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Methane Hydrates: Major Energy Source for the Future or Wishful Thinking?

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Abstract

Methane hydrates are methane bearing, ice-like materials that occur in abundance in permafrost areas such as on the North Slope of Alaska and Canada and as well as in offshore continental margin environments throughout the world including the Gulf of Mexico and the East and West Coasts of the United States. Methane hydrate accumulations in the United States are currently estimated to be about 200,000 Tcf, which is enormous when compared to the conventional recoverable resource estimate of 2300 Tcf. On a worldwide basis, the estimate is 700,000 Tcf or about two times the total carbon in coal, oil and conventional gas in the world. The enormous size of this resource, if producible to any degree, has significant implications for U.S. and worldwide clean energy supplies and global environmental issues.

Historically the petroleum industry's interests in methane hydrates have primarily been related to safety issues such as wellbore stability while drilling, seafloor stability, platform subsidence, and pipeline plugging. Many questions remain to be answered to determine if any of this potential energy resource is technically and economically viable to produce. Major technical hurdles include: 1) methods to find, characterize, and evaluate the resource; 2) technology to safely and economically produce natural gas from methane hydrate deposits; and 3) safety and seafloor stability issues related to drilling through gas hydrate accumulations to produce conventional oil and gas. The petroleum engineering profession currently deals with gas hydrates in drilling and production operations and will be key to solving the technical and economic problems that must be overcome for methane hydrates to be part of the future energy mix in the world.

Introduction

Natural gas hydrates consisting mostly of methane have been identified in numerous locations in permafrost regions of the Arctic and beneath the sea floor along outer continental margins of the world's oceans. The evidence for gas hydrate accumulations has come from direct sampling in a few wells in Arctic permafrost regions, mostly North Slope of Alaska and the Mackenzie Delta in Canada, and from seafloor cores taken as part of the Ocean Drilling Program in numerous locations in ocean margins and most recently by Japan in the Nankai Trough, offshore Japan. Gas hydrates have been inferred to occur in about 50 locations worldwide as depicted in Figure 1. Mostly the evidence is indirect and inferred from seismic reflections, well logs, drilling data, pore-water salinity data, and a few direct observations in cores. A good review of the current evidence is presented by Collett.[1]

In a recent paper discussing the estimates of worldwide gas hydrate resources, [2] it was argued that there was still no clear cut convergence of estimates over the last twenty years and that the number of estimates is so small that serious doubt can be raised about the inferences drawn from the estimates. Hence, much research lies ahead to obtain a trustworthy estimate of global gas hydrate resources. However, the enormous estimates of 200,000 Tcf for the United States and 700,000 Tcf worldwide are so large that interest continues to be very high in methane hydrates as a potential resource.

The United States Department of Energy's (USDOE) Office of Fossil Energy through its National Energy Technology Laboratory (NETL) reinitiated a hydrates research program in 1998 with publication of "*A Strategy for Methane Hydrates Research and Development*" in August 1998, followed by the "*National Methane Hydrate Multi-Year R&D Program Plan*" in June 1999, which demonstrates the renewed interest by the United States in methane hydrate research.[3] The USDOE conducted a 10-year research program from 1981 through 1992 at USDOE's Morgantown Energy Technology Center, now part of the National Energy Technology Laboratory (NETL). Although the USDOE program was mostly dormant from 1992 to 1998, research continued at the United States Geological Survey (USGS), universities, other laboratories, and overseas. Recent results from the Ocean Drilling Program, expanding industry activity in hydrate-prone areas of the Arctic and the deep-water continental shelves has increased the importance and urgency of better understanding the extent and properties of these deposits as they impact development of conventional oil and gas. Japan and India have significant hydrate R&D programs for methane hydrates and Japan has entered into its second 5-yr Methane Hydrates R&D program The interest by Japan and India is motivated by their lack of indigenous energy resources that causes them to pay high prices for imported liquefied natural gas and oil and the potential for recovery of gas from indigenous oceanic hydrate accumulations.

This paper provides an overview of methane hydrates characteristics, regions of occurrence, and assessment methods. The objective is to increase the understanding and involvement of the petroleum engineering community in determining whether this apparently enormous accumulation of clean energy is truly a potential resource or just a problem to be dealt with in production of conventional oil and gas.

Hydrate Characteristics and Stability Conditions

Methane hydrates are a subset of gas hydrates or gas clathrates that occur when water forms cage-like crystalline structures around smaller guest molecules. Their overall appearance is similar to ice. A detailed review of gas hydrates and their fundamental characteristics is provided by Sloan.[4] Gas hydrates of most current interest are composed of water and one or more of eight molecules: methane, ethane, propane, isobutane, normal butane, nitrogen, carbon dioxide, and hydrogen sulfide. The predominant component of naturally occurring hydrates is methane. The structure of hydrates concentrates gas such that one cubic foot (ft^3) of hydrates may contain up to 180 standard cubic feet (scf) of gas - for methane, the value is about 164 scf/ft^3. Because of this large gas storage capacity, gas hydrates potentially represent an important source of natural gas.[1, 3, 4]

Gas hydrates occur in sedimentary deposits under conditions of moderately high pressures and moderately low temperatures present in permafrost regions and beneath the sea in outer continental margins. These conditions are illustrated in Figure 2 where the vertical axis is plotted in terms of depth below the ground surface or seafloor representing an increase in pressure versus temperature in Kelvin on the horizontal axis.[1] Fig. 2 (a) is illustrative of permafrost regions and Fig. 2 (b) of offshore regions. The presence of salt in the water shifts the phase boundary to the left and the presence of carbon dioxide, hydrogen sulfide, and hydrocarbons other than methane shifts the phase boundary to the right. Different geothermal gradients also will cause a shift in the depth and width of the gas-hydrate stability zone. Like ice, crystalline methane hydrate is less dense than water, so if hydrate forms in water it floats upward and breaks down (dissociates) at lower pressures and higher temperatures. Therefore, the hydrate stability zone in seafloor sediments can range from just below the seafloor to hundreds of feet below the seafloor.[5]

A recent book edited by Michael D. Max entitled *Natural Gas Hydrate in Oceanic and Permafrost Environments*, Kluwer Academic Publishers, 2000, provides a large collection of papers by distinguished authors summarizing the current knowledge and research efforts related to natural gas hydrates.[6]

Methane from microbial and thermogenic sources has been reported to be present in gas hydrates.[1,5,6] Carbon isotope analyses indicate that the methane in many oceanic hydrates is derived from microbial sources. However, molecular and isotopic analyses indicate a thermal origin for the methane in several offshore Gulf of Mexico and onshore Alaskan gas-hydrate occurrences. Methanogenic bacteria have been cultured from sediments recovered from the Mallik 2L-39 gas hydrate research well drilled in the Mackenzie Delta in 1998.[7] Analyses of the carbon isotope signature from this well also indicated a thermogenic source at play in this location as well.[8] Methane may be transported through fractures and high permeability pathways from thermogenic origins or formed biogenically near the regions of gas hydrate formation leading to build up of gas hydrate accumulations or a combination of both processes. The rates of hydrate formation coupled with sediment accumulation and compaction rates and geothermal gradients will all affect the location and characteristics of gas hydrate accumulations. These processes are not well understood and continued investigation is required.

Little is known about the true nature of gas hydrate reservoirs. The small number of gas-hydrate samples obtained from research coring operations has not been adequate to provide a clear indication of how hydrates are dispersed in reservoir sediments. In some cases, they appear to range from disseminated to massive (100% hydrate). Figure 3 is an illustration of the possible configurations of hydrates as described by Sloan[4] and Collett.[1] In coarse grained sediments methane hydrate often forms as disseminated grains and pore fillings but in finer silt/clay deposits it commonly appears as nodules and veins.[9]

The textural nature of gas hydrate in the reservoir and the distribution will control the characteristics of the gas hydrate accumulation and the production potential. The ability to define net pay in any normal petroleum-engineering manner is yet to be determined.

Review of Gas Hydrate Assessment Methods and Locations

The assessment methods and evidence for gas hydrate accumulations will be illustrated by looking at five examples of gas hydrate accumulations. These include the Blake Ridge along the southeastern continental margin of the United States, along the Cascadia continental margin off the Pacific coast of the United States, on the North Slope of Alaska, in the Mackenzie River Delta area of northern Canada, and information recently published on the well drilled at the end of 1999 in the Nankai-Trough, offshore Japan.

Blake Ridge Gas Hydrate Occurrence. Seismic profiles along the Atlantic margin of the United States are often marked by large-amplitude bottom simulating reflectors (BSRs), which in this region are believed to be caused by large acoustic impedance contrasts at the base of the gas-hydrate stability zone that immediately overlies sediments containing free gas.[1] BSRs are the most frequent inferred indication of subsea gas hydrates.[1,5,10] A detailed discussion BSRs and their relation to gas migration and the formation of gas hydrate zones and free gas beneath is provided by Dillon.[5]

Figure 4 shows the location of the Blake Ridge off the East Coast of the United States and the area of hydrate occurrence. Figure 5 shows an seismic profile and illustrates the BSR. The crest of the Blake Ridge runs approximately perpendicular to the general trend of the continental rise for more than 310 mi. [500 km] to the southwest from water depths of 6500 to 15,700 ft [2,000 to 4,800 m]. The thickness of the zone for methane-hydrate stability in this region ranges from zero along the northwestern edge of the continental shelf to a maximum thickness of about 2300 ft [700 m] along the eastern edge of the Blake Ridge.[1]

Leg 164 of the Ocean Drilling Program (ODP) was designed to investigate the occurrence of gas hydrate in the sedimentary section beneath the southern flank of the Blake Ridge. Sites 994, 995, 997 are three test holes that penetrated below the base of the gas hydrate stability zone within the same stratigraphic interval over a relatively short distance as shown in Figure 5.[1] Hole 994 penetrated an area where the BSR was not detectable and holes 995 and 997 penetrated an area where an extremely well-developed and distinct BSR exists. The presence of gas hydrates was documented at Sites 994 and 997 by direct sampling; however no gas hydrates were conclusively identified at Site 995.[1] Although a BSR does not occur in the seismic reflection profiles that cross Site 994, several pieces of gas hydrate were recovered from 852.7 ft [259.9 m] below the sea floor and disseminated gas hydrates were observed. One large, solid piece (about 0.5 ft [15 cm] long) of gas hydrate was also recovered from about 1086 ft [331 m] below the sea floor at Site 997. Despite these limited occurrences of gas hydrates, it was inferred, based on geochemical core analyses and downhole logging data, that disseminated gas hydrates occur within the stratigraphic interval from about 623 to 1,476 ft [190 to 450 m] below the sea floor in all the holes drilled on the Blake Ridge.[1]

The depths to the top and base of the zone of gas hydrate occurrence at Sites 994, 995, and 997 were determined using interstitial water chloride concentrations and downhole log data as depicted in Figure 6.[1] Interstitial water chloride concentrations can be used to establish gas hydrate occurrence within a core sample because gas hydrate decomposition during core recovery releases water and methane into interstitial pores, resulting in a freshening of the pore water. The observed chloride concentrations also enable the amount of gas hydrate that occurs in the sediment to be established by calculating the amount of interstitial water freshening that can be attributed to gas hydrate dissociation. The estimated gas-hydrate saturation in the recovered cores ranged from about 7% and 8.4% at Sites 994 and 995 to a maximum of about 13.6% at Site 997.[1]

Natural gas hydrate occurrences are generally characterized by the release of unusually large amounts of methane during drilling and an increase in the downhole log-measured acoustic velocities and electrical resistivities. The well-log-inferred, gas-hydrate-bearing interval in the Blake Ridge of 623 to 1,476 ft [190 to 450 m] below the sea floor (as depicted in Figure 6) is characterized by a distinct stepwise increase in both electrical resistivity (increase of about 0.1 to 0.3 ohm-m) and acoustic velocity (increase of about 0.1 to 0.3 km/sec). The depth of the lower boundary of the log inferred gas-hydrate-bearing interval on the Blake Ridge is in rough accord with the predicted base of the methane hydrate stability zone and it is near the lowest depth of the observed interstitial-water chlorinity anomaly (Figure 6).[1]

Dillon and Max, [5] describe the type of traps that can occur and the relationship to seismic reflections and discuss the free gas zone below the gas hydrate stability zone. They note that there is (1) a general increase in hydrate concentration downward in the gas hydrate stability zone, (2) the seismic profile suggests that significant lateral variations in gas hydrate concentration exist, and (3) the highest concentrations are to be found above sites where the maximum amounts of free gas are trapped beneath the gas hydrates stability zone. They hypothesize that concentration of hydrate results from upward gas transfer from these free-gas traps. The gas traps that use the base of the gas hydrate stability zone as a seal can take many forms as illustrated in Figure 7.

Cascadia Continental Margin Gas Hydrate Occurrence. BSRs have been extensively mapped on the inner continental margin of northern California and inferred from limited seismic data to extend northward to offshore Canada.[1] The area is shown in Figure 8. Several sampling and coring operations have been performed as part of the Ocean Drilling Program (ODP) and confirmed the presence of gas hydrates near the sea floor. Leg 146 of the ODP involved four locations off the Oregon and Vancouver Island as shown in Figure 8. Site 889, located off the west coast of Vancouver Island, provided indirect evidence from recovered cores, downhole geophysical surveys, and borehole logging data that gas hydrates occurred within the interval from about 418.6 to 749.3 ft [127.6 to 228.4 m] below the sea floor as shown in Figure 9. The evidence suggested that most of the gas hydrates at Site 889 occur as finely disseminated pore-filling substances. Temperature measurements of the recovered cores and the dilution of the pore-water salts led to an estimated volume of sediment porosity occupied by gas hydrate ranging from a minimum of about 5% immediately below the sea floor to a maximum of about 39% near the bottom of well-log-inferred occurrence at Site 889.[1]

North Slope of Alaska Gas Hydrate Occurrence.
The occurrence of natural gas hydrate on the North Slope was first confirmed with data from the Northwest Eileen State-2 well located in the northwest part of the Prudhoe Bay oilfield. Studies of pressurized core samples, downhole logs, and the results of formation production testing confirmed the occurrence of three gas-hydrate-bearing stratigraphic units in this well. Gas hydrates are also inferred to occur in an additional 50 exploratory and production wells in northern Alaska based on downhole logs responses calibrated to the known gas hydrate occurrences in the Northwest Eileen State-2 well. All these gas hydrates are geographically restricted to the area

overlying the eastern part of the Kuparuk Field and the western part of the Prudhoe Bay field as shown in Figure 10(a). [1]

The gas-hydrate accumulation in the Prudhoe Bay-Kupurak River is restricted to Tertiary age sediments of the Sagavanirktok Formation, which consists of shallow-marine shelf and delta-plain deposits composed of sandstone, shale, and conglomerate.[1] The Sagavanirktok Formation also includes the West Sak and Ugnu sands, which are estimated to contain from 26 to 44 billion barrels of in-place heavy oil.[1, 11]

Many of the wells have multiple gas-hydrate-bearing units, with individual occurrences ranging from 10- to 100-ft [3- to 30-m] thick. Most of the well-log-inferred gas hydrates occur in six laterally continuous sandstone and conglomerate units as shown in Figure 10(b). Additionally, 3-D seismic surveys and downhole logs from wells in the western part of the Prudhoe Bay Field indicate the presence of several large free-gas accumulations trapped stratigraphically downdip below four of the log-inferred gas hydrate units as depicted in Figure 10(b). [1]

The volume of gas within the gas hydrates of the Prudhoe Bay-Kuparuk River area is estimated to be about 35 to 42 Tcf.[1] The presence of such a large volume of methane at the same location as the West Sak and Ugnu heavy oil deposits raises the possibility that this gas can be used in enhanced recovery operations for this heavy oil.

Mackenzie River Delta of Canada Gas Hydrate Occurrence. Assessments of gas hydrate occurrences in the Mackenzie Delta-Beaufort Sea area have been made mainly on the basis of data obtained during the course of hydrocarbon exploration conducted over the past three decades.[1] A total of 25 wells have been identified as containing possible or probable gas hydrates as shown in Figure 11. The gas hydrate research well (JAPEX/JNOC/GSC Mallik 2L-38) was designed to investigate the occurrence of in-situ natural gas hydrates in the Mallik area (Figure 11). The Mallik 2L-38 well was drilled in 1998 near the location of the existing Mallik L-38 well, which was drilled by Imperial in 1972, and was believed to have encountered at least ten significant gas-hydrate-bearing stratigraphic units. A major emphasis for the Mallik 2L-38 well was to obtain core from the log-inferred gas hydrate zones identified in the Mallik L-38 well. Thirteen coring runs resulted in about 121 ft [37 m] of core being recovered from the gas hydrate interval (2,880 to 3,097 ft [878 to 944 m]). Pore space gas hydrate and several forms of visible gas hydrate were observed in a variety of sediment types. The Kugmallit Sequence consists of interbedded sandstone and siltstone. The well log inferred gas hydrate is from 2920 to 3609 ft [890 to 1100 m] as shown in Figure 12. Archie-calculated Hydrate saturations calculated from log data by the Archie method of up to 90% are reported.[1]

Microbial cell communities were obtained and characterized from the gas-hydrate-bearing sediments from the Mallik 2L-38 well from depths of more than 2,950 ft [900 m]. [7] Although the stable carbon isotope signature of the methane in the MacKenzie Bay Sequence suggests a thermogenic source for the gas, [8] the presence of methanogenic bacteria in the gas hydrate bearing cores suggests a biogenic source may be contributing as well. The relative importance and impact of biogenic production of methane in the formation of gas hydrates remains to be fully quantified and understood.

An additional MacKenzie Delta well is planned by the Japan National Oil Company (JNOC) for February 2002 in collaboration with the Geological Survey of Canada (GSC), United States Geological Survey (USGS), United States Department of Energy (USDOE) and the GeoForschungs Zentrum, Germany (GFZ) to test production of natural gas from the Mackenzie Delta gas hydrate zone.

Nankai-Trough Offshore Japan Gas Hydrate Occurrence. About a dozen areas have been identified by BSR as potential gas-hydrate reservoirs off Japan. From November 1999 to February 2000, an exploration well was drilled by a group led by the Japan Ministry of International Trade and Industry (MITI) to seek a new source of energy for Japan.[12] The well was drilled at the location shown in Figure 13 by JNOC in collaboration with the Japan Petroleum Exploration Company (JAPEX). Six wells were drilled; two pilot holes 98 ft [30 m] from the main hole and three additional survey holes to obtain additional logs and core. The wells were drilled through the BSR horizon and a hydrate rich formation was confirmed between 3,724 and 3,980 ft [1135 and 1213 m] below mean sea level; the wells were drilled in 3,100 ft [945 m] water depth. The two pilot holes were drilled before the main hole to determine drilling safety issues and coring depths in the main hole. The main hole was cored and logged in the expected hydrate interval and then drilled to a total depth of 9,186 ft [2800 m] to explore for conventional gas and oil potential. No conventional oil and gas was observed. Three additional survey holes were then drilled from 32.8 ft to 328 ft [10 m to 100 m] from the main hole for additional logging and coring through the gas hydrate interval.

The coring operation included a conventional core barrel and a pressure-temperature core sampler (PTCS). [12] The PTCS runs had an average recovery of 37% (95 ft [29 m] in 260 ft [79 m] cut interval). Most samples were silt and clay and showed little or no evidence of hydrate. However, some sand zones up to 6.6 ft [2 m] thick showed gas bubbling on the surface. Analysis of pore water from this area showed chlorine anomalies indicative of gas hydrates. Temperature probes inserted into these sand samples registered lowered temperatures indicative of an endothermic reaction proceeding inside the cores, which is attributed to disassociation of gas hydrates. A white hydrate crystal was visible in one core sample from a depth of 3783 ft [1153 m] from survey hole No. 2. From the core and logging and drilling evidence it was concluded that gas hydrate was present in several sand layers between 3,724 and 3,980 ft [1135 and 1213 m] in this area at saturations up to 80%. See Reference 12 (OTC 13040, Takahasi et al.) for a complete description of the well program and results.

Current estimates indicate a potential for as much as 1,750 Tcf of gas may exist in the gas hydrate in the Nankai Trough.[13]

Additional results from these wells, presented at the Poster Session at the Annual AAPG Meeting, Denver 4-6, 2001 showed evidence that gas hydrates were present as intergranular pore filling in sand layers.[14] Photographs also showed that the areas of highest hydrate concentration were completely collapsed. It appears from the evidence that the formations will be highly unconsolidated when the pore-filling gas hydrate has been dissociated. Therefore, production of gas can be expected to be accompanied by high levels of sand and water production and the potential of significant formation compaction.

Discussion of Gas Hydrate Assessments. The examples discussed above demonstrate the nature of the evidence for gas hydrate accumulations and the basis for the widely varying estimates in the literature.[2] Gas hydrates clearly exist in many locations throughout the world and can form wherever the necessary temperature and pressure conditions, gas source, water, and a trapping mechanism exist. However, the evidence is still quite sparse and, although very encouraging, does not provide the type of information essential to making major investments for significant pilot testing of production technology. Clearly much remains to be learned to provide the basis for the level of economic evaluation required for industry investment in gas hydrates development.

It is also evident that this is an area where government supported research is essential. Industry is interested and involved but to a large degree concerned more about the impact of gas hydrates on safety and stability issues related to deepwater development than as a resource to be developed. The research budget available to the USDOE to advance its research program was $500K in fiscal year (FY) 1999, $2.9 million in FY 2000, and about $10 million in FY 2001. It is currently expected to be about $10 million in FY 2002 as well. This is not a sufficient level of funding to make rapid progress in developing the understanding and the technology required to answer the critical questions essential to making methane hydrates a significant part of the nation's energy future.

Production Options

Proposed methods of producing gas hydrates have been discussed by numerous authors.[1,4,15] All involve some method to dissociate or melt the hydrate. The methods include (1) heating the reservoir beyond the hydrate formation temperature, (2) decreasing the reservoir pressure beyond the dissociation temperature, or (3) injecting an inhibitor, such as methanol or glycol, into the reservoir to decrease hydrate stability conditions. These methods are illustrated in Figure 14.

The use of horizontal wells with producers above or below injectors is an obvious possibility to improve contact and economics. Such an option was included in a thermal reservoir simulation model of production from naturally occurring gas hydrate accumulations by Swinkels, et al.[14] Their paper provides a good summary of the type of data needed to perform a reservoir simulation of the potential for production from a gas hydrate accumulation. Information they identified as essential but not currently available includes saturation of the gas-hydrate phase, the water or ice phase, and potentially a free gas phase; relative permeability of each phases; the heat capacity and thermal conductivity of the hydrate-containing formations; compaction parameters; and rates of hydrate decomposition in sediments under field conditions. Before confidence can be established in simulations of production schemes most of this information must be developed.

Production of gas from a hydrate zone will require technology to produce from mostly unconsolidated formations that can be expected to collapse and flow when hydrates melt or dissociate. The resulting formation compaction and water and sand production may be significant and difficult to manage.

Technology and Data Needs

All the technology currently used for conventional oil and gas resource and reserve calculations must be developed and confirmed for gas hydrate accumulations. Technology must be developed to better interpret seismic and other indirect evidence for hydrate accumulations to provide a better estimate of the area and volume of the accumulations. The ability to determine the amount of gas hydrate in those accumulations must also be developed, which includes the ability to determine the character and distribution of gas hydrates in sediments as illustrated in Figure 3. To determine such a value, it is essential that a better understanding of how gas hydrates form in sediments of various types and characteristics be developed. Some of this work can be done by making gas hydrates in the laboratory under simulated reservoir conditions and in a variety of sediment types but it will be essential to confirm that laboratory cores are representative of natural accumulations by obtaining representative (preferably native state) cores from gas hydrate formations. The technology must not only be developed to obtain and preserve the cores but to prepare the cores for laboratory measurements without destroying them or altering them significantly. This is not an easy task for any oil or gas field cores but even more challenging when dealing with unconsolidated cores where the cementing material will melt.

Significant effort is underway by many research groups to make gas hydrates in sediments in the laboratory in controlled environments. For such measurements to be useful, it is essential that these laboratory cores be representative of in-situ conditions. However, at the present time there is no way to confirm that laboratory cores will provide information that is representative of in-situ conditions. Therefore, it seems imperative that the ability to obtain cores from in-situ gas-hydrate zones and successfully analyze them in the laboratory is essential. The only alternative to developing this capability would be to conduct long-term production tests to confirm log-calculated values. This option will be expensive and difficult to justify to industry management in the near term.

Conclusions

1. The amount of natural gas believed to be contained in gas-hydrate accumulations world wide may be twice that of all other hydrocarbon sources, which makes it impossi-

ble to ignore them for their potential value as an energy resource.

2. The evidence for gas hydrate accumulations is steadily mounting in the offshore areas around continental margins and in Arctic permafrost regions based on seismic data showing BSR's in many locations and through the drilling of test wells in these locations.
3. The evidence from recent coring operations offshore Japan and in the MacKenzie Delta of Canada indicate that gas hydrate saturation may be high (80 to 90%) in sand sections, which provides hope that some accumulations will have resource potential. However, in areas that only contain dispersed gas hydrates at low saturation levels, it may not be possible to obtain high enough rates of production under any scheme to make them attractive as potential resources. Locations, such as the Alaska North Slope, where infrastructure already exists and the gas from hydrates could be used to enhance heavy oil production may provide the best motivation to develop and test technology.
4. The technology to make good assessments of the size and character of gas hydrate accumulations must be developed and demonstrated by continued drilling in the most promising areas.
5. Technology to obtain representative cores, transport them to laboratories and analyze them for the basic data essential to reservoir evaluation must be developed.
6. Technology must be developed and demonstrated that gas can be produced from gas hydrates accumulations at sufficient sustained rates at low enough operating costs to provide adequate economic incentives to continue the development of the technology.
7. The technology to characterize and produce gas hydrates will require the involvement of petroleum industry professionals of all disciplines.
8. The long term nature of gas hydrates potential makes it essential that governments join with industry to provide the funding necessary to develop the knowledge and essential technologies to determine if gas hydrates will become a resource or remain a problem.

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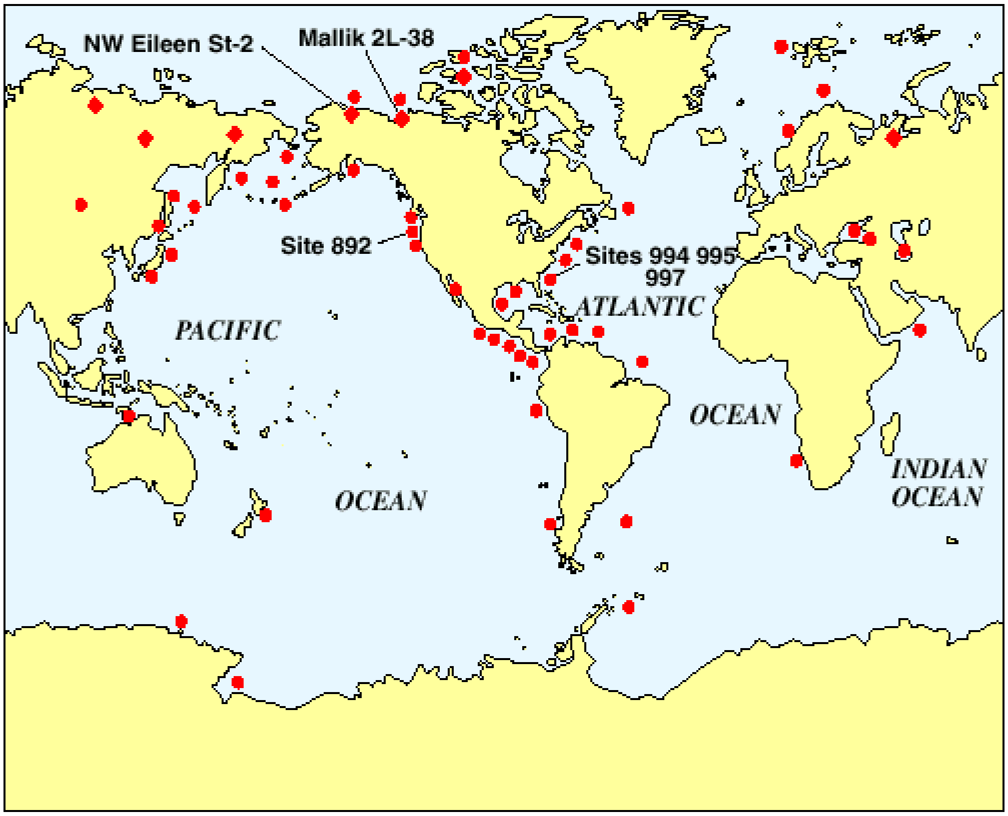
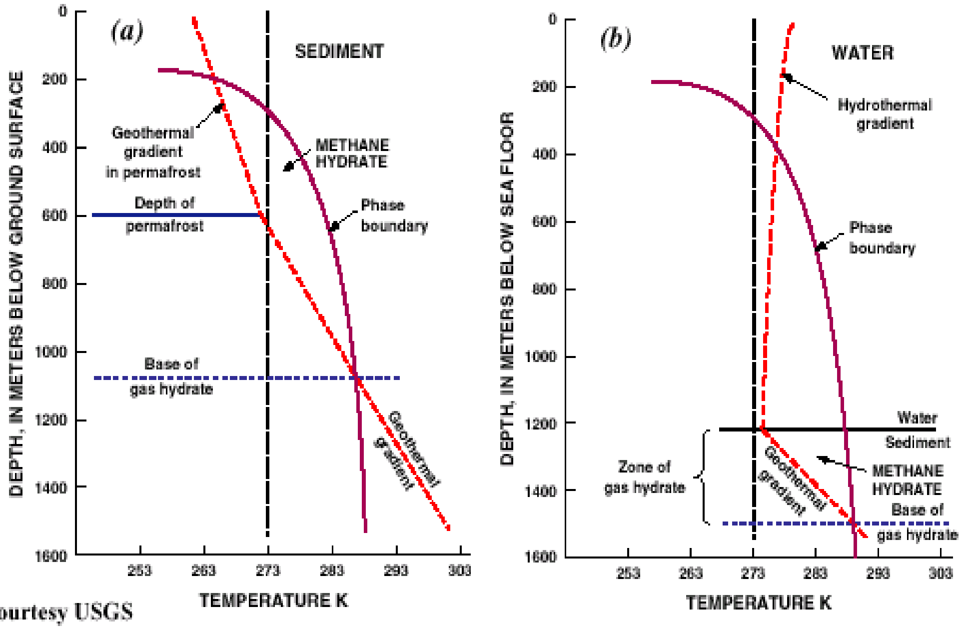


Fig. 1 – Locations on known and inferred gas hydrate occurrences in oceanic sediment of outer continental margins (●), and permafrost regions (♦) (Collett;[1] modified from Kvenvolden, 1993).



Courtesy USGS

Figure 2. Illustration of methane hydrate stability zones: (a) permafrost regions, (b) seafloor regions (from Collett[1]).

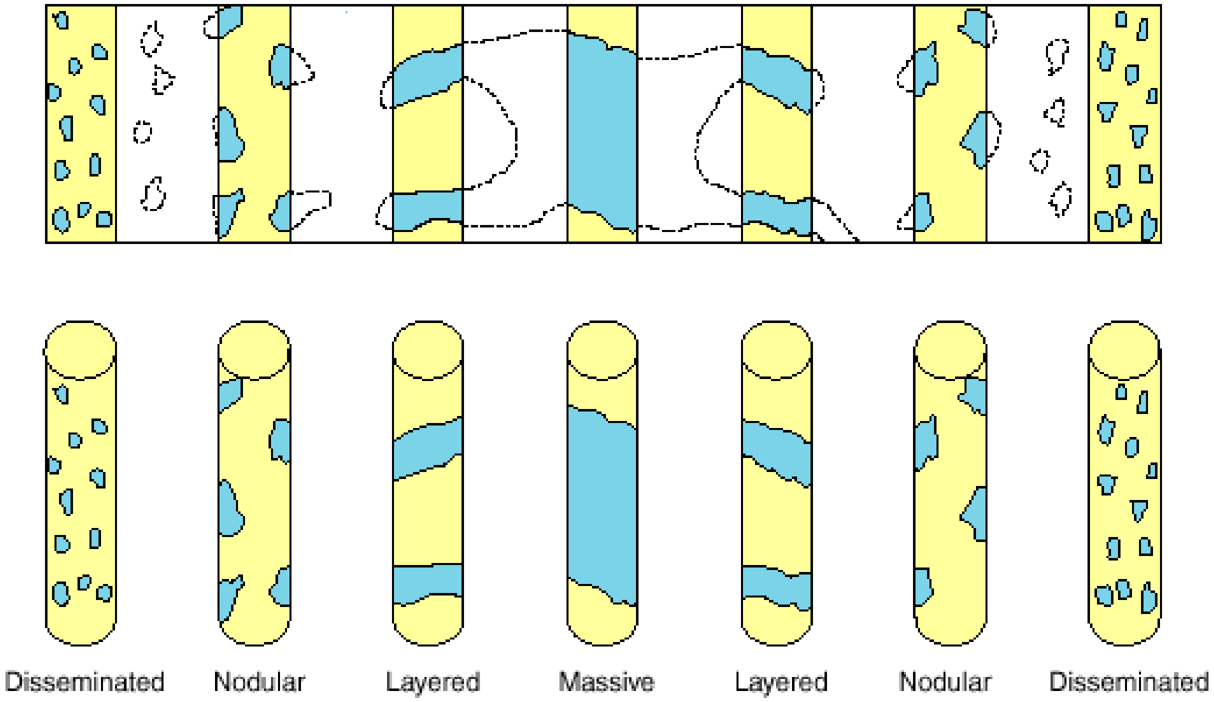


Figure 3. Representations of potential gas hydrate occurrences and configurations, Collett,[1] Sloan.[2]

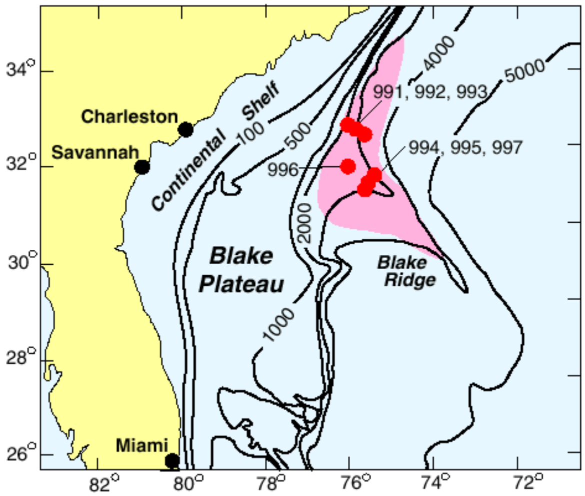


Figure 4. The Blake Ridge topographic feature. (Courtesy USGS, Collett[1])

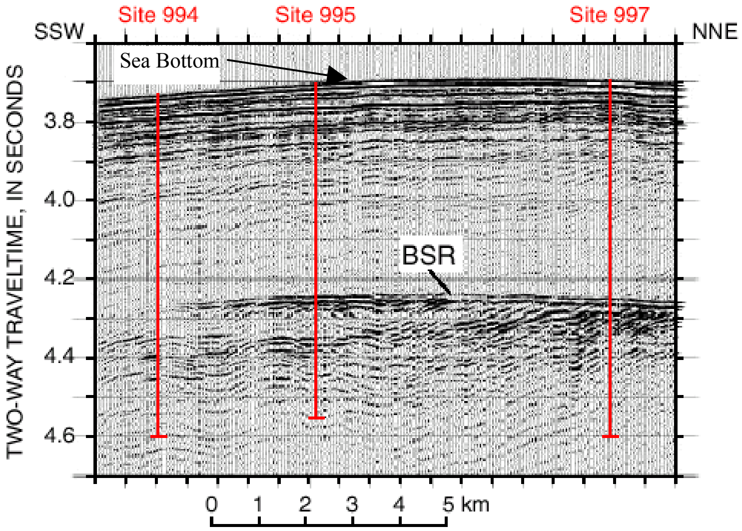


Figure 5. Example of bottom-simulating reflector (BSR) along portion of the Blake Ridge. (Courtesy USGS, Collett[1])

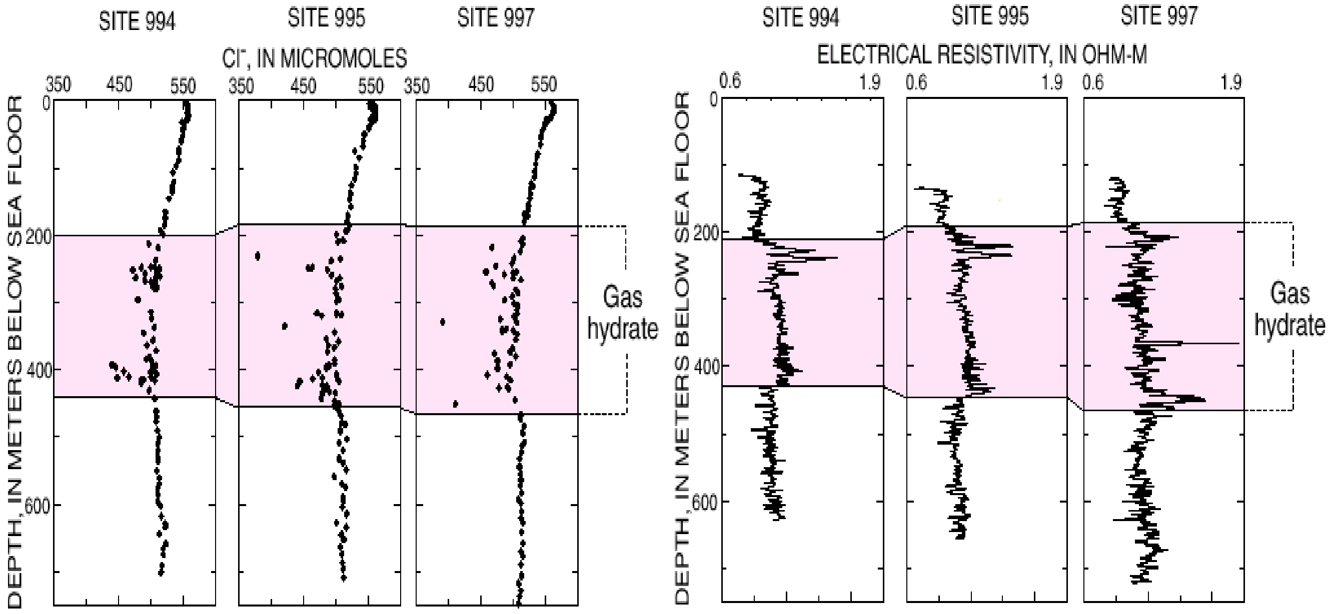


Figure 6. Interstitial chloride concentrations and downhole log data from ODP Leg 164, Blake Ridge, Sites 994, 995, 997. (Courtesy USGS, Collett[1])

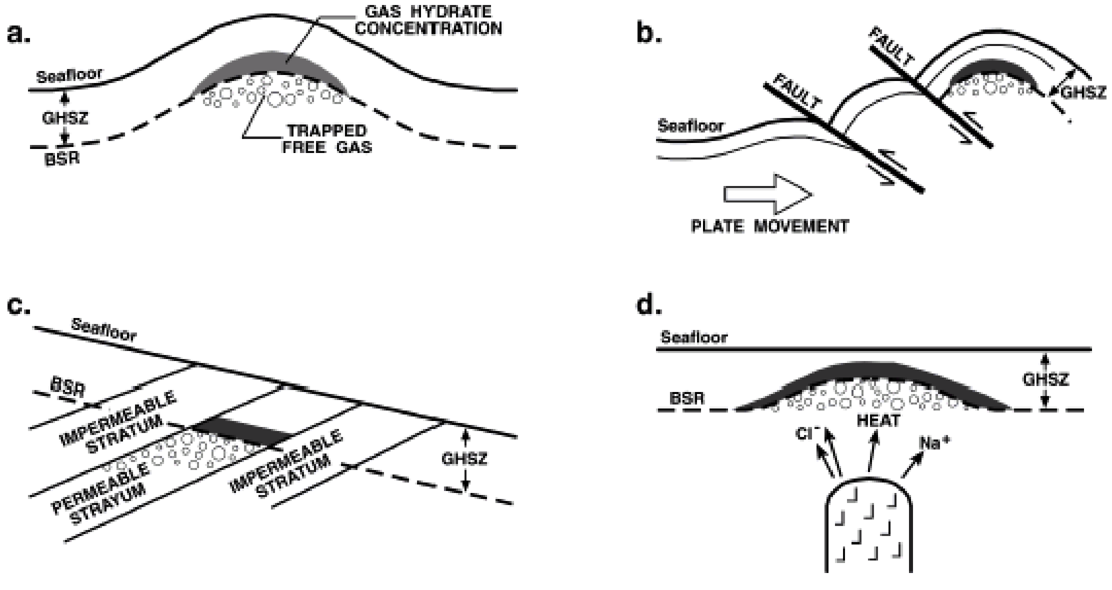


Figure 7. Diagrammed examples of types of gas traps beneath the gas bearing-sediments of the gas hydrates stability zone (GHSZ). After Dillon and Max[5,6]

(a) A simple hill on the seafloor. The base of the GHRZ, marked by a BSR, tends to follow an isotherm and thermal gradients generally remain fairly constant resulting in the base of the GHSZ tending to parallel the seafloor.

(b) A seafloor hill similar to (a), but formed by tectonic folding.

(c) A simple trap in which strata dipping into the seafloor are sealed at their updip ends by gas hydrate.

(d) A gas trap formed by doming of the base of the GHSZ above a salt diapir.

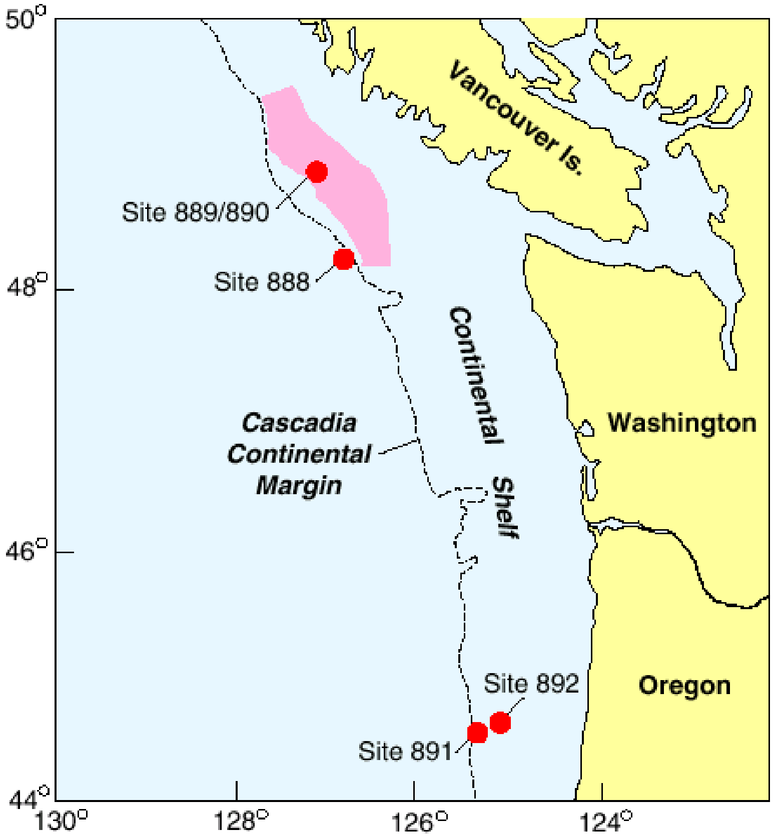


Figure 8. Cascadia Continental Margin Hydrate Occurrence area. (Courtesy USGS, Collett[1])

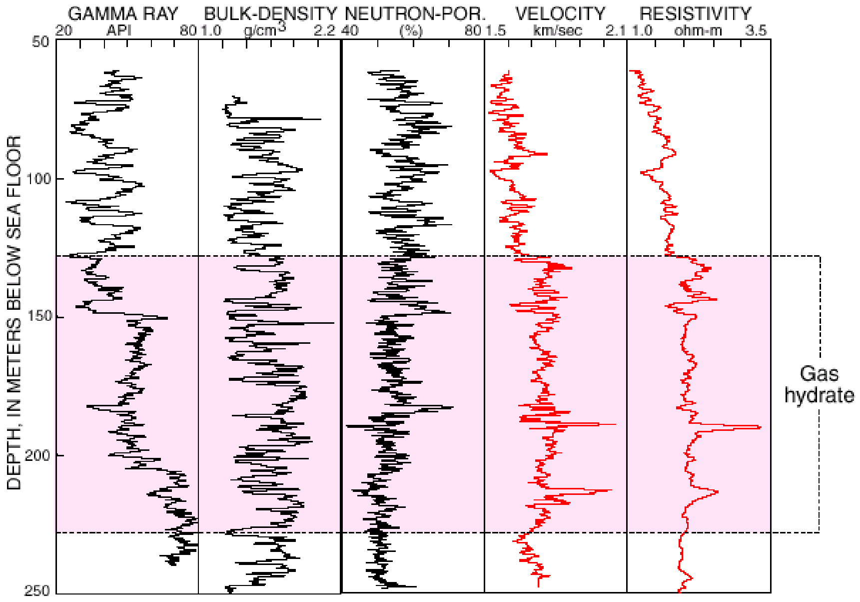
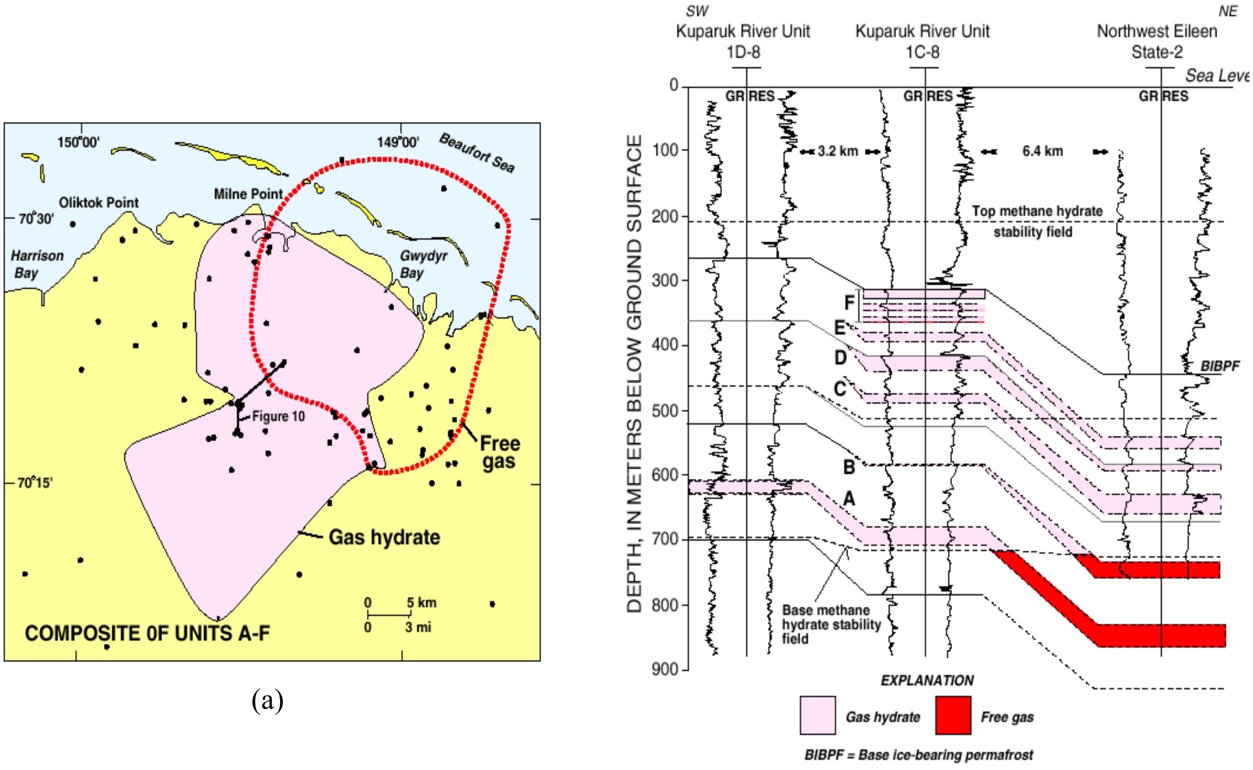


Figure 9. Log inferred gas hydrate zone in Cascadia Margin, Site 889.[1]



(a)

(b)

Figure 10. Locations of Prudhoe Bay–Kuparuk River field gas hydrates and free gas accumulations (from Collett[1]).

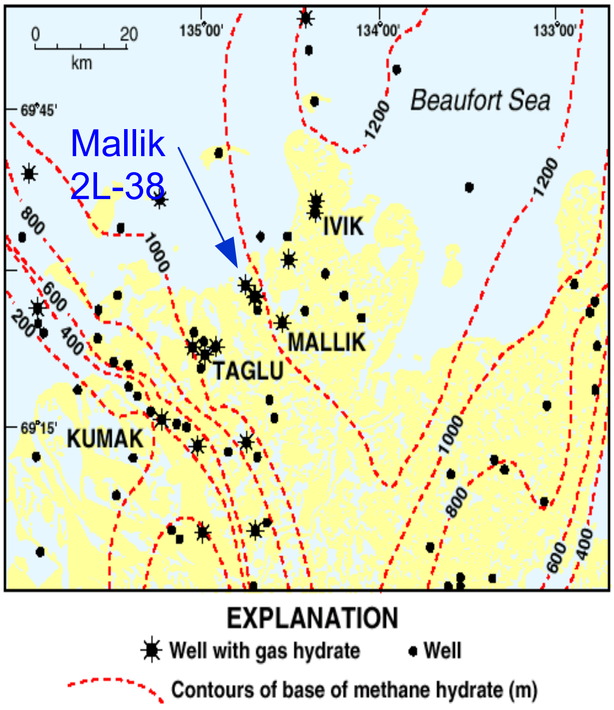


Figure 11. Mackenzie River Delta of Canada area with gas hydrate containing wells identified. (Collett[1]).

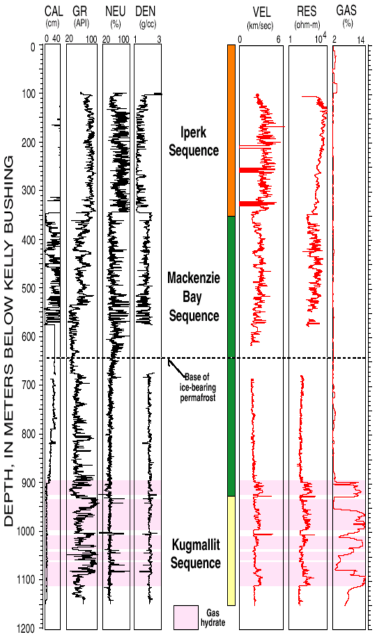


Figure 12. Mallik 2L-38, Mackenzie Delta Canada, core and well-log inferred gas hydrate occurrence. (Collett[1])

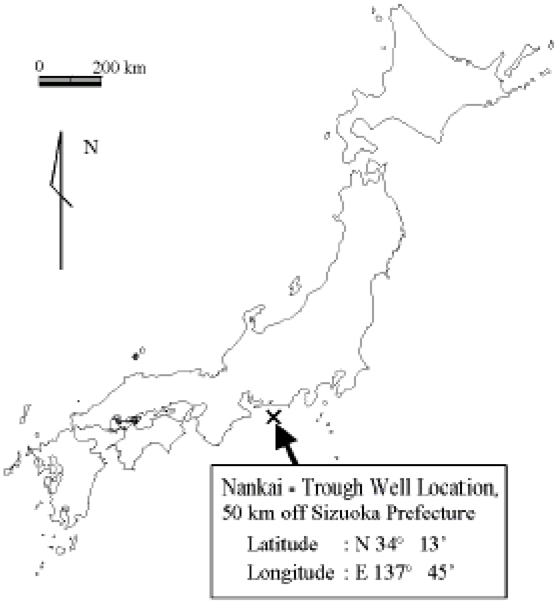


Figure 13. Nankai-Trough, Offshore Japan, gas hydrate well location. Hideaki, et al.. OTC 13040

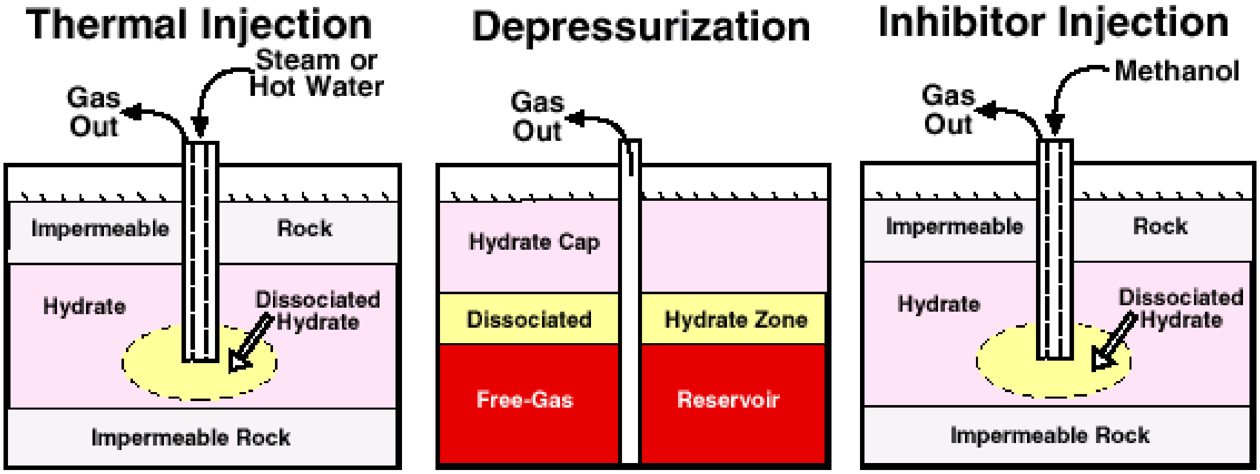


Figure 14. Gas hydrate production options. (Collett USGS[1])