calculations of the depth to the base of methane hydrate stability zone (indicated by arrows) as a function of geothermal gradient for a water column of 1 km and a sea bottom temperature of +3 degrees C. Examples are shown for geothermal gradients of, 45 mK/m, 35 mK/m and 25 mK/m.

Figure 3. An illustration of the influence of the water depth on methane hydrate stability zone thickness for water column thicknesses of, 0.75km, 1.5km, 2km.

Figure 4. Calculated potential methane hydrate stability zone thickness with a 1km thick water column as a function of geothermal gradient for cold, -1 degree C, and warm, +3 degree C, sea bottom temperatures.

Figure 5. Methane hydrate stability zone thickness as a function of water column thickness for a geothermal gradient of 30 mK/m with sea bottom temperatures of either -1 degree C or +3 degree C.

Figure 6. Methane hydrate thermal stability illustrated by the depth to the base of stable hydrate, as a function of both water depth and geothermal gradient, in the sediments below a sea bottom with a temperature of -1 degree C.

Figure 7. Probable gas hydrate occurrences inferred from well logs in, a) the Mackenzie Delta Beaufort Sea, b) the Canadian Arctic Archipelago, and c) on the Atlantic Margin (modified from Judge, Jones and Lewis, 1990 and Judge, Smith and Majorowicz, 1994).

Figure 8. Histograms illustrating the thickness of gas hydrate zones inferred from wells in, a) the Mackenzie Delta Beaufort Sea, b) the Canadian Arctic Archipelago, and c) on the Atlantic Margin, for map area shown in Figure 7a-7c, respectively.

Figure 9. Region of methane hydrate stability in the Mackenzie Delta-Beaufort Sea region at depths of, a) -800 m, b) -1000 m and c) -1200 m. Notice the progressive decrease of the potential area of hydrate stability with increasing depth.

Figure 10. Calculated depth of the base of the methane hydrate stability zone in the Mackenzie Delta-Beaufort Sea region.

Figure 11. Calculated depth of the base of the methane hydrate stability zone onshore in the Canadian Arctic Archipelago.

Figure 12 Calculated depth of the base of the methane hydrate stability zone in the inter-island waterways of the Canadian Arctic Archipelago.

Figure 13. Area of potential methane hydrate stability on the Atlantic Margin of Canada.

Figure 14. Area of potential methane hydrate stability on the Pacific Margin of Canada.

Figure 15. Comparison of gas hydrate occurrences to the locaton of significant conventional hydrocarbon discoveries in the Mackenzie Delta-Beaufort Sea region.

Figure 16. Calculated times, 5,000 and 30,000 years respectively, to destabilize all methane hydrates in a permafrost layer. Two examples are shown. The upper illustration is for a 400 m thick ice-free permafrost layer. The lower illustration is for a 600 m thick ice-bearing permafrost layer. Surface warming of 10 K was assumed in both models. The lower figure also illustrates the effect of the latent heat effect required to melt ice-bearing permafrost.

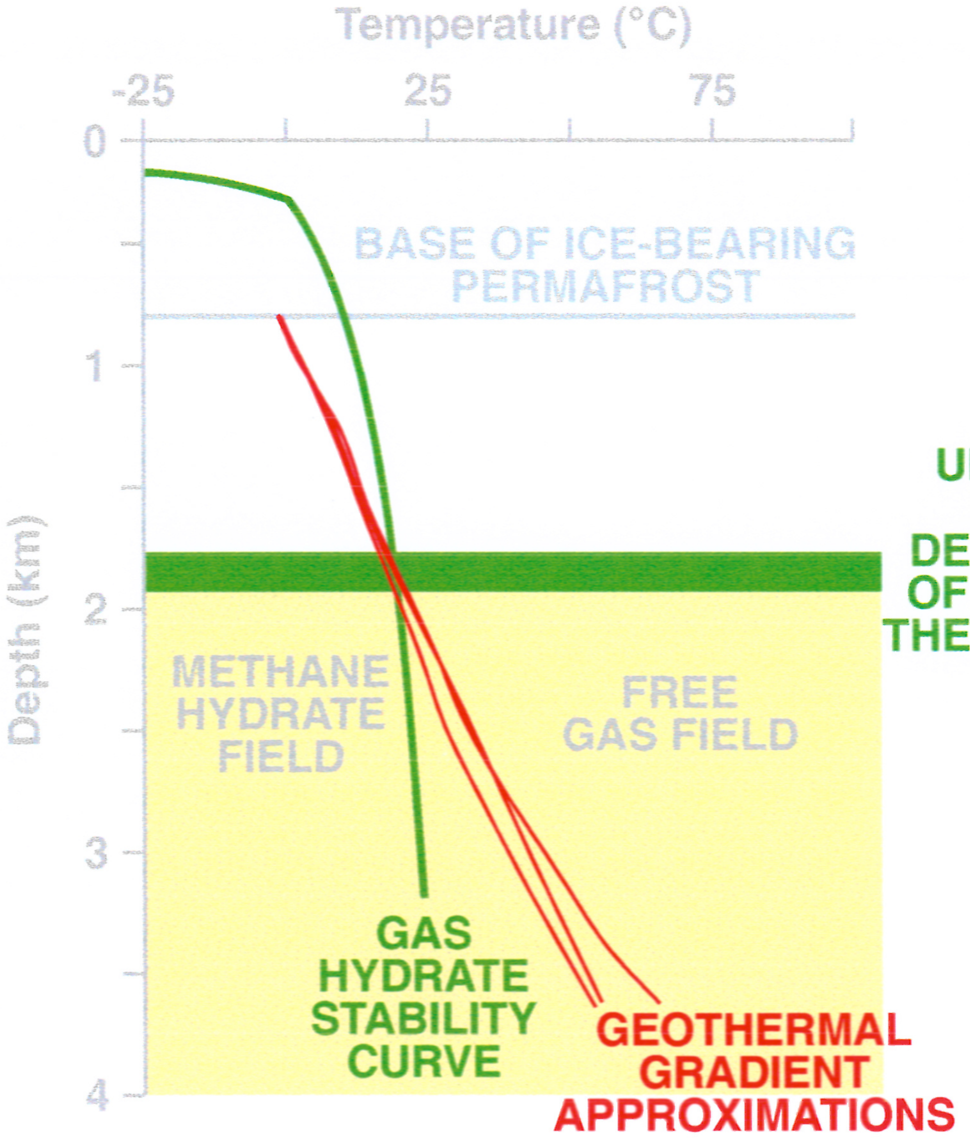
TABLE 1: Preliminary estimates of Canadian natural gas resources in gas hydrates.

REGION	AREA (km^2)	THICKNESS (km)	VOLUME OCCUPIED (%)	POROSITY (%)	HYDRATE CONCENTRATION (%)	METHANE VOLUME (m^3)
Mackenzie Delta and Beaufort Sea	124,727	0.082	29	10-20	20-30	$9.3*10^{12}$-$2.7*10^{13}$
Arctic Archipelago	766,500	0.065	52	10-20	20-30	$8.3*10^{13}$-$2.6*10^{14}$
Atlantic Margin	402,000	0.079	54	10-20	20-30	$5.4*10^{13}$-$1.6*10^{14}$
Pacific Margin	29,500	0.110	30	10-20	20-30	$3.0*10^{12}$-$9.3*10^{12}$
Canada (Total)						$1.5*10^{14}$-$4.6*10^{14}$

EXAMPLE DETERMINATION OF THE METHANE HYDRATE STABILITY DEPTH INTERVAL

Well: Panarctic Hecla J-60

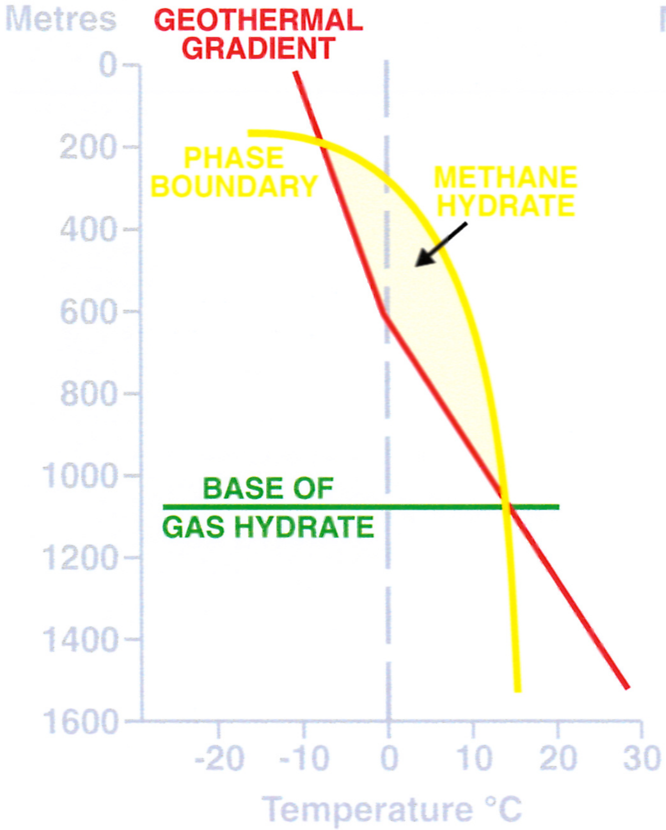
Base of Permafrost Layer: -1°C



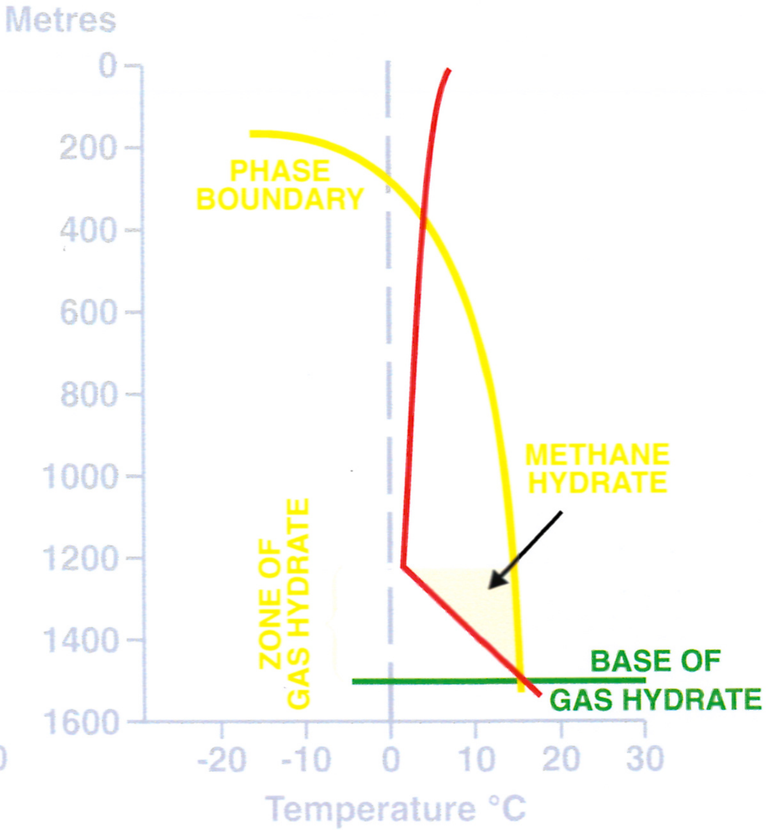
UNCERTAINTY IN THE DETERMINATION OF THE BASE OF THE GAS HYDRATE ZONE

EXAMPLES OF DIFFERENT DEPTH-TEMPERATURE ZONES IN WHICH GAS HYDRATES ARE STABLE

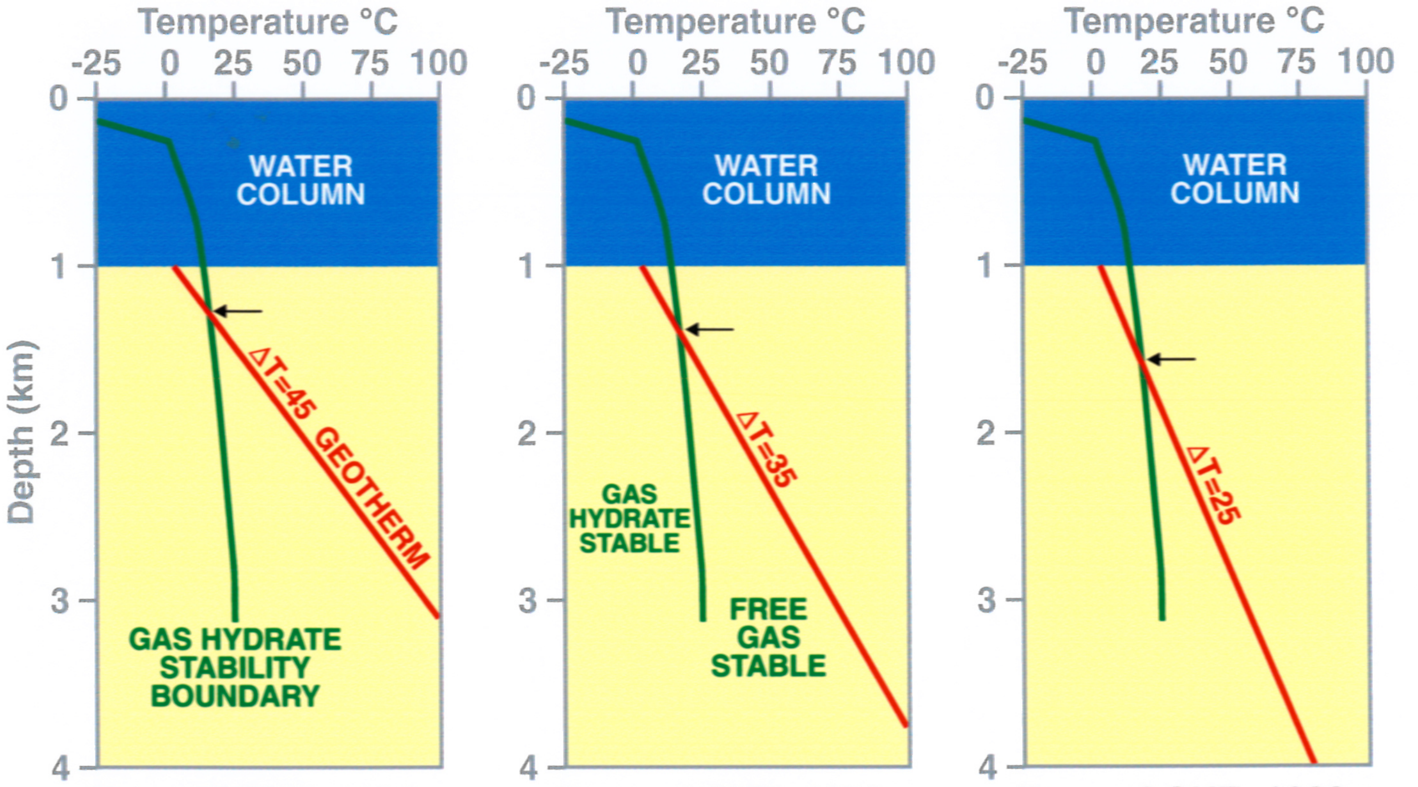
PERMAFROST REGION



OFFSHORE CONTINENTAL MARGIN



CHANGES IN THE DEPTH OF THE BASE OF THE GAS HYDRATE ZONE AS A FUNCTION OF THERMAL GRADIENT

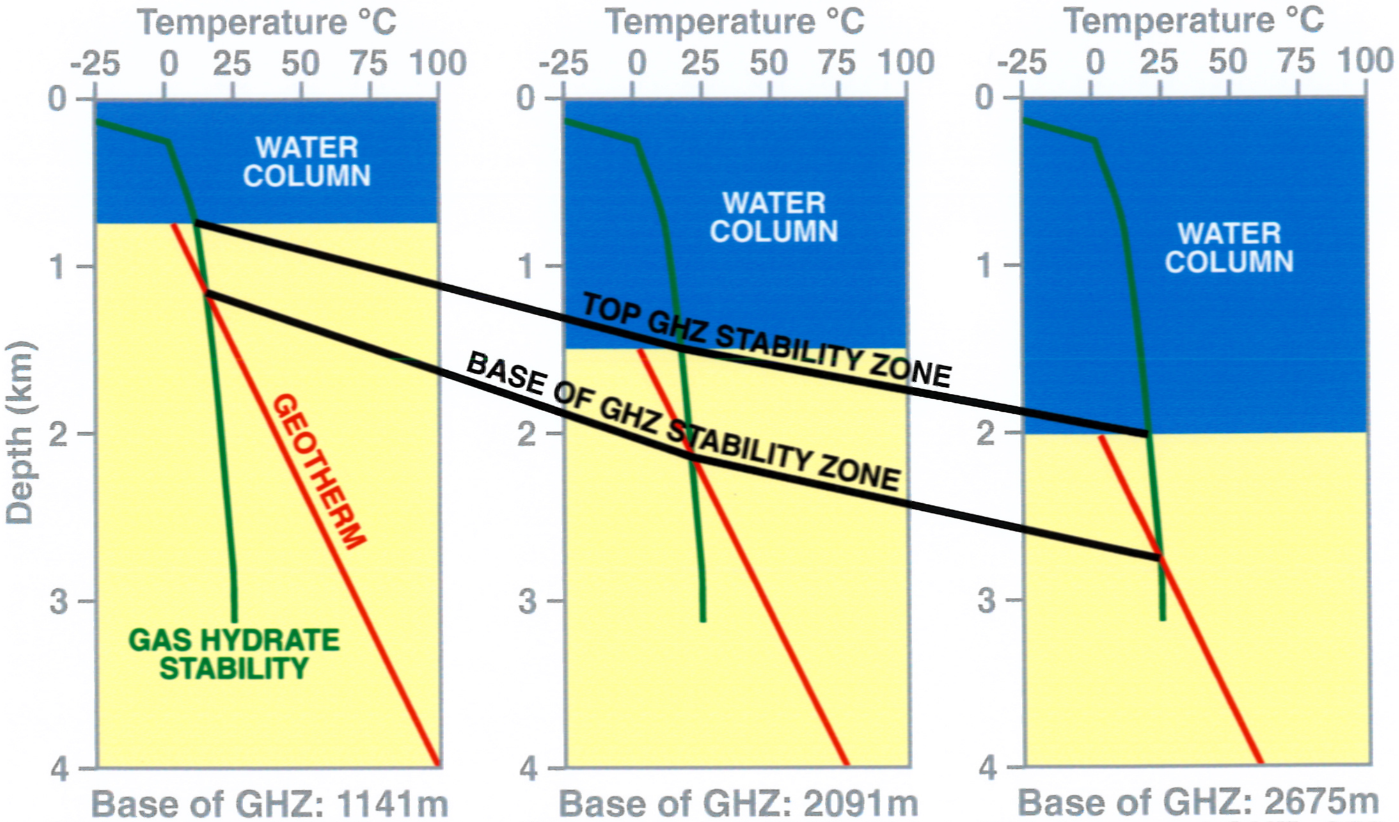


Base of GHZ: 1207m
Thickness of GHZ: 207m

Base of GHZ: 1350m
Thickness of GHZ: 350m

Base of GHZ: 1603m
Thickness of GHZ: 603m

INFLUENCE OF WATER COLUMN THICKNESS ON GAS HYDRATE STABILITY ZONE THICKNESS

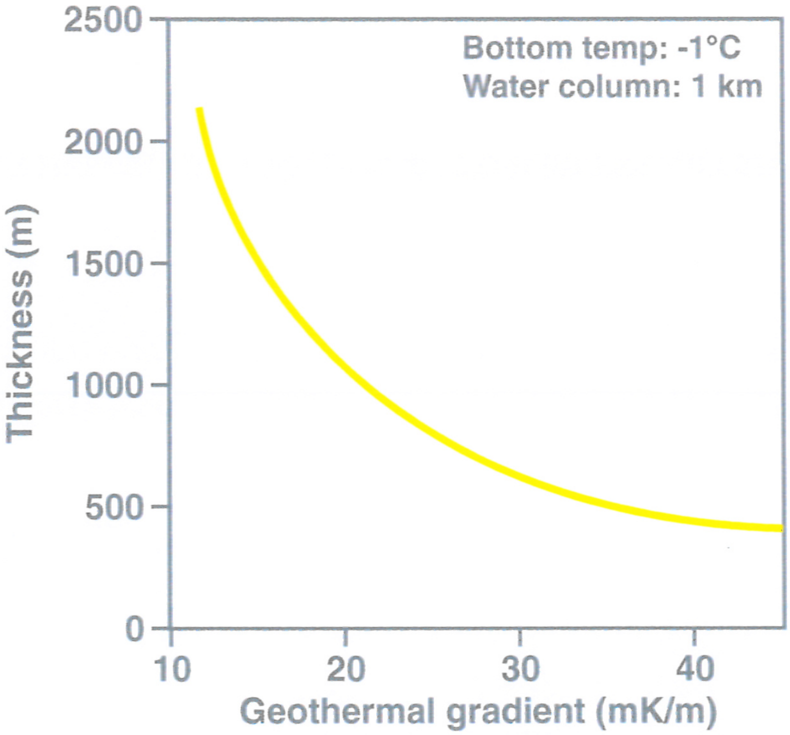


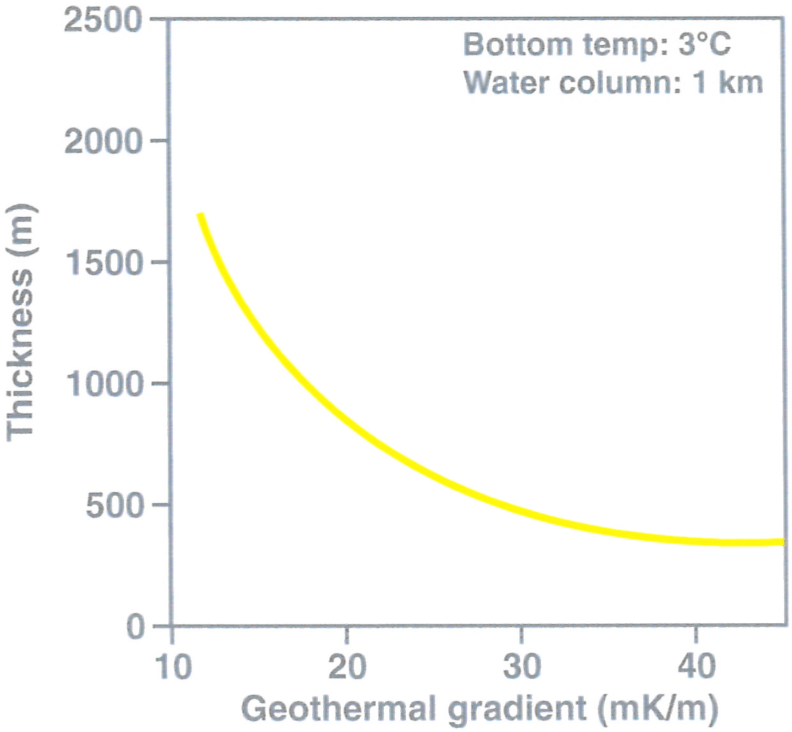
Base of GHZ: 1141m
Thickness of GHZ: 391m

Base of GHZ: 2091m
Thickness of GHZ: 591m

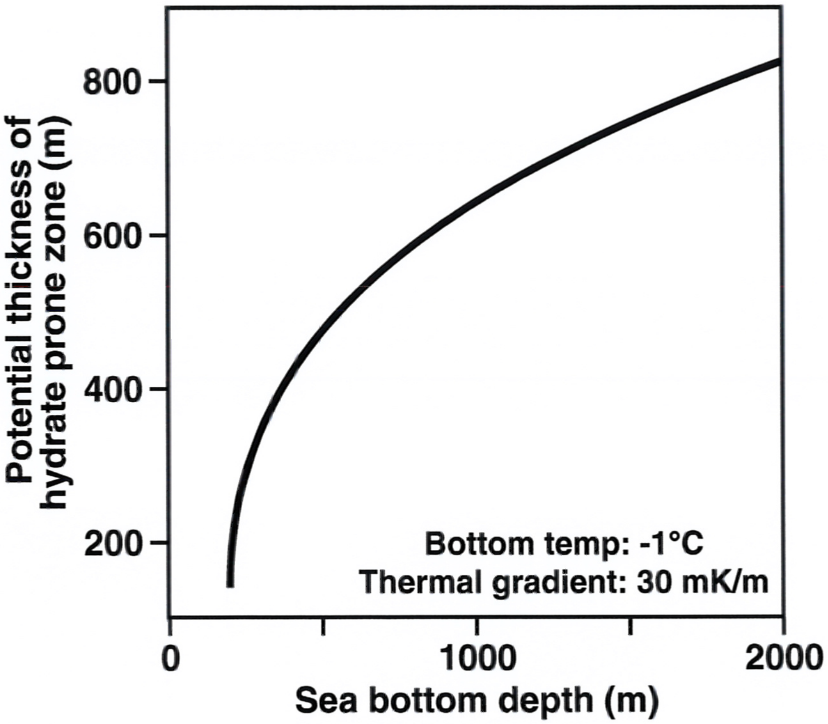
Base of GHZ: 2675m
Thickness of GHZ: 675m

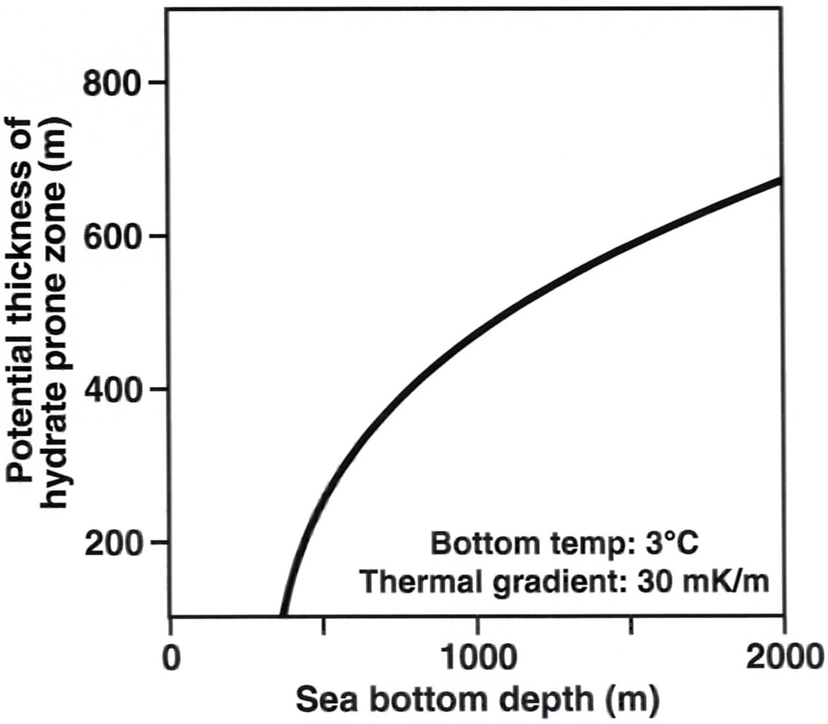
POTENTIAL THICKNESS OF METHANE GAS HYDRATE



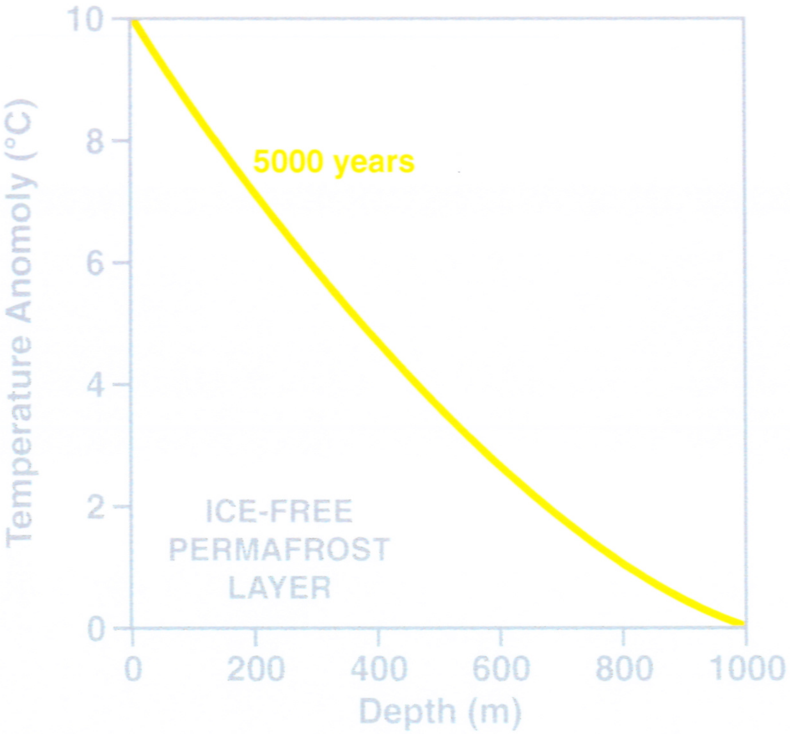


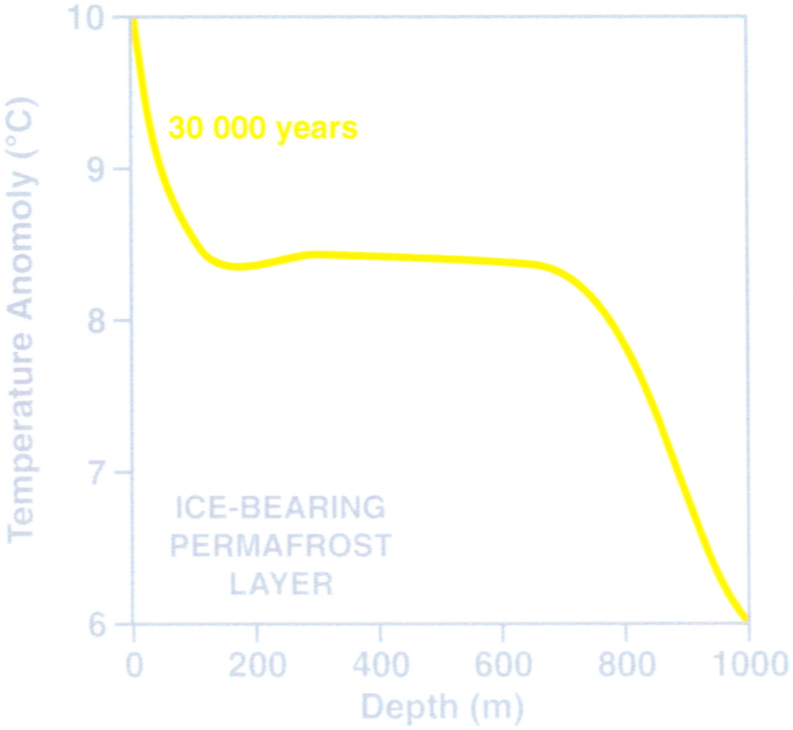
POTENTIAL THICKNESS OF THE GAS HYDRATE STABILITY ZONE AS A FUNCTION OF WATER COLUMN THICKNESS



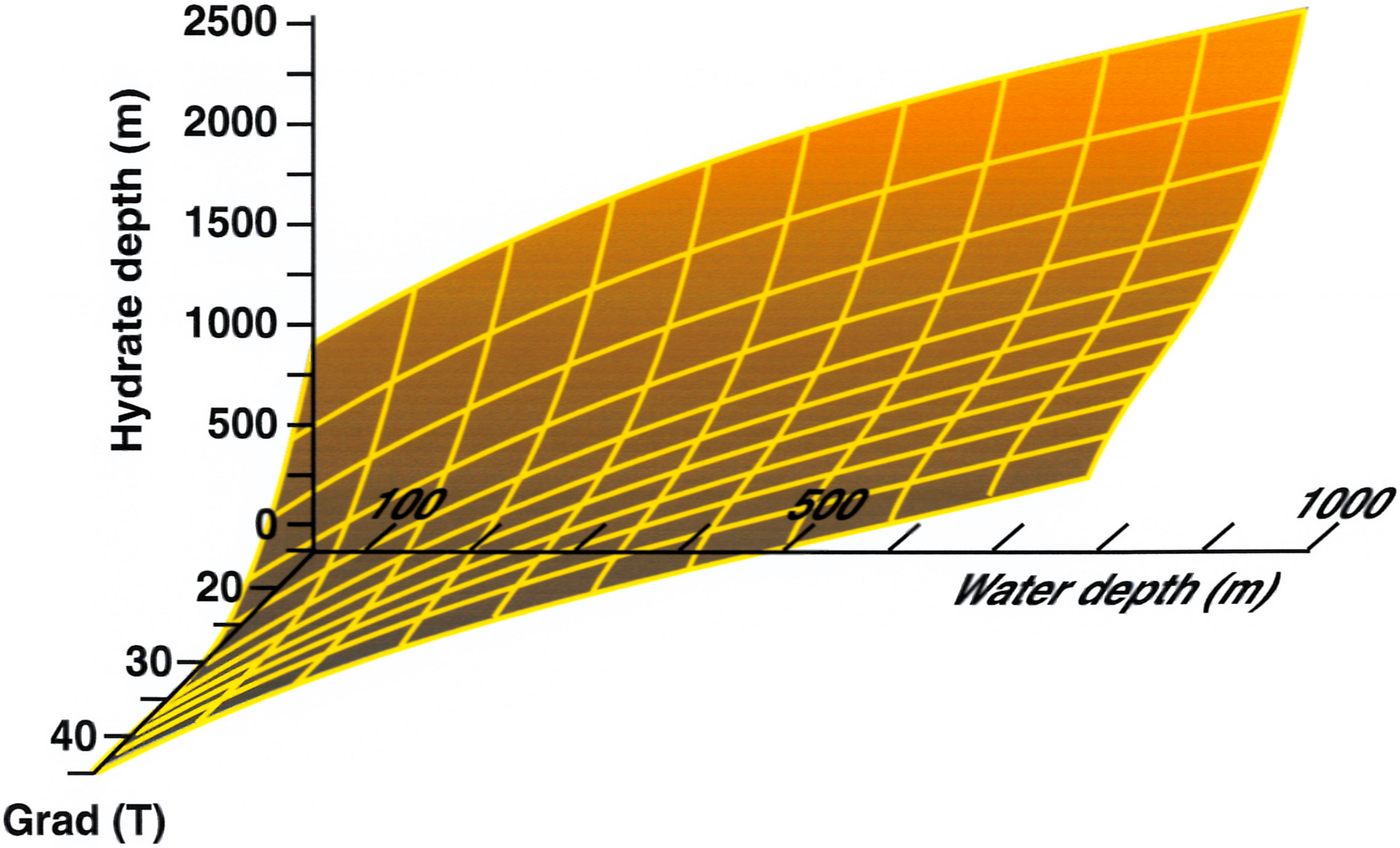


GAS HYDRATE DESTABILIZATION MODELS FOR 10°C SURFACE WARMING

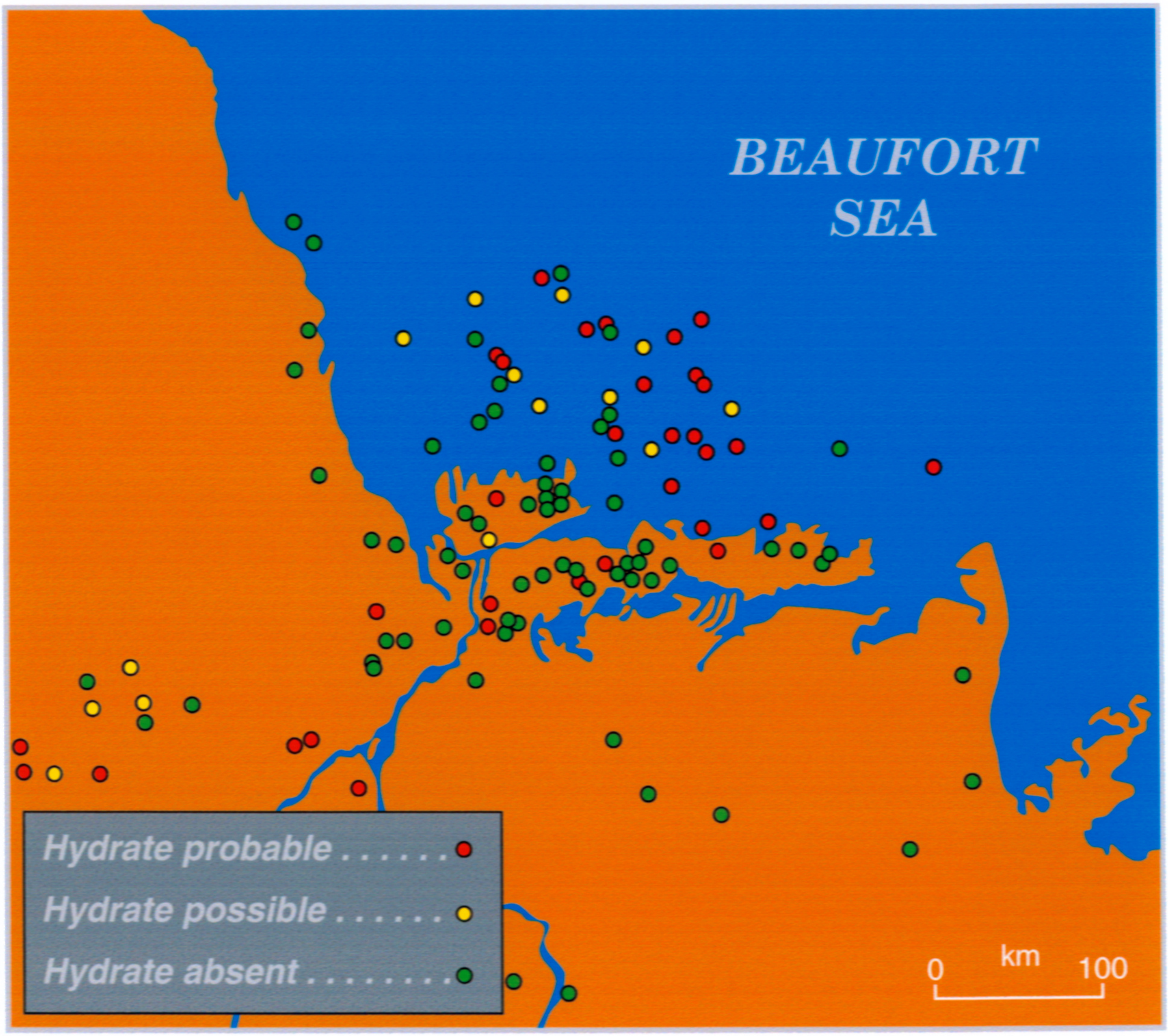




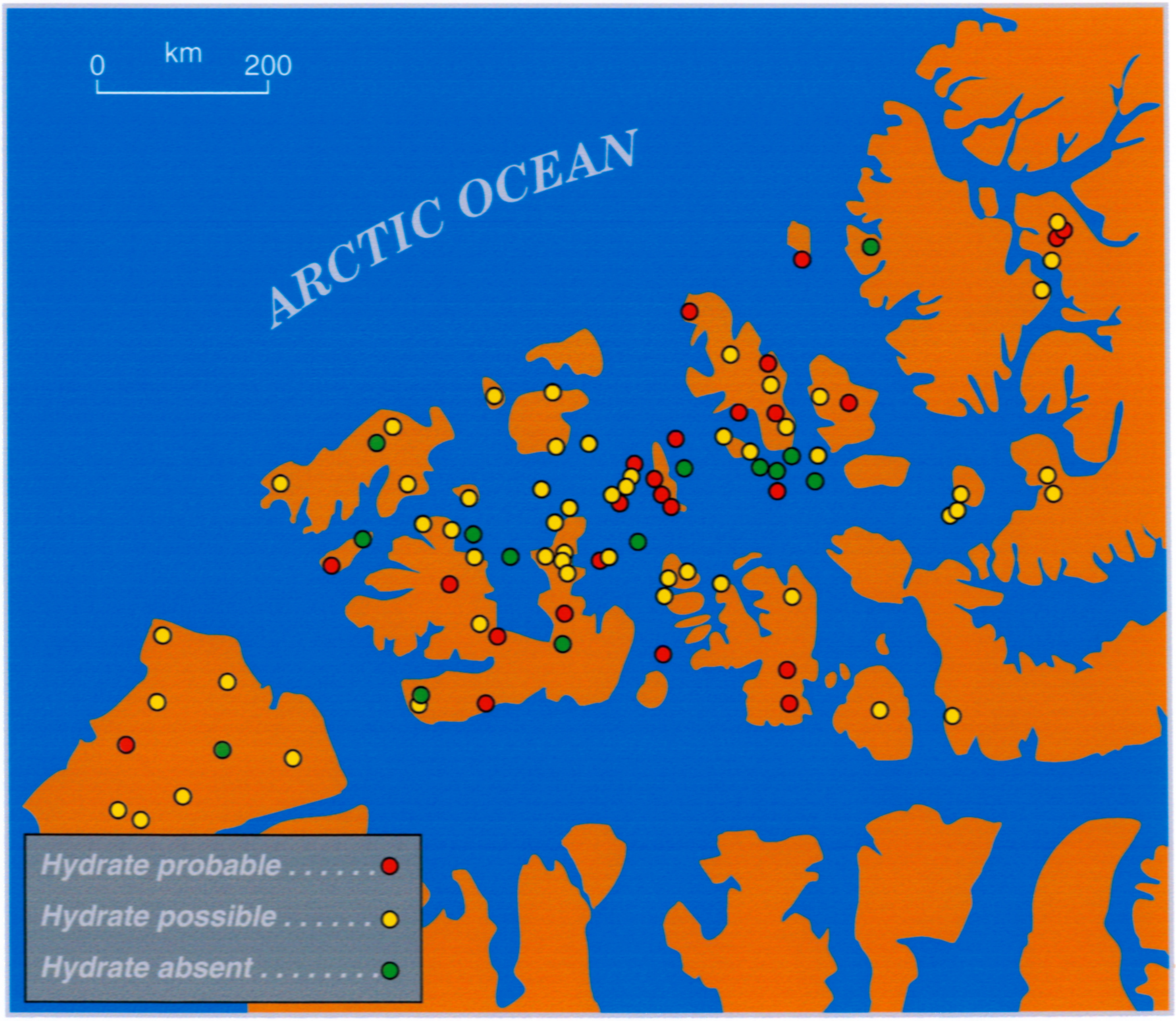
METHANE HYDRATE THERMAL STABILITY



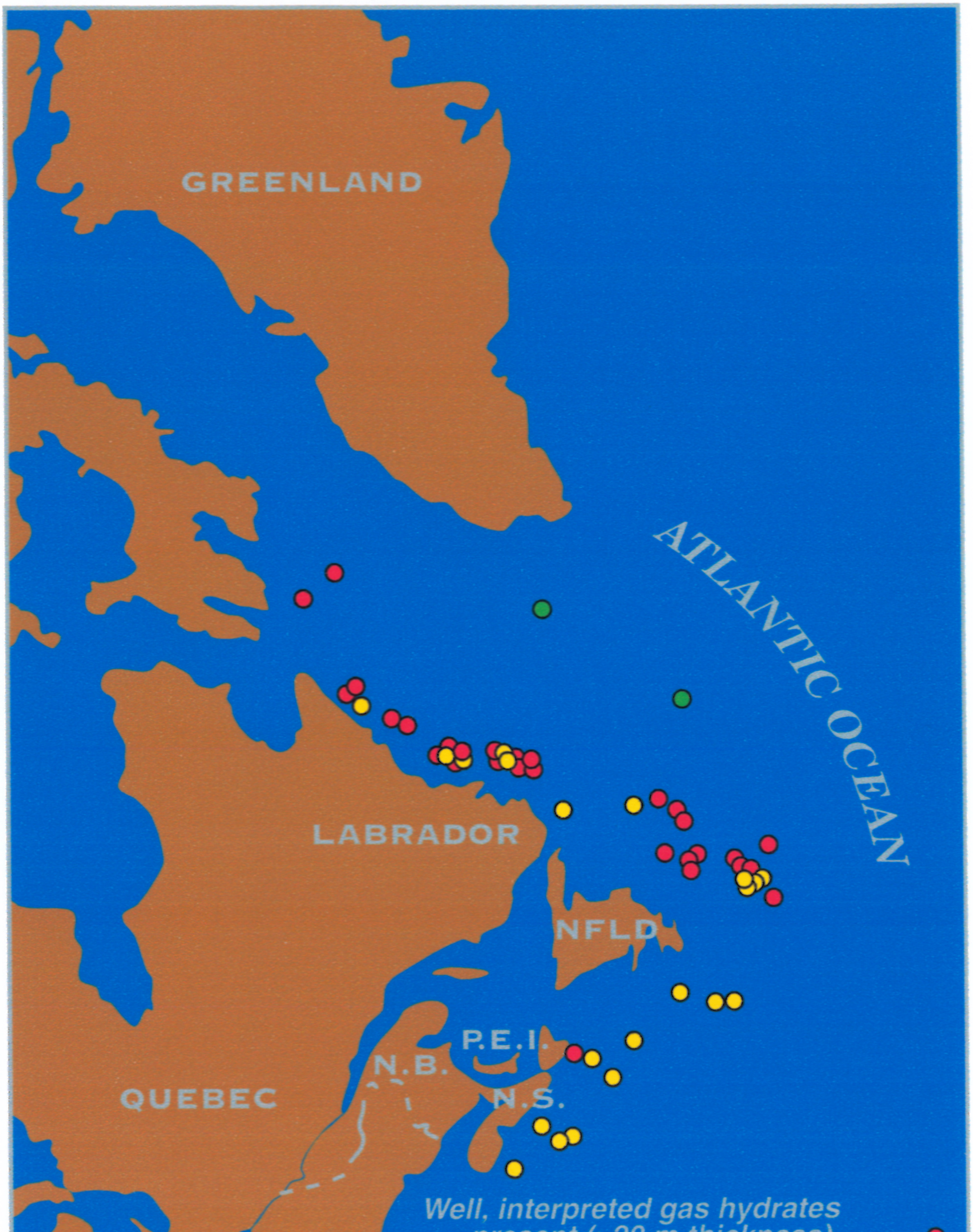
GAS HYDRATE OCCURRENCES IN THE MACKENZIE DELTA-BEAUFORT SEA REGION



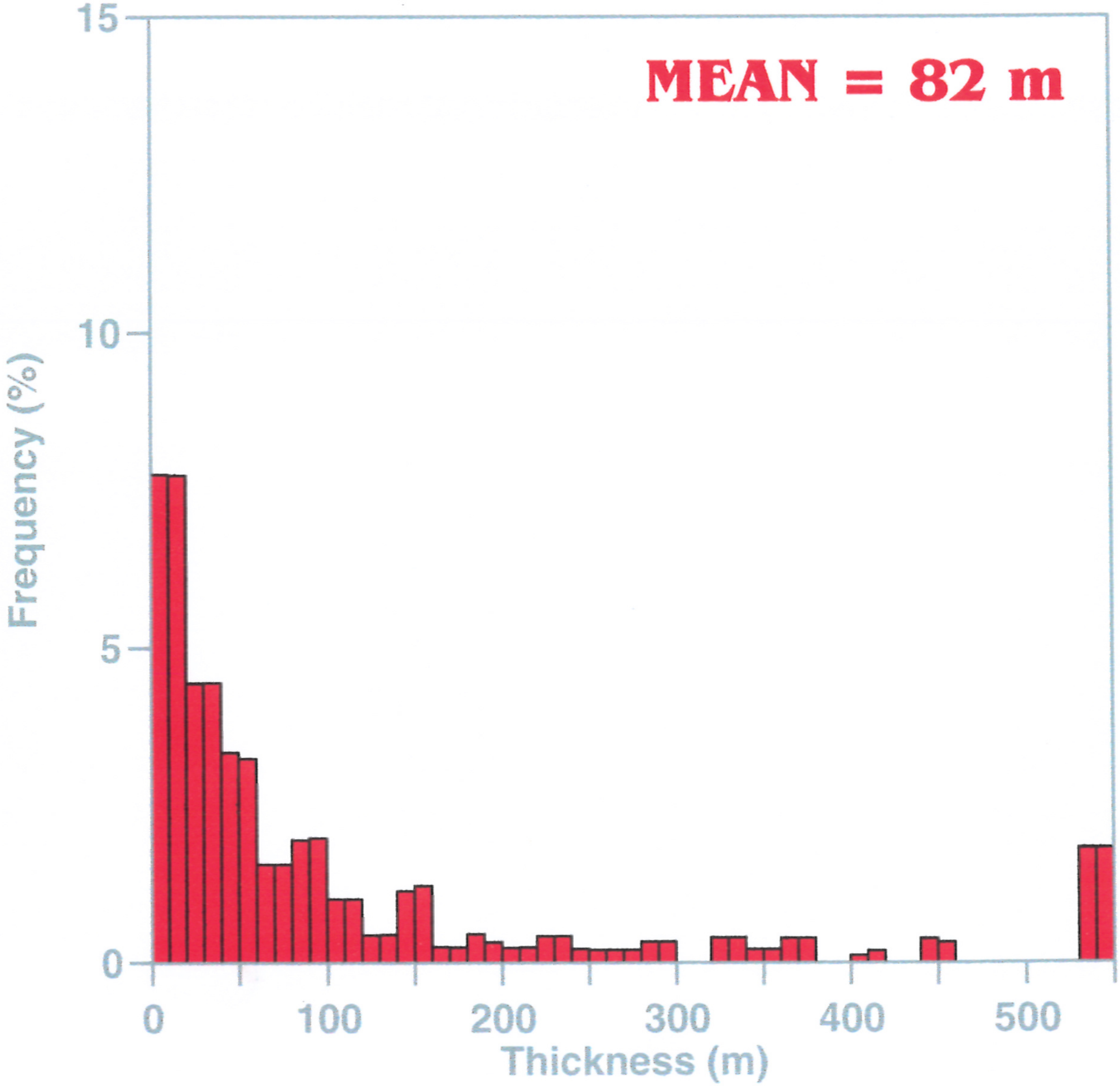
GAS HYDRATE OCCURRENCES IN THE CANADIAN ARCTIC ARCHIPELAGO



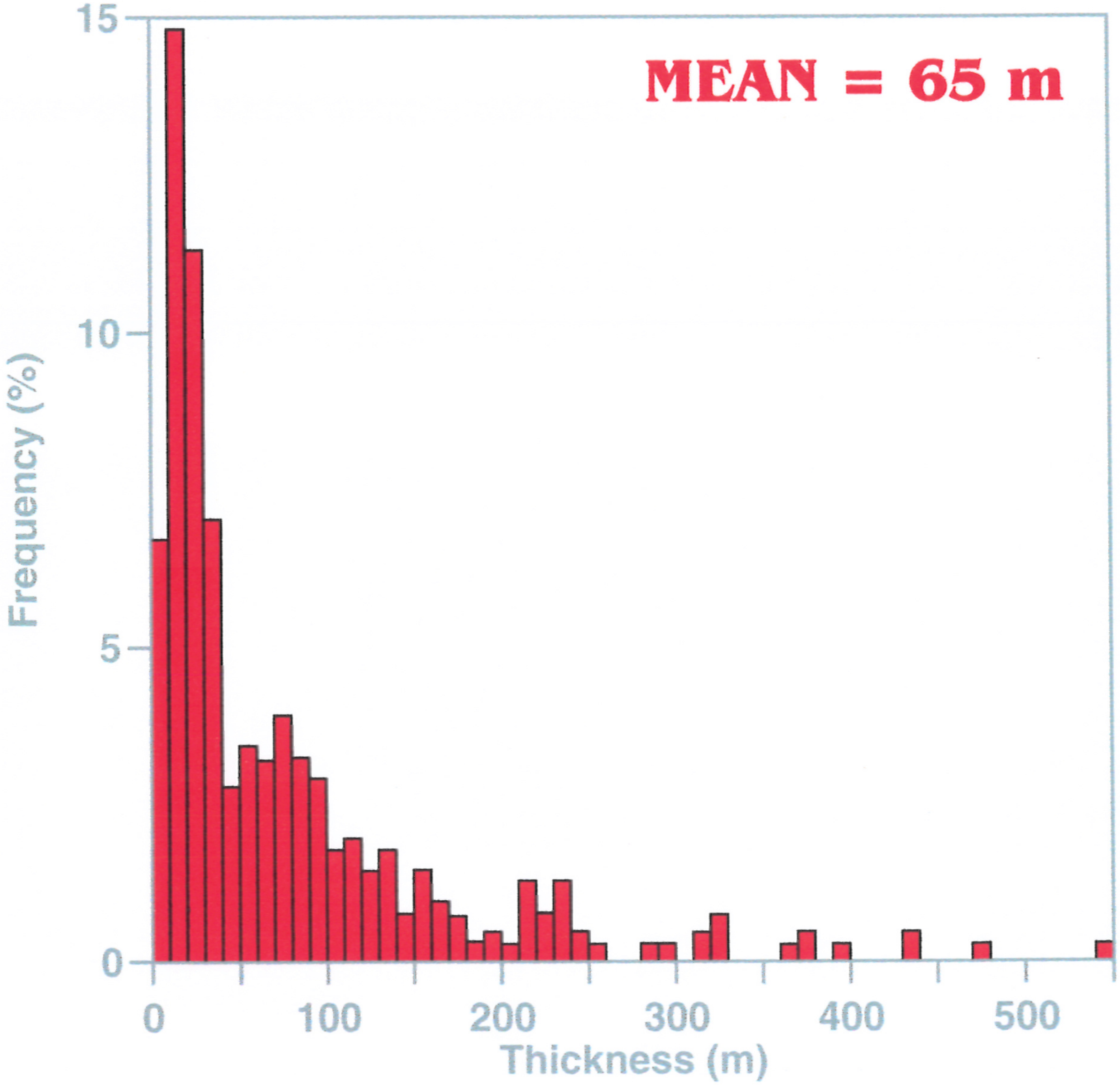
GAS HYDRATE OCCURRENCES ON THE ATLANTIC MARGIN OF CANADA



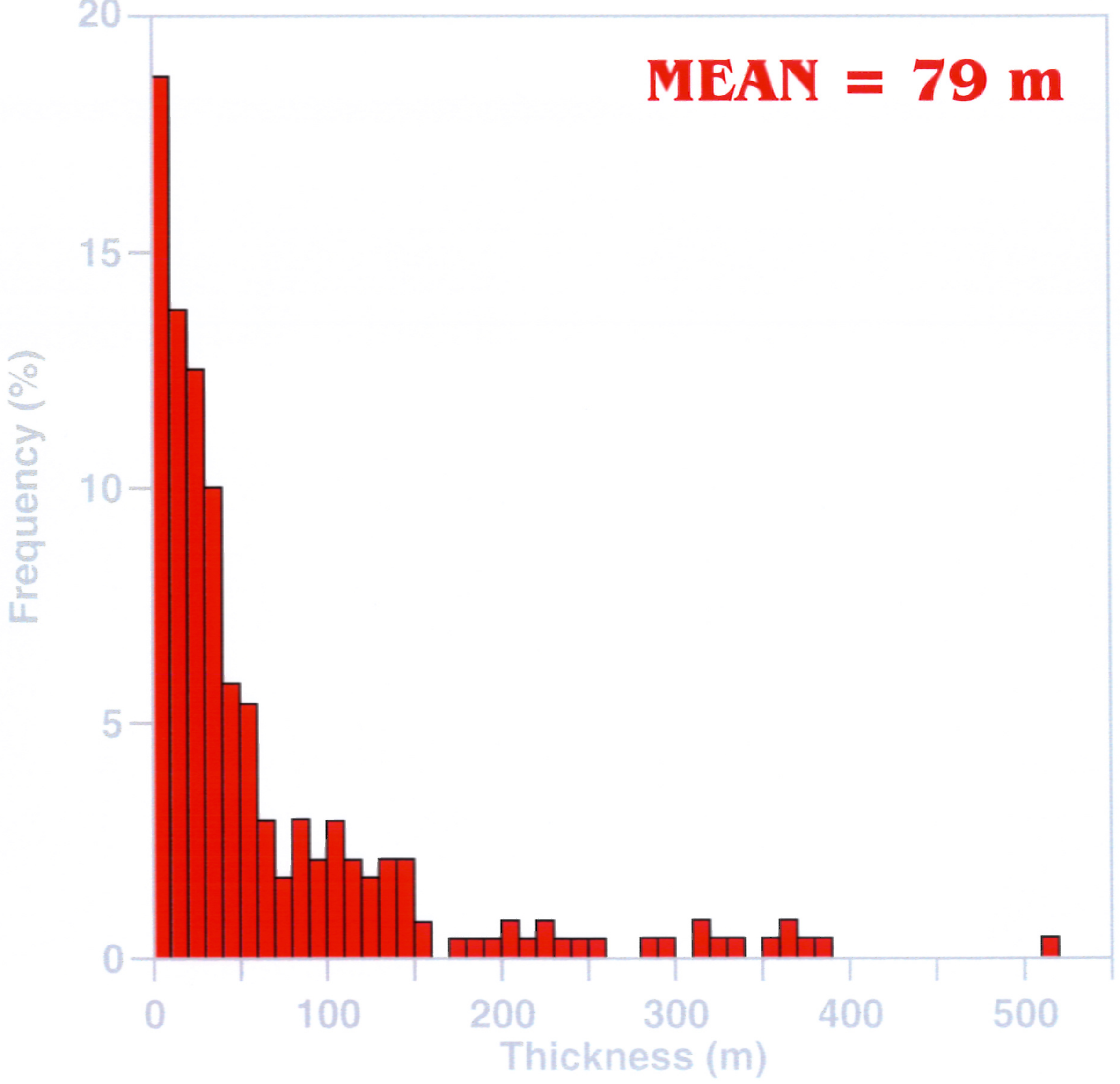
INTERPRETED THICKNESS OF GAS HYDRATE OCCURRENCES IN THE MACKENZIE DELTA-BEAUFORT SEA REGION



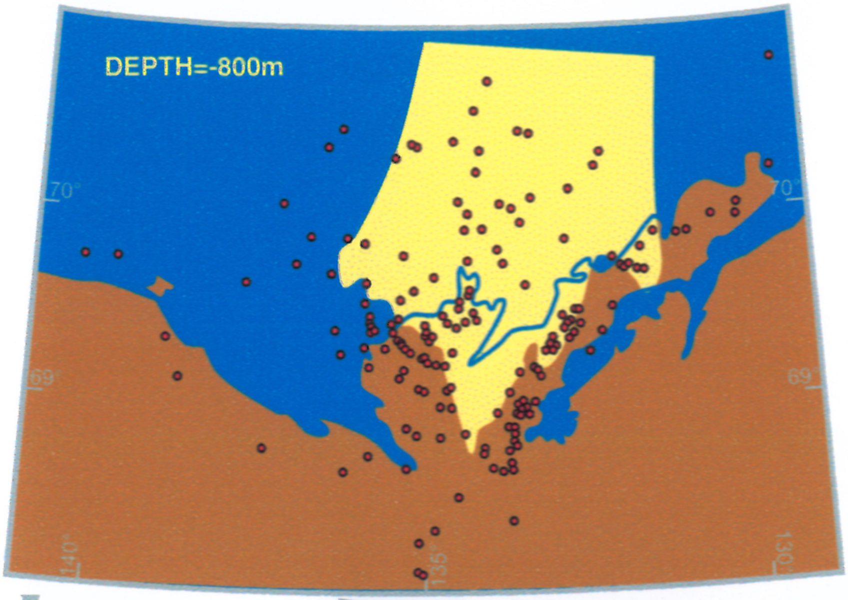
INTERPRETED THICKNESS OF GAS HYDRATES IN THE ARCTIC ARCHIPELAGO



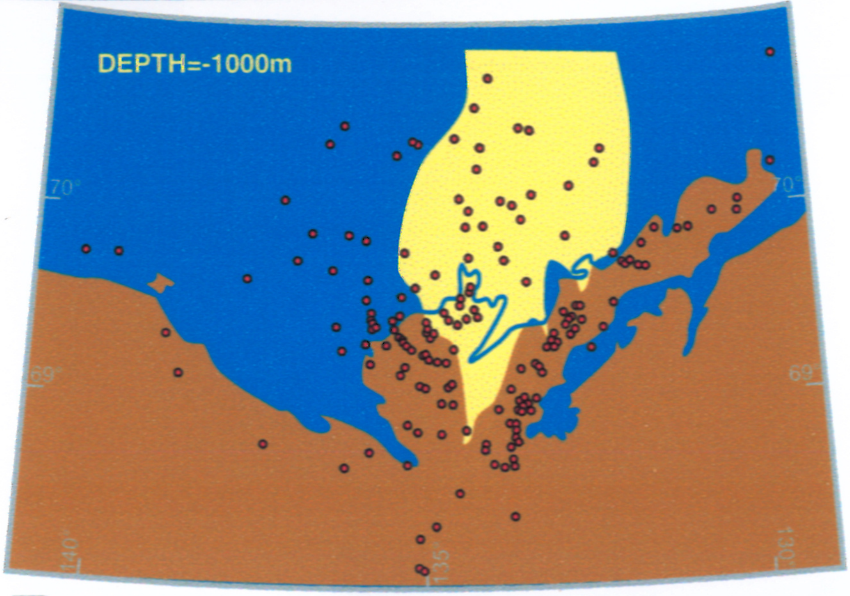
INTERPRETED THICKNESS OF GAS HYDRATES ON CANADA'S ATLANTIC MARGIN



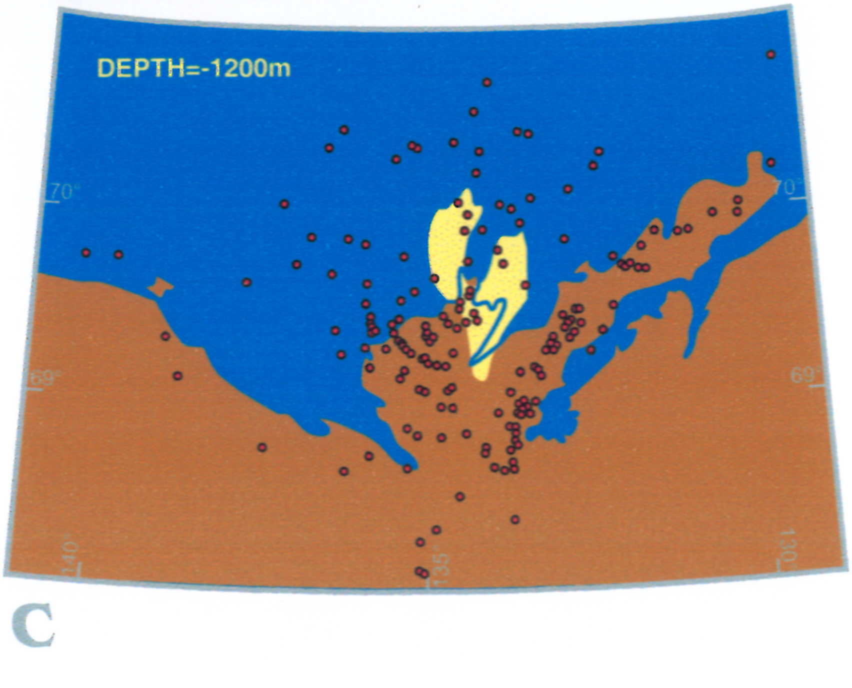
REGION OF HYDRATE STABILITY IN THE MACKENZIE DELTA-BEAUFORT SEA REGION



A

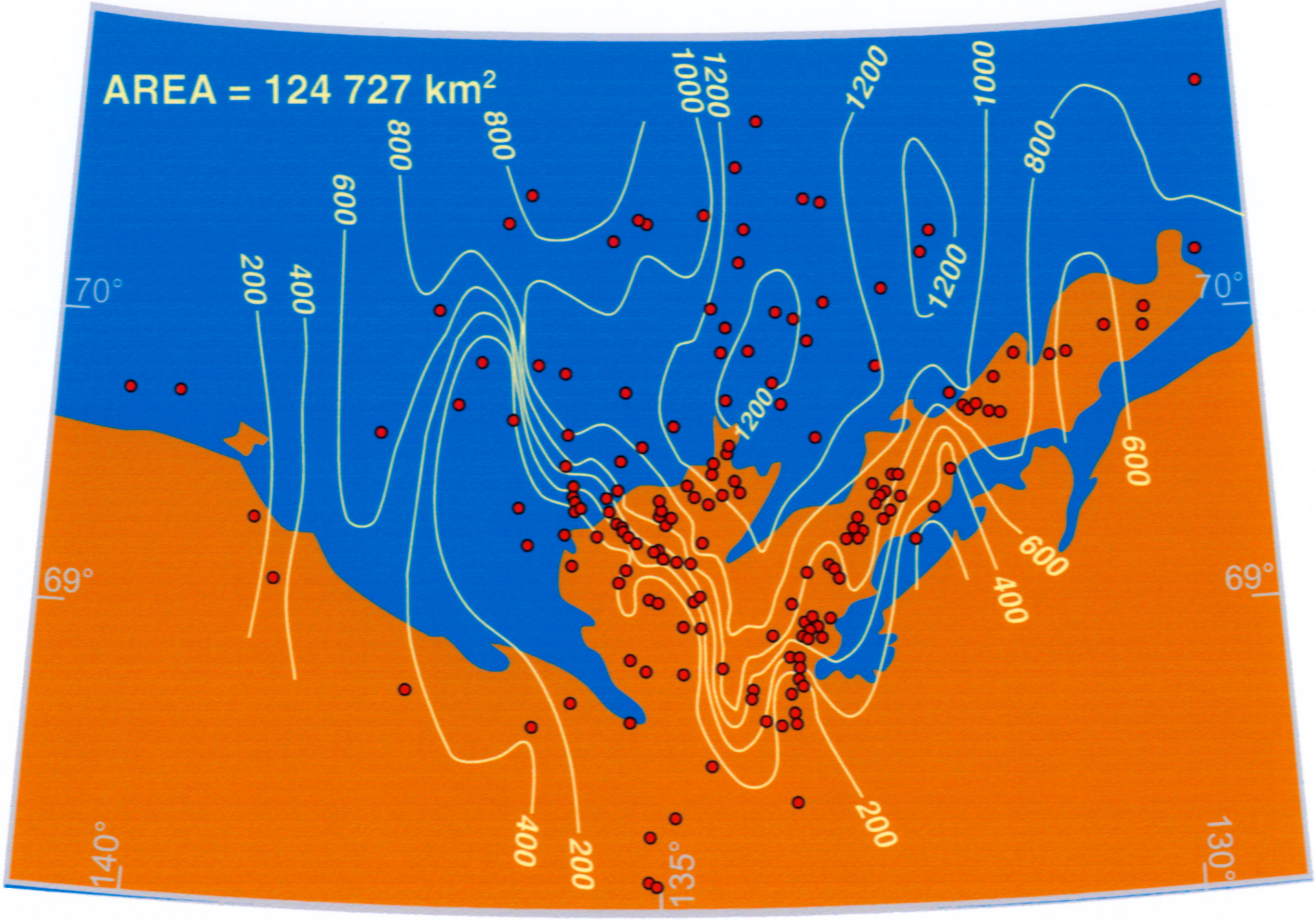


B

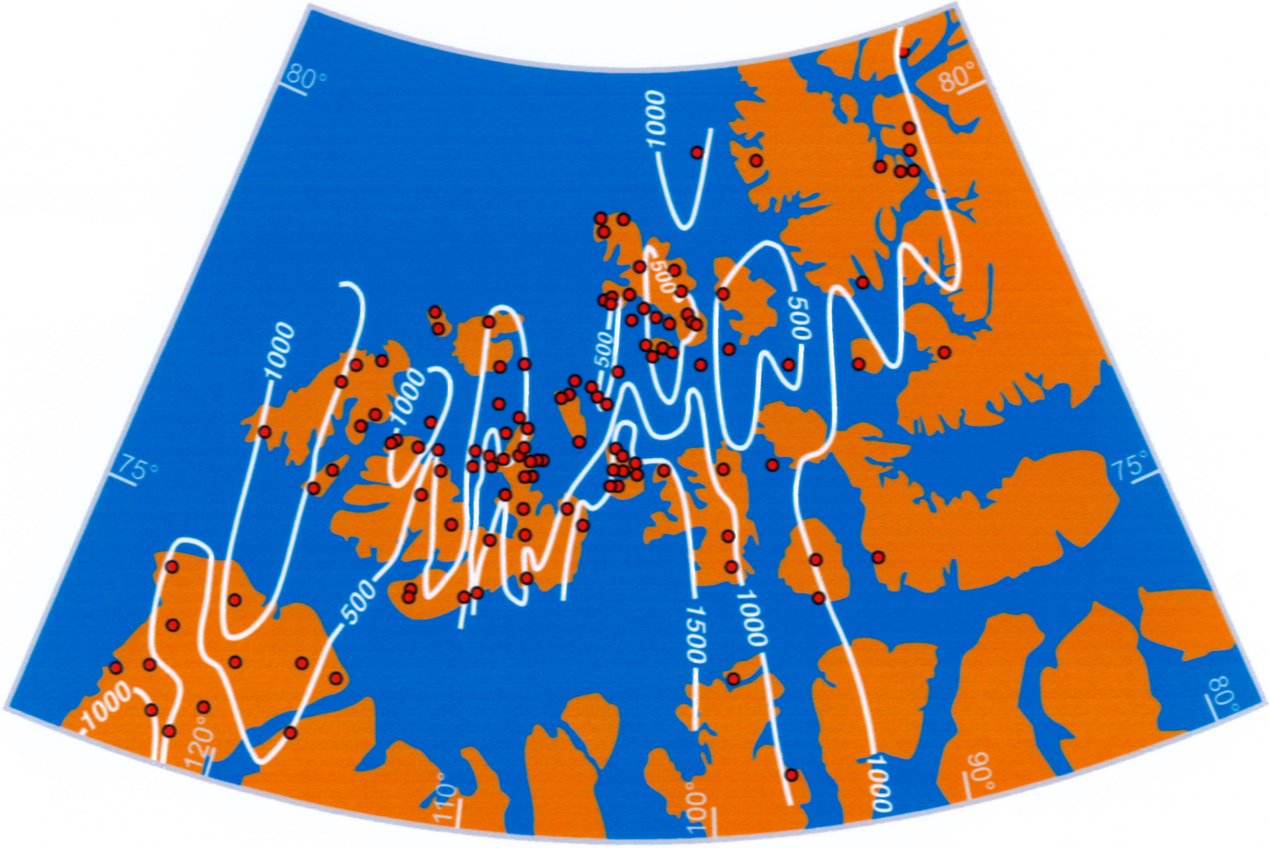


C

CALCULATED DEPTH TO BASE OF METHANE HYDRATE STABILITY ZONE

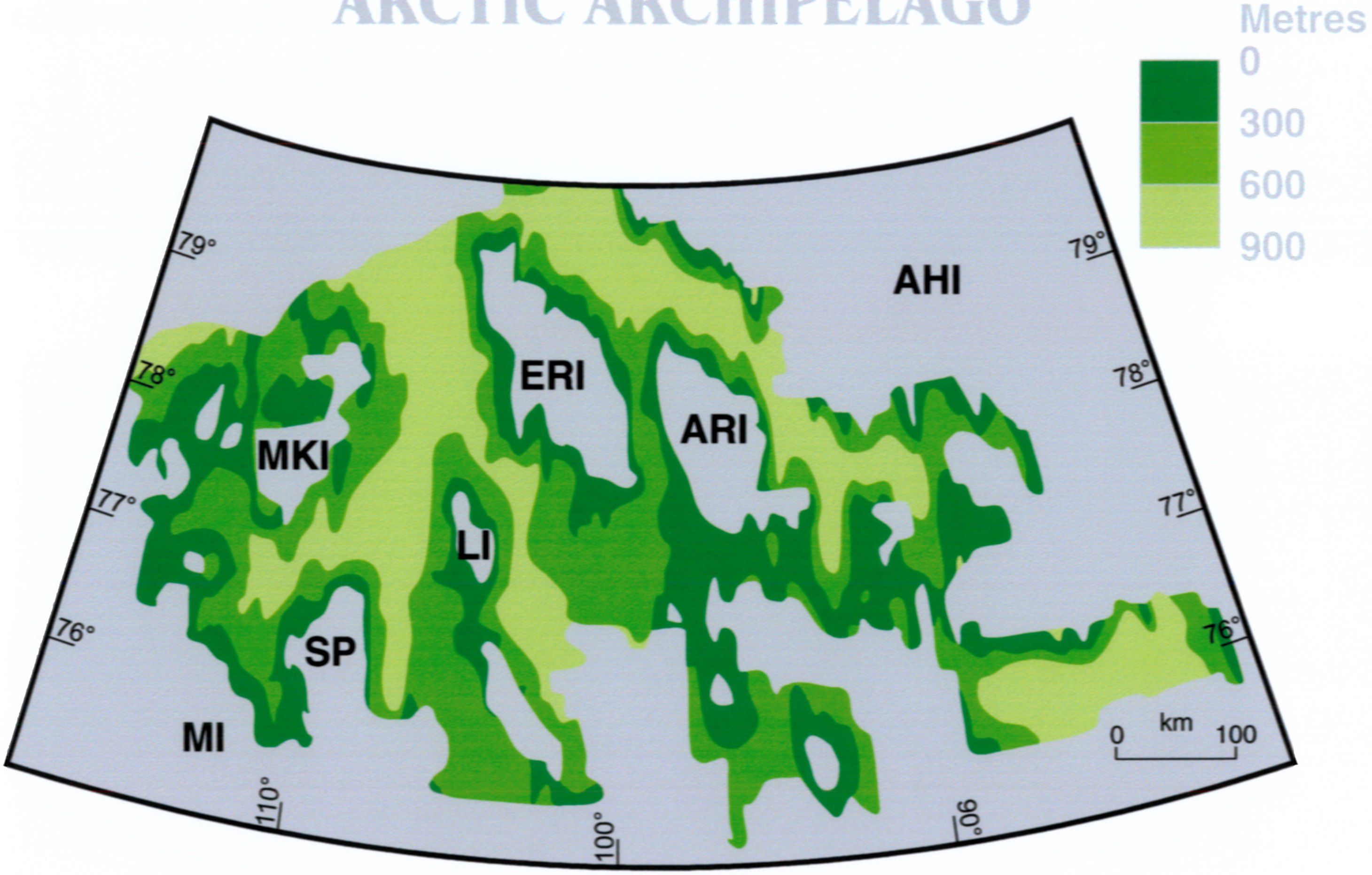


CALCULATED DEPTH TO THE BASE OF METHANE HYDRATE STABILITY ARCTIC ARCHIPELAGO

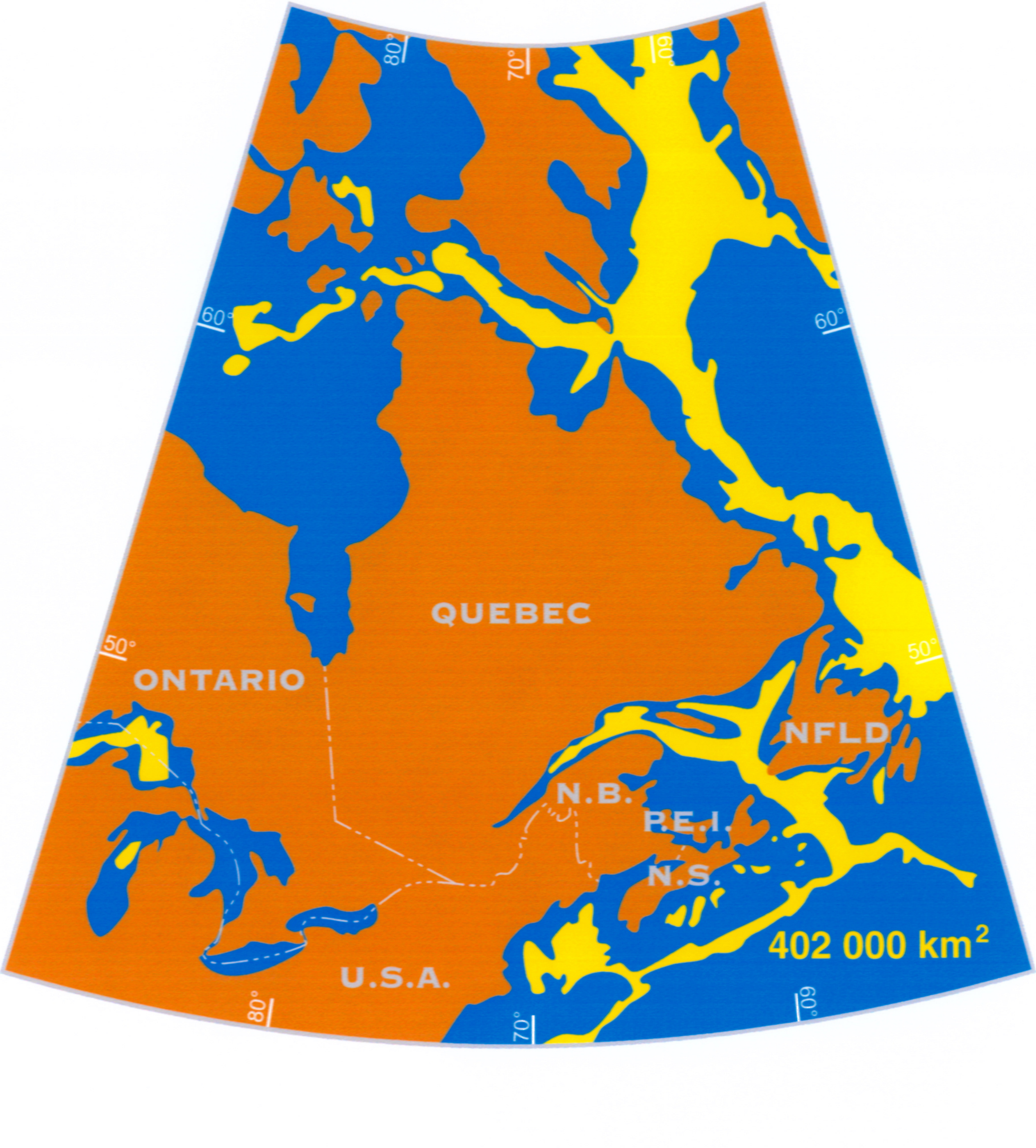


AREA = 766 500 km^2

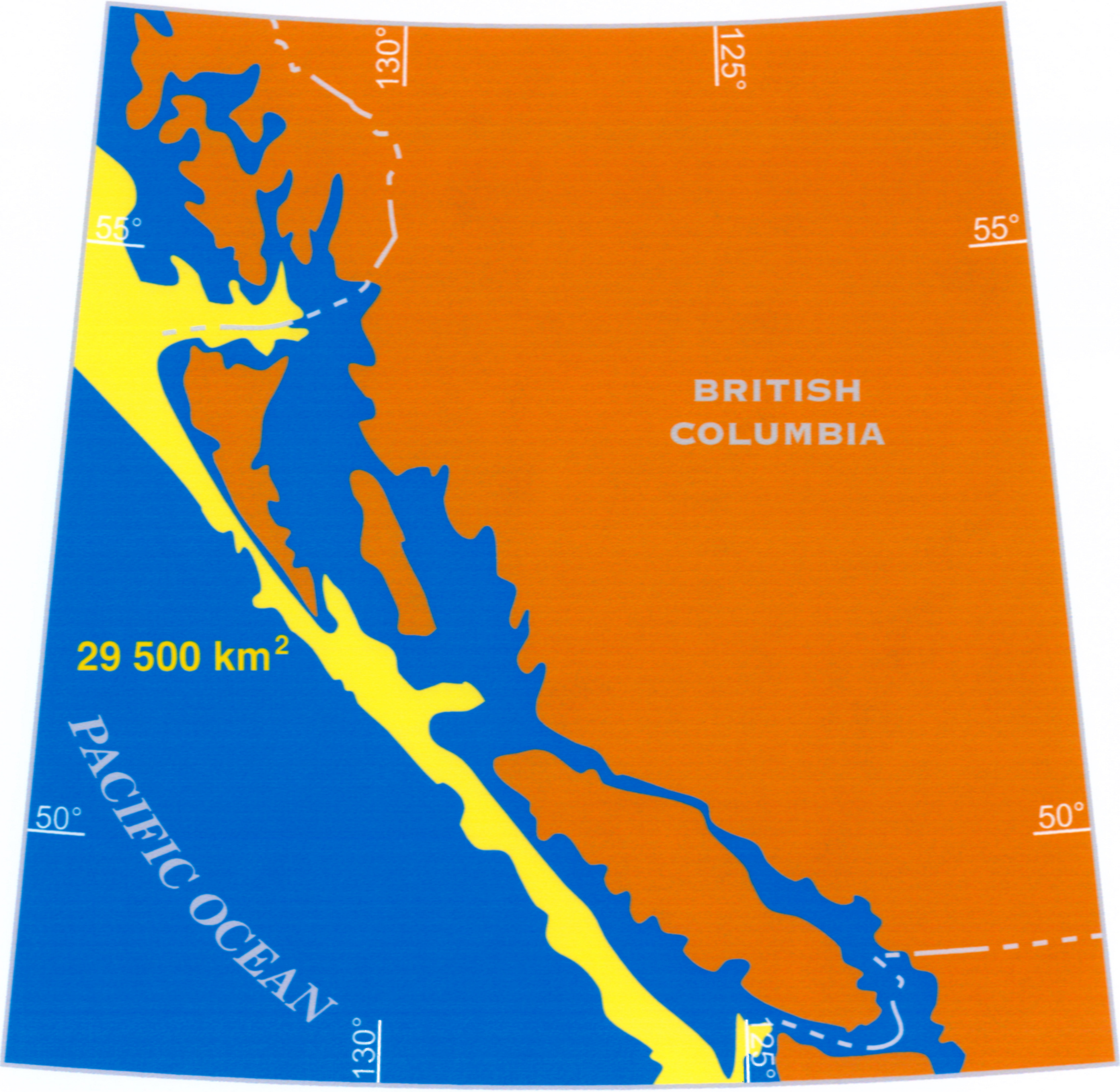
AREAS OF POTENTIAL OFFSHORE METHANE HYDRATE STABILITY AND THICKNESS OF THE STABILITY ZONE ARCTIC ARCHIPELAGO



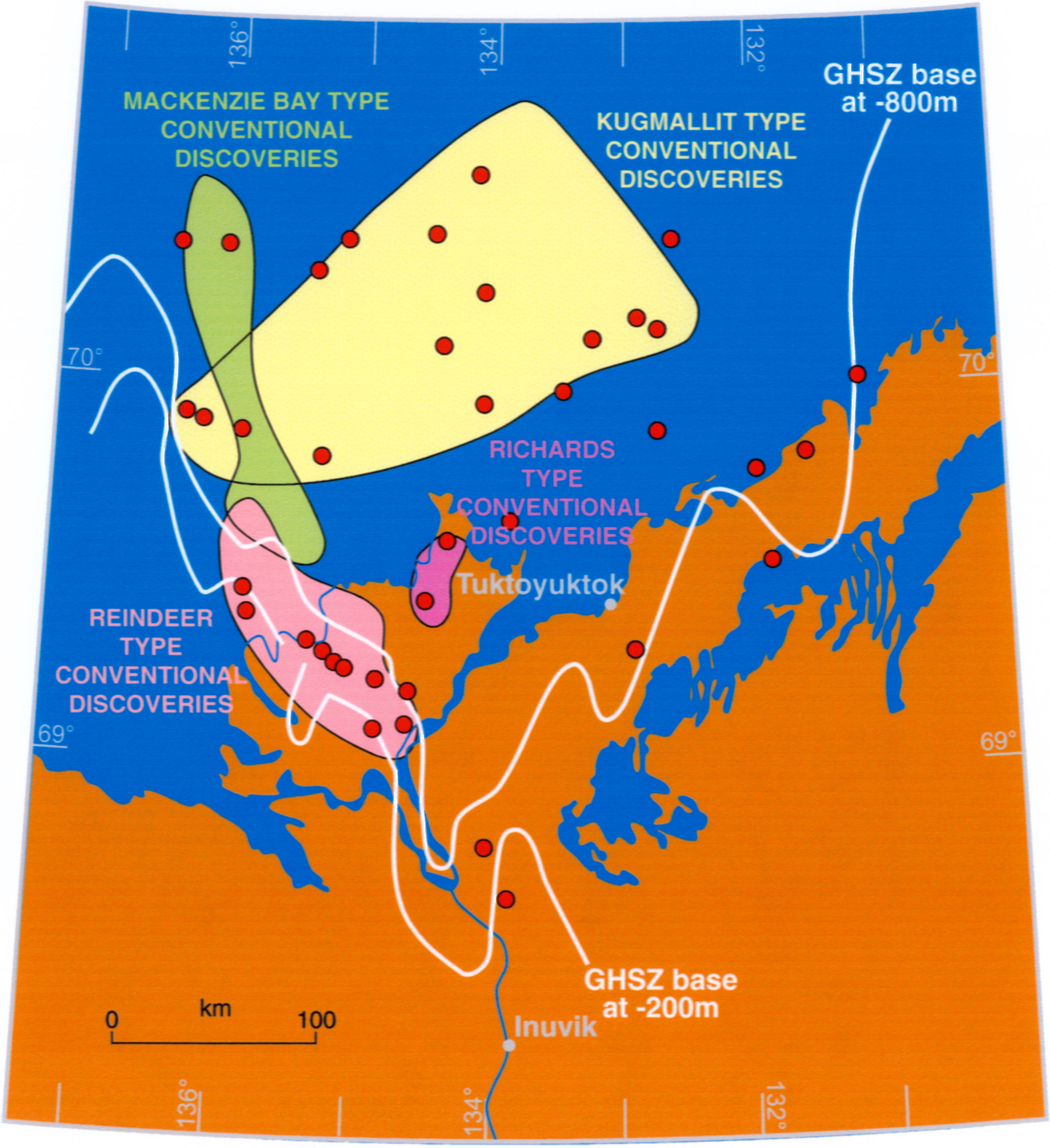
REGIONS OF POTENTIAL METHANE HYDRATE STABILITY ON THE ATLANTIC MARGIN



REGIONS OF POTENTIAL METHANE HYDRATE STABILITY ON THE PACIFIC MARGIN



CO-LOCATION OF GAS HYDRATE AND CONVENTIONAL PETROLEUM REGIONS IN THE MACKENZIE DELTA-BEAUFORT SEA



Gas hydrate occurrences . . . . ●