Natural gas hydrates in Canada

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The presence of hydrate in at least 20 northern Canadian wells on- and off-shore has been inferred by the nature of gas release from formations and from geophysical well-log interpretations. In addition, hydrates have been identified in gas fields in Siberia and on the north slope of Alaska. There are extensive data on temperature - pressure relationships for different hydrate compositions. Relating such curves to depth within the earth and superimposing measured geothermal gradients provides a means of predicting the depth zones of occurrence. Maximum thicknesses probably do not exceed 1800 m.

In water depths greater than 200 to 300 m, gas-hydrates may be found in sediments at, or close to, the sea-floor. The destruction of the hydrate by changing the thermal regime may lead to problems similar to those associated with bottom-founded structures or pipelines in permafrost terrain. Decomposition of gas-hydrates may occur naturally in areas such as the Beaufort shelf. The resulting large volumes of natural gas may weaken the sediments leading to instability with respect to natural or induced loads such as earthquakes.

The Soviets estimate that as much as 10^{13}m^3 (525 Tcf) of gas hydrate may underlie the on-shore areas of the northern Soviet Union. In addition, as much as 10^{18}m^3 of gas hydrate may underlie the earth's oceans. A rough calculation based on known gas-hydrate horizons in the northern Mackenzie Delta suggest the presence of sufficient additional gas to increase reserves by 15 per cent.

Dissociation of hydrates either by heat absorbed from drilling mud or from the pressure decrease at the drill-bit can be a significant hazard to the safety of drilling operations in the north. The problems which might result by producing conventional hydrocarbons from depths below a hydrate zone have yet to be solved.

La nature du gaz dégagé par les formations et des interprétations géophysiques de diagrammes de forages permettent de déduire la présence d'hydrates dans au moins 20 puits du Nord canadien forés tant au large que sur les terres émergées. On a de plus reconnu la présence d'hydrates dans des champs de gaz en Sibérie et sur le versant nord de l'Alaska. Il existe une quantité considérable de données sur les relations entre la température et la pression pour des hydrates de compositions différentes. La mise en rapport de ces données avec les données sur la profondeur et avec les gradients géothermiques mesurés fournit un moyen de prédire les profondeurs des zones renfermant des hydrates. Les profondeurs maximales ne dépassent probablement pas 1800 m.

Sous des épaisseurs d'eau supérieures à 200 ou 300 m, on peut trouver des hydrates gazeux dans des sédiments du fond de la mer ou près de celui-ci. La destruction des hydrates par une modification du régime thermique peut entraîner des problèmes comparables à ceux des constructions ou pipelines dont les fondations reposent sur le fond en zone de pergélisol. La décomposition des hydrates gazeux peut se produire naturellement dans des régions comme la plate-forme de la mer de Beaufort. Le dégagement d'importants volumes de gaz naturel qui en résulte peut affaiblir les sédiments au point de les rendre instables lorsque soumis à des contraintes naturelles ou artificielles comme les séismes.

Les Soviétiques ont estimé qu'il peut exister jusqu'à 10^{13}m^3 (525×10^9 pi^3) d'hydrates gazeux sous les zones côtières du nord de l'Union Soviétique. Il peut de plus exister jusqu'à 10^{18} m^3 d'hydrates gazeux sous les océans du globe. Une estimation grossière, basée sur les horizons dont on sait qu'ils renferment des hydrates gazeux dans le nord du delta du Mackenzie, suggère l'existence de quantités de gaz suffisantes pour accroître les réserves de 15 pour cent.

La décomposition des hydrates soit par la chaleur absorbée des boues de forage, soit par la diminution de pression au trépan peut constituer un danger important pendant les opérations de forage dans le Nord. Les problèmes que pourrait poser la production d'hydrocarbures classiques sous une zone renfermant des hydrates n'ont pas encore été résolus.

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Introduction

Generally, natural gas hydrates have been found in two different and distinct environments; first, associated with areas of relatively thick permafrost where many aspects of their behaviour and geophysical response are similar to those of water-ice, (i.e. to ice-bonded permafrost), and secondly, in the sediments of the deep oceans. The recognition of hydrates in nature is relatively recent resulting primarily from Soviet research by Makogon (1974) in the on-shore environment and by the Lamont–Columbia group in the deep ocean. Most research to date has been conducted by chemists and chemical engineers concerned with fundamental structure and behaviour.

Due to the large changes that occur in the physical properties of hydrates during dissociation into gas and water, they present many geotechnical problems similar to those caused by the change of state of pore moisture from ice to water in permafrost terrain. The very rapid release and expansion of the entrapped gas during dissociation leads to additional problems during either drilling or production through such naturally occurring zones.

Such zones, however, are a "concentrated" form of gas storage and may prove to hold important, relatively shallow reserves of natural gas. The present difficulties associated with releasing the gas in commercially recoverable quantities and disposing of the associated volumes of water make gas hydrates probably an unconventional and possibly uneconomic source of natural gas.

The Soviets estimate their reserves of available gas in hydrates at 10^{13} m^3, tied up in some 30 deposits; the total reserve is larger than the North Sea gas reserves. In addition, as much as 10^{18} m^3 of hydrate may underlie the earth's oceans. This greatly exceeds all previous estimates of available methane.

Gas hydrates may well have acted in the past as an impermeable trap for the accumulation of conventional hydrocarbons, as an "accumulation" agent for the giant northern Soviet gas fields, as an agent in the formation of heavy oil and tar sands, as an associated factor affecting the performance and flow characteristics of shallow conventional hydrocarbon reservoirs in northern regions, and, possibly, in the lithification of sediments. During the Pleistocene, all of Canada would have lain within the stability field of gas hydrates.

Natural Occurrence of Gas Hydrates on- and off-shore in the Arctic

Reported occurrences of gas hydrates are becoming relatively widespread, as they are being inferred from a wide variety of different techniques. (Figure 1). A summary account of the evidence (Judge 1980; Kvenvolden and McMenamin 1980) illustrates the possible broad concern to ocean science and engineering. In this section, the description is confined to the Arctic environment.

The first substantiated report of hydrate occur-

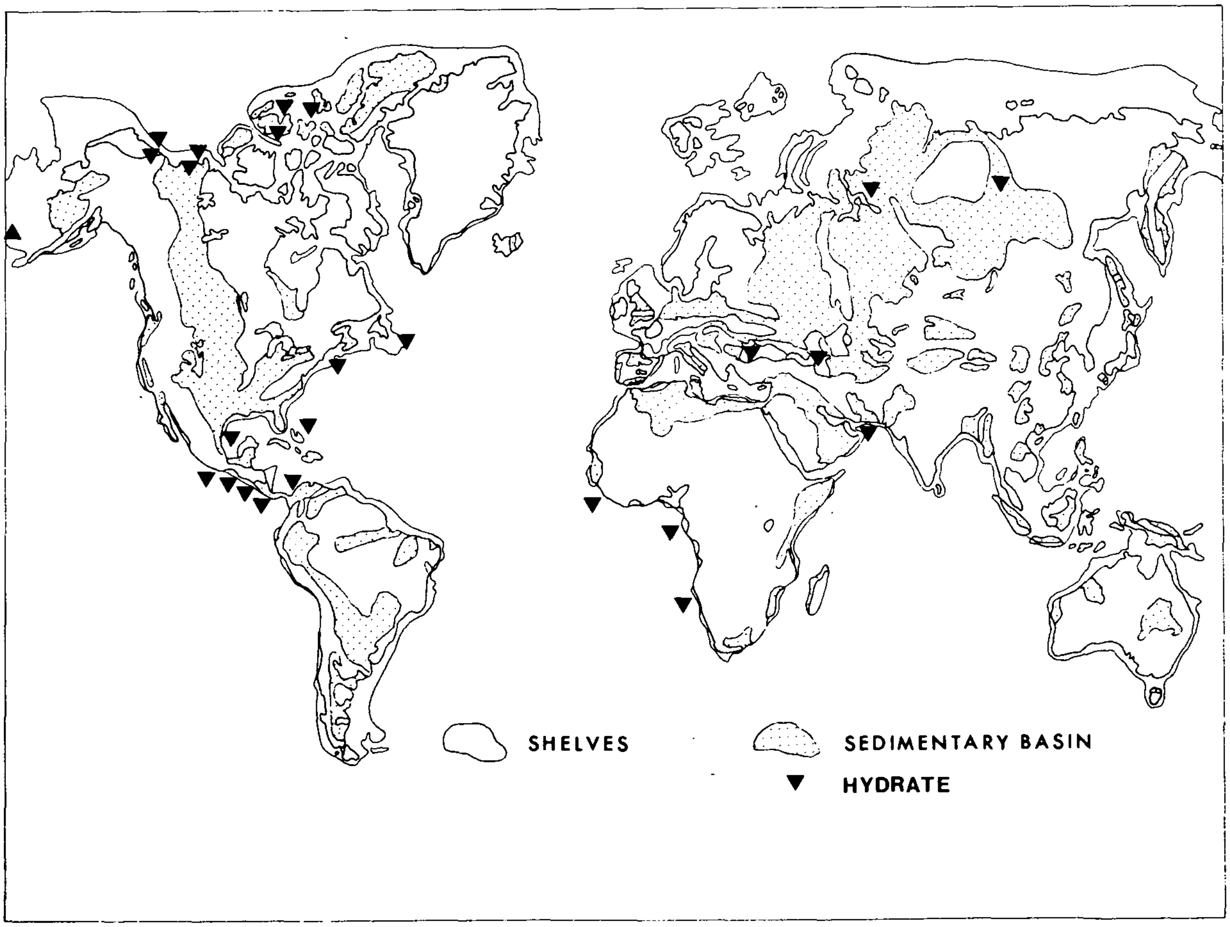

FIGURE 1. World-wide distribution of gas hydrates as deduced from published accounts.

rence in the Arctic was in the Messoyakha field in the West Siberian Basin of the USSR (Cherskii *et al.* 1972). Subsequently, more of the shallow fields within the West Siberian and Vilyuy basins of the USSR and, most recently, areas of north-western Siberia including the Yamal and Taimyr peninsula (Trofimuk *et al.* 1980) have been reported to be underlain by hydrates. In the Arctic regions of North America, Bily and Dick (1974) first documented occurrences in the Mallik-Ivik area of the Canadian Mackenzie Delta. Since then, hydrates have been reported in a number of other wells in the Mackenzie Delta (Davidson *et al.* 1978; Hood 1980) in the Sverdrup Basin (Hood 1980) and on the Alaskan north slope (Hitchon 1974; Judge 1980). Reported depths of occurrence range from 200 m to over 1700 m, with individual zones up to 100 m in thickness.

Hydrates are believed to have been detected extensively off-shore although many of the reported occurrences are based on the interpretation of seismic reflectors rather than on direct drilling evidence. Hydrates have been encountered extensively in offshore wells in the Sverdrup Basin (Goodman and Franklin 1982; Hood 1980) and the Canadian section of the Beaufort Sea (Weaver and Stewart 1982) and inferred from seismic profiles in the Canadian Beaufort Sea (Neave *et al.* 1978), in the Alaskan Beaufort Sea (Grantz *et al.* 1980), and in the Bering Sea (Scholl and Creager 1973). Depths of water above reported occurrences range from a few metres to 4.4 km and the hydrates are detected to depths as great as 1800 m sub-bottom. The occurrences on the Beaufort shelf in water depths of 100 m or less probably originated in a continental environment during the Ice Ages. Outside of this quasi-continental environment, hydrates have been detected close to the sea-floor in water depths of greater than 300 m persisting to water depths of 4400 m and to depths within the sediment of 1100 m.

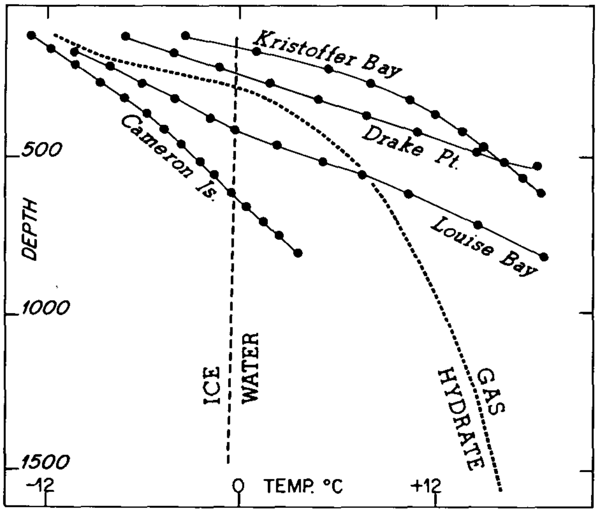

FIGURE 2. Typical temperatures found at increasing depth in Arctic regions superimposed on methane stability curves.

Thermal Prediction of Hydrate Occurrence

The actual distribution of gas hydrates is dependent on the right conditions of temperature and pressure and on the availability of hydrocarbon gases. Identification of potential zones of occurrence using pressure and temperature data alone can provide predictive insight. The maximum depth intervals which might be of some concern in the assessment of potential hazard or energy potential are readily apparent.

Equilibrium subsurface temperature measurements, such as reported by Judge *et al.* (1979), can be superimposed on top of the hydrate stability curves to determine whether or not hydrates may be encountered in an area and, if so, the depth range over which their occurrence might be expected. Some typical temperature results from the Arctic Islands have been superimposed on the methane stability curve (Figure 2). Two of the superimposed temperature curves lie outside the methane-hydrate zone because, although mean surface temperatures are very low (typical of the far north), and geothermal gradients are high, averaging 80 mK/m. At these sites (Drake Point on northern Melville Island and Louise Bay on northern Ellef Ringnes Island), only free gas would be encountered within and below the permafrost. By contrast, the lower geothermal gradients coupled with low subsurface temperatures at Kristoffer Bay on southern Ellef Ringnes, and at Bent Horn on Cameron Island, indicate zones of possible gas-hydrate presence. Above a depth of 100 m in the vicinity of the Cameron Island well, free gas might be expected in association with ice in the pore structure; between 100 and 725 m, gas and water will be in the form of hydrate and permafrost; below 725 m hydrate will co-exist with water to a depth below 1400 m, where free gas might again occur in association with water.

The relation between mean surface temperature and temperature gradient may be generalized (Figure 3). Just as permafrost thickness is a function of surface temperature, geothermal heat flux and thermal conductivity of earth materials, the zone prone to gas-hydrate formation can be similarly defined (Judge 1973). Low surface temperature, low heat flow, and high thermal conductivity lead to a thick hydrate-prone zone. At a typical Arctic site with a mean surface temperature of −16°C, a geothermal gradient of 65 mK/m is necessary for no hydrates, whereas at 0°C a gradient of only 15 mK/m will ensure their absence. High gradients are typical of

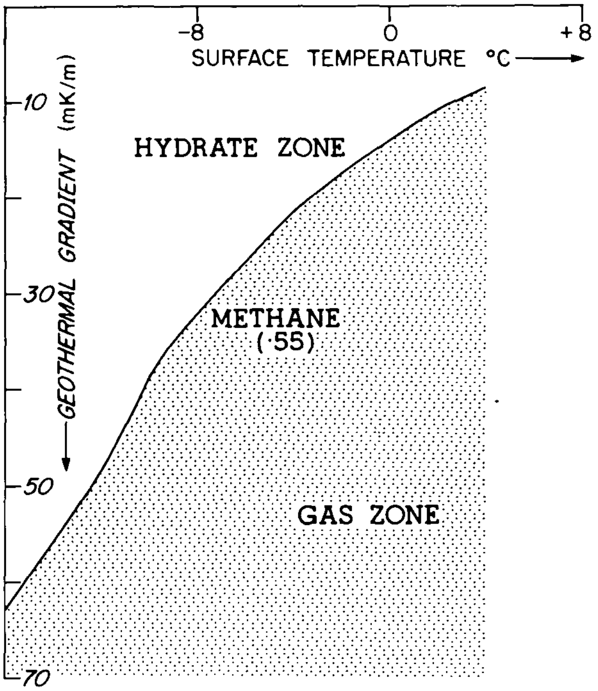

FIGURE 3. Relationship between mean surface temperature and temperature gradient for the occurrence of gas hydrate.

young tectonic areas, low ones of ancient platforms such as the Canadian Shield.

Determinations of the hydrate-prone zone have been made for each northern area for which reliable temperature data are available. The depth range of potential methane-hydrate occurrence is summarized for a number of areas of the north (Table 1). In general, the top of the hydrate-prone zone is shallowest in the Arctic Islands in response to the very low mean annual ground temperatures. The region indicated as having hydrates to the greatest depth is the eastern part of the Mackenzie Delta, comprising Richards Island and the Tuktoyaktuk Peninsula. This may be an erroneous conclusion since simple thermal arguments suggest that the Palaeozoic rocks of the Arctic Platform would host the thickest zone. Although mean surface temperatures are very low within the Sverdrup Basin, the high geothermal gradients place the subsurface in regions such as Drake Point outside the zone of stable hydrates.

Represented in Figure 4 is a preliminary attempt at mapping the possible maximum depth to which methane hydrate might occur in northern on-shore areas. These results do not mean that hydrates are present within the stable zone, rather, they indicate that, if methane gas and water co-exist in any horizon within that zone, hydrates will form given sufficient time. Structure II hydrates, formed by molecules such as propane and isobutane, are stable at both shallower and greater depths than structure I hydrates, formed by small gas molecules such as methane and ethane. Hence, in regions where natural gas containing heavier hydrocarbons is present, hydrates may be encountered outside the rough boundaries suggested by Table 1. Given the chemical composition of the natural gas found in a particular formation it is possible to construct a specific stability curve (Parrish and Prausnitz 1972).

Similar predictions of gas-hydrate zones off-shore are limited by lack of deep-borehole, subsurface temperature data. Taylor *et al.* (1979) attempted to show how such predictions might be made for the Labrador shelf. At present, little is known about subsurface

TABLE 1. Depth range of possible occurrence of methane hydrate in Arctic regions

Area	No. of wells	Minimum depth (m)	Maximum depth (m)	Thickness of hydrate zone (m)	Comments
Arctic Islands					
Western	5	140	1100	960	
Eastern	3	140	960	820	
Sverdrup Basin	11	140	1270	1130	Often gradient too high for hydrate.
Arctic Platform	3	140	1400	1260	Few locations: Thickness to 2000 m possible.
Mackenzie Delta					
East	11	190	1860	1670	
West	4	340	730	390	Often gradient too high for hydrate.
Mackenzie Valley and Yukon Territory	6	—	—	—	Generally absent: Yukon coastal plain excepted.

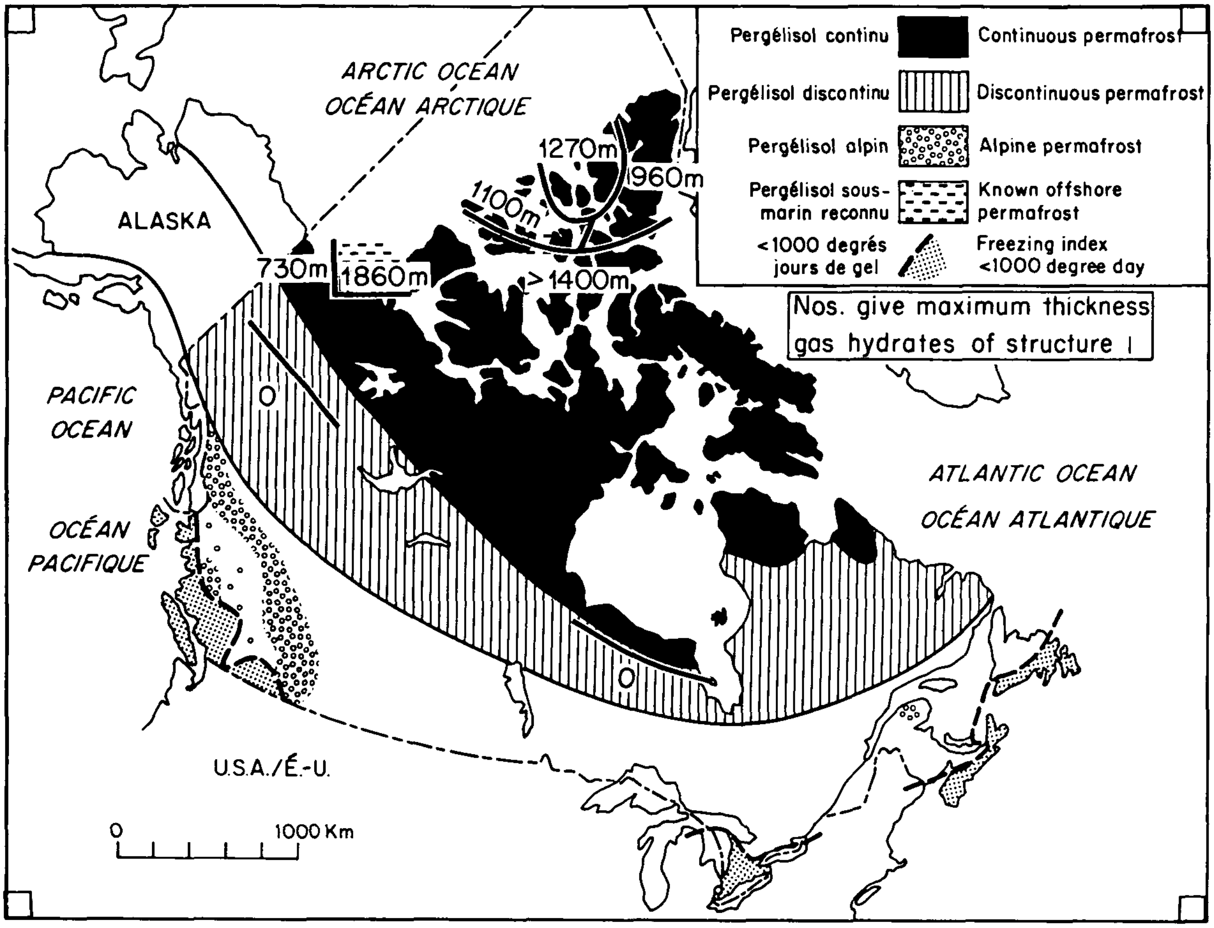

FIGURE 4. Preliminary spatial distribution of gas-hydrate thickness in northern Canada superimposed on a permafrost distribution map.

temperature or terrestrial heat flux conditions on the off-shore continental shelf and slope areas. In regions not underlain by ice-bonded sediments and not recently submerged, reasonable predictions can be made of the thermal field using data on bottom-water temperatures, lithology, and the heat flux. Limited information on heat flux is available from off-shore of eastern North America and in the eastern Canadian arctic. Pye and Hyndman (1972) reported a flux of about 56 mW/m^2 for the Labrador Sea and Baffin Bay, based on thermal gradient measurements at ten locations in the upper few metres of sediment. Hyndman *et al.* (1979) reported a flux of 68 mW/m^2 from a well on the Scotian shelf. Although the mean temperature gradient to 4500 m was determined to be 26 mK/m, the gradient in individual formations varied from 17 mK/m in sand to 35 mK/m in shale, illustrating the importance of lithology in predicting ground temperatures and, hence, thickness of the hydrate-prone zone. A mean temperature gradient of 27 mK/m recently determined from the eastern continental shelf of the United States shows the general consistency of mean regional gradients. Using a gradient of 26 mK/m as applicable in general to the Scotia and Labrador shelves and using a typical bottom-water temperature of 0°C, (Figure 5), the resulting depths of hydrate stability are plotted for different water depths. In general, hydrates will not be found in sediments beneath water depths less than 150 m unless temperature gradients are depressed in the sediments. Beneath water depths of 300 to 400 m, hydrates may occur in the sea-floor sediments and extend to depths of 600 m. The thickness of the hydrate-prone zone probably does not increase dramatically at greater water depths, since it is more sensitive to temperature gradient than increasing pressure. Similar arguments probably apply to much of off-shore Alaska where Erickson *et al.* (1975) have reported an average heat flux of 44 ± 5 mW/m^2, which is approximately 20 per cent lower than the east

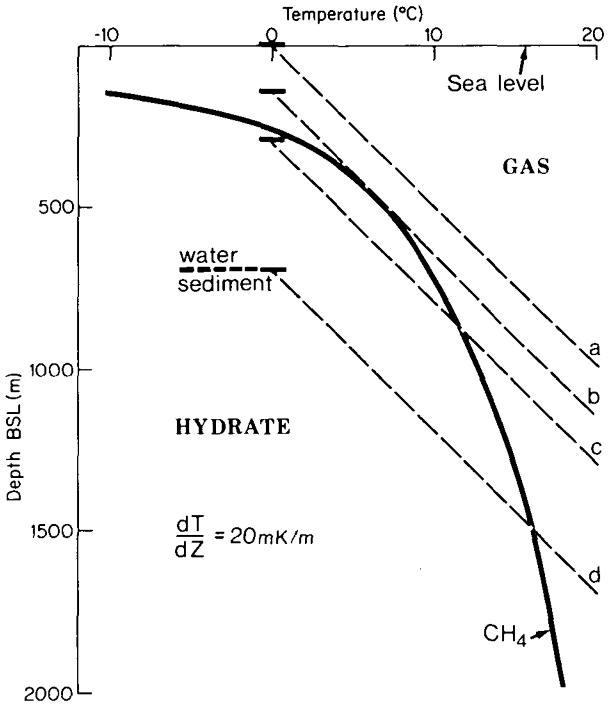

FIGURE 5. Hydrate-prone zones in different water depths based on a typical bottom-water temperature and geothermal gradient.

coast. Using similar arguments to those for the eastern areas, the hydrate-prone horizons would increase to an average thickness of 750 m.

The thermal condition of sediments in the channels and continental shelves between the Arctic Islands is poorly known. Bottom-water temperatures of Arctic waters vary from − 1.5°C in 300 m to 0°C in 1000 m of water (Collier and Judge 1977). Assuming a range of temperature gradients similar to on-shore areas of similar tectonic setting, the maximum hydrate thickness is unlikely to exceed 700 m off-shore, except perhaps in the southern channels bordering the Canadian Shield from Foxe Basin to Amundsen Gulf. In the latter two areas, very low geothermal gradients may favour a hydrate-prone layer up to 1800 m thick. This estimate assumes a quasi-thermal equilibrium, i.e. that the subsurface thermal field is largely controlled by the thermal flux of the earth and the present bottom-water temperature. During the Pleistocene, sea-levels changed by several hundreds of metres and some areas of the continental shelves, such as the Beaufort Sea, were exposed to extremely low air temperatures. Consequently, permafrost grew to thicknesses in excess of 600 m (Judge 1974; Mackay 1972). Hydrate-prone layers to depths of 1800 m were created. The thicknesses of such horizons are difficult to predict since they are dependent more on recent geological history than on the earth's thermal field. At water-depths greater than several hundred metres on the Beaufort Shelf, where prolonged exposure was unlikely, conditions will parallel more closely the quasi-thermal equilibrium state. Mean heat flux measured in the deep water of the southern Beaufort Sea (Judge and Jessop 1978) suggests a hydrate zone not exceeding 600 m in thickness. Similar conditions may exist on the Alaskan Beaufort shelf and the continental shelf to the west of Banks Island. Since the warm hydrate–permafrost zone of the continental shelf is being heated by present day higher sea-bottom temperatures, hydrate is dissociating into gas and water.

Hydrate and Conventional Resource Development

As well as being a possible energy resource, gas hydrates pose potential problems to conventional frontier development as Davidson *et al.* (1978) and Goodman and Franklin (1982) have outlined.

For example, the interpretation of exploration seismic reflection records is complicated by the presence of a substantial thickness of unsuspected high-velocity material (Card 1979). Stoll *et al.* (1971) and Stoll and Bryan (1979) have shown from laboratory studies that hydrate velocities may be 30 per cent higher than those in normal unconsolidated sediments. In fact, the theoretically determined velocity in a single crystal of hydrate is only 10 per cent less than in ice (Whalley 1980). Clouter and Kiefte (1981) confirmed recently the slightly lower velocity for methane hydrate. Thus, many problems of interpretation resulting from variations in lateral thickness in permafrost areas will also occur in the presence of hydrates.

Since the decomposition of hydrate yields approximately 160 times the volume of gas which can be obtained in the same volume at the same temperature and pressure, heat input due to drilling and circulating warm mud may cause serious problems in well control. The decomposition of the hydrate may cause a pressure increase in the well-bore, gasification, and a possible blowout. Bily and Dick (1974) showed that hydrate decomposition during, and subsequent to, penetration of the hydrate zone can be controlled by lowering the temperature of the circulating mud. It remains important, however, to detect the presence of a hydrate zone since, in deeper drilling, higher mud temperature cannot be avoided, and such zones require adequate casing. Davidson *et al.* (1978) reported several examples of gas kicks associated with hydrate decomposition. Chilling of the drilling mud, close density control, and continuous monitoring of mud gases are now routine procedures in drilling hydrate-prone areas of northern Canada.

At present there are no wells in Canada producing through hydrate-bearing zones. Long-term production of conventional oil and gas from deeper horizons commonly at temperatures of 70 to 80°C flowing past the shallower hydrate zones will result in hydrate decomposition behind the production string. The effect of such decomposition is not yet determined, although problems have been encountered in the Soviet Union (Cieslewicz 1971; Makogon 1974). Hydrate zones may require high strength and/or insulated casing strings, or special measures to bleed-off hydrate-produced gas.

The potential formation of hydrate plugs from moist gas in the well-bore is a common production problem in the Soviet Union and Canada. In fact the first industrial research on hydrates was triggered by the blockage of gas pipelines in the United States due to gas-hydrate formation (Hammerschmidt 1934; Makogon and Sarkis'yants 1966).

As Katz (1972) and Verma *et al.* (1975) showed, gas hydrates form in the presence of water, from gases dissolved in hydrocarbon liquids. The consequent denudation of lighter hydrocarbons from shallow northern oil reservoirs and the subsequent low reservoir pressures may add to production difficulties. Hitchon (1974) reported low pressures in a 1140- to 1245-m deep oil reservoir discovered in Upper Cretaceous sandstones on the Alaskan north slope. Similar pressure reductions and loss of permeability might result from attempts to stimulate further production of hydrocarbons by water injection into shallow reservoirs unless the water is heated prior to injection.

The presence of hydrates above a gas reservoir may constitute an impermeable trap through which free gas cannot permeate (Evrenos *et al.* 1971). Several examples of such traps beneath the sea-floor were described by Wilson (1977) and White (1977, 1979). Trofimuk *et al.* (1979) speculated on the volumes of hydrate enclosed within the oceans and the trapped volumes of gas beneath.

Safe drilling and production of this gas is problematical since the gas hydrate constitutes the impermeable trap. Adequate cement bonds between the well-casing and the formation, to ensure no uncontrolled escape of reservoir fluids, may prove difficult to achieve. In general, cementing of wells in hydrate areas poses similar problems to those associated with ground ice, with the further complication of low volumes of gas at high pressures (Goodman 1978).

At water depths greater than 200 m, hydrates may occur at, or close to, the sea-floor. This poses problems of either thaw settlement or heave to sea-bottom installations, due to the decomposition or formation of hydrate lenses. Problems associated with resource development in regions with sea-floor permafrost are described by the National Academy of Sciences (1976). The presence of large volumes of gas in the sediments resulting from the dissociation of hydrate may compound the problems.

These types of problems result from perturbations of the natural state by human activity. In fact, natural thermal conditions of the crust change over periods ranging from tens to thousands of years either due to changes in climate, sea level, local topography, and hydrological conditions or through the expansion or contraction of ice-sheets. The aggradation or degradation of permafrost and/or gas hydrates due to natural variations in subsurface temperatures can lead to significant engineering implications such as under-consolidated sediments, horizons of low strength or high gas content, extensive shallow gas deposits etc. Such sediments will respond in rather different ways to natural and induced loads caused by earthquakes, waves, ice, or human-generated activity.

Hydrates as a Gas Resource

Hydrates may constitute an additional, if unconventional, "concentrated" source of natural gas for the future. In the USSR, it has been estimated that 10^{13} m^3 of natural gas, larger than the reserves of conventional gas estimated for the North Sea, are present in hydrate form (Cherskii and Makogan 1970; Trofimuk *et al.* 1980).

Davidson *et al.* (1978) suggested that 10^{11} m^3 of gas hydrates, in addition to conventional gas, might be present in the Mackenzie Delta. Recent drilling in the Beaufort Sea by Dome Petroleum (Weaver and Stewart 1982) will probably increase these reserve estimates. The Gas Research Institute of the United States is actively assessing the hydrate resources of Alaska and of the off-shore areas around the rest of the country (Cox 1979). Soviet scientists have calculated that over 10^{18} m^3 of methane are frozen in the submarine areas of the world (Makogon 1982). Since previous estimates put the quantity of natural gas in the lithosphere and hydrosphere at one-sixth of this amount, off-shore resources need careful evaluation.

The recovery of the gas is not as simple as producing from a conventional reservoir. Decomposition of hydrates can be accomplished by supplying heat to the reservoir (approximately 20 per cent more than that required to melt the same volume of ice), by reducing reservoir pressure, or by injecting antifreeze solvents (such as brine or methanol). After decomposition of the hydrate and recovery of the fluids, there are six molecules of water to be disposed of for each molecule of gas recovered. Cherskii and Bondarev (1972), Makogon (1974), and Kolodeznyi and Arshinov (1970) described Soviet experiments on artificial stimulation of hydrate reservoirs by heat input and methanol injection and reported some success. However, Bily and Dick (1974) reported little success with methanol stimulation of Mackenzie Delta wells. The work of Kobayashi *et al.* (1951), on the effect of brine solutions on the phase stability of hydrates, suggests that injection of saline formation waters might offer a cheaper method of hydrate reservoir stimulation.

Recently, Holder (*pers. commun.*) and McGuire (1982) have examined methods of steam and hot-water injection, the latter using mathematical models developed for the recovery of oil *in situ* from tar sands and for "hot dry rock" geothermal recovery systems. Such calculations must be considered very preliminary in nature since very little is known about the physical characteristics of gas hydrates. Very recently, Ross *et al.* (1981) have shown that the thermal conductivity of gas hydrates may be closer to that of water than the ice values normally assumed. The thermal properties of hydrates will be key parameters in the design of thermal stimulation techniques.

Two simples approaches to recovering hydrate gas in an economic fashion do exist. Where hydrate is underlain by free gas, production of the gas will reduce the reservoir pressure causing dissociation of hydrate and a consequent pressure increase. Indirectly, the gas from the hydrate is produced slowly, along with the conventional reservoir gas and thus, the pressure in the reservoir is maintained, perhaps prolonging the lifetime of the field. Messoyakha, from published accounts, is a field of this type with hydrate occupying the upper part of the reservoir and free gas the remainder. Lateral zoning may be found in shallow reservoirs that cross Arctic shore-lines; under the cold shore-line, gas may exist bound in hydrate form, whereas under the warm nearby ocean free gas may occur.

Conclusions

Research is needed to establish the geological implications of the existence of gas hydrates. It is becoming recognized that, as well as behaving as an unconventional trap for conventional hydrocarbon reservoirs, gas hydrates may act as a geological agent in the global distribution of hydrocarbons. Judge (1980) and Neave *et al.* (1978) have speculated that shallow gas deposits observed beneath the Beaufort Sea might be derived from decomposing hydrates formed originally during the colder periods of the Pleistocene. Trofimuk (1977) suggested that gas hydrates might also have acted as an "accumulation" agent in the formation of the giant northern Soviet gas fields during the periods of continental glaciation. Gas hydrates may have played a role in the formation of heavy oils, tar sands, and in the modern characteristics of shallow conventional hydrocarbon reservoirs.

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