

This paper was presented at the National Academy of Sciences colloquium “Geology, Mineralogy, and Human Welfare,” held November 8–9, 1998 at the Arnold and Mabel Beckman Center in Irvine, CA.

Potential effects of gas hydrate on human welfare

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ABSTRACT For almost 30 years, serious interest has been directed toward natural gas hydrate, a crystalline solid composed of water and methane, as a potential (i) energy resource, (ii) factor in global climate change, and (iii) submarine geohazard. Although each of these issues can affect human welfare, only (iii) is considered to be of immediate importance. Assessments of gas hydrate as an energy resource have often been overly optimistic, based in part on its very high methane content and on its worldwide occurrence in continental margins. Although these attributes are attractive, geologic settings, reservoir properties, and phase-equilibria considerations diminish the energy resource potential of natural gas hydrate. The possible role of gas hydrate in global climate change has been often overstated. Although methane is a “greenhouse” gas in the atmosphere, much methane from dissociated gas hydrate may never reach the atmosphere, but rather may be converted to carbon dioxide and sequestered by the hydrosphere/biosphere before reaching the atmosphere. Thus, methane from gas hydrate may have little opportunity to affect global climate change. However, submarine geohazards (such as sediment instabilities and slope failures on local and regional scales, leading to debris flows, slumps, slides, and possible tsunamis) caused by gas-hydrate dissociation are of immediate and increasing importance as humankind moves to exploit seabed resources in ever-deepening waters of coastal oceans. The vulnerability of gas hydrate to temperature and sea level changes enhances the instability of deep-water oceanic sediments, and thus human activities and installations in this setting can be affected.

The potential effects of gas hydrate on human welfare are not understood with certainty, but enough information has been collected and enough knowledge gained over the past 30 years to make preliminary assessments possible. To make these assessments, however, some geoscience background is necessary.

Definition. Naturally occurring gas hydrate is a solid, ice-like substance, composed of rigid cages of water molecules that enclose molecules of gas, mainly methane. Chemically, this substance is a water clathrate of methane, where “water clathrate” refers to the rigid cage structure of hydrogen-bonded water molecules, but is commonly called “methane hydrate” or, in general terms, “gas hydrate.” The maximum amount of methane is fixed by the geometry of the clathrate. In an ideally saturated methane hydrate, the molar ratio of methane to water is 1:5.75, that is equal to a volumetric ratio at standard conditions of methane gas to water of 216:1 or a volumetric ratio of methane gas to solid hydrate of 164:1 (1).

Occurrence. Gas-hydrate deposits occur under specific conditions of pressure and temperature, where the supply of methane is sufficient to initiate the formation of, and to stabilize, the hydrate (clathrate) structure (2). These conditions exist on earth in the upper 2,000 m of sediments in two

regions: (i) continental, including continental shelves, at high latitudes in polar regions, where surface temperatures are very cold ($<0^{\circ}\text{C}$) and (ii) submarine continental slopes and rises, where not only is bottom water cold ($\approx 0^{\circ}\text{C}$) but also pressures are high ($>3\text{ MPa}$). Thus, in polar regions, gas hydrate is found where temperatures are cold enough for onshore and offshore permafrost to be present. In offshore sediment of outer continental and insular oceanic margins, gas hydrate is found at water depths $>300\text{--}500\text{ m}$, depending on bottom-water temperatures.

The presence of gas-hydrate deposits in these oceanic margins has been inferred mainly from the appearance on marine seismic profiles of an anomalous reflection (Fig. 1) that coincides with the predicted boundary (based on assumed pressure/temperature considerations) of the base of the gas-hydrate stability zone (Fig. 2). This reflection is commonly called a bottom-simulating reflection (BSR) because it approximately mimics sea floor topography. BSRs have been mapped at depths below the sea floor, ranging from near the sea floor to $\approx 1,100\text{ m}$ (5); the upper limit of the gas-hydrate zone in outer continental margin sediment is ordinarily the sea floor. Gas-hydrate samples have been recovered at 27 oceanic continental margin locations (6), providing direct confirmation of gas-hydrate occurrence. The worldwide locations of known and inferred gas hydrate are shown in Fig. 3.

Estimates of Methane Content. Chersky and Makogon (8) proposed that the amount of methane in naturally occurring gas hydrate is potentially “enormous,” but the estimated amounts were highly speculative because of incomplete knowledge of gas-hydrate occurrence. The Potential Gas Committee (9) summarized the early estimates for the world: methane in gas-hydrate deposits ranging from 3.1×10^{15} to $7,600 \times 10^{15}\text{ m}^3$ for oceanic sediments and from 0.014×10^{15} to $34 \times 10^{15}\text{ m}^3$ for permafrost regions. Because oceanic gas hydrate apparently contains significantly more methane, it is emphasized in global estimations of the methane content of gas hydrate. The upper limit estimates above are from Dobrynin *et al.* (10) and appear to be overly optimistic. They are “rough estimates” based on permafrost coverage and zones of gas-hydrate stability in oceanic sediments without apparent regard for distributions of sedimentary basins or sources of methane.

Estimates made during the period from 1980 to 1990 of the amounts of methane in oceanic sediments were summarized by Kvenvolden (11). During this decade, an increased understanding of gas-hydrate occurrence has generally resulted in estimates within the lower ranges of previous ones (Fig. 4). For example, Kvenvolden (7) estimated the methane content of global gas-hydrate occurrence at $21 \times 10^{15}\text{ m}^3$. The calculated amount of gas hydrate in the outer continental margin of the Arctic Basin of $1.1 \times 10^{15}\text{ m}^3$ (12) was extrapolated to outer continental margins of the remainder of the world by multi-

Abbreviations: GCM, general circulation model; BSR, bottom-simulating reflection; LPTM, latest Paleocene thermal maximum.

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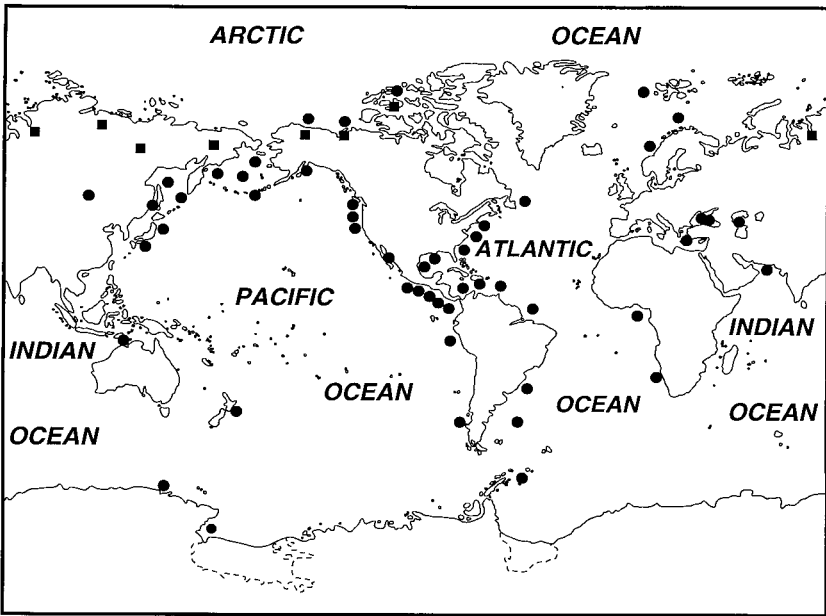


FIG. 3. The Earth showing locations of known and inferred gas-hydrate deposits in oceanic sediment of outer continental margins and in permafrost (continental) regions. Modified from ref. 7.

believes that only the hazard aspect is of immediate importance in considerations of human welfare.

Potential Energy Resource. Two factors make gas hydrate attractive as a potential energy resource: (i) the enormous amount of methane that is apparently sequestered at shallow sediment depths within 2,000 m of the surface of the Earth and (ii) the wide geographical distribution of gas hydrate (Fig. 4). According to MacDonald (27), the energy density (volume of methane at standard conditions per volume of sediment) of methane hydrate is 10-fold greater than the energy density of other unconventional sources of gas, such as coal beds, tight sands, black shales, and deep aquifers, and 2- to 5-fold greater than the energy density of conventional natural gas.

Given these attractive factors, it is reasonable to conclude that natural gas hydrate could serve as a future energy resource, as suggested recently by Collett and Kuuskraa (28). However, there are some negative factors that suggest that overly optimistic assessments are being made of gas hydrate as a future energy resource. One such factor is the overall petroleum geology of the gas-hydrate deposits. As Levorsen (29) pointed out years ago, an essential element in any oil or gas reservoir is permeability. Without permeability, there can be little gas accumulation, nor can the accumulated gas be produced by drilling, for it cannot move into production wells quickly enough. Low-permeability sediments (mainly clay and claystone) are the principal lithologies in gas hydrate-bearing sections of the Blake Ridge, offshore from the southeastern United States (30). Dillon *et al.* (31) recognized the low permeability of the sediments in this region and suggested that faults act both as permeability barriers to gas and as conduits for gas. The idea of trying to produce gas from such a system

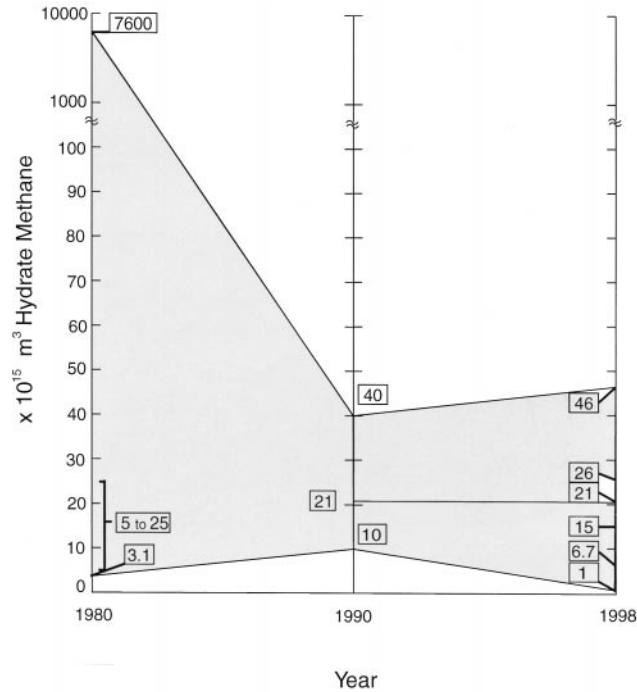


FIG. 4. Changing magnitude of estimates of the methane content ($\times 10^{15} \text{ m}^3$) of worldwide gas-hydrate deposits from 1980 to 1998.

Table 1. Summary of world estimates of methane content $\times 10^{15} \text{ m}^3$ of oceanic gas hydrate

	Methane estimate $\times 10^{15} \text{ m}^3$		Reference
	Best estimate	High, Low Value	
Before 1988	3.1	—	McIver (21)
	—	5–25	Trofimuk <i>et al.</i> (22)
	7,600	—	Dobrynin <i>et al.</i> (10)
After 1988	40	—	Kvenvolden and Claypool (14)
	10	—	Makogon (cited in ref. 2)
	21	—	Kvenvolden (7)
	21	—	MacDonald (13)
	26	26–140	Gornitz & Fung (15)
	46	23–91	Harvey & Huang (16)
	1	—	Ginsburg & Soloviev (20)
	7	—	Holbrook <i>et al.</i> (17)
	15	—	Makogon (19)
	—	2–20	Dickens <i>et al.</i> (18)

Estimates are rounded to two significant figures.

of clay and claystone does not appear to be particularly attractive, especially with current technology. This one example certainly does not apply to all regions of oceanic gas-hydrate occurrence, but it is the best known example discovered and described thus far and warns of the potential petroleum geologic problems that may be found elsewhere.

Although there is a large amount of methane in naturally occurring gas hydrate, there is a constraint on this amount that is often not appreciated. Hunt (32) pointed out that the gas-hydrate enrichment factor decreases with depth. That is, the gas-hydrate reservoir can hold, ideally at standard condition, "about six times as much gas as free gas held in the same space." However, this enrichment factor decreases with depth because free gas compresses considerably with depth and gas hydrate does not. In the example given by Hunt (32), the enrichment factor decreased from 6 to 1.25 in the depth range from 274 to 1,219 m. Thus, with increasing depth, the presence of gas hydrate can be a disadvantage in that a given volume of gas hydrate will contain less gas than could be present if the gas were in a free state.

Interest in gas hydrates by the gas industry has waxed and waned over the past 30 years. At present, however, interest appears to be increasing, and certainly nations such as Japan and India, with immediate energy needs, have undertaken major efforts to investigate gas hydrate as an energy source (28). Successful recovery of methane from gas hydrate will require the attention and infrastructure of the gas industry. In fact, the location of this infrastructure is likely to dictate where, if ever, gas hydrate is to be first produced commercially. Although naturally occurring gas hydrate was recognized in the 1960s, the gas industry has been slow to develop methodologies to recover methane from this substance. This slowness is due, in part, to generally abundant gas supplies and a lack of economic incentives leading to recent assessments such as those of Rogner (33), who wrote that "in the foreseeable future, there will be little need for the development of gas hydrates." Various schemes have been considered at an academic level (34), but application of these schemes and successful results have not been documented. Development of the Messoyakha gas field in Western Siberia during the past 30 years (19) is often cited as an example of successful gas-hydrate exploitation (35), but even this single example is now questioned (36) because the observed gas hydrate may be secondary, a result of production of conventional gas from this field.

Therefore, all of these discouraging factors, such as low permeability sediments, decreasing enrichment factor with depth, lack of sustained gas-industry interest, current limited gas-industry infrastructure at most gas-hydrate locations, and no good field example yet of successful methane production from gas hydrate, diminish the potential for gas hydrate becoming a significant energy resource. As far as human welfare is concerned, methane hydrate as an energy resource is not of immediate interest. Any attempts at full scale production will probably not happen until well into the 21st century (2).

Global Climate Change. Methane is an important trace component of the atmosphere, having a concentration of about $6.9 \times 10^{12} \text{ m}^3$. This concentration was increasing at a rate of $0.9\% \text{ yr}^{-1}$, (37–39) until a few years ago, when this rate decreased (40). Because methane is radiatively active, it is a "greenhouse" gas that has a global warming potential 20 times greater than an equivalent weight of carbon dioxide when integrated over 100 years (41). The earth's atmosphere has a wide variety of sources and sinks for methane (42), including methane hydrate. Methane hydrate exists in metastable equilibrium and is affected by changes in pressure and temperature that occur mainly with changes in sea level. The amount of methane that is present in gas hydrate onshore and offshore is perhaps 3,000 times the amount in the present atmosphere; an instantaneous release of methane from this source could have

an impact on atmospheric composition and thus on the radiative properties of the atmosphere that affect global climate (13).

There are obstacles, however, to methane from gas hydrate ever reaching the atmosphere. Instead of instantaneous release, much methane associated with gas hydrate could vent slowly over geologic time, providing opportunities for its oxidation to carbon dioxide by microbial and chemical processes; the oceans could then act as a sink for the produced carbon dioxide. If any methane did reach the atmosphere, it should react with hydroxyl radicals (42) in about 10 years, unless the supply of radicals is overwhelmed. Thus, the role for methane hydrate in global climate change undoubtedly depends on the rate of methane release, and that rate is largely unknown. Evidence for slow gas release from oceanic sediments is provided by the widespread occurrence of pockmarks on the ocean floor (43) and direct observations of slow release of methane from sea-floor gas hydrate and associated vents in the Gulf of Mexico (44). In contrast, a possible example of rapid release is given by a 700-km² collapse depression on the crest of the Blake Ridge (45). The amount of methane released from this depression during its formation might have been limited, however, by rehydration of escaping methane caused by a combination of hydrostatic pressure and cold bottom waters reaching the floor of the newly formed feature.

Two ideas have been proposed to explain the possible role of methane hydrate in global climate change, but neither of these ideas considered the powerful effect of oxidation on the methane released from gas hydrate. Nisbet (46) suggested that methane from continental gas hydrates contributed to the rapid rise in atmospheric methane at the end of the last major glaciation about 13,500 years ago. In this scenario, polar continental gas-hydrate deposits are destabilized by pressure reduction of melting ice sheets, causing temperature increases because of the released methane. The resulting warming provides a strong positive feedback that amplifies methane emissions and ultimately helps to end the ice age.

A different scenario was proposed by Paull *et al.* (47). They suggested that outer continental margin gas-hydrate deposits release methane during a falling sea level, that is, during global cooling. The resulting decrease in pressure causes this gas hydrate to dissociate. The released methane enhances global warming and triggers deglaciation. Thus, methane derived from outer continental margin gas-hydrate deposits in this scenario is believed to be an important factor in limiting the extent of glaciation during a glacial cycle.

As interesting as both of these scenarios are, they are both quite speculative, because it is not even known how gas hydrates behave in the present climate regime. Kvenvolden (48) suggested that gas-hydrate deposits of the polar continental shelves are presently most vulnerable to climate change. These areally extensive shelves, formerly exposed to very cold surface temperatures (-10° to -20°C) have been and are being transgressed by a much warmer polar ocean ($\approx 0^\circ\text{C}$). The polar shelf surface, therefore, has experienced a $+10^\circ\text{C}$ or more change in temperature over at least the past 10,000 years. If this suggestion is correct, then escape of methane from assumed gas-hydrate deposits of polar continental shelves should be observable.

To test this idea, methane concentrations in water overlying the Beaufort Sea continental shelf of Alaska have been measured when ice is present and absent during 1990–1995 (Fig. 5). Preliminary results (49) showed that methane concentrations in the Beaufort Sea under the winter ice canopy were greater than when the ice is absent. Continued studies (50, 51) confirmed these observations and showed that the average difference in methane concentrations between ice-covered and ice-free conditions is $\approx 15 \text{ nM}$; however, carbon isotopic determinations indicated that most of the methane came from coastal microbial processes and not from gas

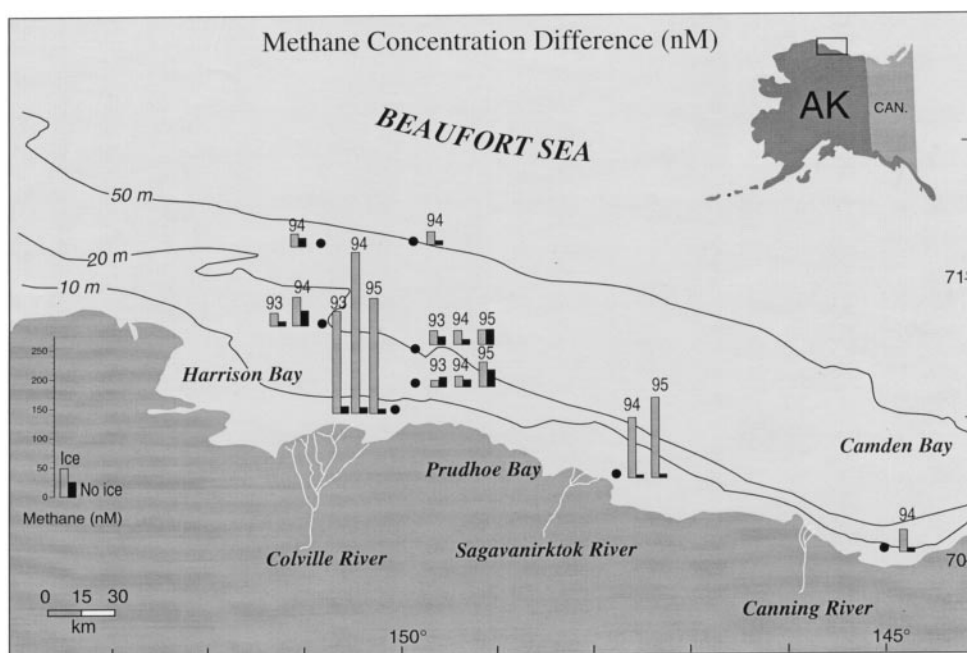


FIG. 5. Map of a portion of the Beaufort Sea continental shelf offshore from Alaska showing station locations and concentrations of methane (in nM) in water samples collected when ice was present and absent from 1993 through 1995. Based on data from refs. 50 and 51.

hydrate. Nevertheless, the Beaufort Sea continental shelf of Alaska appears to be a seasonal source of a very minor contribution of methane to the atmosphere. Although this test failed to show significant release of methane from assumed gas-hydrate occurrence, the test remains inconclusive until similar research is carried out on the broad continental shelves of the Siberian Arctic Ocean.

Large excursions in the carbon isotopic record of carbonate in oceanic sediments from the latest Paleocene thermal maximum (LPTM) have been attributed to massive dissociation of gas hydrate (52, 53). Although this idea is attractive in explaining the isotopic record, the processes and consequences of this idea need further examination. With an increase in temperature or a decrease in pressure, gas hydrate dissociates. Slow dissociation of massive amounts of gas hydrate could take place, with the methane becoming trapped. If this trap is breached then the methane release could be very rapid, causing a "blast of gas" as suggested by Dickens *et al.* (53). Evidence for trapping of gas beneath gas hydrate is provided by the worldwide occurrence of BSRs marking the interface between gas hydrate above and free gas below. As discussed previously, it is the rate of release of trapped methane or the size of the "blast" that is unknown. Also unknown is the effectiveness of the water column in oxidizing the methane as it passes through toward the atmosphere. The amount of methane that can actually reach the atmosphere to affect global climate change is uncertain; however, the oxidized methane, now present as carbon dioxide in the water of the ocean, may cause change in the carbon isotopic record of sediments as observed during the LPTM (52, 53).

Excursions in the atmospheric concentration of methane during the Holocene have been noted in ice cores from Antarctica (54). Consideration has been given to the role that gas hydrate might have played in producing these excursions (55), and the conclusion was reached, based on ice cores from both Antarctica and Greenland, that gas hydrate was a relatively small source of methane during at least the later Holocene.

The potential impact of methane hydrate on future global warming has been evaluated in a GCM study (16). This study concluded that even for worst case scenarios, the impact on future global warming caused by gas hydrate will be small; the

uncertainty in future global warming due to gas-hydrate destabilization is smaller than the uncertainty due to warming caused by fossil fuel use.

Therefore, the potential role for gas hydrate in global climate change is diminished because of the possibility of rapid oxidation of the released methane to carbon dioxide, thus enhancing the solubility of the methane carbon in the ocean water. Scenarios of past global climate change caused by methane released from gas hydrate are all very speculative; one test in the Arctic of methane release during the current climate cycle failed to show much methane from gas hydrate; one GCM study demonstrated little impact of gas hydrate on future global warming; and records of excursions of methane concentrations during the Paleocene and Holocene, although possibly caused by gas-hydrate dissociation, do not provide compelling evidence that this methane actually affected global climate. With respect to human welfare, it is not immediately important whether gas hydrate has a role in global climate change. To be on the safe side, however, it would be best in the future not to perturb natural gas-hydrate stability by continuing societal practices that enhance global warming.

Geologic Hazard. Gas hydrate as a geohazard has been considered in detail previously (56). Before gas hydrate forms in usual geologic settings, vast quantities of methane and water are free to migrate within the interstitial pore spaces of consolidating sediment. During gas-hydrate formation, methane and water become immobilized as a solid, restricting pore space and retarding the migration of fluids. Solid water (rather than liquid water) occupies the pore spaces, and the sedimentological processes of consolidation and mineral cementation are greatly inhibited, although gas hydrate itself can act as metastable cementation (bonding) agent. The permeability of the sediment to gases and liquids decreases as more gas hydrate forms. Eventually, gas hydrate may occupy much of the pore space within the zone of gas-hydrate stability. Continued sedimentation leads to deeper burial of the gas hydrate. Finally, the gas hydrate will be buried so deeply that temperatures at the base of the stability zone will be reached at which the gas hydrate is no longer stable. The solid gas/water mixture (i.e., the gas hydrate) will become a liquid gas/water mixture. Thus, the basal zone of the gas hydrate becomes underconsolidated and possibly overpressured because of the newly

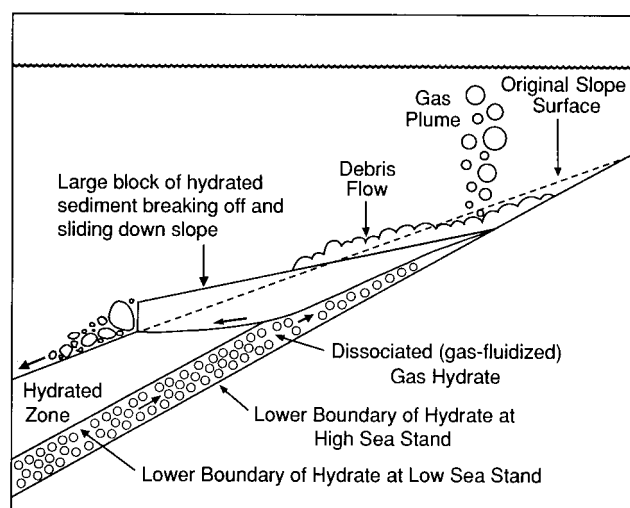


FIG. 6. Diagram showing the effects of changes in sea level on submarine gas hydrate and the resulting failures and gas release. Adapted from McIver (57).

released gas, leading to a zone of weakness (low shear strength, where failure could be triggered by gravitational loading or seismic disturbances), and submarine landslides result (57).

The same conditions that cause gas-hydrate dissociation during continued sedimentation can also be brought about by the lowering of sea level or by an increase in bottom-water temperatures. These processes change the *in situ* pressure or temperature regime. In adjusting to the new pressure/temperature conditions, the gas hydrates dissociate, producing an enhanced fluidized layer at the base of the gas-hydrate zone. Submarine slope failure can follow, giving rise to debris flows, slumps, slides, and collapse depressions such as described by Dillon *et al.* (45). Failure would be accompanied by the release of methane gas at least into the water column, but much of the methane is likely to be oxidized unless the gas release is catastrophic. A scenario illustrating submarine slope failure is shown in Fig. 6.

The possible connection between gas-hydrate boundaries and submarine slide and slump surfaces was first recognized by McIver (58), and several possible examples were described later. These examples include surficial slides and slumps on the continental slope and rise of West Africa (59), slumps on the U.S. Atlantic continental slope (60), large submarine slides on the Norwegian continental margin (61, 62), sediment blocks on the sea floor in fjords of British Columbia (63), and massive bedding-plane slides and rotational slumps on the Alaskan Beaufort Sea continental margin (64).

Periodic Pleistocene eustatic sea level transgressions and regressions provide mechanisms to account for the waxing and waning of submarine gas hydrate (64). For example, during the last Pleistocene regression, sea level lowered approximately 100 m between about 28,000 and 17,000 years before present, resulting in a reduction of total stress acting on the seafloor. The reduction in the total pressure initiates dissociation at the base of the gas hydrate, releasing excess methane and water. Failure follows on moderate slopes unless the increased fluid pressures can be adequately vented. On the Beaufort Sea continental slope is a zone of massive slides and slumps that coincides with a region of sediment inferred, from seismic reflection studies, to contain gas hydrate. Fluctuations in global climate, reflected in Pleistocene sea-level lowerings, likely caused these submarine slides and perhaps caused other slides on other continental margins where gas hydrate is present (64).

These submarine disruptions of the seafloor, caused by gas-hydrate dissociation, impact human welfare if human-

made structures are located in regions of potential failure. As humankind expands its interest in the seafloor at increasing water depth, such as in the petroleum industry's search for oil and gas, stability of the seafloor becomes increasingly important for any engineering structures. The potential vulnerability of engineering structures to gas-hydrate dissociation in oceanic sediments has been recently recognized and described (65, 66). Risks to drilling and production through gas hydrate-bearing sediment have been addressed by Yakushev and Collett (67) for gas hydrate in Arctic regions, and these same concerns, such as casing collapse, gas leakage outside the conductor casing, and gas blowouts, will be applicable to gas hydrate of deep oceanic regions, only the problems will likely be more severe, but not necessarily as severe as suggested by Bagirov and Lerche (68), who discuss possible gas-hydrate hazards in the Caspian Sea. The geohazard aspects of gas hydrate provide an additional constraint on exploiting oceanic gas hydrate as a future energy resource.

CONCLUSIONS

The amount of methane sequestered in gas hydrate is undoubtedly very large, probably $>10^{15}$ m³, but considerable $<10^{17}$ m³. How this methane can or will affect human welfare is not yet defined. There is much current interest in gas hydrate as a potential (i) energy resource, (ii) factor in global climate change, and (iii) submarine geohazard. Of these three issues, only the third is considered here to be important at the present time for human welfare. It is argued that gas hydrate as a future energy resource has received overly optimistic assessments because of inadequate evaluation of the reservoir qualities of the geologic settings in which oceanic gas hydrate is found. Vacillating interest by the gas industry and the absence of good industrial examples of successful methane production from gas hydrate diminish enthusiasm for gas hydrate as a potential energy resource. It is also argued that gas hydrate is likely not a major factor in global climate change in that much of the methane that could be released from the dissociation of gas hydrate is probably oxidized to carbon dioxide, which dissolves in the water; most hydrate methane never reaches the atmosphere where it could function as a powerful "greenhouse" gas. Scenarios of climate change caused by methane release from gas hydrate in the geologic past are all speculative, and one test of methane release from gas hydrate in the current climate cycle failed. Gas hydrate may be an agent in global change (for example, altering the isotopic record of oceanic sediments), but not necessarily in global climate change. The evidence seems clear that gas hydrate is a geohazard, particularly in the oceans. As a geohazard, gas hydrate will affect human welfare as humankind moves to exploit the seafloor at ever increasing water depths. Human activities and installations in regions of gas-hydrate occurrence must take into account the presence of gas hydrate and deal with the consequences of gas-hydrate dissociation.

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