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## **Natural Gas Hydrates: Resource of the 21<sup>st</sup> Century?**

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### **ABSTRACT**

The estimated amount of gas in the hydrate accumulations of the world greatly exceeds the volume of known conventional gas reserves. However, the role that gas hydrates will play in contributing to the world's energy requirements will depend ultimately on the availability of sufficient gas hydrate resources and the "cost" to extract them. Yet considerable uncertainty and disagreement prevails concerning the world's gas hydrate resources.

Gas hydrates occur in sedimentary deposits under conditions of pressure and temperature present in permafrost regions and beneath the sea in outer continental margins. The combined information from Arctic gas-hydrate studies shows that, in permafrost regions, gas hydrates may exist at subsurface depths ranging from about 130 to 2,000 m. The presence of gas hydrates in offshore continental margins has been inferred mainly from anomalous seismic reflectors known as bottom-simulating reflectors, that have been mapped at depths below the sea floor ranging from about 100 to 1,100 m. Current estimates of the amount of gas in the world's marine and permafrost gas hydrate accumulations are in rough accord at about 20,000 trillion cubic meters.

Gas hydrate as an energy commodity is often grouped with other unconventional hydrocarbon resources. In most cases, the evolution of a non-producible unconventional resource to a producible energy resource has relied on significant capital investment and technology development. To evaluate the energy resource potential of gas hydrates, will also require the support of sustained research and development programs.

Despite the fact that relatively little is known about the ultimate resource potential of natural gas hydrates, it is certain that gas hydrates are a vast storehouse of natural gas and significant technical challenges need to be met before this enormous resource can be considered an economically producible reserve.

## **INTRODUCTION**

The discovery of large gas hydrate accumulations in terrestrial permafrost regions of the Arctic and beneath the sea along the outer continental margins of the world's oceans has heightened interest in gas hydrates as a possible energy resource. However, significant to potentially insurmountable technical issues need to be resolved before gas hydrates can be considered a viable option for affordable supplies of natural gas.

Disagreements over fundamental issues such as volume of gas stored within delineated gas hydrate accumulations and the concentration of gas hydrates within hydrate-bearing reservoirs have demonstrated that we know very little about gas hydrates. Recently, however, several countries, including Japan, India, and the United States, have launched ambitious national projects to further examine the resource potential of gas hydrates. These projects may help answer key questions dealing with the properties of gas hydrate reservoirs, the design of production systems, and, most importantly, the costs and economics of gas hydrate production.

It is proposed in this paper that the evolution of gas hydrates as a viable source of natural gas, like any other unconventional energy resource (e.g., deep gas, shale gas, tight gas sands, and coalbed methane), will follow a predictable path from research and

discovery to implementation (Figure 1); however, insurmountable barriers may exist along this pathway.

Today, most of the gas hydrate research community is focused on three fundamental issues: WHERE do gas hydrates occur, HOW do gas hydrates occur in nature, and WHY do gas hydrates occur in a particular setting. However, relatively little has been done to integrate these distinct research topics or evaluate how collectively they affect the ultimate resource potential of gas hydrates. Only after understanding the fundamental aspects of WHERE-HOW-WHY gas hydrates occur in nature will we be able to make accurate estimates of how much gas is trapped within the gas hydrate accumulations of the world. Even with the confirmation that gas hydrates may exist in considerable volumes, significant technical, economic, and political issues need to be resolved before gas hydrates can be considered a viable energy resource.

In this paper, I have attempted to review the status of gas hydrates as a future energy resource. The technical and non-technical factors controlling the ultimate resource potential of gas hydrates have been identified and assessed. The fundamental questions of WHERE do gas hydrates occur, HOW do gas hydrates occur in nature, and WHY do gas hydrates occur in a particular setting have been individually reviewed and discussed. In addition, published gas hydrate volume assessments have been summarized and the production technology needed to extract the world's gas hydrate resources are assessed. The paper concludes with a discussion of the economic and political motivations that may eventually lead to gas hydrate production. However, before proceeding with the assessment of the future energy resource potential of gas hydrates, this paper begins with a technical overview of gas hydrate physical properties and a review of four relatively well characterized gas hydrate accumulations.

## GAS HYDRATE TECHNICAL REVIEW

Under appropriate conditions of temperature and pressure (Figure 2), gas hydrates usually form one of two basic crystal structures known as Structure-I and Structure-II (Figure 3). Each unit cell of Structure-I gas hydrate consists of 46 water molecules that form two small dodecahedral voids and six large tetradecahedral voids. Structure-I gas hydrates can only hold small gas molecules such as methane and ethane, with molecular diameters not exceeding 5.2 angstroms. The chemical composition of a Structure-I gas hydrate can be expressed as  $8(\text{Ar}, \text{CH}_4, \text{H}_2\text{S}, \text{CO}_2)46\text{H}_2\text{O}$  or  $(\text{Ar}, \text{CH}_4, \text{H}_2\text{S}, \text{CO}_2)5.7\text{H}_2\text{O}$  (Makogon, 1981). The unit cell of Structure-II gas hydrate consists of 16 small dodecahedral and 8 large hexakaidecahedral voids formed by 136 water molecules. Structure-II gas hydrates may contain gases with molecular dimensions in the range of 5.9 to 6.9 angstroms, such as propane and isobutane. The chemical composition of a Structure-II gas hydrate can be expressed as  $8(\text{C}_3\text{H}_8, \text{C}_4\text{H}_{10}, \text{CH}_2\text{Cl}_2, \text{CHCl}_3)136\text{H}_2\text{O}$  or  $(\text{C}_3\text{H}_8, \text{C}_4\text{H}_{10}, \text{CH}_2\text{Cl}_2, \text{CHCl}_3)17\text{H}_2\text{O}$  (Makogon, 1981). At conditions of standard temperature and pressure (STP), one volume of saturated methane hydrate (Structure-I) will contain as much as 189 volumes of methane gas -- because of this large gas-storage capacity, gas hydrates are thought to represent an important source of natural gas.

An overview of gas hydrate structures would not be complete without mentioning the newly discovered hydrate structure, Structure H. The existence of this structure was determined by laboratory nuclear magnetic resonance studies of Ripmeester et al. (1987), and is characterized by three types of cages. Structure H hydrates have been shown to be unique, with a number of large molecules able to fit into the largest cage of these newly discovered gas hydrate. Structure H guest molecules include numerous naturally occurring substances, including adamantane, gasoline range hydrocarbons, and naphthalene ingredients. For a complete description of the structure and properties of gas hydrates see the summary by Sloan (1998).

Gas hydrates have been inferred to occur at about 50 locations throughout the world (Figure 4, modified from Kvenvolden, 1988). However, only a limited number of gas hydrate accumulations have been examined in any detail. In the following section of this paper, four of the best known marine and onshore permafrost-associated gas accumulations are introduced and described. Discussions pertaining to the volume of gas within each of the gas hydrate accumulations described in the following section are included later in the energy resource assessment section of this paper. The four gas hydrate accumulations considered include those (1) on the Blake Ridge along the southeastern continental margin of the United States, (2) along the Cascadia continental margin off the Pacific coast of the United States, (3) on the North Slope of Alaska, and (4) in the Mackenzie River Delta of northern Canada.

## **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) (Dillon et al., 1993; Lee et al., 1993), which in this region are believed to be caused by large acoustic impedance contrasts at the base of the gas-hydrate stability zone that juxtaposes sediments containing gas hydrates with sediments containing free-gas. BSRs have been extensively mapped at two locations off the east coast of the United States -- along the crest of the Blake Ridge and beneath the upper continental rise of New Jersey and Delaware (Tucholke et al., 1977; Dillon et al., 1993).

The Blake Ridge is a positive topographic sedimentary feature on the continental slope and rise of the United States (Figure 5). The crest of the ridge extends approximately perpendicular to the general trend of the continental rise for more than 500 km to the southwest from water depths of 2,000 to 4,800 m. The Blake Ridge is thought to be a large sediment drift that was built upon transitional continental to oceanic crust by the complex accretion of marine sediments deposited by longitudinal drift currents (Tucholke et al., 1977). The Blake Ridge consists of Tertiary to Quaternary sediments of hemipelagic muds and silty clay (Shipboard Scientific Party, 1996). The thickness of the methane-hydrate stability zone in this region ranges from zero along the northwestern edge of the continental shelf to a maximum thickness of about 700 m along the eastern edge of the Blake Ridge (Collett, 1995). The occurrence of gas hydrates on the Blake Ridge was confirmed during Leg 76 of the Deep Sea Drilling Project (DSDP) when a sample of gas hydrate was recovered from a sub-bottom depth of 238 m at Site 533 (Shipboard Scientific Party, 1980).

Leg 164 of the Ocean Drilling Program (ODP) (Shipboard Scientific Party, 1996) was designed to investigate the occurrence of gas hydrate in the sedimentary section beneath the Blake Ridge (Figure 5). Sites 994, 995, and 997 comprise a transect of holes that penetrate below the base of gas hydrate stability within the same stratigraphic interval

over a relatively short distance (Figure 6). This transect of holes on the southern flank of the Blake Ridge extends from an area where a BSR is not detectable to an area where an extremely well-developed and distinct BSR exists (Figure 6). The presence of gas hydrates at Sites 994 and 997 was documented by direct sampling; however, no gas hydrates were conclusively identified at Site 995 (Shipboard Scientific Party, 1996). Although a BSR does not occur in the seismic reflection profiles that cross Site 994, several pieces of gas hydrate were recovered from 259.90 mbsf (mbsf = meters below sea floor) in Hole 994C and disseminated gas hydrate was observed at almost the same depth in Hole 994D. One large, solid piece (about 15 cm long) of gas hydrate was also recovered from about 331 mbsf at Site 997 (Hole 997A). 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 190 to 450 mbsf in all the holes drilled on the Blake Ridge (Figure 7).

The depths to the top and the 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 (Figure 7). Interstitial water chloride concentrations were used to establish whether gas hydrate occurred within a given core sample, based on the observation that gas hydrate decomposition during core recovery releases water and methane into the interstitial pores, resulting in a freshening of the pore-waters. The observed chloride concentrations also enable the amount of gas hydrate that occurs on the Blake Ridge to be established by calculating the amount of interstitial water freshening that can be attributed to gas hydrate dissociation. The estimated gas-hydrate saturations in the recovered cores had a skewed distribution, ranging from a maximum of about 7% and 8.4% at Sites 994 and 995 to a maximum of about 13.6% at Site 997. For a more complete discussion on the chlorinity calculated gas hydrate contents see Shipboard Scientific Party (1996).

Natural gas hydrate occurrences are generally characterized by the release of unusually large amounts of methane during drilling and an increase in downhole log-measured acoustic velocities and electrical resistivities. The well log inferred gas-hydrate-bearing stratigraphic interval on the Blake Ridge (190-450 mbsf; Figure 7) is characterized by a distinct stepwise increase in both electrical resistivity (increase of about 0.1-0.3 ohm-m) and acoustic velocity (increase of about 0.1-0.2 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 7).

### **Cascadia Continental Margin Gas Hydrate Occurrence**

BSRs have been extensively mapped on the inner continental margin of northern California (Field and Kvenvolden, 1985). These constitute a single, inferred, gas-hydrate accumulation that covers an area of at least 3,000 km<sup>2</sup> on the Klamath Plateau and the upper continental slope at water depths ranging from 800 to 1,200 m. Limited seismic data show that this regionally extensive inferred gas-hydrate occurrence extends northward to offshore Canada (Hyndman et al., 1996) and seaward at least to the base of the slope (3,000 m water depth). The occurrence of gas hydrates on the Pacific margin of the United States was confirmed in 1989 when numerous gas-hydrate samples were obtained during seabed (0-6 mbsf) sediment coring operations (water depths ranging between 510 and 642 m) in the Eel River Basin (Brooks et al., 1991). Recovered gas-hydrate samples consisted of dispersed crystals, small nodules, and layered bands. The location of these gas hydrates coincides nearly, but not exactly, with the area of BSR-inferred gas hydrates described by Field and Kvenvolden (1985) along the northern California coast. Gas hydrates have also been recovered along the Cascadia margin from a relatively restricted zone within 17 m of the sea floor in three research coreholes drilled during Leg 146 of the Ocean Drilling



Program: Holes 892A, 892D, and 892E (Figure 8) (Shipboard Scientific Party, 1994). All of these coreholes are located on the Oregon continental slope in about 675 m of water.

Leg 146 of the Ocean Drilling Program (Shipboard Scientific Party, 1994) was designed to examine fluid movement in the Cascadia continental margin and to provide well-constrained estimates of the volume of fluid associated with accretionary sedimentary wedges. In addition, the presence of distinct BSRs on the Cascadia margin also provided an opportunity to examine the potential interrelation between the occurrence of natural gas hydrates and BSRs. Four locations were drilled off the west coast of Vancouver Island and Oregon (Figure 8). As mentioned above, gas hydrate crystals were recovered in the near-surface (2-17 mbsf) sediments at Site 892. Downhole logs and a vertical seismic profile (VSP) at Site 892 established that locally the BSR is caused by free-gas below about 71 mbsf; however, the borehole surveys yielded relatively little useful gas hydrate data.

Site 889, located off the west coast of Vancouver Island (Figure 8), yielded a wealth of data pertaining to the in-situ nature of gas hydrates on the Cascadia margin. Massive accumulations of gas hydrate were not encountered at Site 889. Rather, indirect evidence from recovered cores and downhole geophysical surveys suggests 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 pore-water salts suggest that about 10 to 40 percent of the pore-space within the sediment is filled with gas hydrate at Site 889 (Shipboard Scientific Party, 1994).

Gas hydrates were not conclusively identified at Site 889 (Shipboard Scientific Party, 1994); however, its presence was inferred, based on geochemical analyses of cores and downhole geophysical surveys (VSPs) and borehole logging data within the depth interval from about 127.6 to 228.4 mbsf (Figure 9). Similar to the observations from the Blake Ridge boreholes, the presence of gas hydrates at Site 889 was inferred on the basis of gas-rich cores, low interstitial water chloride concentrations, and low temperature measurements in the recovered cores (Shipboard Scientific Party, 1994; Spence et al.,

1995; Hyndman et al., 1996). In addition, sediment velocity data from downhole VSP and ocean bottom seismometer (OBS) surveys (Shipboard Scientific Party, 1994; Spence et al., 1995; Hyndman et al., 1996) indicate that gas hydrates occur in the 50- to 80-m-thick interval above the BSR (approximate depth of 230 mbsf) at Site 889. Observed chloride anomalies were also used to estimate the amount of gas hydrate that occurs at Site 889 by calculating the amount of interstitial water freshening that can be attributed to gas hydrate dissociation. The estimated volume of sediment porosity occupied by gas hydrate in the recovered cores ranged from a minimum of about 5% immediately below the sea floor to a maximum of about 39% near the bottom of well log inferred gas hydrate occurrence at Site 889 (Hyndman et al., 1996).

### **North Slope of Alaska Gas Hydrate Occurrence**

Previous North Slope studies (Collett, 1983; Collett et al., 1988; Collett, 1993) indicate that the Prudhoe Bay-Kuparuk River gas hydrate accumulation is restricted to Tertiary age sediments of the Sagavanirktok Formation. The Sagavanirktok Formation consists of shallow-marine shelf and delta-plain deposits composed of sandstone, shale, and conglomerate whose provenance is the Brooks Range, to the south. The Sagavanirktok Formation includes the informally named West Sak and Ugnu sands. These oil-bearing horizons have been extensively described by Werner (1987) and are estimated to contain more than approximately 6 million metric tons of in-place oil.

The occurrence of natural gas hydrate on the North Slope of Alaska was confirmed in 1972 with data from the Northwest Eileen State-2 well located in the northwest part of the Prudhoe Bay Oil Field. Studies of pressurized core samples, downhole logs, and the results of formation production testing have confirmed the occurrence of three gas-hydrate-bearing stratigraphic units in the Northwest Eileen State-2 well (reviewed by Collett, 1993). Gas hydrates are also inferred to occur in an additional 50 exploratory and production wells in northern Alaska based on downhole log responses calibrated to the

known gas hydrate occurrences in the Northwest Eileen State-2 well. Many of these wells have multiple gas-hydrate-bearing units, with individual occurrences ranging from 3- to 30-m-thick. Most of these well-log inferred gas hydrates occur in six laterally continuous sandstone and conglomerate units; all these gas hydrates are geographically restricted to the area overlying the eastern part of the Kuparuk River Oil Field and the western part of the Prudhoe Bay Oil Field (Figures 10 and 11). The six gas-hydrate-bearing sedimentary units have each been assigned a reference letter (Units A through F); Unit A is stratigraphically the deepest (Figure 10). Three-dimensional seismic surveys and downhole logs from wells in the western part of the Prudhoe Bay Oil Field indicate the presence of several large free-gas accumulations trapped stratigraphically downdip below four of the log-inferred gas hydrate units (Figures 10 and 11; Units A through D). The total mapped area of all six gas hydrate occurrences is about 1,643 km<sup>2</sup>; the areal extent of the individual units range from 3 to 404 km<sup>2</sup>. The volume of gas within the gas hydrates of the Prudhoe Bay-Kuparuk River area is estimated to be about 1.0 to 1.2 trillion cubic meters, or about twice the volume of conventional gas in the Prudhoe Bay Field (Collett, 1993).

### **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 (reviewed by Judge et al., 1994). A database presented by Smith and Judge (1993) summarizes a series of unpublished consultant studies that investigated well log data from 146 exploration wells in the Mackenzie Delta area. In total, 25 wells (17%) were identified as containing possible or probable gas hydrates (Figure 12). All of these inferred gas hydrates occur in clastic sedimentary rocks of the Kugmallit, Mackenzie Bay, and Iperk sequences (Dixon et al., 1992). Two of the occurrences were associated with ice-bearing permafrost while the remainder were beneath the permafrost interval. The frequency of gas hydrate occurrence

in offshore wells was greater, with possible or probable gas hydrates identified in 35 out of 55 wells (63%).

The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was designed to investigate the occurrence of in-situ natural gas hydrates in the Mallik area of the Mackenzie River Delta of Canada (Figure 12) (Dallimore et al., 1999). The Mallik 2L-38 gas hydrate research well was drilled near the site of the existing Mallik L-38 well, which was drilled by Imperial Oil in 1972 (Bily and Dick, 1974). As described in Collett and Dallimore (1998), the Mallik L-38 well is believed to have encountered at least 10 significant gas-hydrate-bearing stratigraphic units within the depth interval from 810.1 to 1,102.3 m. Bily and Dick (1974) concluded that each of the gas-hydrate-bearing units in the Mallik L-38 well contained substantial amounts of gas hydrate. However, no attempt was made to quantify the amount of gas hydrate or associated free gas that may have been trapped within the log inferred gas hydrate occurrences.

While drilling the Mallik 2L-38 well, a major emphasis was placed on coring the log inferred gas hydrate intervals identified in the Mallik L-38 well. A total of 13 coring runs were attempted with a variety of coring systems. Approximately 37 m of core was recovered from the gas hydrate interval (878-944 m) in the Mallik 2L-38 well (Dallimore et al., 1999). Pore-space gas hydrate and several forms of visible gas hydrate were observed in a variety of sediment types.

Data from downhole logging in both the Mallik L-38 and 2L-38 (Figure 13) wells and formation production testing in the Mallik L-38 well have been used to assess local geology, permafrost, and gas hydrate conditions. In the upper 1,500 m, three stratigraphic sequences have been identified using reflection seismic records and well data (Jenner et al., 1999): These include the Iperk Sequence (0-337.6 m), the Mackenzie Bay Sequence (337.6-918.1 m), and the Kugmallit Sequence (918.1 m-bottom of hole). The Iperk Sequence appears to be composed almost entirely of coarse grained sandy sediments. Previous coring experience (Dallimore and Matthews, 1997) indicates that the Iperk

sediments are unconsolidated. The Mackenzie Bay sequence is also sand dominated with a distinct fining upward section near its upper contact with the Iperk Sequence. The Kugmallit sequence (>918 m) consists of interbedded sandstone and siltstone. Drill-cuttings and drilling records suggest that the grain cementation in the Mackenzie Bay and Kugmallit Sequences is quite variable. The base of ice-bearing permafrost in the Mallik 2L-38 well is estimated at about 640 m on the basis of available well log information.

The well-log-inferred gas hydrate occurrence in the Mallik 2L-38 well occupies the depth interval between 888.84 and 1,101.09 m (Figures 13 and 14); however, not all of this interval is occupied by gas hydrate. The cored and logged gas hydrate occurrences in the Mallik 2L-38 well (Figure 14) exhibit deep electrical resistivity measurements ranging from 10 to 100 ohm-m and compressional-wave acoustic velocities ( $V_p$ ) ranging from 2.5 to 3.6 km/sec. In addition, the measured shear-wave acoustic velocities ( $V_s$ ) of the confirmed gas-hydrate-bearing units in the Mallik 2L-38 well range from 1.1 to 2.0 km/sec.

Bily and Dick (1974) originally interpreted the presence of free-gas in contact with gas hydrate on the basis of spontaneous-potential well log responses within several intervals of the Mallik L-38 well. They also speculated that rapid pressure responses during a production test (Production Test-1: 1,098-1,101 m) within a suspected free-gas unit are evidence of highly permeable free-gas-bearing sediments. Acoustic transit-time log data from the Mallik 2L-38 well, confirmed the occurrence of a relatively thin free-gas zone (1,100.0-1,101.9 m) at the base of the deepest downhole log-inferred gas-hydrate. As shown in Figure 14, the log-measured compressional-shear-wave velocity ratios ( $V_p / V_s$ ) below 1.8 are indicative of free-gas-bearing sediment.

## **ENERGY RESOURCE POTENTIAL OF GAS HYDRATES**

As noted in the introduction, the remaining portion of this paper deals with the assessment of the geologic, engineering, economic, and political factors that control the ultimate resource potential of gas hydrates.

### **WHERE Do Gas Hydrates Occur?**

The geologic occurrence of gas hydrates has been known since the mid-1960s, when gas-hydrate accumulations were discovered in Russia (reviewed by Makogon, 1981). As discussed in the previous section of this paper, gas hydrates are widespread in permafrost regions and beneath the sea in sediment of outer continental margins (reviewed by Kvenvolden, 1993). Cold surface temperatures at high latitudes on earth are conducive to the development of onshore permafrost and gas hydrate in the subsurface. Onshore gas hydrates (Figure 4) are known to be present in the West Siberian Basin (Makogon et al., 1972) and are believed to occur in other permafrost areas of northern Russia, including the Timan-Pechora province, the eastern Siberian Craton, and the northeastern Siberia and Kamchatka areas (Cherskiy et al., 1985). Permafrost-associated gas hydrates are also present in the North American Arctic. Direct evidence for gas hydrates on the North Slope of Alaska comes from a core-test in the Northwest Eileen State-2 well, and indirect evidence comes from drilling and open-hole industry well logs that suggest the presence of numerous gas hydrate layers in the area of the Prudhoe Bay and Kuparuk River oil fields (as discussed previously in this paper). Well-log responses attributed to the presence of gas hydrates have been obtained in about one-fifth of the wells drilled in the Mackenzie Delta, and more than half of the wells in the Arctic Islands are inferred to contain gas hydrates (Judge and Majorowicz, 1992). The recently completed Mallik 2L-38 gas hydrate research well, confirmed the presence of a relatively thick, highly concentrated, gas hydrate accumulation on Richards Island in the outer portion of the Mackenzie River Delta (Dallimore et al., 1999).

The presence of gas hydrates in offshore continental margins (Figure 4) has been inferred mainly from anomalous seismic reflectors (i.e., BSRs) that coincide with the predicted phase boundary at the base of the gas-hydrate stability zone. Gas hydrates have been recovered in gravity cores within 10 m of the sea floor in sediment of the Gulf of Mexico (Brooks et al., 1986), the offshore portion of the Eel River Basin of California (Brooks et al., 1991), the Black Sea (Yefremova and Zhizhchenko, 1974), the Caspian Sea (Ginsburg et al., 1992), and the Sea of Okhotsk (Ginsburg et al., 1993). Also, gas hydrates have been recovered at greater sub-bottom depths during research coring along the southeastern coast of the United States on the Blake Ridge (Kvenvolden and Barnard, 1983; Shipboard Scientific Party, 1996), in the Gulf of Mexico (Shipboard Scientific Party, 1986), in the Cascadia Basin near Oregon (Shipboard Scientific Party, 1994), the Middle America Trench (Kvenvolden and McDonald, 1985), offshore Peru (Kvenvolden and Kastner, 1990), and on both the eastern and western margins of Japan (Shipboard Scientific Party, 1990, 1991).

### **HOW Do Gas Hydrates Occur in Nature?**

Little is known about the nature of gas hydrate reservoirs. For example, do hydrates occur as pore-filling constituents or are they only found in massive form (Figure 15). Information about the nature and texture of reservoir gas hydrates is needed to accurately determine the amount of gas hydrate and associated gas in a given gas hydrate accumulation. The textural nature of gas hydrate in the reservoir also controls the production potential and characteristics of a gas hydrate accumulation. The physical and chemical conditions that result in different forms (disseminated, nodular, layered, massive) and distributions (uniform or heterogeneous) of gas hydrates are not understood (reviewed by Sloan, 1998). It is necessary, therefore, to systematically review descriptions of known gas hydrate occurrences and evaluate existing gas hydrate reservoir models at both microscopic and macroscopic scales in order to assess the nature of gas-hydrate-bearing

reservoirs. This section of the paper begins with a review of published gas hydrate sample descriptions from both marine and permafrost environments, which is followed by an interpretive discussion of existing and proposed microscopic and macroscopic gas hydrate reservoir models.

### ***Recovered Gas Hydrate Samples***

For this review of the nature of gas hydrate occurrences, I have relied extensively on the offshore gas hydrate sample database recently published by Booth et al. (1996). In this database, Booth et al. (1996) systematically review and describe more than 90 marine gas hydrate samples recovered from 15 different geologic regions. The individual descriptions of the gas hydrate occurrences include information on the number of recovered samples, physiographic province, tectonic setting, geographic position, water depth, sub-sea-floor depth of the recovered sample, geothermal gradient and temperature conditions, depth to the base of the gas hydrate stability zone, presence of a bottom simulating seismic reflector, thickness of the gas-hydrate-bearing sedimentary interval, thickness and size of pure gas hydrate layers and grains, habit or mode of occurrence, host sediment lithologic description, and the origin of the included gas.

In general, most of the recovered gas hydrate samples consist of individual grains or particles, which are often described as inclusions or disseminated in the sedimentary section (Figure 15). Gas hydrates also occur as, what has been described as, a cement, nodules, or as laminae and veins, which tend to be characterized by dimensions of a few centimeters or less. In several cases, thick, pure gas hydrate layers measuring as much as 3- to 4-m-thick have been sampled (DSDP Site 570; Shipboard Scientific Party, 1985). In both marine and terrestrial permafrost environments, the thickness of identified gas-hydrate-bearing sedimentary sections varies from a few centimeters to as much as 30 m (Collett, 1993; Booth et al., 1996; Dallimore et al., 1999). Most pure gas hydrate laminae and layers, however, are often characterized by thicknesses of millimeters to centimeters



(Booth et al., 1996; Dallimore and Collett, 1995; Dallimore et al., 1999). Booth et al. (1996) conclude that gas-hydrate-bearing sedimentary sections tend to be tens of centimeters to tens of meters thick, but thick zones of pure hydrate are relatively rare and only represent a minor constituent of potential gas hydrate accumulations.

The Booth et al. (1996) review along with recently published gas hydrate sample descriptions from the Mackenzie Delta (Dallimore and Collett, 1995; Dallimore et al., 1999) and the Blake Ridge (ODP Leg 164, Shipboard Scientific Party 1996), confirm that gas hydrates are usually uniformly distributed within sediments as mostly pore-filling constituents.

### ***Gas Hydrate Reservoir Models***

Most discussions on the nature or texture of gas hydrate occurrences deal with macroscopic issues (reviewed by Booth et al., 1996). However, information on the occurrence of gas hydrates at the pore-scale are needed, since many gas hydrate reservoir physical properties are controlled by microscopic parameters (Dvorkin and Nur, 1993). Of particular concern is the acoustic nature and the fluid-flow permeability characteristics of gas-hydrate-bearing sediments (Lee et al., 1993; Dvorkin and Nur, 1993).

Dvorkin and Nur (1993) along with Ecker et al. (1996) have proposed and examined two "micromechanical" models that represent the two extreme cases of gas hydrate occurrence at the pore-scale: (Model-1) gas hydrate cement grain contacts and increases the stiffness of the sediment; and (Model-2) gas hydrate is located away from grain contacts in the "bulk" pore volume, and it does not affect the stiffness of the sediment frame. Dvorkin and Nur (1993) experimentally demonstrated that even small amounts of intergranular cementation, such as proposed by gas hydrate Model-1, can dramatically increase the stiffness of granular material. Dvorkin and Nur (1993) used the intergranular gas hydrate cementation model (Model-1) to explain the occurrence of seismic bottom-simulating-reflectors (BSR's), which they attributed to a strong increase of the elastic

moduli of the rock due to the occurrence of gas hydrates at the base of the gas hydrate stability zone. Ecker et al. (1996) amplitude-versus-offset (AVO) analyses of the BSR on the Blake Ridge, however, concluded that only reservoir Model-2 could qualitatively reproduce the observed BSR, and that gas hydrates at the pore-scale are located away from the intergranular contacts, in large pores. Ecker et al. (1996) further concluded that the sediment above the BSR is uncemented and mechanically weak. However, they do not explain the acoustic parameters that control the occurrence of the BSR on the Blake Ridge. At this time, we must consider the conclusions of Dvorkin and Nur (1993) and Ecker et al. (1996) preliminary until additional laboratory field observations become available.

Before attempting to assess the volume of gas hydrate in a particular reservoir, we need to develop and define a series of reservoir models for the occurrence of gas hydrates in nature. Most reservoir models are based on simple mixing rules, where complex multi-component systems consist of simple mixtures of rock matrix (consisting of quartz, calcite, and/or clay), water (including clay-bound- and free-water), and hydrocarbons (gas and/or oil). In permafrost and relatively deep marine environments, however, other reservoir constituents can include gas hydrates and permafrost ice. The first two reservoir models to be considered represent complex gas-hydrate-bearing reservoirs both below (Model A; Figure 16a) and above (Model B; Figure 16b) the base of ice-bearing permafrost in a terrestrial setting. In both of these models the sediment matrix consists of a simple mixture of quartz, calcite, and a relatively small amount of clay. Gas hydrate reservoir Models A and B assume no free-gas phase, since all of the available gas is in the gas hydrate. The only difference between Models A and B is that Model B assumes that all of the free-water and some of the clay-bound-water are frozen. Reservoir Model C (Figure 16c) has been designed to represent a clay-rich marine gas hydrate reservoir. Reservoir Models C and A are similar, but Model C assumes the clay content of the sediment and associated volume of bound-water are higher in most marine gas-hydrate reservoirs. The last gas hydrate reservoir model to be considered may not occur in nature. Reservoir Model D (Figure 4d)

assumes that a free-gas phase exists, and that all of the available water is included in the gas hydrate. Water, being relatively abundant in nature, should not be a gas hydrate limiting factor in most reservoirs.

### **WHY Do Gas Hydrates Occur in a Particular Setting?**

Review of previous gas hydrate studies indicates that the formation and occurrence of gas hydrates is controlled by formation temperature, formation pore-pressure, gas chemistry, pore-water salinity, availability of gas and water, gas and water migration pathways, and the presence of reservoir rocks and seals (reviewed by Collett, 1995). In the following section, these geologic controls on the stability and formation of gas hydrates are reviewed and assessed.

#### ***Formation-Temperature, Formation Pore-Pressure, Gas Chemistry***

Gas hydrates exist under a limited range of temperature and pressure conditions such that the depth and thickness of the zone of potential gas-hydrate stability can be calculated. Depicted in the temperature/depth plot of Figure 17 are a series of subsurface temperature profiles from an onshore permafrost area and two laboratory-derived gas-hydrate stability curves for different natural gases (modified from Holder et al., 1987). This gas-hydrate phase-diagram (Figure 17) illustrates how variations in formation-temperature and gas composition can affect the thickness of the gas-hydrate stability zone. In Figure 17, the mean-annual surface temperature is assumed to be  $-10^{\circ}\text{C}$ ; however, the depth to the base of permafrost ( $0^{\circ}\text{C}$  isotherm) is varied for each temperature profile (assumed permafrost depths of 305 m, 610 m, and 914 m). Below permafrost, three different geothermal gradients ( $4.0^{\circ}\text{C}/100\text{ m}$ ,  $3.2^{\circ}\text{C}/100\text{ m}$ , and  $2.0^{\circ}\text{C}/100\text{ m}$ ) are used to project the sub-permafrost temperature profiles. The two gas-hydrate stability curves represent gas hydrates with different gas chemistries. One of the stability curves is for a

100% methane hydrate, and the other is for a hydrate that contains 98% methane, 1.5% ethane, and 0.5% propane.

The zone of potential gas-hydrate stability in Figure 17 lies in the area between the intersections of the geothermal gradient and the gas-hydrate stability curve. For example, in Figure 17, which assumes a hydrostatic pore-pressure gradient, the temperature profile projected to an assumed permafrost base of 610 m intersects the 100% methane-hydrate stability curve at about 200 m, thus marking the upper boundary of the methane-hydrate stability zone. A geothermal gradient of 4.0°C/100 m projected from the base of permafrost at 610 m intersects the 100% methane-hydrate stability curve at about 1,100 m; thus, the zone of potential methane-hydrate stability is approximately 900 m thick. However, if permafrost extended to a depth of 914 m and if the geothermal gradient below permafrost is 2.0°C/100 m, the zone of potential methane-hydrate stability would be approximately 2,100 m thick.

Most gas-hydrate stability studies assume that the pore-pressure gradient is hydrostatic (9.795 kPa/m; 0.433 psi/ft). Pore-pressure gradients greater than hydrostatic will correspond to higher pore-pressures with depth and a thicker gas-hydrate stability zone. A pore-pressure gradient less than hydrostatic will correspond to a thinner gas-hydrate stability zone. For example, in Figure 17, which assumes a hydrostatic (9.795 kPa/m; 0.433 psi/ft) pore-pressure gradient, the thickness of the 100% methane-hydrate stability zone with a 610 m permafrost depth and a sub-permafrost geothermal gradient of 2.0°C/100 m would be about 1,700 m. However, if a pore-pressure gradient of 11.311 kPa/m (0.500 psi/ft) is assumed, the thickness of the methane-hydrate stability zone would be increased to about 1,850 m.

The gas-hydrate stability curves in Figure 17 were obtained from laboratory data published in Holder et al. (1987). The addition of 1.5% ethane and 0.5% propane to the pure methane gas system shifts the stability curve to the right, thus deepening the zone of potential gas-hydrate stability. For example, assuming a hydrostatic pore-pressure gradient

(Figure 17), a permafrost depth of 610 m, and a sub-permafrost geothermal gradient of 4.0°C/100 m, the zone of potential methane (100% methane) hydrate stability would be about 900 m thick; however, the addition of ethane (1.5%) and propane (0.5%) would thicken the potential gas-hydrate stability zone to 1,100 m.

### ***Pore-Water Salinity***

Salt, such as NaCl, when added to a gas-hydrate system, lowers the temperature at which gas hydrates form. Pore-water salts in contact with the gas during gas hydrate formation can reduce the crystallization temperature by about 0.06°C for each part per thousand (ppt) of salt (Holder et al., 1987). Therefore, a pore-water salinity similar to that of seawater (32 ppt) would shift the gas-hydrate stability curves in Figure 17 to the left about 2°C and reduce the thickness of the gas-hydrate stability zone.

### ***Availability of Gas and Water***

Most naturally occurring gas hydrates are characterized by two crystal structures known as Structure I and Structure II (reviewed by Sloan, 1998). The ideal gas/water ratio of Structure I gas hydrate is 8/46, whereas the ideal gas/water ratio of Structure II gas hydrate is 24/136. These ideal ratios confirm the observation that gas hydrates contain a substantial volume of gas. The ideal hydrate gas/water ratios also indicate that there is a substantial amount of water stored in the gas-hydrate structure. These high gas and water concentrations demonstrate that the formation of gas hydrate requires a large source of both gas and water. Thus, it becomes necessary to quantify the potential sources of gas and water when assessing a potential gas-hydrate accumulation. In previous studies, this evaluation is based on assessing a set of minimum source-rock criteria that includes organic richness (total organic carbon), sediment thickness, and thermal maturity. It has been shown that the availability of large quantities of hydrocarbon gas from both microbial and thermogenic sources is an important factor controlling the formation and distribution of natural gas hydrates (Kvenvolden, 1988; Collett, 1993). 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.

### ***Gas and Water Migration Pathways***

Other factors controlling the availability of gas and water are the geologic controls on fluid migration. As previously shown, gas hydrates contain a substantial volume of gas and water that must be supplied to a developing gas-hydrate accumulation. If effective migration pathways are not available, it is unlikely that a significant volume of gas hydrates would accumulate. Therefore, geologic parameters such as rock permeability and the nature of faulting must be evaluated to determine if the required gas and water can be delivered to the potential hydrate reservoir.

### ***Presence of Reservoir Rocks and Seals***

The study of gas-hydrate samples recovered during research coring operations in oceanic sediments suggests that the physical nature of in-situ gas hydrates may be highly variable (Figure 15, as previously discussed in this paper). Gas hydrates were observed to be (1) occupying pores of coarse-grained rocks; (2) nodules disseminated within fine-grained rocks; (3) a solid, filling fractures; or (4) a massive unit composed mainly of solid gas hydrate with minor amounts of sediment. This review suggests that porous rock intervals serve as reservoir rocks in which gas and water can be concentrated in the amounts necessary for gas-hydrate formation. Therefore, the presence of reservoir rocks may play a role in gas-hydrate formation, particularly in well-consolidated rock intervals.

It is also speculated that the presence of effective reservoir seals or traps may play a role in gas-hydrate formation. Gas generated at depth moves upward, generally along tilted permeable carrier beds, until it either seeps at the surface or meets an impermeable barrier (trap) that stops or impedes its flow. As migrating gas accumulates below an effective seal, the total gas concentrations may reach the critical amounts necessary for the formation of gas hydrates. Thus, impermeable seals can provide a mechanism by which the required gas can be concentrated within reservoir rocks.

Besides conventional reservoirs and trapping mechanisms, it is possible for gas hydrate to form its own reservoir and trap. As gas migrates into the zone of gas-hydrate stability, it may interact with the available pore water to generate gas hydrate. With the appropriate volumes of gas and water, the pore space within the reservoir rock could be completely filled, thus making the rock impermeable to further hydrocarbon migration. The plugging of gas pipelines and production tubing by gas hydrates is testimony to the sealing potential of gas hydrates (Sloan, 1998). It has also been shown that, in marine environments, gas hydrates can mechanically displace sediments to form their own reservoir. Thus, the availability of reservoir quality rocks may not always be a limiting factor.

### **HOW MUCH Gas is Trapped Within Gas Hydrate Accumulations?**

The amount of methane sequestered in gas hydrates is probably enormous, but estimates of the amounts are speculative and range over three orders-of-magnitude from about 3,114 to 7,634,000 trillion cubic meters (reviewed by Kvenvolden, 1993). It is likely, however, that the amount of gas in the hydrate reservoirs of the world greatly exceeds the volume of known conventional gas reserves. Before reviewing assessments of the world gas hydrate resources it is necessary to examine the quality and variability of gas hydrate assessments at the accumulation and reservoir scale.

### ***Gas Hydrates at the Reservoir and Accumulation Scale***

Estimates of the amount of gas hydrates and associated gas within a given gas hydrate accumulation can vary considerably. For example, recent estimates of the volume of gas that may be contained in the gas hydrates and free-gas beneath the gas hydrates on the Blake Ridge range from about 70 trillion cubic meters of gas over an area of 26,000 km<sup>2</sup> (Dickens et al., 1997) to about 80 trillion cubic meters of gas for an area of 100,000 km<sup>2</sup> (Holbrook et al., 1996). The difference between these two estimates has been



attributed to the observation that the amount of free-gas directly measured within pressure-core samples (Dickens et al., 1997) from beneath the gas hydrates is significantly larger than that estimated from borehole vertical seismic profile data (Holbrook et al., 1996). Other published studies indicate that the gas hydrates at the crest of the Blake Ridge alone (area of about 3,000 km<sup>2</sup>) may contain more than 18 trillion cubic meters of gas (Dillon and Paull, 1983). The broad range of these estimates demonstrates the need for high-resolution measurements of the gas hydrate and associated free-gas volumes within any gas hydrate accumulation of interest.

It has been suggested that the volume of gas that may be contained in a gas hydrate accumulation depends on five "reservoir" parameters (modified from Collett, 1993): (1) areal extent of the gas-hydrate occurrence, (2) "reservoir" thickness, (3) sediment porosity, (4) degree of gas-hydrate saturation, and (5) the hydrate gas yield volumetric parameter which defines how much free-gas (at STP) is stored within a gas hydrate (also known as the hydrate number). In the following section, the five "reservoir" parameters (Table 1) needed to calculate the volume of gas associated with the gas hydrates on the Blake Ridge (ODP Sites 994, 995, and 997; Shipboard Scientific Party, 1996), along the Cascadia continental margin (ODP Site 889; Shipboard Scientific Party, 1994), on the North Slope of Alaska (Northwest Eileen State-2 well; Collett, 1993), and in the Mackenzie River Delta of Canada (Mallik 2L-38 well; Dallimore et al., 1999) are assessed.

The following "resource" assessment (modified from Collett, 1998) has been conducted on a site-by-site basis; that is, for each site examined the volume of gas hydrate and associated gas within a one square kilometer area surrounding each drill-site have been individually calculated (Table 1). For this "resource" assessment, I have defined the thickness of the gas-hydrate-bearing sedimentary section at both the marine and permafrost drill sites to be the total thickness of the downhole log inferred gas-hydrate accumulation (Table 1). Average core derived sediment porosities for the gas-hydrate-bearing reservoirs at Sites 994, 995, 997 and 889 range from about 52 to 58 percent (Table 1). The

"corrected" density log derived sedimentary porosities for the three gas-hydrate-bearing units identified in the Northwest Eileen State-2 (Units C, D, and E) range from an average value of about 36 to 39 percent (Table 1). The density log derived sediment porosities for the gas-hydrate-bearing interval in the Mallik 2L-38 well averages about 31% (Table 1). Gas-hydrate saturations at the marine drill-sites (Sites 994, 995, 997 and 889), calculated from available downhole logs, range from an average value of about 3 to 6 percent (Table 1). Gas-hydrate saturations in all three gas-hydrate-bearing units (Units C, D, and E) in the Northwest Eileen State-2 well, calculated from available downhole log data, range from an average value of about 33 to 61 percent (Table 1). The resistivity well log derived gas-hydrate saturations in the Mallik 2L-38 well average about 44% (Table 1). In this assessment, I have assumed a hydrate number of 6.325 (90% gas filled clathrate) which corresponds to a gas yield of 164 m<sup>3</sup> of methane (at STP) for each cubic meter of gas hydrate. The log inferred gas hydrates at Sites 994, 995, and 997 on the Blake Ridge contain between 670,000,000 and 1,450,000,000 cubic meters of gas per square kilometer (Table 1). The volume of gas within the log inferred gas hydrates at Site 889 on the Cascadia continental margin is about 467,000,000 cubic meters of gas per square kilometer (Table 1). Cumulatively, all three log inferred gas-hydrate-bearing stratigraphic units (Units C, D, and E) drilled and cored in the Northwest Eileen State-2 well may contain about 1,511,000,000 cubic meters of gas in the one square kilometer area surrounding this drill-site (Table 1). It was also determined that the log inferred gas-hydrate-bearing stratigraphic interval drilled in the Mallik 2L-38 well contains about 4,750,000,000 cubic meters of gas in the one square kilometer area surrounding the Mallik drill-site (Table 1).

A close examination of the gas hydrate saturations in Table 1 reveals a potential problem associated with production of gas from marine gas hydrates. Even though vast portions of the world's continental shelves appear to be underlain by gas hydrates, the concentration of hydrates within most marine accumulations appears to be very low. Low

gas hydrate concentrations may significantly affect the economic production potential of marine gas hydrates (gas hydrate production is discussed in more detail later in this paper).

### ***Gas Hydrates at the World and National Scale***

World estimates for the amount of natural gas in gas hydrate deposits range from 14 to 34,000 trillion cubic meters for permafrost areas and from 3,100 to 7,600,000 trillion cubic meters for oceanic sediments (modified from Kvenvolden, 1993). The estimates in Table 2 show considerable variation, but oceanic sediments seem to be a much greater resource of natural gas than continental sediments. Current estimates of the amount of methane in the world's gas hydrate accumulations are in rough accord at about 20,000 trillion cubic meters (reviewed by Kvenvolden, 1993). If these estimates are valid, the amount of methane in gas hydrates is almost two orders of magnitude larger than the estimated total remaining recoverable conventional methane resources, estimated to be about 250 trillion cubic meters (Masters et al., 1991).

The recently completed 1995 National Assessment of United States Oil and Gas Resources, conducted by the U.S. Geological Survey, focused on assessing the undiscovered conventional and unconventional resources of crude oil and natural gas in the United States (Gautier et al., 1995). This assessment included for the first time a systematic resource appraisal of the in-place natural gas hydrate resources of the United States onshore and offshore regions (Collett, 1995). In this assessment, 11 gas-hydrate plays were identified within four offshore and one onshore gas hydrate provinces. The offshore gas hydrate provinces assessed lie within the U.S. Exclusive Economic Zone adjacent to the lower 48 States and Alaska. The only onshore province assessed was the North Slope of Alaska. In-place gas resources within the gas hydrates of the United States are estimated to range from about 3,200 to 19,000 trillion cubic meters of gas, at the 0.95 and 0.05 probability levels, respectively. Although this wide range of values shows a high degree of uncertainty, it does indicate the potential for enormous quantities of gas stored as

gas hydrates. The mean in-place value for the entire United States is calculated to be about 9,000 trillion cubic meters of gas.

### **Gas Hydrate Production Technology**

Even though gas hydrates are known to occur in numerous marine and Arctic settings, little is known about the technology necessary to produce gas hydrates. Most of the existing gas hydrate "resource" assessments do not address the problem of gas hydrate recoverability. Proposed methods of gas recovery from hydrates (Figure 18) usually deal with dissociating or "melting" in-situ gas hydrates by (1) heating the reservoir beyond hydrate formation temperatures, (2) decreasing the reservoir pressure below hydrate equilibrium, or (3) injecting an inhibitor, such as methanol or glycol, into the reservoir to decrease hydrate stability conditions. Gas recovery from hydrates is hindered because the gas is in a solid form and because hydrates are usually widely dispersed in hostile Arctic and deep marine environments. First order thermal stimulation computer models (incorporating heat and mass balance) have been developed to evaluate hydrate gas production from hot water and steam floods, which have shown that gas can be produced from hydrates at sufficient rates to make gas hydrates a technically recoverable resource (Sloan, 1998). However, the economic cost associated with these types of enhanced gas recovery techniques would be prohibitive. Similarly, the use of gas hydrate inhibitors in the production of gas from hydrates has been shown to be technically feasible (Sloan, 1998), however, the use of large volumes of chemicals such as methanol comes with a high economic and environmental cost. Among the various techniques for production of natural gas from in-situ gas hydrates, the most economically promising method is considered to be the depressurization technique. However, the extraction of gas from a gas hydrate accumulation by depressurization may be hampered by the formation of ice and/or the reformation of gas hydrate due to the endothermic nature of gas hydrate dissociation.

The Messoyakha gas field in the northern part of the West Siberian Basin is often used as an example of a hydrocarbon accumulation from which gas has been produced from in-situ natural gas hydrates. Production data and other pertinent geologic information have been used to document the presence of gas hydrates within the upper part of the Messoyakha field (Makogon, 1981). It has also been suggested that the production history of the Messoyakha field demonstrates that gas hydrates are an immediate producible source of natural gas, and that production can be started and maintained by conventional methods. Long-term production from the gas-hydrate part of the Messoyakha field is presumed to have been achieved by the simple depressurization scheme. As production began from the lower free-gas portion of the Messoyakha field in 1969, the measured reservoir-pressures followed predicted decline relations; however, by 1971 the reservoir pressures began to deviate from expected values. This deviation has been attributed to the liberation of free-gas from dissociating gas hydrates. Throughout the production history of the Messoyakha field, it is estimated that about 36% (about 5 billion cubic meters) of the gas withdrawn from the field has come from the gas hydrates (Makogon, 1981). Recently, however, several studies suggest that gas hydrates may not be significantly contributing to gas production in the Messoyakha field (reviewed by Collett and Ginsburg, 1998).

It should be noted, that our current assessment of proposed methods for gas hydrate production do not consider some of the more recently developed advanced oil and gas production schemes. For example, the usefulness of downhole heating methods such as in-situ combustion, electromagnetic heating, or downhole electrical heating have not been evaluated. In addition, advanced drilling techniques and complex downhole completions, including horizontal wells and multiple laterals, have not been considered in any comprehensive gas hydrate production scheme. Gas hydrate provinces with existing conventional oil and gas production may also provide us with the opportunity to test relatively more advanced gas hydrate production methods. For example, in northern

Alaska existing "watered-out" production wells are being evaluated as potential sources for hot geopressured brines that will be used to thermally stimulate gas hydrate production.

As previously noted, the low concentration of hydrates in most of the world's marine gas hydrate occurrences raises a concern over the production technology required to produce gas from highly disseminated gas hydrate accumulations. In addition, the host-sediments also represent a significant technical challenge to potential gas hydrate production. In most cases, marine gas hydrates have been found in clay-rich unconsolidated sedimentary sections that exhibit little or no permeability. Most of the existing gas hydrate production models require the establishment of reliable flow paths within the formation to allow the movement of produced gas to the wellbore and injected fluids into the gas-hydrate-bearing sediments. It is unlikely, however, that most marine sediments possess the mechanical strength to allow the generation of significant flow paths. It is possible that in basins with significant input of coarse-grained clastic sediments, such as the Gulf of Mexico or along the eastern margin of India, gas hydrates may be reservoired at high concentrations in more conventional clastic reservoirs; which is more analogous to the nature of gas hydrate occurrences in onshore permafrost environments (Collett, 1993; Dallimore et al., 1999).

### **Motivations Leading to Gas Hydrate Production**

As previously discussed in this paper, significant if not insurmountable technical issues need to be resolved before gas hydrates can be counted as a viable option for future supplies of natural gas. In most cases, the viability of an energy resource is based almost solely on economics. It is important to note, however, that in some cases the viability of a particular hydrocarbon resource can be controlled by unique local economic and non-technical factors. For example, countries with little domestic energy production usually pay considerably more for their energy needs since they rely more on imported hydrocarbons, which often come with additional tariffs and transportation expenses.

Energy security is often a concern to resource poor countries, which in comparison to energy rich countries will often invest more money in relatively expensive unconventional domestic energy resources. In some cases the uniqueness of a particular location, such as distance to a conventional energy resource, may lead to the development of otherwise non-economic unconventional resource. In the following section, the economic and non-economic motivations that may eventually lead to sustained production of gas from hydrates will be discussed.

### ***Economic Motivations***

Because of uncertainties about the geologic settings and feasible production technology, few economic studies have been published on gas hydrates. The National Petroleum Council, in its major 1992 study of gas (National Petroleum Council, 1992), published one of the few available economic assessments of gas hydrate production (Table 3). This information, extracted from MacDonald (1990), assessed the relative economics of gas recovery from hydrates using thermal injection and depressurization. It also benchmarks the cost of gas hydrate production with the costs of conventional gas production on Alaska's North Slope. Since the 1992 NPC report, the costs of conventional gas production on the North Slope and elsewhere have declined. However, within countries with considerable production of cheaper conventional natural gas, hydrates appear not to be an economically viable energy resource in a competitive energy market.

Japan, India, and South Korea, like many other countries with little indigenous energy resources, pay a very high price for imported liquid natural gas (LNG) and oil. The high cost of imported hydrocarbon resources is one reason why in the last two years government agencies in Japan, India, and South Korea have begun to develop hydrate research programs to recover gas from oceanic hydrates. One of the most notable gas hydrate projects is underway in Japan, where the Japan National Oil Corporation (JNOC), with funding from the Ministry of International Trade and Industry (MITI), has launched a

five year study to assess the domestic resource potential of natural gas hydrates. In numerous press releases, MITI has indicated that "methane hydrates could be the next generation's source of producible domestic energy". JNOC is scheduled to drill a gas hydrate test well in the Nankai Trough area, near Tokyo, in the later part of 1999. As much as 50 trillion cubic meters of gas may be stored within the gas hydrates of the Nankai Trough. In 1998, JNOC also drilled the Mallik 2L-38 gas hydrate research well with the Geological Survey of Canada in the Mackenzie Delta of northern Canada (Dallimore et al., 1999).

India, like Japan, has also initiated a very ambitious national gas hydrate research program. In March of 1997, the government of India announced new exploration licensing policies which included the release of several deep water (>400m) lease blocks along the east coast of India between Madras and Calcutta. Recently acquired seismic data have revealed possible evidence of widespread gas hydrate occurrences throughout the proposed lease blocks. Also announced was a large gas hydrate prospect in the Andaman Sea, between India and Myanmar, which is estimated to contain as much as six trillion cubic meters of gas. The government of India has indicated that gas hydrates are of "utmost importance to meet their growing domestic energy needs". The National Gas Hydrate Program of India calls for drilling as many as five gas hydrate test wells.

Most recently the United States, through the U.S. Department of Energy, has launched a national level research program to assess the resource potential of both marine and permafrost-associated gas hydrates.



### ***Political Motivations***

The world will consume increasing volumes of natural gas well into the 21st century if reliable, low cost supplies can be discovered and exploited. In the near term, natural gas is expected to take on a greater role in power generation and transportation because of increasing pressure for cleaner fuels and reduced carbon dioxide emissions. Gas demand is also expected to grow throughout the first half of the next century because of the expanding role of gas as a competitive transportation fuel due to the commercial development of gas-to-liquids technology. The drive to increased reliance on natural gas will only be in part based on economics. Government regulatory and taxation policy may also dictate the viability of a particular energy commodity such as gas hydrate. In the recent past, government subsidies for unconventional gas resources such as coalbed methane contributed to their technical and economic viability. Similar forms of government support may have a significant impact on the resource viability of gas hydrates. Another non-economic factor that may affect the resource potential of gas hydrates in a particular country is the concerns dealing with national security and dependence on foreign energy resources. The governments of many countries, including the United States, often express concerns over reliance on imported energy resources. Most certainly the international gas hydrate research programs of Japan, India, and South Korea have been established in part to address concerns over their reliance on foreign energy resources.

### ***Unique Motivations***

The first gas hydrate accumulations to be produced may have unique characteristics, such as location, that may make them technically and economically viable. For example, gas associated with conventional oil fields on the North Slope of Alaska is used to generate electricity in support of local field operations, for miscible gas floods, gas lift operations in producing oil wells, and is reinjected to maintain reservoir pressures in producing fields. In the future, gas may be used to generate steam that may be needed to produce the known vast quantities of heavy oil on the North Slope. Existing and emerging operational needs for natural gas on the North Slope are outpacing the discovery of new conventional resources and at least one of the operators in Alaska is looking at gas hydrates as a potential source of gas for field operations. The North Slope of Alaska contains vast, highly concentrated, gas hydrate accumulations that may be exploited because of a unique local need for natural gas.

### **CONCLUSIONS**

World estimates of the amount of methane sequestered in gas hydrates are enormous, but published estimates are highly speculative. It is generally believed, however, the amount of gas in the hydrate reservoirs of the world greatly exceeds the volume of known conventional gas reserves. Until recently, relatively little work has been done to assess the availability and production potential of gas hydrates. Gas recovery from hydrates is hindered because hydrates occur as a solid in nature and are commonly widely dispersed in hostile Arctic and deep marine environments. Proposed methods of gas recovery from hydrates usually deal with dissociating in-situ gas hydrates by heating and/or depressurizing the reservoir. Among the various techniques for production of natural gas from in-situ gas hydrates, the most economically promising method is considered to be the depressurization scheme.

Despite the fact that relatively little is known about the ultimate resource potential of natural gas hydrates, it is certain that gas hydrates are a vast storehouse of natural gas and the national gas hydrate research programs of Japan, India, and the United States will significantly contribute to our understanding of the technical challenges needed to turn this enormous resource into an economically producible reserve.

In conclusion, will gas hydrates become a significant energy resource? It is unlikely that we will see significant worldwide gas production from hydrates for the next 30 to 50 years. However, in certain parts of the world characterized by unique economic and/or political motivations, gas hydrates may become a critical sustainable source of natural gas within the foreseeable future, possibly in the next five to ten years.

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## FIGURE AND TABLE CAPTIONS

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Figure 2--Graphs showing the depth-temperature zone in which methane hydrates are stable in (a) a permafrost region and (b) an outer continental margin marine setting (modified from Collett, 1995).

Figure 3--Two gas hydrate crystal structures: (a) Structure I; and (b) Structure II (modified from Sloan, 1998).

Figure 4--Location of known and inferred gas hydrate occurrences (modified from Kvenvolden, 1993).

Figure 5--Physiographic map of the southeastern continental margin of North America. Location of ODP Leg 164 drill sites are indicated. Also shown is the area (horizontally shaded area) where gas hydrate occurrence has been mapped on the basis of bottom simulating reflectors (BSRs). Contours are in meters.

Figure 6--Seismic profile along which Sites 994, 995, and 997 are located. Note that Site 994 is not associated with a distinct BSR although a very strong BSR occurs at Sites 995 and 997.

Figure 7--Chloride concentration profiles for interstitial waters collected from cores at Sites 994, 995, and 997. Downhole electrical resistivity log data from Sites 994, 995, and 997. Also shown is the chloride concentration and electrical resistivity inferred gas hydrate distribution (modified from Shipboard Scientific Party, 1996).

Figure 8--Physiographic map of the Cascadia continental margin of North America. Location of ODP Leg 146 drill sites are indicated. Also shown is the area (horizontally shaded area) where gas hydrate occurrence has been mapped on the basis of bottom simulating reflectors (modified from Hyndman et al., 1996).

Figure 9--Downhole log data from Site 889. Data shown include the natural gamma ray log, bulk-density data, neutron porosities, compressional-wave acoustic velocities, and deep-reading electrical resistivities.

Figure 10-- Cross section showing the lateral and vertical extent of gas hydrates and underlying free-gas occurrences in the Prudhoe Bay-Kuparuk River area in northern Alaska. See Figure 11 for location of cross section. The gas-hydrate-bearing units are identified with the reference letters A through F (modified from Collett, 1993).

Figure 11--Composite map of all six gas-hydrate/free-gas units (Units A-F) from the Prudhoe Bay-Kuparuk River area in northern Alaska. Also shown is the location of the cross section in Figure 10 (modified from Collett, 1993).

Figure 12--Map of part of the Mackenzie Delta region showing the calculated depth to the base of the methane hydrate stability zone (modified from Judge and Majorowicz, 1992). Exploration wells with well log inferred gas hydrate occurrences are shown. Contours are in meters.

Figure 13--Well log display for the Mallik 2L-38 well showing gas hydrate occurrences (highlighted with gray shading) and interpreted geology. Data shown includes the caliper log (CAL), natural gamma ray log (GR), neutron porosity (NEU), bulk-density (DEN), compressional-wave acoustic velocity (VEL), deep-reading electrical resistivity (RES), and total gas from the mud log (GAS).

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Figure 15--Various morphological forms of natural gas hydrate occurrence (modified from Sloan, 1998).

Figure 16a--Permafrost associated gas-hydrate reservoir model for conditions below the base of ice-bearing permafrost (Model A).

Figure 16b--Permafrost associated gas-hydrate reservoir model for conditions above the base of ice-bearing permafrost (Model B).

Figure 16c--Marine (clay-rich) gas-hydrate reservoir model (Model C).

Figure 16d--Free-gas- and gas-hydrate-bearing reservoir model (Model D).

Figure 17--Graph showing the depth-temperature zone in which gas hydrates are stable in a permafrost region [assuming a 9.795 kPa/m pore-pressure gradient] (modified from Holder et al., 1987).

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Table 3. Economic study of gas hydrate production

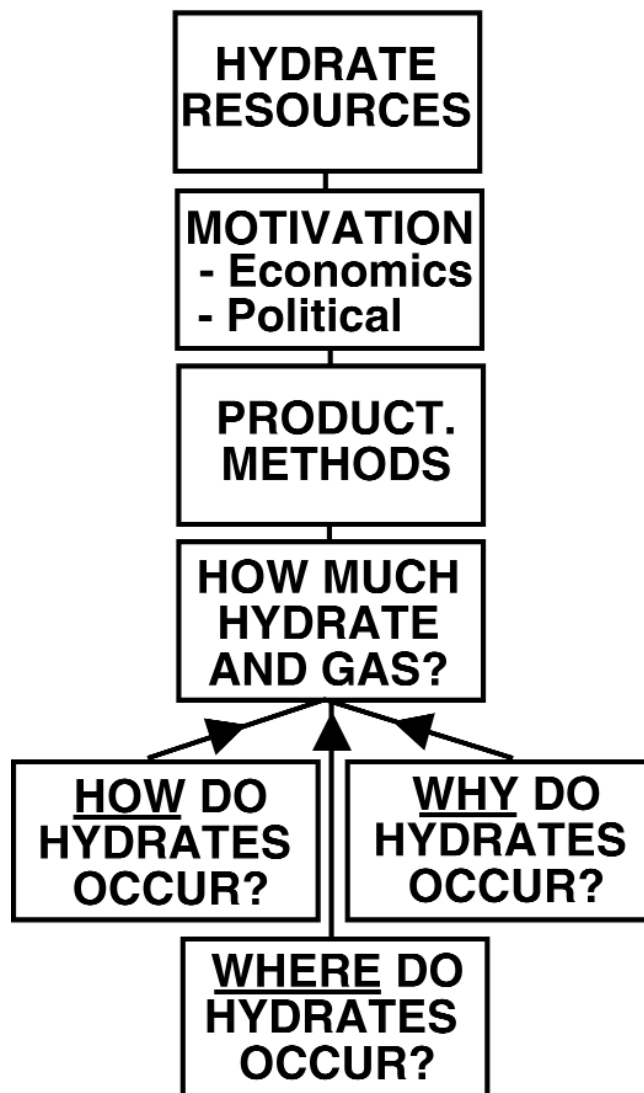


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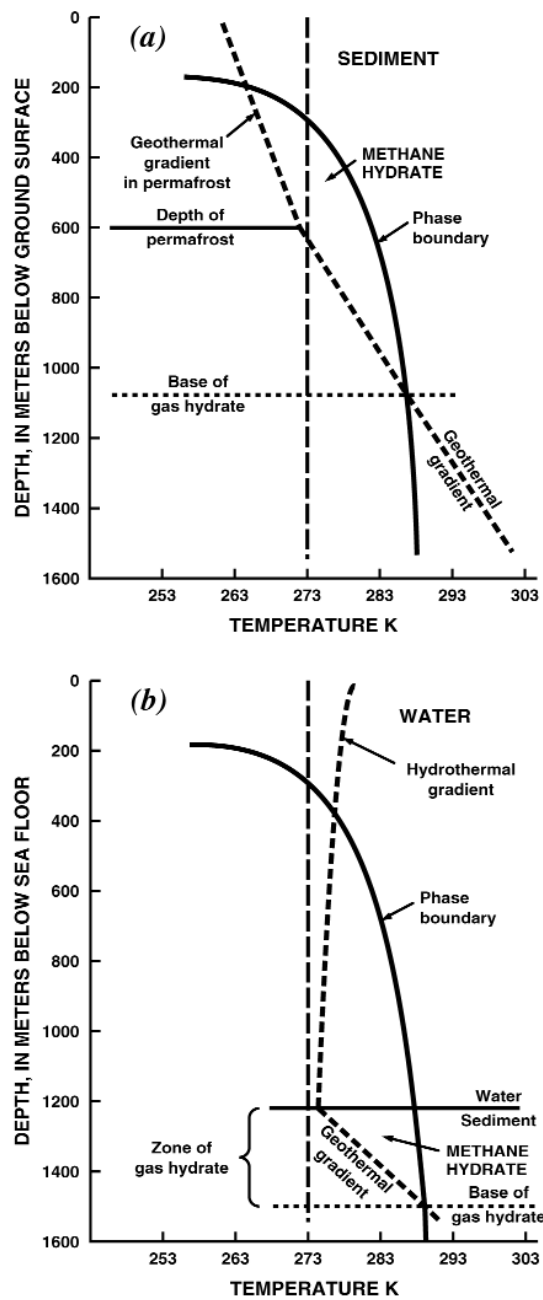


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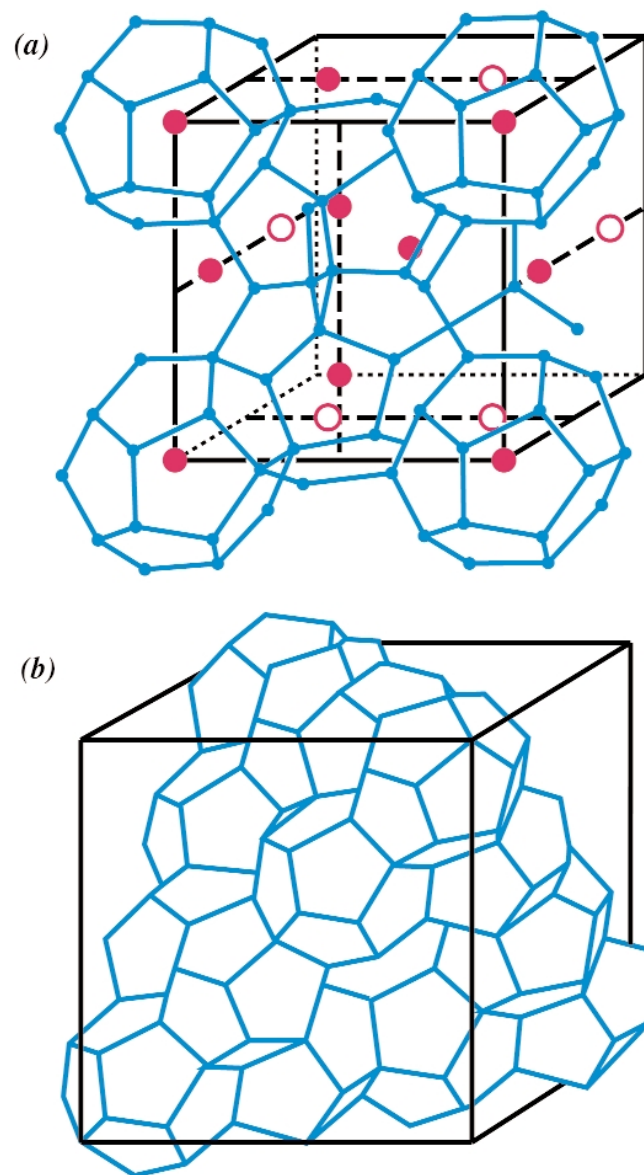


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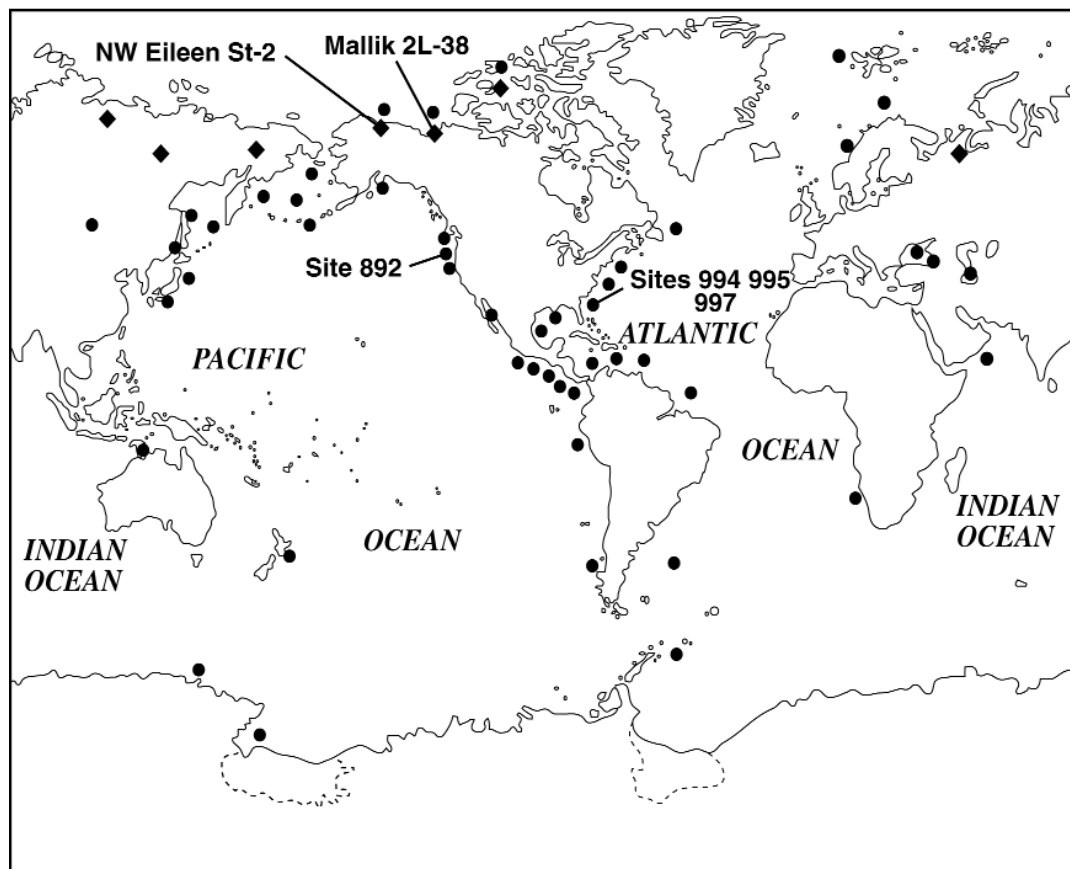


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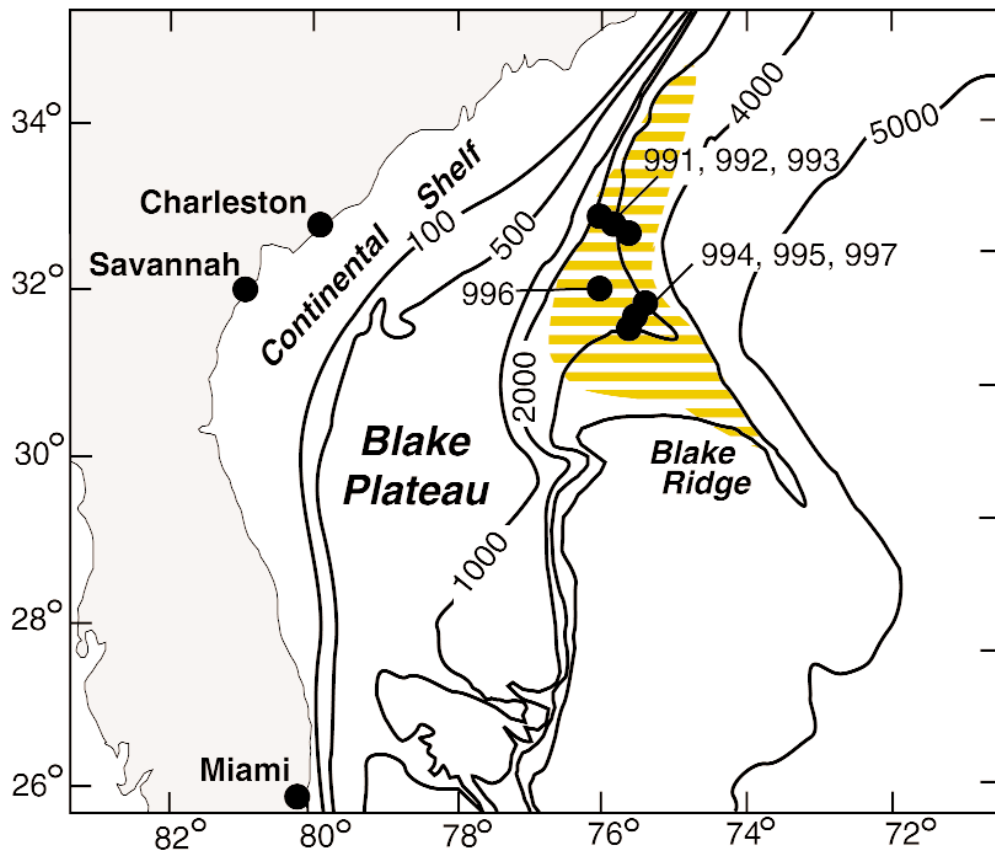


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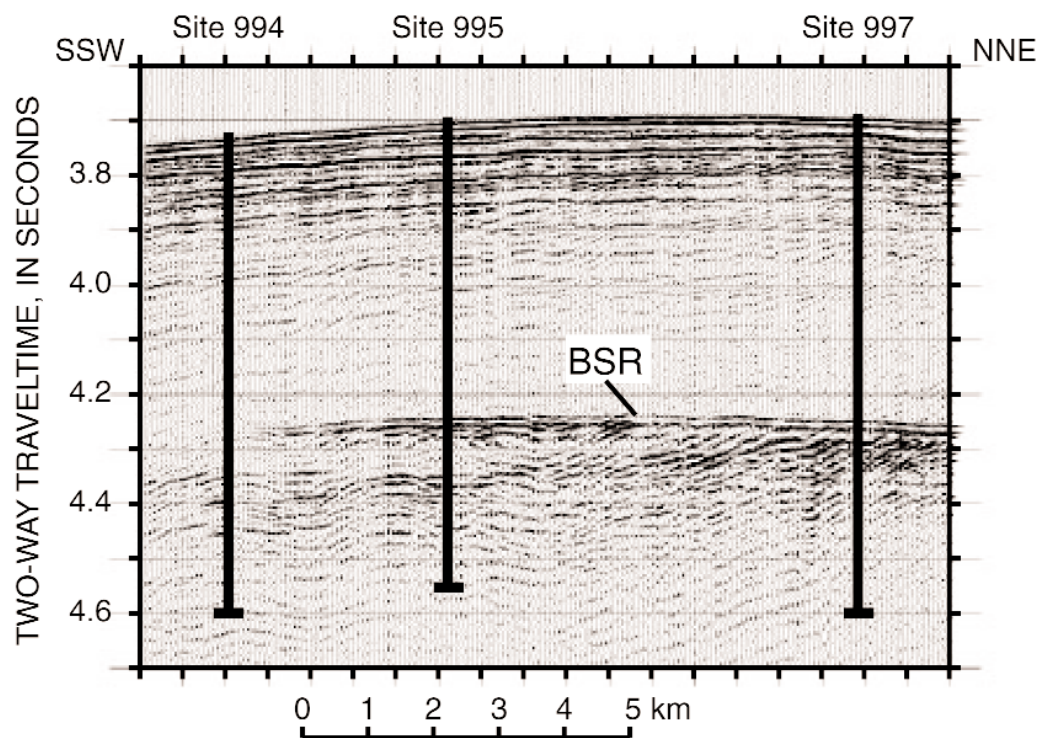


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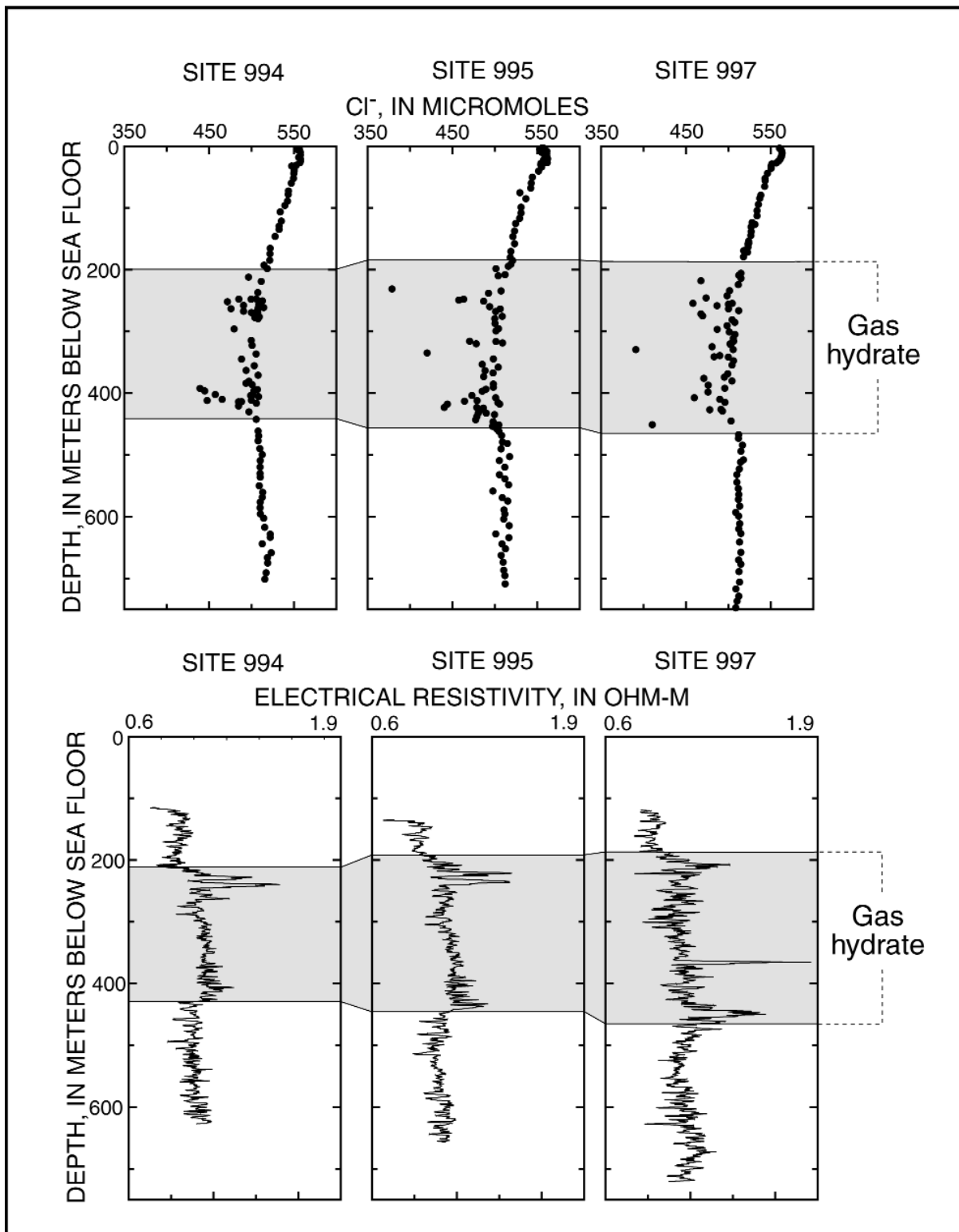


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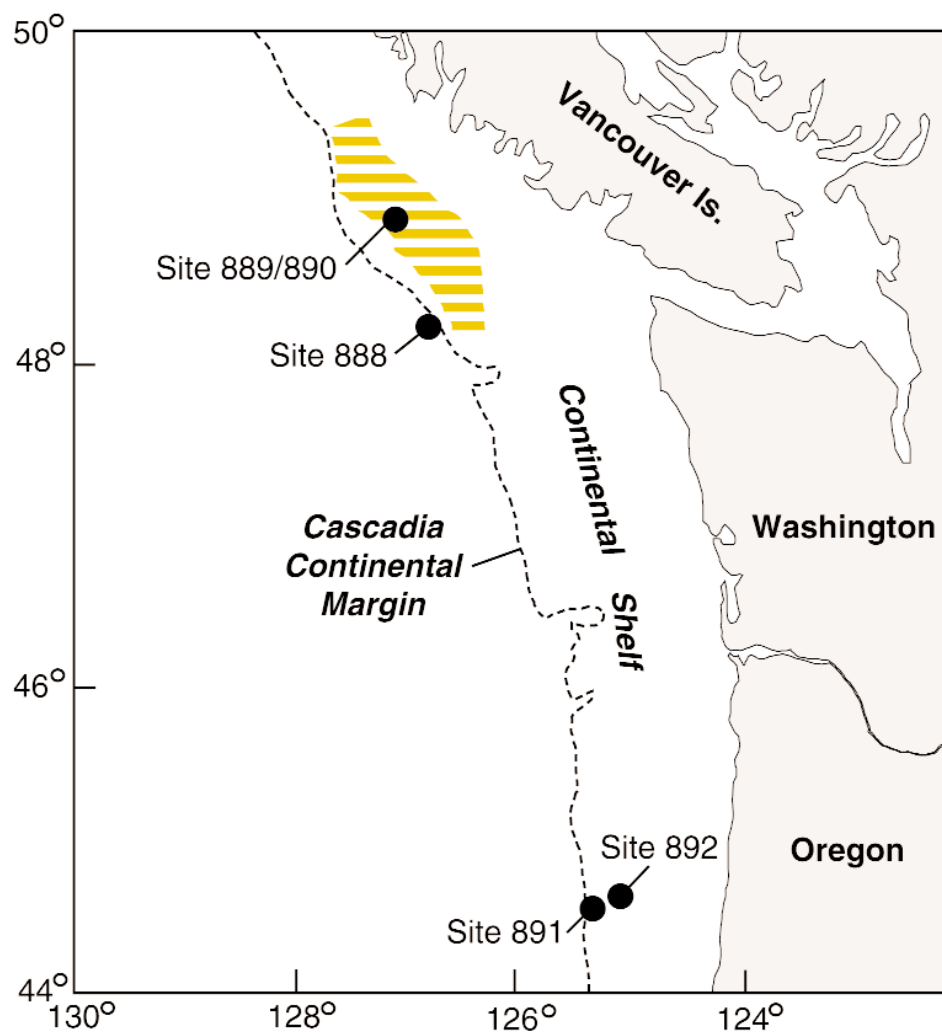


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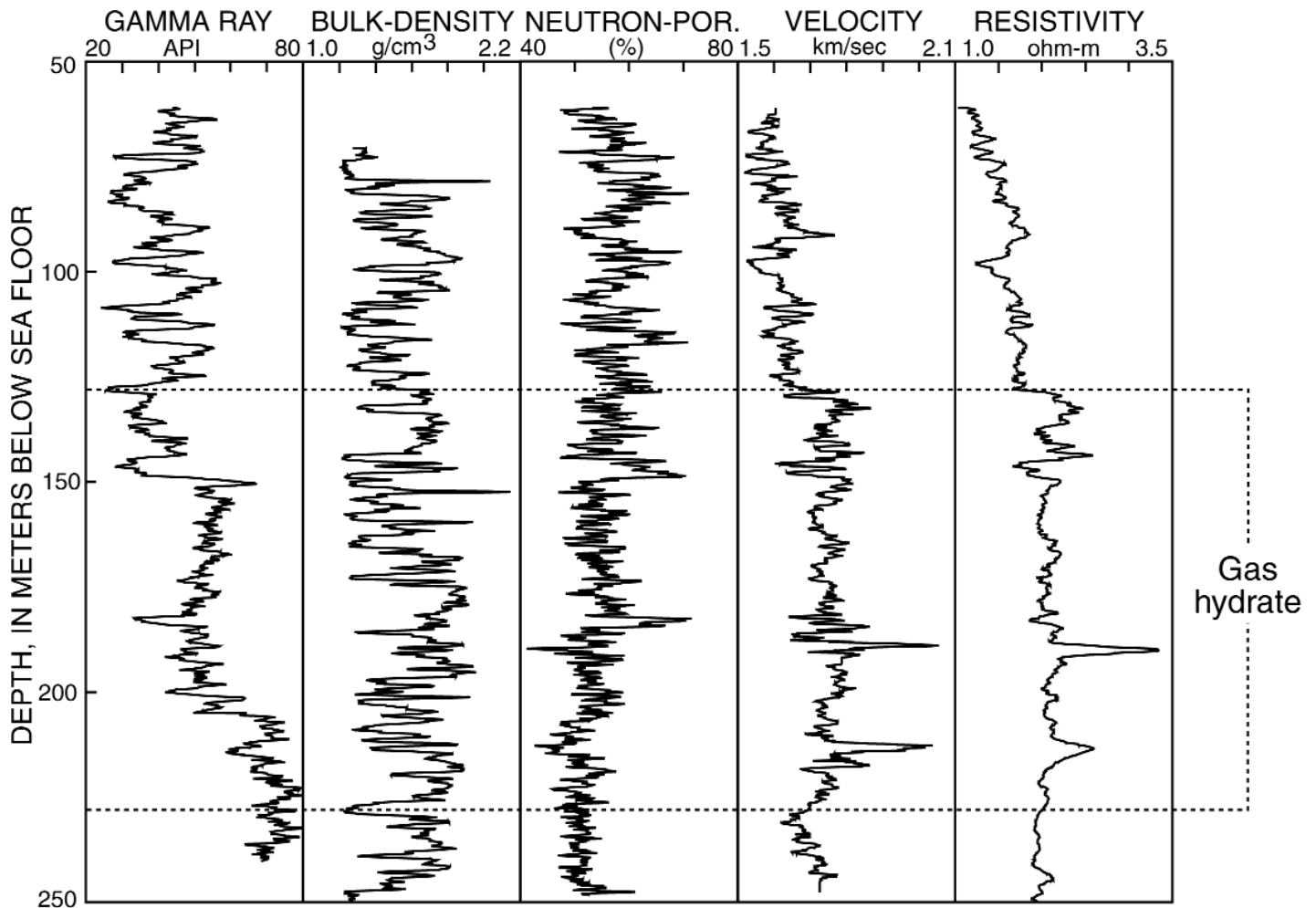


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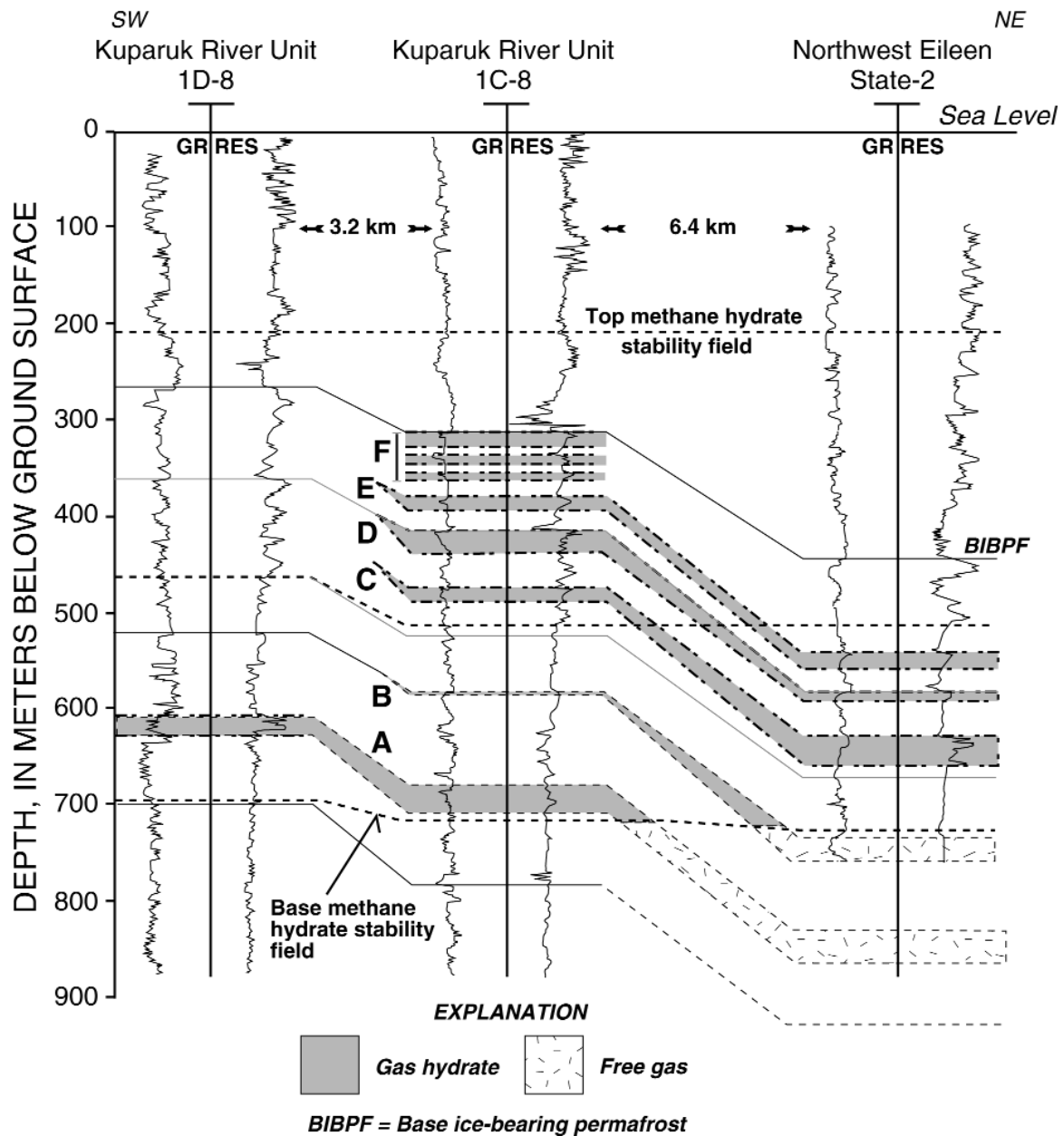


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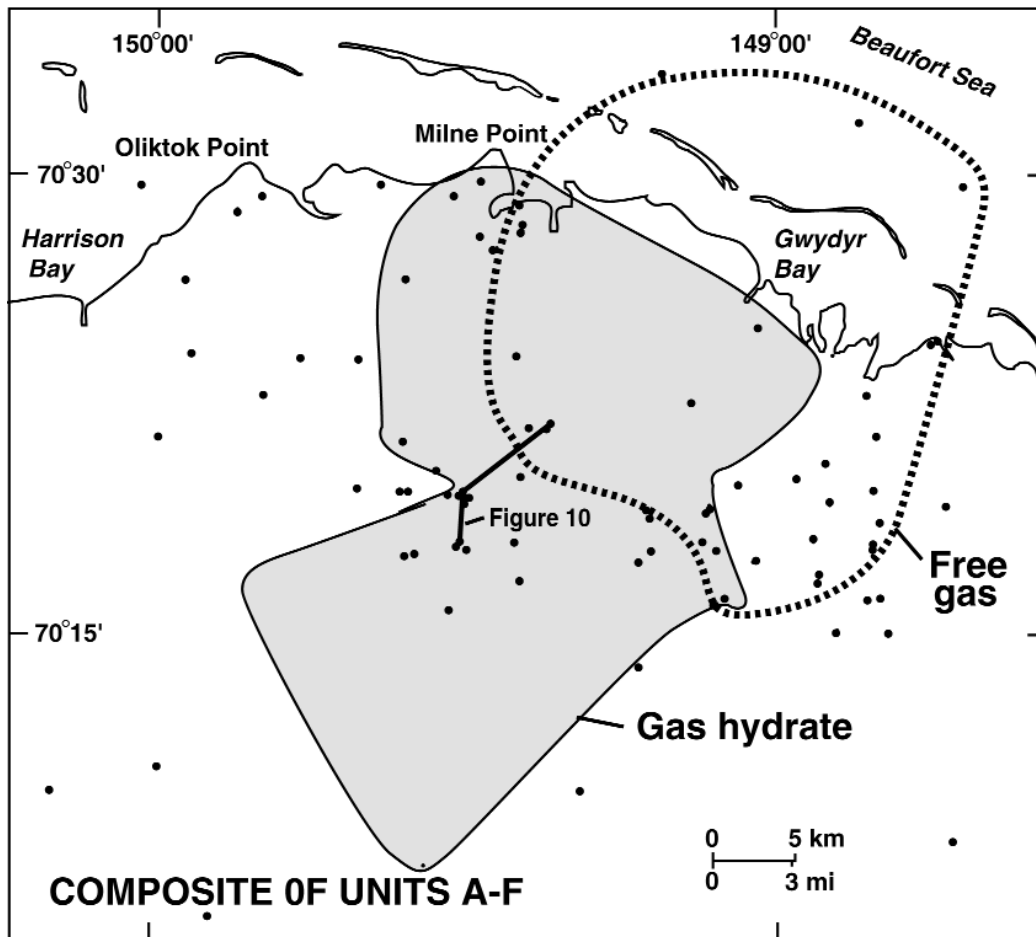


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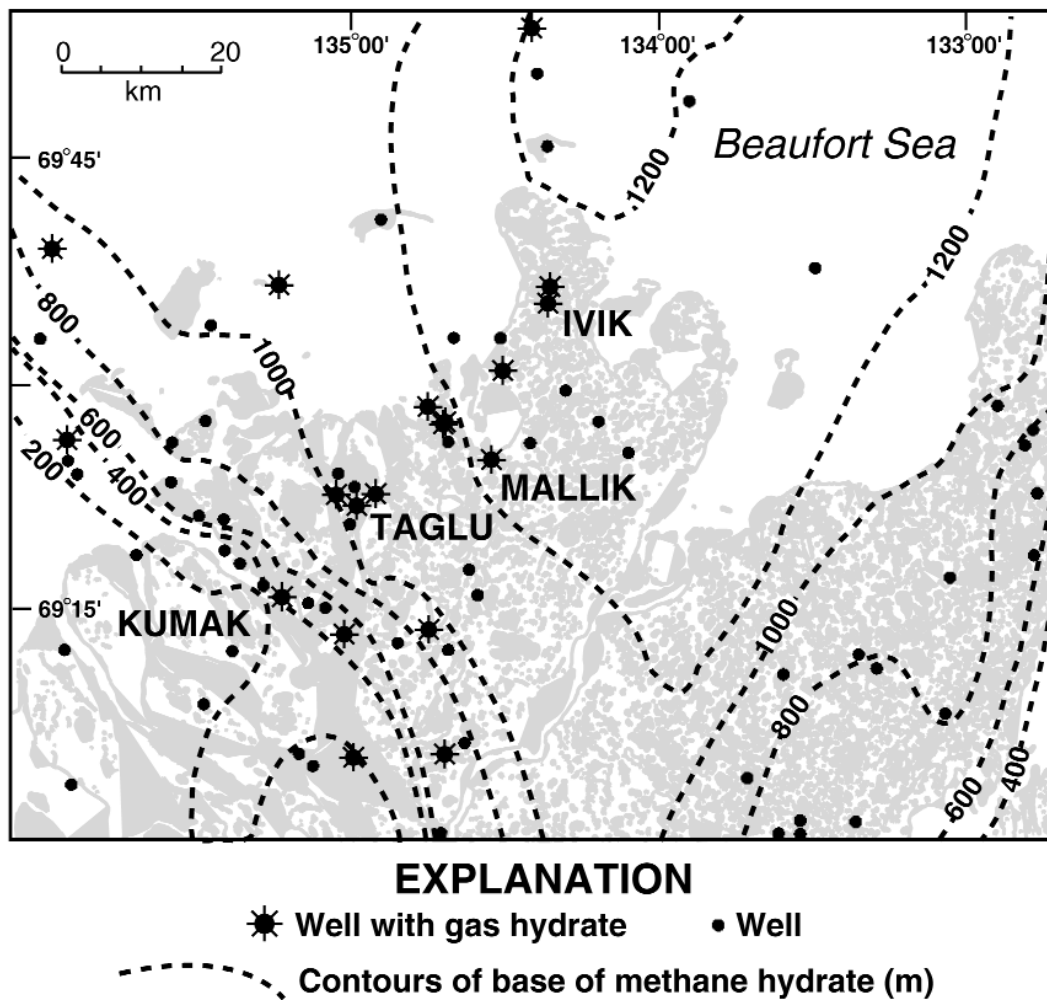


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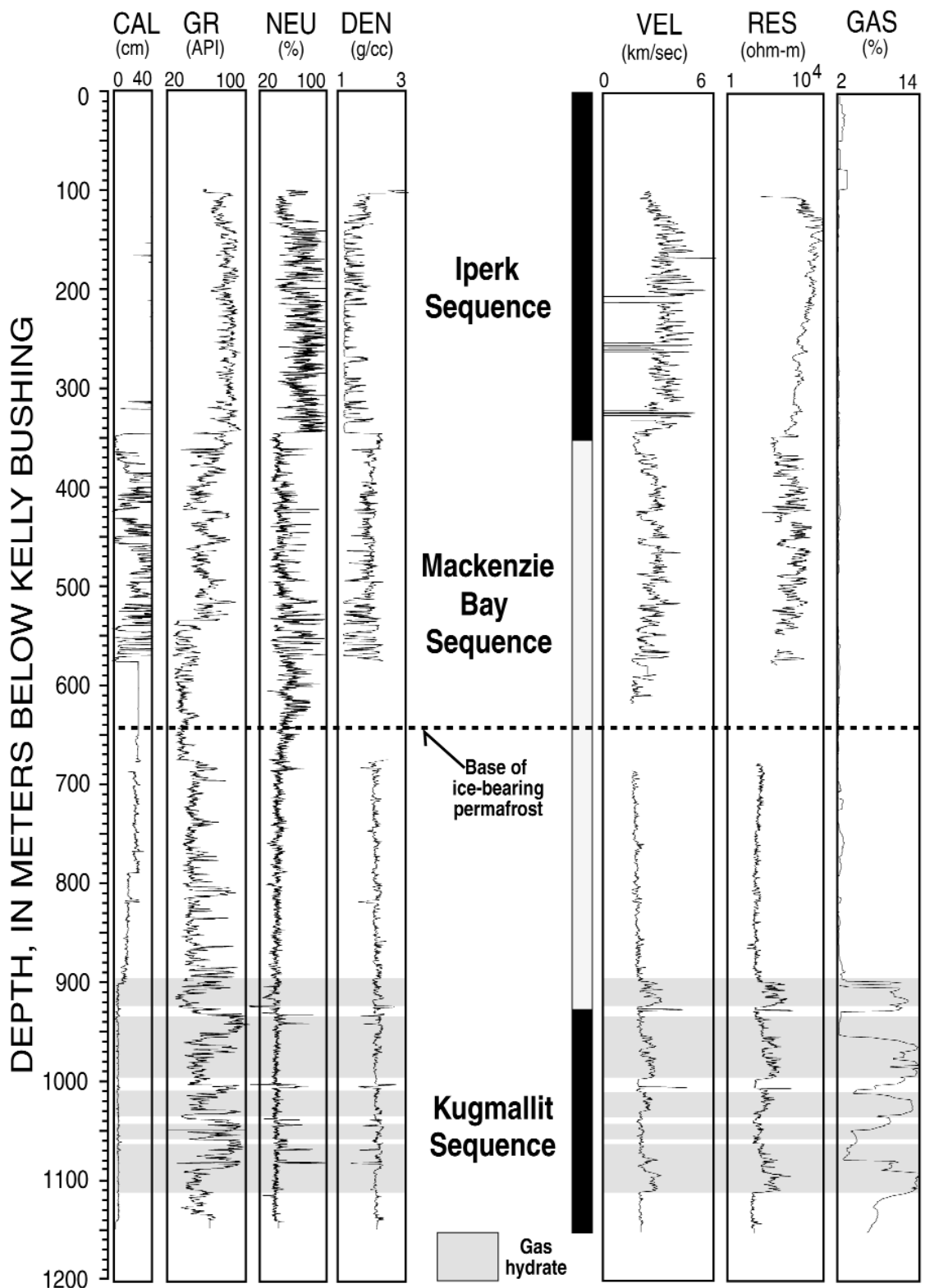


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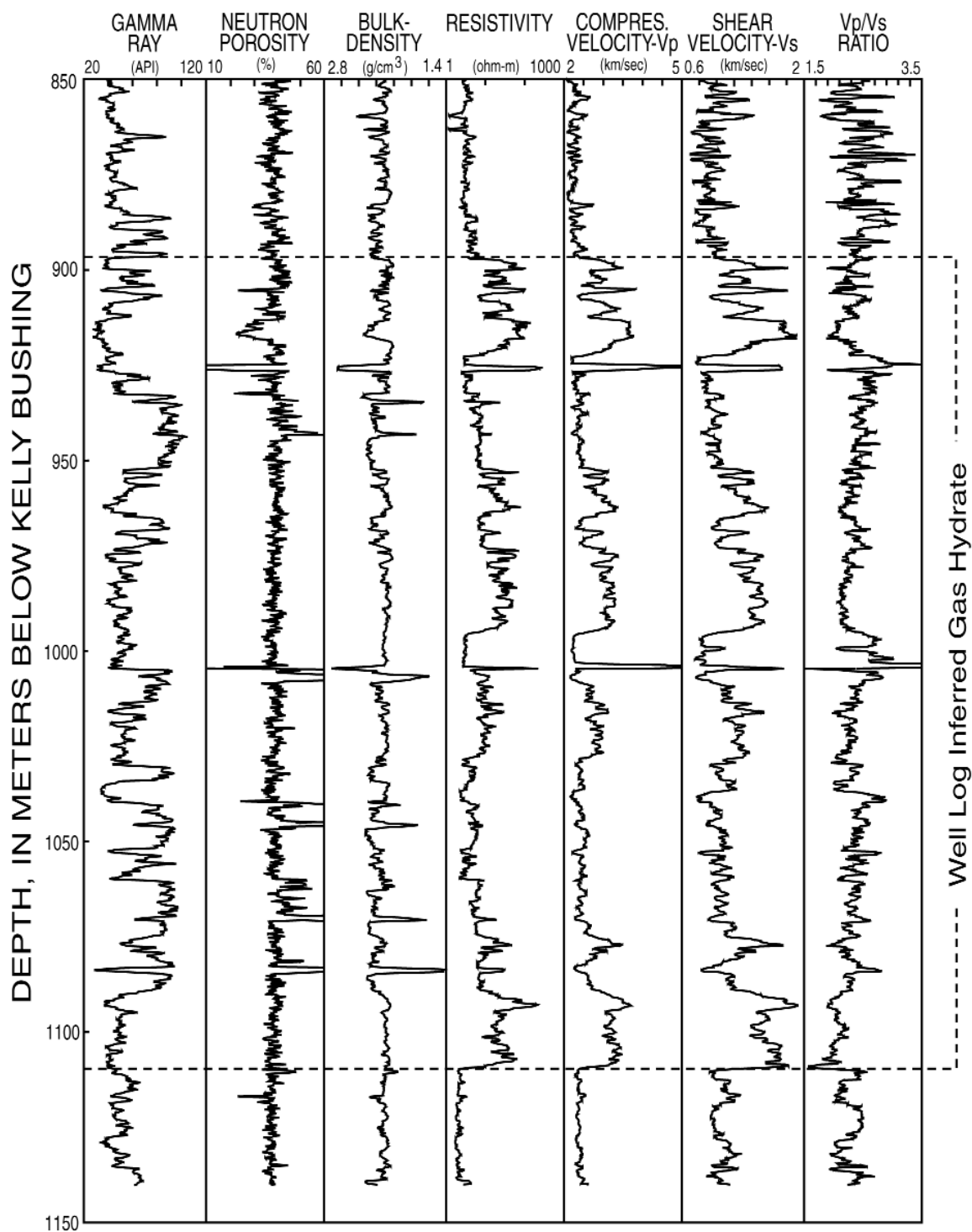


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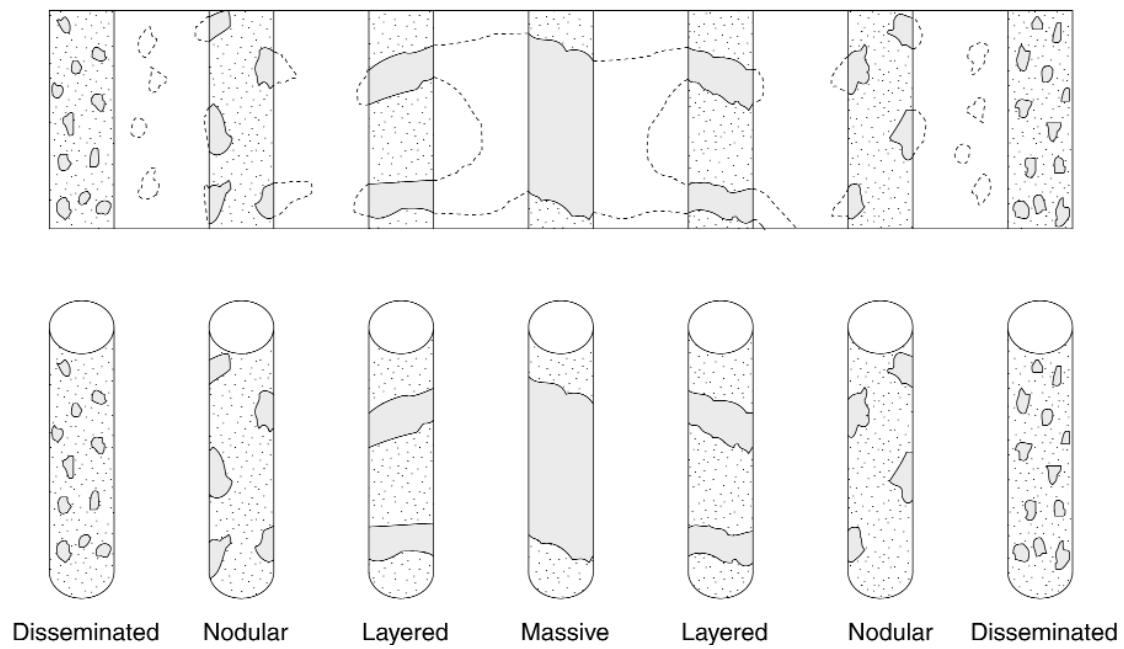


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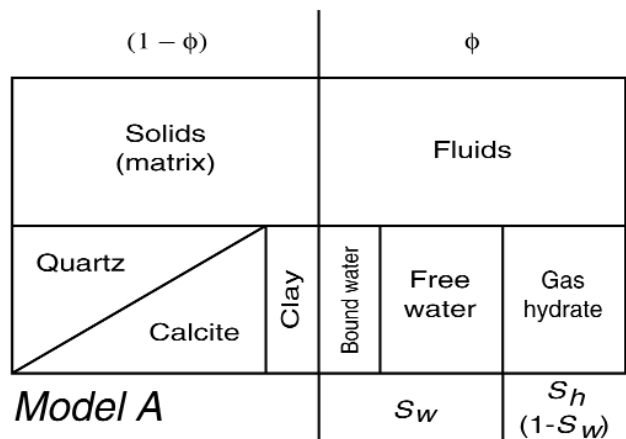


Figure 16a--Permafrost associated gas-hydrate reservoir model for conditions below the base of ice-bearing permafrost (Model A).

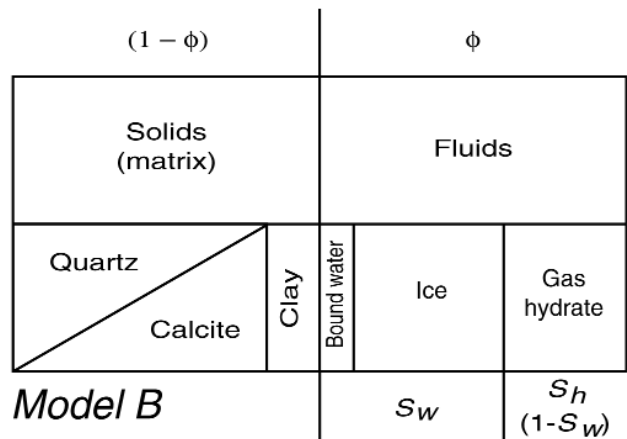


Figure 16b--Permafrost associated gas-hydrate reservoir model for conditions above the base of ice-bearing permafrost (Model B).

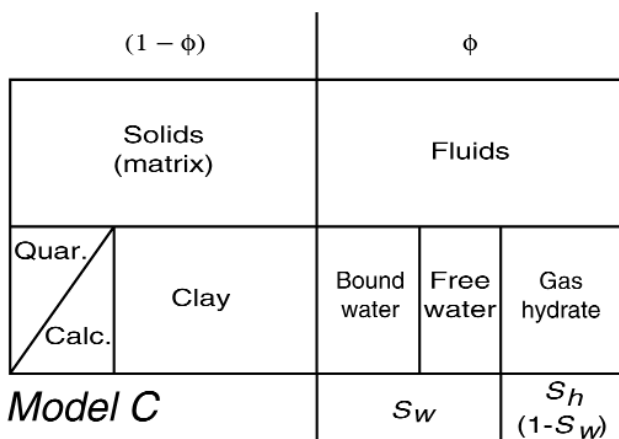


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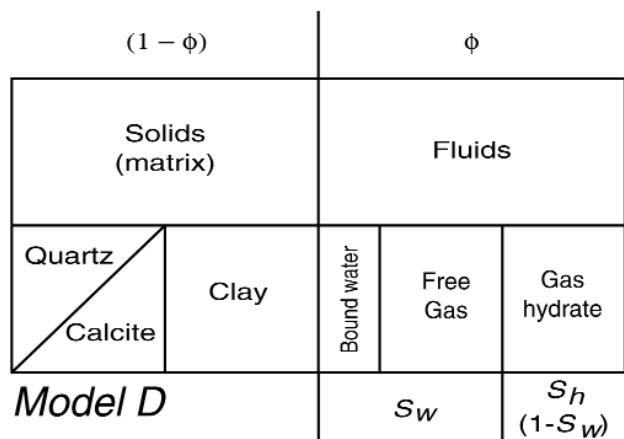


Figure 16d--Free-gas- and gas-hydrate-bearing reservoir model (Model D).

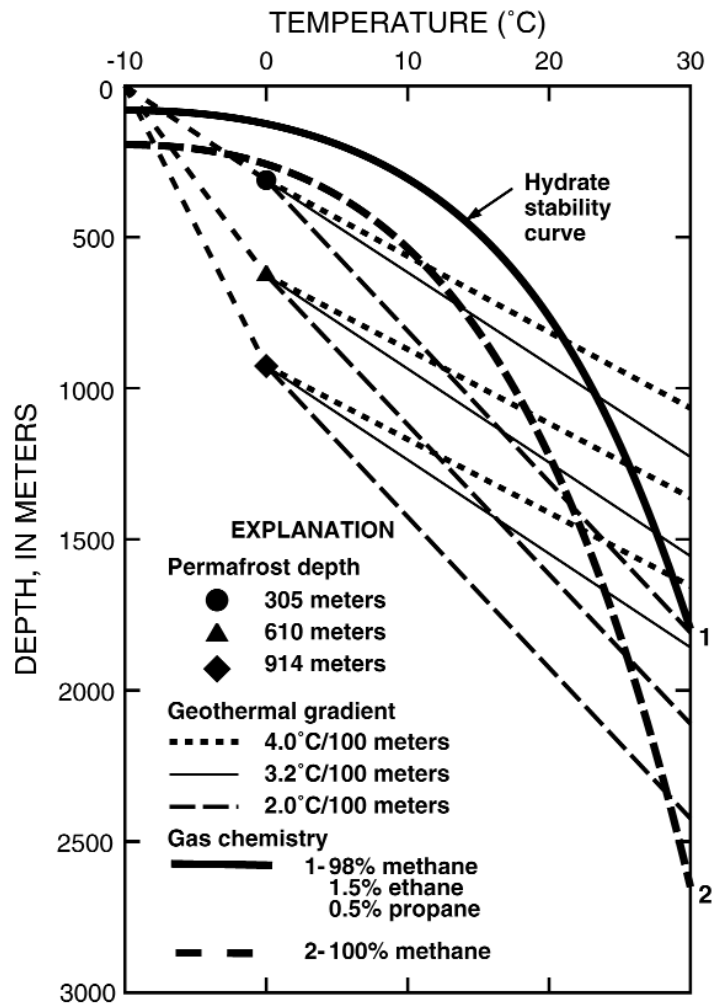


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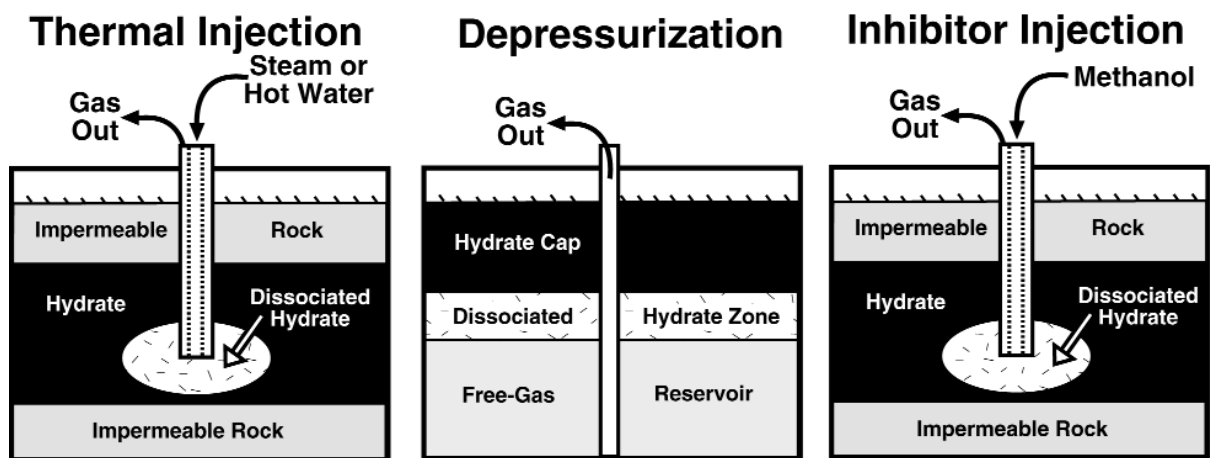


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Table 1

Volume of gas within the downhole log inferred gas hydrate occurrences at ODP Sites 994, 995, 997, and 889, and in the Northwest Eileen State-2 and Mallik 2L-38 wells

Site/Well identification	Depth of log inferred gas hydrates (m)	Thickness of hydrate-bearing zone (m)	Sediment porosity (%)	Gas-hydrate saturation (%)	Volume of gas within hydrate per square km (m <sup>3</sup> )
<b>Ocean Drilling Program Drill-Sites:</b>					
Site 994	212.0-428.8	216.8	57.0	3.3	669,970,673
Site 995	193.0-450.0	257.0	58.0	5.2	1,267,941,673
Site 997	186.4-450.9	264.5	58.1	5.8	1,449,746,073
Site 889	127.6-228.4	100.8	51.8	5.4	466,635,705
<b>Northwest Eileen State-2 Drill-Site:</b>					
Unit C	651.5-680.5	29.0	35.6	60.9	1,030,904,796
Unit D	602.7-609.4	6.7	35.8	33.9	133,382,462
Unit E	564.0-580.8	16.8	38.6	32.6	346,928,811
Total for Northwest Eileen State-2 --					1,511,216,069
<b>Mallik 2L-38 Drill-Site:</b>					
Hydrate Unit	888.8-1101.1	212.3	31.0	44.0	4,749,066,080

Table 2

World estimates of the amount of gas within hydrates

In-Place Natural Gas Resources Terrestrial Gas Hydrates	
<u>Cubic meters</u>	<u>Reference</u>
1.4 x 10 <sup>13</sup>	Meyer (1981)
3.1 x 10 <sup>13</sup>	McIver (1981)
5.7 x 10 <sup>13</sup>	Trofimuk et al. (1977)
7.4 x 10 <sup>14</sup>	MacDonald (1990)
3.4 x 10 <sup>16</sup>	Dobrynin et al. (1981)
In-Place Natural Gas Resources Oceanic Gas Hydrates	
<u>Cubic meters</u>	<u>Reference</u>
3.1 x 10 <sup>15</sup>	Meyer (1981)
5 to 25 x 10 <sup>15</sup>	Trofimuk et al. (1977)
2 x 10 <sup>16</sup>	Kvenvolden (1988)
2.1 x 10 <sup>16</sup>	MacDonald (1990)
4 x 10 <sup>16</sup>	Kvenvolden and Claypool (1988)
7.6 x 10 <sup>18</sup>	Dobrynin et al. (1981)

Table 3

Economic study of gas hydrate production

	Thermal injection*	Depressurization	Conventional gas
Investment (M\$)	5,084	3,320	3,150
Annual cost (M\$)	3,200	2,510	2,000
Total production (MMcf/year)**	900	1,100	1,100
Production cost (\$/Mcf)	3.60	2.28	1.82
Break-even wellhead price (\$/Mcf)	4.50	2.85	2.25
* Assumed process: injection of 30,000 b/d of water at 150°C			
** Assumed reservoir properties: h=7.3m, $\phi$ =40%, k=600md			