THE FUTURE OF ENERGY GASES

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An examination of the origin and distribution of natural gases and the economics and environmental effects of developing gas resources for energy

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PREFACE

The ever-present concern of meeting U.S. energy needs led the Geological Survey in 1992 to initiate a series of publications that addresses the potential for an expanding role of energy gases to help sustain our domestic energy needs. This series is drawn from the Survey's own wealth of research as well as from academic, business, other government facilities, and private sources. We use the term "energy gases" to distinguish those natural gases, primarily methane, that have utility for energy purposes from the many other forms of natural gas.

Recent discussions among economists, environmentalists, lobbyists, and scientific research groups within the energy industry have focused on the contributions of energy gases to the world's energy requirement. These discussions center around questions of gas supplies, assessing economic risk, future prices, and uncertainties of deliverability. What is often missing from these discussions, however, is a firm understanding of the fundamentals of energy gases: What are they? How do they form? Where are they found? How can they be exploited and at what costs? What are the environmental consequences associated with an expanded role of energy gases?

Energy gases, particularly methane, are commonly associated with oil, and, indeed, huge supplies of methane have been found while exploring for oil. But only a small share of all methane is associated with oil and, importantly, methane forms in some settings totally independent of oil. Methane is found in association with coal; it is a byproduct of metabolic processes in microorganisms; it originates from great depths in the Earth's crust (it may even occur in the mantle); it occurs in the molecular lattice of ice in the Arctic and offshore areas below the sea floor; and it is often dissolved in water in large aquifers. Thus exploration efforts for gas are in many ways fundamentally different from exploration strategies for oil. Additionally, a variety of these settings contain truly enormous amounts of gas, but it is either dispersed throughout low-permeability horizons or concentrated in an ice lattice (hydrates); therefore, exploitation of these resources involves unique engineering problems rather than exploration uncertainties.

To start the process of addressing these energy-gas issues, we organized a workshop in October of 1992 to which a spectrum of researchers was invited from government, universities, and the gas industry. Approximately 75 specialists participated in discussions ranging from the origin of energy gases to how methane may provide a bridge to a hydrogen-based energy system in the future. This volume reflects the themes discussed at the workshop; it makes no attempt to offer new resource assessments because a variety of such studies already exists. Rather, its goal is to provide the fundamental information about energy gases, describe the attributes that make gas a beneficial fuel, provide ideas on how gas could be more fully integrated into an energy strategy, and explore the problems that may lie ahead if society shifts toward heavier use of energy gases. Woven throughout the volume are indications that a great deal is still unknown; these unknown factors may provide the focus for future research.

Besides this volume, two additional companion products have been produced as follow-up products to the workshop. One is a 30-minute video entitled *The Future of Energy Gases* that is directed to nontechnical audiences and provides a general introduction to energy gases. The second is a pamphlet, also entitled *The Future of Energy Gases* (U.S. Geological Survey Circular 1115), which provides a nontechnical summary of energy-gas issues with numerous illustrations. Together, the three products constitute a package offering a look at the topic of energy gases ranging from very general to highly technical. We would appreciate comments from readers, both in terms of the effectiveness of each piece as well as any suggestions for future products and research directions.

And finally, we of the U.S. Geological Survey ad hoc Energy Gases committee must credit Gary Hill for challenging us to take on this project. Additionally, we would like to express our thanks and gratitude to the large cast of authors, editors, and production staffers whose collective effort allowed this volume to be conceived, written, and published in record time. Not included in the list of credits are Jim Pinkerton and Jeffrey Troll without whose confidence and guidance we could not have completed this volume. Special mention must go to Carolyn Donlin, the technical editing coordinator of the professional paper, whose patience, flexibility, and tenacity helped steer the 57 chapters through a rigorous and complicated review and production schedule.

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Natural Gas Production from Arctic Gas Hydrates

By Timothy S. Collett[1]

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ABSTRACT

The natural-gas hydrates of the Messoyakha field in the West Siberian basin of Russia and those of the Prudhoe Bay-Kuparuk River area on the North Slope of Alaska occur within a similar series of interbedded Cretaceous and Tertiary sandstone and siltstone reservoirs. Geochemical analyses of gaseous well-cuttings and production gases suggest that these two hydrate accumulations contain a mixture of thermogenic methane migrated from a deep source and shallow, microbial methane that was either directly converted to gas hydrate or was first concentrated in existing traps and later converted to gas hydrate. Studies of well logs and seismic data have documented a large free-gas accumulation trapped stratigraphically downdip of the gas hydrates in the Prudhoe Bay-Kuparuk River area. The presence of a gas-hydrate/free-gas contact in the Prudhoe Bay-Kuparuk River area is analogous to that in the Messoyakha gas-hydrate/free-gas accumulation, from which approximately 5.17×10^9 cubic meters (183 billion cubic feet) of gas have been produced from the hydrates alone. The apparent geologic similarities between these two accumulations suggest that the gas-hydrate-depressurization production method used in the Messoyakha field may have direct application in northern Alaska.

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INTRODUCTION

Large quantities of natural gas, composed mainly of methane, can occur in sediments in the form of gas hydrates. These substances are solids, composed of rigid cages of water molecules that trap molecules of gas. Cold surface temperatures at high latitudes are conducive to the development of onshore permafrost and gas hydrate in the subsurface. Gas hydrates are known to be present in the western Siberian platform (Makogon and others, 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 Siberian and Kamchatka areas (Cherskiy and others, 1985). Permafrost-associated gas hydrates are also present in the North American Arctic. Well-log responses attributed to the presence of gas hydrates have been observed in about one-fifth of the wells drilled in the Mackenzie Delta, and in the Arctic Islands over half of the wells are inferred to contain gas hydrates (Bily and Dick, 1974; Judge, 1988). Direct evidence for gas hydrates on the North Slope of Alaska comes from a core test, and indirect evidence comes from drilling and open-hole well logs that suggest the presence of numerous gas-hydrate layers in the area of the Prudhoe Bay and Kuparuk River oil fields (Collett, 1983; Collett and others, 1988). 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. Because large quantities of gas hydrates are widespread in permafrost regions they may be a potential energy resource. Worldwide estimates of the amount of gas within continental gas hydrates range from 1.4×10^{13} to 3.4×10^{16} cubic meters (5.0×10^{2} to 1.2×10^{6} trillion cubic feet) (reviewed by the Potential Gas Committee, 1981).

The gas-hydrate accumulations of the Russian Messoyakha field, located in the West Siberian basin, and those of the Prudhoe Bay-Kuparuk River area of northern Alaska (fig. 1) are the most studied gas-hydrate accumulations in the world; however, language barriers have hindered previous attempts to compare these two hydrocarbon accumulations. The primary objectives of this paper are (1) to describe the geologic and geochemical nature of both the Messoyakha and the Prudhoe Bay-Kuparuk River gas-hydrate accumulations and (2) to characterize the potential for gas production from the Alaskan gas hydrates on the basis of the production history of the Messoyakha accumulation.

PRUDHOE BAY-KUPARUK RIVER GAS-HYDRATE ACCUMULATION

Gas hydrates exist under a limited range of temperature and pressure conditions, and the depth and thickness of the zone of potential gas-hydrate stability can be calculated (Makogon, 1981). Depicted in figure 2 is the calculated thickness of the potential methane-hydrate stability zone in the N.W. Eileen State No. 2 well of the Prudhoe Bay oil field in northern Alaska. The zone of potential methane-hydrate stability in the N.W. Eileen State No. 2 well lies within the depth interval from approximately 210 to 950 m. Regional analysis of subsurface gas chemistry, temperatures, pore pressures, and pore-water salinities indicates that methane hydrate would be stable beneath most of the

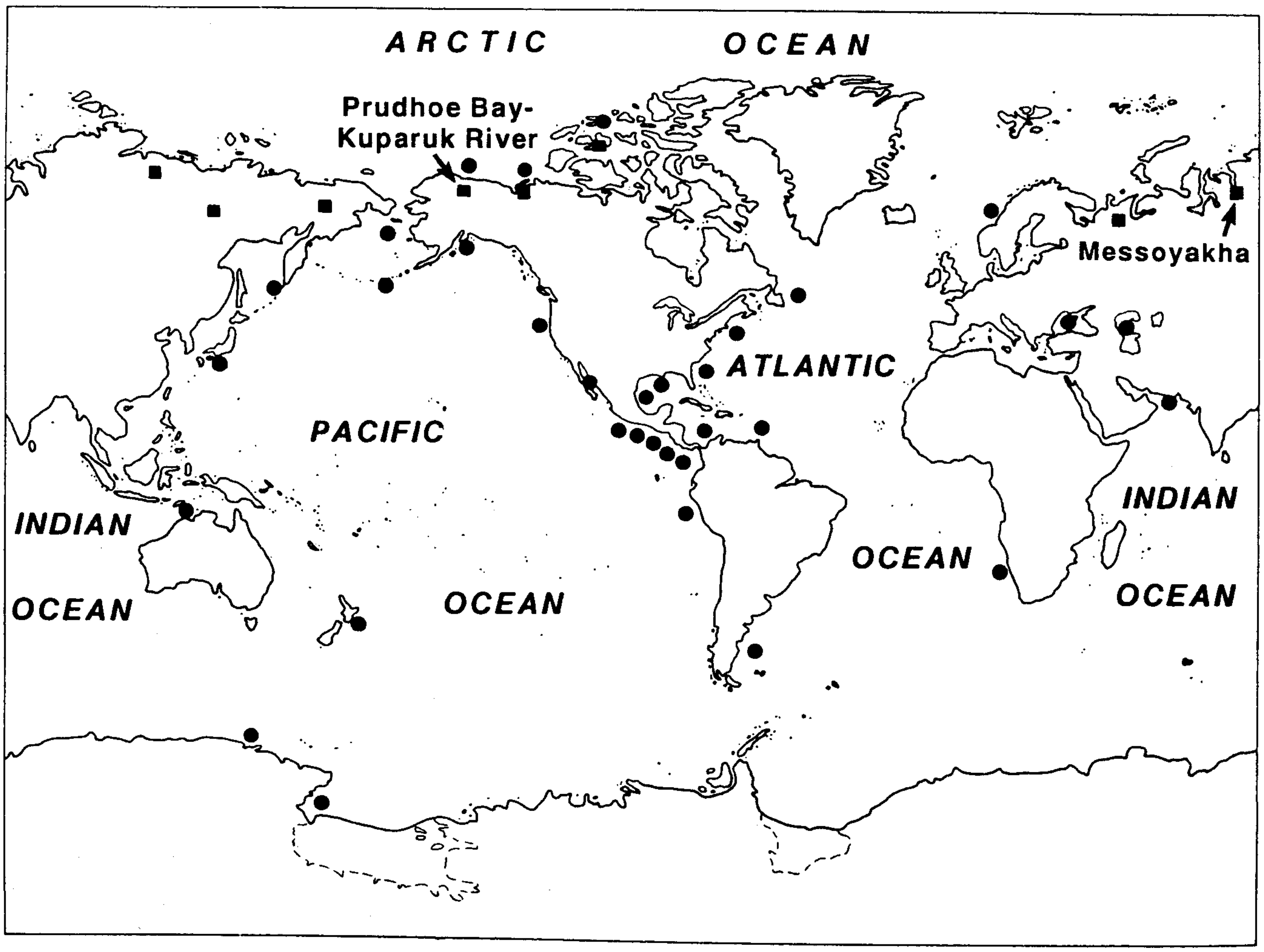


Figure 1. Locations of known and inferred gas hydrates in marine sediments of outer continental margins (dots), and in continental permafrost (squares). Dashed lines in Antarctica indicate edges of ice shelves. Modified from Kvenvolden (1988).

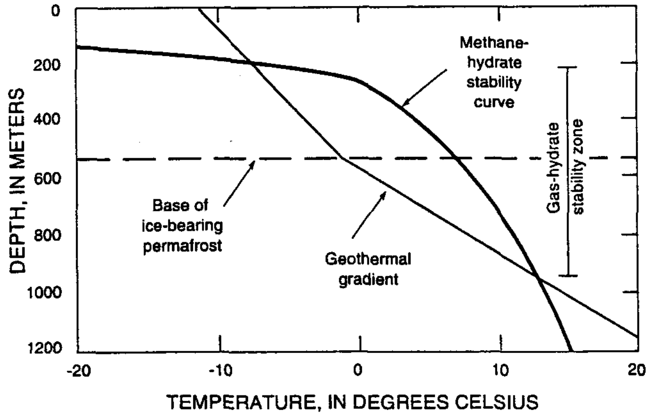


Figure 2. Phase diagram illustrating depth-temperature zones in which methane hydrates would be stable in N.W. Eileen State No. 2 well on North Slope of Alaska (modified from Collett, 1983). See figure 5 for well location.

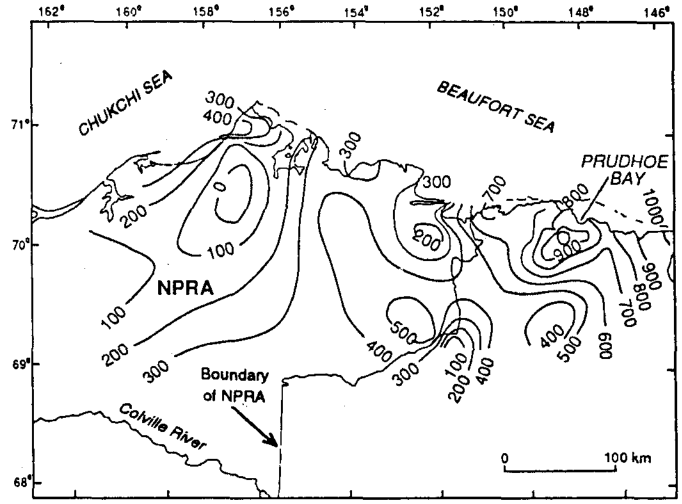


Figure 3. Isopach map of north-central Alaska showing calculated thickness (in meters) of methane-hydrate stability field. Isopachs are based on gas-hydrate-stability calculations from 124 wells (Collett and others, 1988). NPRA, National Petroleum Reserve in Alaska.

coastal plain province of northern Alaska and that the stability zone would be thicker than 1,000 m in parts of the Prudhoe Bay oil field (fig. 3) (Collett and others, 1988).

Previous North Slope studies (Collett, 1983; Collett and others, 1988) indicate that gas hydrates occur only in rocks of the Cretaceous and Tertiary Sagavanirktok Formation (fig. 4) and are limited to the area overlying the Prudhoe Bay and Kuparuk River oil fields. 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. In the Prudhoe Bay area, the Sagavanirktok Formation thickens from southwest (about 1,000 m) to northeast (about 2,000 m), and conformably overlies marine shale of the Canning Formation. The regional structure of the Sagavanirktok Formation in the study area is a gentle (1°–2°) northeasterly-dipping monocline. 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 (40 billion barrels) of in-place low-gravity oil. In the Prudhoe Bay-Kuparuk River area, the Sagavanirktok Formation is cut by northwesterly striking high-angle normal faults, generally downthrown to the east (Werner, 1987). A similar set of northwesterly striking faults cuts the older rocks in this area, suggesting a genetic linkage to the faults within the Sagavanirktok Formation. These faults are important in that they are interpreted to have served as conduits for oil and gas migration from the underlying Prudhoe Bay field (Carman and Hardwick, 1983).

The only confirmation of natural-gas hydrate on the North Slope was obtained in 1972 when Arco and Exxon successfully recovered gas hydrate in a core (reviewed by Kvenvolden and McMenamin, 1980). This gas-hydrate sample was from a depth of about 666 m in the N.W. Eileen State No. 2 well (cored interval 664 to 667 m). After completion of this well, the gas-hydrate-bearing interval was perforated and tested. A drill-stem test of the perforated interval from 663 to 671 m flowed gas at a maximum rate of 112 cubic meters per day (3,960 cubic feet per day). Geochemical analyses (table 1) reveal that methane was the dominant gas recovered during the drill-stem test (93 percent methane, 7 percent nitrogen) and from the core sample

Table 1. Geochemical analysis of gas samples obtained from the hydrate-bearing core (664–667 m) and production flow test (663–671 m) in the N.W. Eileen State No. 2 well at Prudhoe Bay, Alaska

[From written commun., 1983, P. Barker, Arco Alaska Inc., Anchorage, Alaska. %, percent of total gas volume; ---, not detected]

Sample type	Interval depth (m)	Carbon dioxide (%)	Oxygen (%)	Nitrogen (%)	Methane (%)	Ethane (%)	Propane (%)
Core	664–667	---	0.52	12.53	86.95	Trace	---
Core	664–667	---	0.02	0.84	99.14	Trace	---
Core	664–667	---	0.03	0.80	99.17	Trace	---
Core	664–667	---	0.05	1.46	98.49	Trace	---
Flow test	663–671	Trace	---	7.19	92.79	0.02	Trace
Flow test	663–671	Trace	---	7.23	92.76	0.01	Trace

(87 to 99 percent methane) (written commun., 1983, P. Barker, Arco Alaska Inc., Anchorage, Alaska).

Well-log data from an additional 445 North Slope wells were examined for possible gas-hydrate occurrences (Collett and others, 1988). This review of all available data revealed that gas hydrates probably occur in 50 of the surveyed wells. Many of these wells have multiple gas-hydrate-bearing units, and individual occurrences range from 3 to 31 m thick. The gas hydrates inferred from well logs occur in six laterally continuous sandstone and conglomerate units and are geographically restricted to the east end of the Kuparuk River production unit and the west end of the Prudhoe Bay production unit (figs. 5, 6). The six gas-hydrate-bearing rock units have each been assigned a reference letter (units A

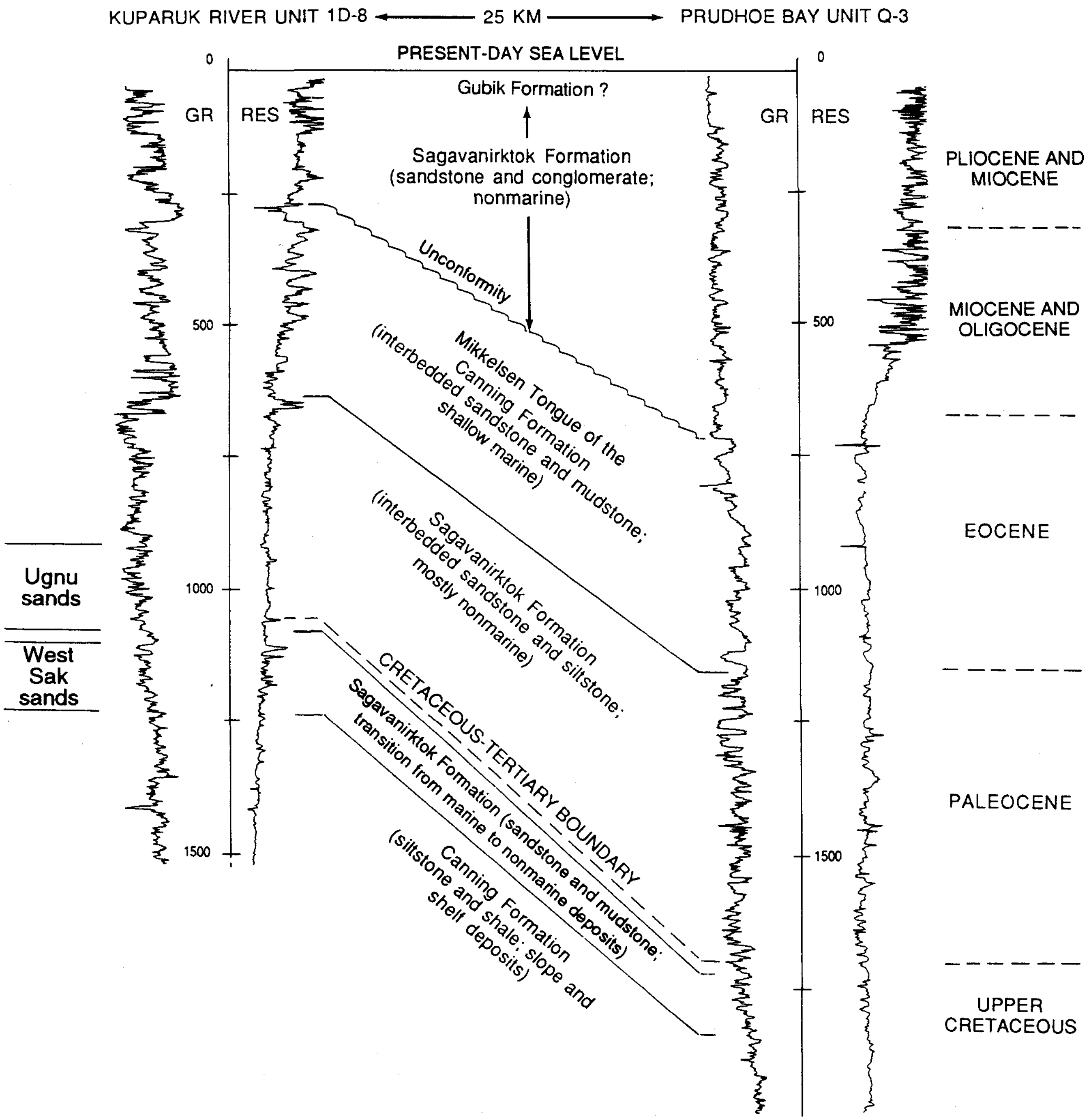
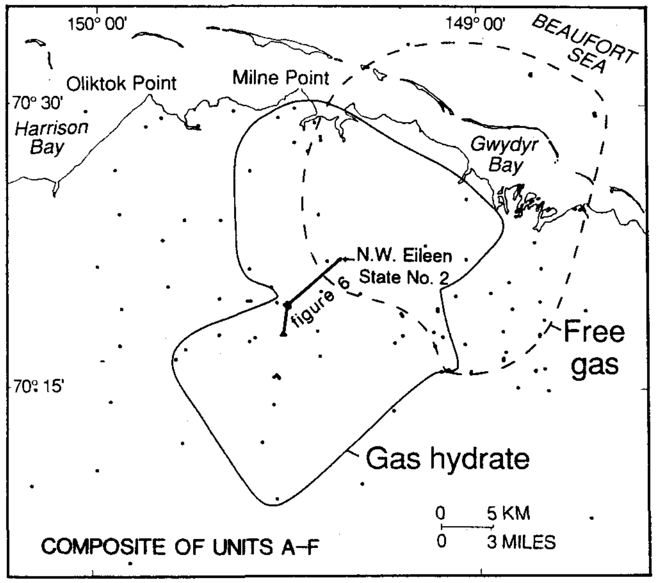


Figure 4. Well-log correlations between Kuparuk River Unit 1D-8 and Prudhoe Bay Unit Q-3 wells showing the North Slope stratigraphic relations and terminology used in this report. Locally the Sagavanirktok Formation is overlain by the Gubik Formation. Depths are in meters measured from the kelly bushing. GR, gamma ray; RES, resistivity.

through F); unit A is stratigraphically the deepest (fig. 6). Recently completed three-dimensional seismic surveys have documented the probable occurrence of a gas-hydrate/free-gas contact at the base of the methane-hydrate stability field in the west end of the Prudhoe Bay production unit (public presentation, 1987, C.G. Guderjahn, British Petroleum Exploration Inc., Anchorage, Alaska). Open-hole logs from wells in the west end of the Prudhoe Bay field also indicate the presence of a large free-gas accumulation trapped stratigraphically downdip from four of the log-inferred gas hydrates (figs. 5, 6; units A, B, C, D). The total mapped area of



► **Figure 5.** Composite map showing location of all six gas-hydrate/free-gas units (A–F) in Prudhoe Bay-Kuparuk River area (modified from Collett and others, 1988). Also shown are locations of the N.W. Eileen State No. 2 well and the cross section in figure 6. Dots, well locations.

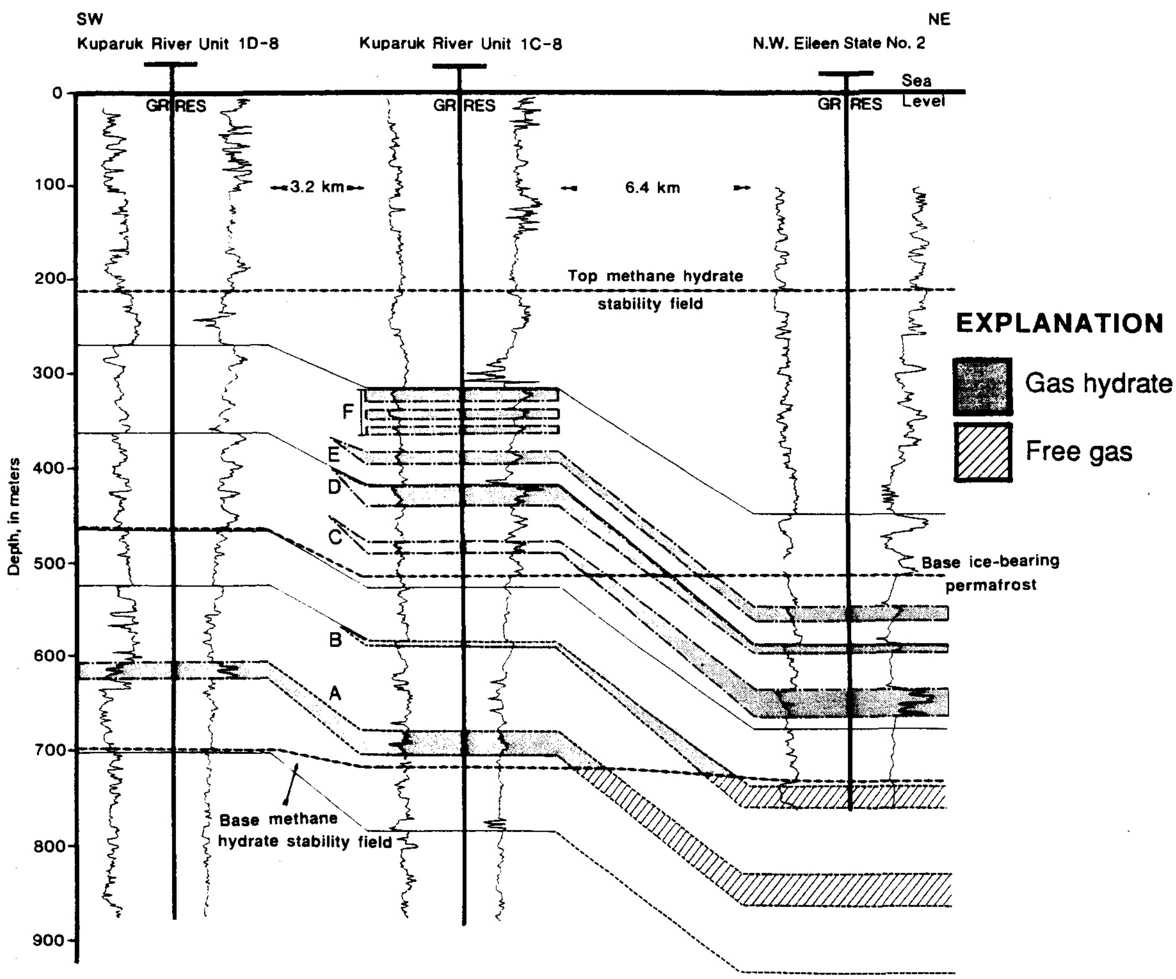


Figure 6. Cross section showing lateral and vertical extent of gas hydrates and underlying free-gas occurrences in Prudhoe Bay-Kuparuk River area. See figure 5 for location of cross section. Gas-hydrate-bearing units are identified with reference letters A through F. Gamma-ray (GR) and resistivity (RES) logs are shown for three wells. Solid lines are log correlation markers used to construct regional stratigraphic framework. Dot-and-dashed lines bounding units are known boundaries; dashed lines are inferred boundaries. Modified from Collett and others (1988).

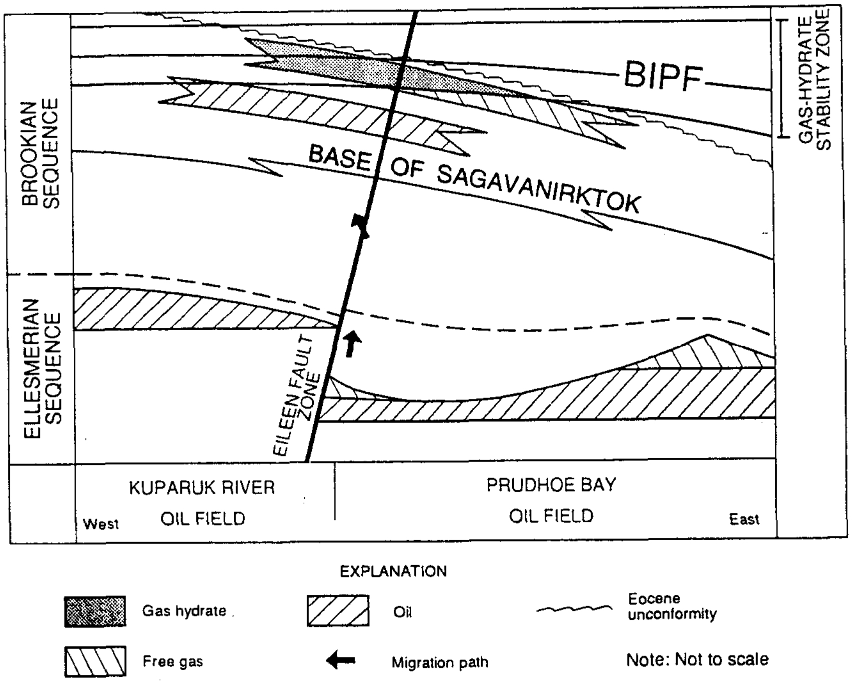


Figure 7. Schematic west-to-east cross section through Prudhoe Bay-Kuparuk River area illustrating possible gas migration paths and spatial relations between gas hydrates, free gas, oil, Eileen fault zone, base of ice-bearing permafrost (BIPF), and gas-hydrate stability field (modified from Carman and Hardwick, 1983, fig. 13). The Brookian sequence is primarily a passive-margin deposit composed of clastic sedimentary rocks derived from the Brooks Range to the south. The Ellesmerian sequence is composed of clastic and carbonate strata that were deposited on a south-facing margin of a stable continental landmass.

all six gas-hydrate occurrences is about 1,643 km^2; the areal extent of the individual units ranges from 3 to 404 km^2 (Collett and others, 1988). Porosities calculated from well logs and measured from core samples of the gas-hydrate reservoir rocks range from 37 to 42 percent, and the average degree of gas-hydrate saturation within these reservoirs is about 85 percent (Collett and others, 1988). The potential volume of gas within the identified gas hydrates (exclusive of the associated free gas) of the Prudhoe Bay-Kuparuk River area is approximately 1.0×10^{12} to 1.2×10^{12} cubic meters, or approximately 37 to 44 trillion cubic feet, of gas at standard temperature and pressure (STP).

Geochemical similarities suggest that oil, and presumably the associated gas, within the Sagavanirktok Formation was "spilled" from the underlying reservoirs in the Sadlerochit Group of the Prudhoe Bay field as a consequence of regional tilting during middle to late Tertiary time (Carman and Hardwick, 1983). As shown in figure 7, most of the gas hydrates and shallow heavy oils occur either updip from or near the Eileen fault zone. This fault zone may have acted as a conduit for free-gas and oil migration from deeper hydrocarbon accumulations. Geochemical analysis of headspace gases evolved from drill cuttings collected from seven development wells drilled in the Prudhoe Bay and Kuparuk River oil fields suggests that methane is the principal hydrocarbon gas in the near-surface (0 to 1,500 m) strata (Collett and others, 1990). The plot of the carbon ($\delta^{13}C$) and hydrogen (δD) stable isotopic compositions of the methane (fig. 8) from the hydrate-bearing rock units indicates that most of the methane is from mixed microbial and thermogenic sources. The natural-gas genetic classification diagram in figure 8 also suggests that the microbial gas was generated by biogenic carbon dioxide reduction of the in-situ organic matter. Vitrinite reflectance (R_o) measurements of about 0.4 percent show that the gas-hydrate-bearing rocks have never been subjected to temperatures within the thermogenic hydrocarbon window, which

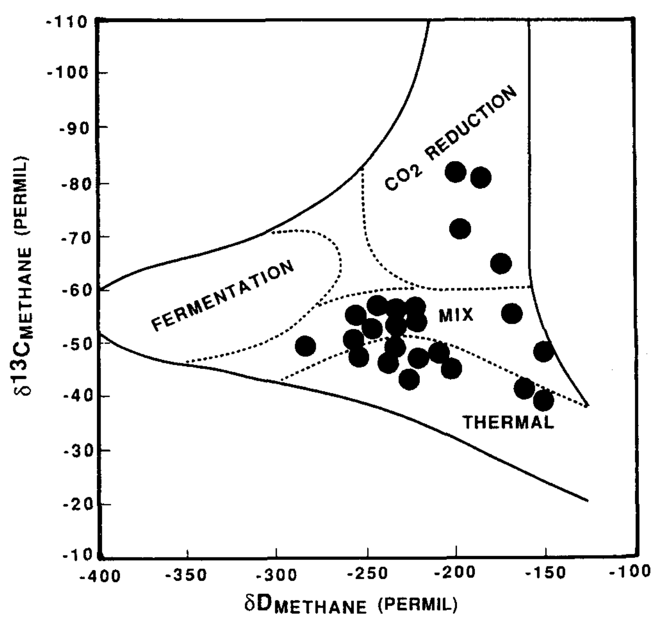


Figure 8. Natural-gas genetic classification diagram (modified from Whiticar and others, 1986) depicting the carbon ($\delta^{13}C$) and hydrogen (δD) stable isotopic compositions (dots) of the methane within the hydrate-bearing rock units of two wells drilled in the west end of the Prudhoe Bay production unit. MIX indicates mixture of microbial (FERMENTATION and CO_2 REDUCTION) and thermogenic (THERMAL) gases.

ranges from about 0.6 to 2.0 percent. Thus, the thermogenic gas must have migrated from greater depths.

The gas cap of the Prudhoe Bay field is composed primarily of methane (83 to 88 percent) along with small quantities of ethane (5 to 7 percent) and propane (1 to 2 percent) (written commun., 1989, M.C. Davidson, BP Exploration, Anchorage, Alaska). If the gas within the near-surface sediments migrated from deeper structures, the shallow gas should have geochemical constituents similar to those of the deeper gas; however, no significant amounts of ethane or propane were detected within the interval of gas-hydrate stability. The depletion of heavier hydrocarbons such as ethane and propane from gas mixtures by stripping during migration has been suggested by Schoell (1983) and Jenden and Kaplan (1986) to explain natural gases containing thermogenic methane but only minor amounts of heavier hydrocarbons. The thermogenic component of the gas within the interval of gas-hydrate stability may have been stripped of most of its heavier hydrocarbons. Such a process could account for the molecular and isotopic compositions observed.

The carbon isotopic composition of the methane ($\delta^{13}C$) within the gas-hydrate-bearing rock units averages approximately -49 permil, suggesting that the hydrates contain a mixture of thermogenic and microbial gases. By comparing the methane carbon isotopic composition ($\delta^{13}C$) of this apparent gas mixture to the isotopic composition of the Prudhoe Bay gas cap it is possible to calculate the relative volume of gas from thermogenic versus microbial sources within the hydrate stability field. The methane-carbon isotopic value ($\delta^{13}C$) of the Prudhoe Bay gas cap averages approximately -39 permil (written commun., 1989, M.C. Davidson, BP Exploration, Anchorage, Alaska). The methane component from a microbial source likely had an original methane isotopic composition ranging from -60 to -70 permil. Because the mixing of two gases results in a linear and proportional change in isotopic composition (Schoell, 1983), it is estimated that about 50 to 70 percent of the methane within the hydrate stability field has migrated from the Prudhoe Bay gas cap. Thus, the occurrence of gas hydrates is controlled by the availability of a significant quantity of migrated thermogenic hydrocarbon gas.

To describe the history of gas-hydrate formation, I have modified a generalized cross section (fig. 7) from Carman and Hardwick (1983, fig. 4). As thermogenic gas moved up the Eileen fault zone, some of the gas may have been rechanneled updip along relatively porous and permeable northeast-dipping sandstone units of the Sagavanirktok Formation. The updip-migrating gas probably mixed with the in-situ microbial methane and collected in structural or stratigraphic traps where subsequent temperature changes deepened the permafrost sequence and converted the trapped gas into gas hydrate. Conversely, the updip migrating gas may have been converted to gas hydrate upon entering the pressure-temperature regime of gas-hydrate stability, thus forming its own trap. Because so little is known about the history of temperatures on the North Slope and the presence of traps for free gas in this area, either of these models is plausible.

Thermal conditions conducive to the formation of gas hydrates have probably persisted in northern Alaska since the end of the Pliocene (about 1.65 Ma); however, regional temperature fluctuations throughout the Pleistocene (about 1.65 to 0.01 Ma) have been great enough to repeatedly thicken and thin the zone of gas-hydrate stability (Collett and others, 1988). At this time adequate knowledge of climate and geologic changes on the time scale necessary to accurately assess the history of gas-hydrate formation in northern Alaska is not available; however, it is safe to say that the North Slope gas hydrates are likely no older than Pleistocene, and they could be as young as late Pleistocene (Wisconsin Stage; about 0.07 to 0.01 Ma).

MESSOYAKHA GAS-HYDRATE ACCUMULATIONS

The Messoyakha gas field was discovered in 1968, and it was the first producing field in the northern part of the West Siberian basin (fig. 1). By the mid-1980's, more than 66 gas fields had been discovered in the West Siberian basin, containing an estimated total gas reserve of 22 trillion cubic meters (777 trillion cubic feet)—approximately one-third of the world's reserves (Grace and Hart, 1986). Between 1969 and 1987 about 14.4 billion cubic meters (508 billion cubic feet) of gas were produced from the Messoyakha field and delivered by pipeline to the city of Noril'sk (Makogon, 1988). The geology (fig. 9) and petroleum geochemistry of the West Siberian basin is described in detail in many English language publications (Kortsenshteyn, 1970; Makogon and others, 1972; Alekseyev, 1974; Trofimuk and others, 1977; Kruglikov and others, 1983; Krason and Ciesnik, 1985; Grace and Hart, 1986; Galimov, 1988; Makogon, 1988; and Peterson and Clarke, 1989). Production in the northern part of the West Siberian basin is principally from the Neocomian reservoirs of the Vartov and Megion suites (average depth, 2,800 m) and the Cenomanian reservoirs of the Pokur suite (average depth, 1,100 m); about two-thirds of the region's gas production is from the Cenomanian reservoirs (Grace and Hart, 1986). The Pokur suite is a 700- to 800-m-thick complex of interbedded marine and nonmarine sandstone and shale that was deposited during an Aptian to Coniacian marine regression. Coal and plant debris are also prevalent within the nonmarine parts of the Pokur suite. The Pokur suite is overlain by the shale sequence of the Kuznetsov suite, which forms a regional seal for most of the gas in the underlying sandstone reservoirs. Regional analyses of subsurface temperatures, formation pressures, and pore-water salinities suggest that the methane-hydrate stability zone may extend

System	Series	Stage	Grace and Hart (1986)
Overlying beds			Tibeysalin suite (Tertiary)
CRETACEOUS	Upper	Maestrichtian	Gankin suite
		Campanian	
		Santonian	Kuznetsov suite
		Coniacian	
		Turonian	Pokur suite
		Cenomanian	
	Lower	Albian	
		Aptian	Vartov suite
		Barremian	
	Neocomian	Hauterivian	Megion suite
		Valanginian	
		Berriasian	
Underlying beds			Bazhenov suite (Jurassic)

Figure 9. Stratigraphic column for northern West Siberian basin (modified from Grace and Hart, 1986).

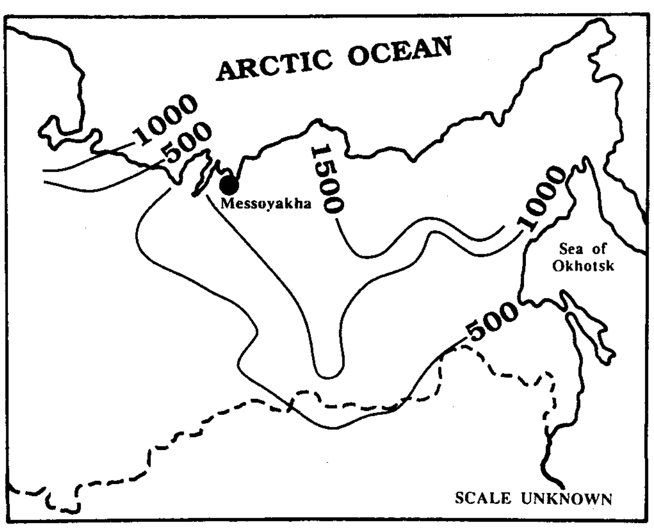


Figure 10. Depth (in meters) to base of methane-hydrate stability field in continental areas of Russia. Dashed line is southern boundary of former U.S.S.R. Modified from Makogon (1981).

to depths of approximately 1,000 m in the northern part of the West Siberian basin (fig. 10). The Messoyakha gas accumulation is confined to the Dolgan Formation of the Pokur suite, and production has been established from the depth interval between 720 and 820 m. The upper part (about 40 m) of the Messoyakha field lies within the zone of predicted methane-hydrate stability (fig. 11). By assuming a reservoir pressure of 78 kg/cm^2, Makogon and others (1972) determined that the 10°C isotherm defines the lower limit of the in-situ gas hydrates, thus separating the Messoyakha field into an upper gas-hydrate accumulation and a lower free-gas accumulation (fig. 12).

Unusually low gas yields from production tests in the upper part of the Messoyakha reservoir were the first physical evidence of possible in-situ gas-hydrate occurrences (production data discussed in more detail later in this paper). Analysis of spontaneous-potential, caliper, and gamma-ray well logs from 62 wells drilled in the Messoyakha field reveal the presence of apparently "frozen" rock intervals within the Dolgan Formation (Makogon and others, 1972). Because these "frozen" layers are more than 250 to 350 m below the zone of permafrost and are at equilibrium formation temperatures near 10°C, they have

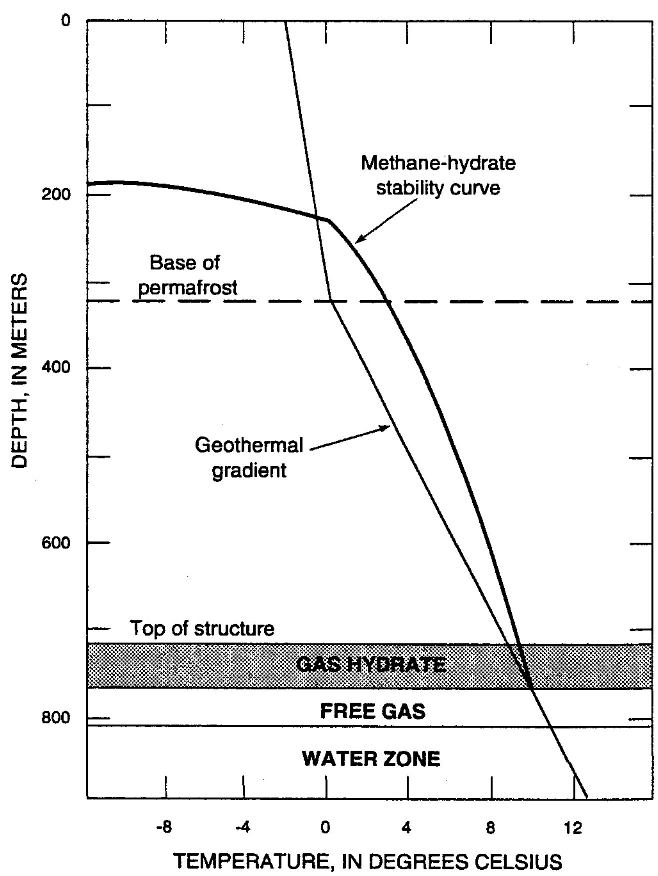


Figure 11. Phase diagram illustrating depth-temperature zone in which methane hydrates are stable in the area of the Messoyakha field of the West Siberian basin (modified from Sloan, 1990).

been interpreted to contain in-situ gas hydrates rather than ice. Further analysis of electrical-resistivity well logs also indicates the presence of gas hydrates in the upper part of the Messoyakha gas accumulation (Makogon, 1981). The gas-hydrate and free-gas parts of the Messoyakha field are depicted in the generalized cross section in figure 12. The detailed cross sections in figure 13 (Makogon and others, 1972; fig. 3) reveal that the well-log-inferred gas hydrates occur within a series of discrete, laterally continuous sandstone sequences that are separated by interbedded shales and siltstones. The Messoyakha structure as described by Makogon and others (1972) is a dome having dimensions

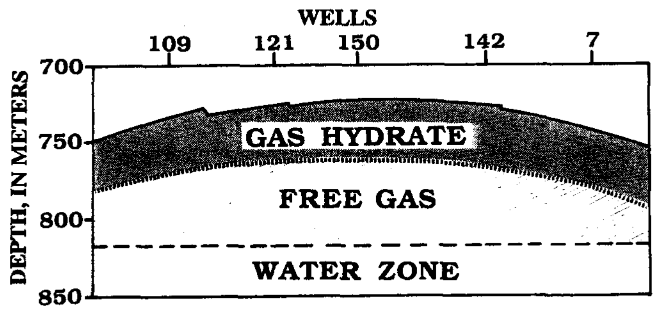


Figure 12. Generalized cross section illustrating the distribution of the gas-hydrate and free-gas parts of the Messoyakha field (modified from Makogon, 1988).

of 12.5 by 19 km (fig. 14). Studies of cores, well cuttings, and well logs show that in the free-gas part of the Messoyakha field the Dolgan Formation is characterized by porosities ranging from 16 to 38 percent; permeabilities average about 125 millidarcies. Water saturations in the Dolgan Formation are reported to average about 40 percent (Makogon and others, 1972). Prior to production, the calculated total gas reserves within the gas-hydrate and free-gas parts of the Messoyakha accumulation were estimated to be about 80×10^9 cubic meters (2.8 trillion cubic feet), with about one-third of the reserves within the gas hydrates (Krason and Ciesnik, 1985).

The Cenomanian reservoirs of the Pokur suite in northern West Siberia contain mostly methane (92.5 to 99 percent), the source of which is a matter of controversy (reviewed by Grace and Hart, 1986). Elemental and isotopic compositions of the hydrocarbon gases within the West Siberian basin are available from several sources, including Yermakov and others (1970), Alekseyev (1974), and Galimov (1988). Most of the published isotopic data are limited to only stable methane carbon compositions. Additional isotopic data are required to accurately ascertain the source of a gas. However, by assuming that a gas with a stable methane-carbon isotopic composition of -50 permil and heavier is thermally generated and that an isotopic composition of -60 permil or lighter is indicative of methane from a microbial source (isotopic ranges from Schoell, 1983), it

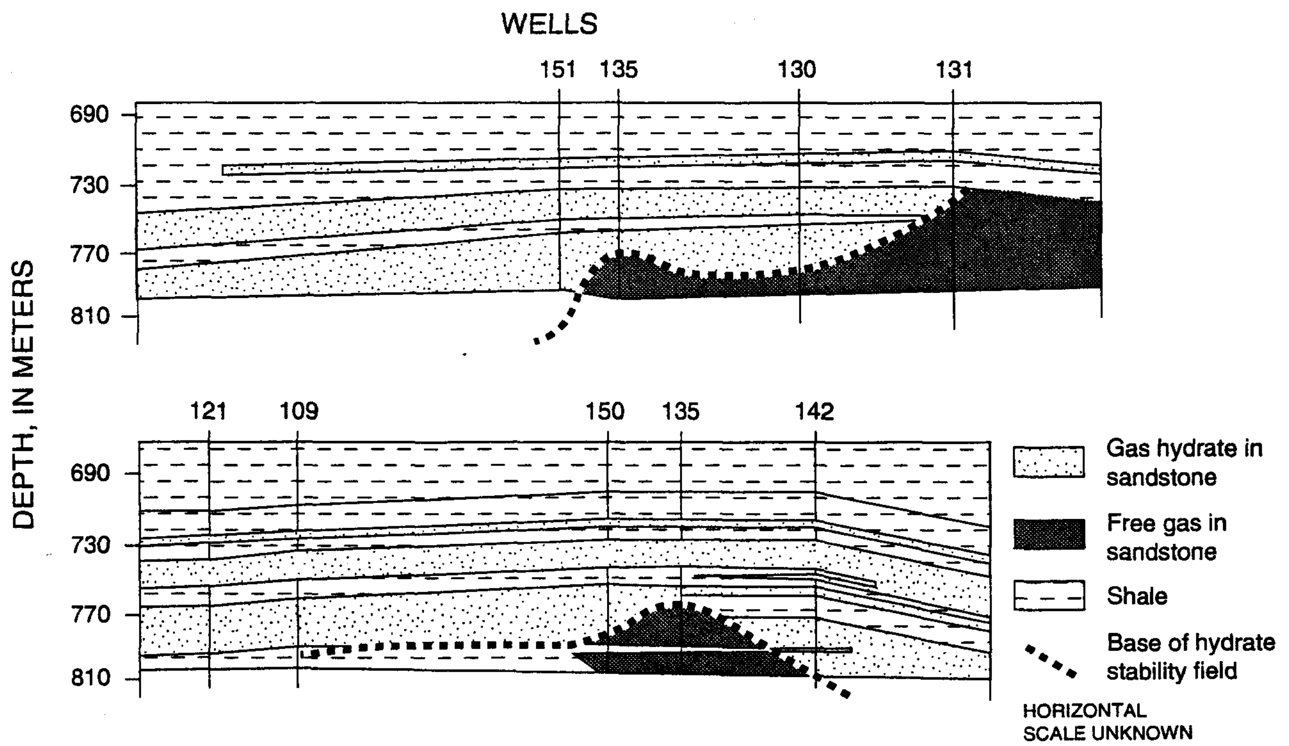
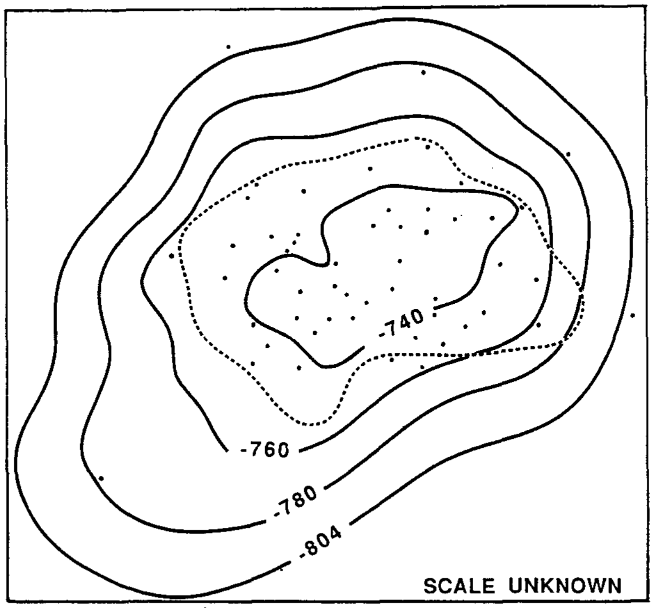


Figure 13. Multi-well cross sections showing the lateral and vertical extent of gas hydrates and underlying free gas in the Messoyakha field (modified from Makogon and others, 1972). Specific location of cross sections and horizontal scale are unknown.



EXPLANATION

Gas-hydrate/free-gas contact

Depth, in meters, to top of Dolgan Formation

Well

Figure 14. Structure map of the top of the gas-hydrate-bearing Dolgan Formation in the Messoyakha field (modified from Krason and Ciesnik, 1985).

is possible to approximate the source of a gas. Due to the arbitrary nature of these analytical boundaries, I have defined an isotopic transitional or mixing zone (values ranging from -65 to -45 permil) between the thermogenic and microbial end-members. The reported stable carbon isotopic compositions ($\delta^{13}C$) of the methane within the Neocomian reservoirs of the West Siberian basin range from -48 to -38 permil (Messoyakha values range from -44.2 to -38.5 permil), which are indicative of gases generated by mostly thermogenic processes. The Cenomanian reservoirs, however, contain methane with a stable carbon isotopic composition ranging from -68 to -41 permil (Messoyakha values range from -48.0 to -41.0 permil) (reviewed by Grace and Hart, 1986), which falls mostly within the transitional or mixing zone between the thermogenic and microbial end-member gases. The Messoyakha Cenomanian reservoirs, therefore, may contain gas that was formed by either microbial or thermogenic processes. The thermogenic gas component within the near-surface (<900 m) Cenomanian reservoirs of the Messoyakha field may have migrated from the deeper (about 2,600 m) Neocomian reservoirs or directly from Jurassic hydrocarbon source rocks. Kruglikov and others (1983) conclude from studies of argon isotopic data from the West Siberian basin that both deep (thermogenic) and shallow (microbial) sources have contributed to the Cenomanian reservoirs. Galimov (1988), however, has suggested that the methane within the Cenomanian reservoirs may have been generated in situ by early-stage (low-temperature) geochemical transformation of terrestrial organic matter. His geochemical model suggests that the humic organic matter in the Cenomanian sedimentary deposits has a high methane-generation capacity at relatively low maturities and that the observed stable methane-carbon isotopic compositions indicate this low-temperature alteration. Some fraction of the methane in the hydrates of the Messoyakha field is probably from the microbial alteration of in-situ organic matter in the Cenomanian sediments; however, there is evidence that some methane has migrated from deep thermogenic sources. Most certainly, additional geochemical data are required to fully assess the source of the gas within the Cenomanian reservoirs of the West Siberian basin.

Several authors (Kortsenshteyn, 1970; Trofimuk and others, 1977; and DuRochet, 1980) suggest that conditions conducive to the formation of permafrost and gas hydrates have persisted in the northern part of the West Siberian basin since the early Pleistocene (about 1.65 Ma). Russian geologists generally conclude that pre-existing free-gas accumulations were converted to gas hydrates during Pleistocene glacial advances and that the gas-hydrate pools were transformed back into free-gas accumulations during subsequent interglacial periods. The present-day Messoyakha field is in transition from a gas-hydrate to a free-gas accumulation and it has not completely converted back to its preglacial free-gas state.

MESSOYAKHA PRODUCTION HISTORY

Production tests in the early development history of the Messoyakha field yielded highly variable results (table 2). Measured flow rates from the free-gas part of the reservoir were substantially greater than those from the gas hydrates. To confirm the presence of gas hydrates within the upper part of the Messoyakha field, a series of hydrate-inhibitor injection tests were conducted (table 3). During these tests, substances, such as methanol and calcium chloride, which destabilize and prevent the formation of gas hydrates, were injected into the suspected gas-hydrate-bearing rock units.

Table 2. Production-test data from the Messoyakha field, West Siberia (Makogon, 1981)

Well No.	Depth of tested interval (m)	Distance above (–) or below (+) the gas-hydrate/free-gas contact (m)	Gas flow (1,000 m^3/day)
121	716–727	–64	26
109	748–794	–6	133
150	741–793	+6	413
195	779–795	+29	626
131	771–793	+59	1,000

Table 3. Production results from gas-hydrate-inhibitor injection test in the Messoyakha field, West Siberia (from Sumetz, 1974, and Makogon, 1981)

Well No.	Type of inhibitor	Gas flow before treatment (1,000 m^3/day)	Gas flow after treatment (1,000 m^3/day)
129	Methanol	30	150
131	Methanol	175	275
133	Methanol	25	50
		50	100
		100	150
		150	200
		200	250
138	Methanol and $CaCl_2$	200	300
139	Methanol and $CaCl_2$	120	180
141	Methanol and $CaCl_2$	150	200
142	Methanol	5	50
		10	100
		25	150
		50	200

Most of these tests (summarized by Sumetz, 1974, and Makogon, 1981) resulted in dramatic increases in production rates, which was attributed to the dissociation of the in-situ gas hydrates.

Long-term production from the gas-hydrate part of the Messoyakha field has been achieved by a simple depressurization scheme. The reservoir-pressure and production history of the Messoyakha field are depicted in figure 15. As production began in 1969, the reservoir-pressure decline curve followed the predicted path; however, in 1971 the measured reservoir pressures began to deviate from the predicted values. This deviation has been attributed to the liberation of free gas from dissociating gas hydrates. The 17-yr production history of the Messoyakha field has been divided into five stages (fig. 15):

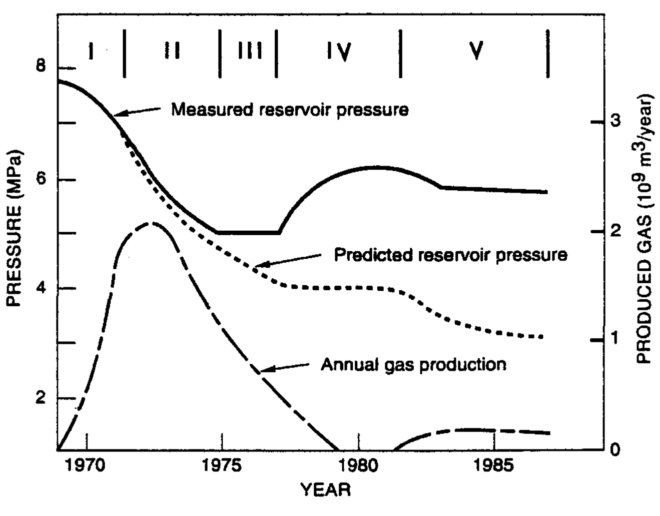


Figure 15. A plot of reservoir pressures and production history as a function of time for the Messoyakha field (modified from Makogon, 1988). The roman numerals across the top of the figure denote the stages of production discussed in the text. MPa, megapascal.

Stage I. From 1969 to 1971, the reservoir pressure did not fall below gas-hydrate stability conditions and gas production was only from the deeper free-gas part of the field.

Stage II. From 1971 to 1975, the actual reservoir pressures exceeded predicted reservoir pressures. This departure marked the start of gas-hydrate dissociation and gas production from the gas-hydrate part of the field.

Stage III. From 1976 to 1977, the volume of gas withdrawn from the reservoir was equal to the amount of gas liberated from the dissociating gas hydrates.

Stage IV. From 1978 to 1981, production from the Messoyakha field was reduced and eventually halted. The reservoir pressures began to rise as the gas hydrates continued to dissociate.

Stage V. Since 1982 there has been only modest production from the Messoyakha field. During this period the amount of gas liberated from the hydrates has been equal to the amount of gas produced.

Throughout the production history of the Messoyakha field, the depth of the gas-water contact has not changed, and it is estimated that about 36 percent (about 5.17×10^9 cubic meters or about 183 billion cubic feet) of the gas withdrawn from the field has come from the gas hydrates (Makogon, 1988). For more information on gas-hydrate production methods, see Yousif and others (1988) and Sloan (1990).

POTENTIAL PRODUCTION FROM THE PRUDHOE BAY-KUPARUK RIVER GAS-HYDRATE ACCUMULATION

Production data from the Prudhoe Bay-Kuparuk River gas-hydrate accumulation are limited to a single drill-stem test of the cored gas-hydrate interval of the N.W. Eileen State No. 2 well. The maximum gas-flow rate from the N.W. Eileen State No. 2 well of 112 cubic meters per day is similar to the production rates reported by Makogon (1981) for the untreated gas-hydrate intervals in the Messoyakha field (table 2). Other similarities between the Messoyakha and the Prudhoe Bay-Kuparuk River gas-hydrate accumulations suggest that the production history of the Messoyakha field may be used as an analog to predict the production potential of the Alaskan gas hydrates. For example, both the Messoyakha and the Prudhoe Bay-Kuparuk River gas-hydrate accumulations are in a series of friable sandstone reservoirs that are characterized by high porosities and low water saturations. Geochemical analyses suggest that the gas hydrates of the Messoyakha and Prudhoe Bay-Kuparuk River fields are almost identical in composition, and they have been interpreted to contain a mixture of thermogenic methane that migrated from deep, mature sources and in-situ, microbial methane. These similarities suggest that the origin of both accumulations may be similar. The presence of a significant volume of free gas trapped below both the Messoyakha and the Prudhoe Bay-Kuparuk River gas-hydrate accumulations is most important when considering the potential production characteristics of the gas hydrates in Alaska. Use of the gas-hydrate-depressurization method of production requires that a portion of the accumulation be in a free-gas state. Therefore, the presence of free gas below the Prudhoe Bay-Kuparuk River gas hydrates suggests that the depressurization production method used in the Messoyakha field may work in northern Alaska. The most striking difference between the Messoyakha and the Prudhoe Bay-Kuparuk River gas-hydrate/free-gas accumulations is their size. The total mapped area of all six gas-hydrate occurrences in the Prudhoe Bay-Kuparuk River area is about 1,643 km^2, whereas the Messoyakha field covers an area of only about 238 km^2. This difference in field size accounts for the vast difference between the estimated gas reserves in the Messoyakha gas-hydrate/free-gas accumulation (80×10^9 cubic meters; 2.8 trillion cubic feet) and those in the Prudhoe Bay-Kuparuk River gas-hydrate accumulation (1.2×10^{12} cubic meters; 44 trillion cubic feet). This difference suggests that the ultimate production capacity of the Prudhoe Bay-Kuparuk River gas-hydrate accumulation may be much greater than the historical production from the Messoyakha field.

CONCLUSIONS

The production history of the Messoyakha field in West Siberia has demonstrated that gas hydrates are an immediate producible source of natural gas and that production can be started and maintained by conventional methods. The geologic comparison of the Messoyakha and Prudhoe Bay-Kuparuk River gas-hydrate accumulations suggests that the Alaskan gas hydrates may also be a producible source of natural gas. The gas hydrates of the Prudhoe Bay-Kuparuk River area are estimated to contain approximately 1.0 to 1.2 trillion cubic meters of gas, which is about fifteen times greater than the estimated gas reserves in the Messoyakha field. This estimate indicates that the gas hydrates of northern Alaska may be an important source of natural gas in the near future.

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