

GAS HYDRATES AND SUBMARINE SLOPE INSTABILITY

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ABSTRACT

Gas hydrates are ice-like materials composed of water molecules that encapsulate natural gas molecules in a very compact form. Vast quantities of natural gas hydrates exist within soil and rock in permafrost environments and offshore regions. Gas hydrates represent a significant geohazard that place offshore facilities, structures, and cables at considerable risk of damage. There is substantial evidence that links major seafloor collapses to the presence of gas hydrates. Analyses of reported cases of submarine slides occurring on gentle slopes indicate that the slide scar is either at the top of the hydrate zone or at the base of the hydrate layer. In addition, theoretical and laboratory evidence that shows the soil will experience a dramatic reduction in shear strength due to gas hydrate dissociation (melting), which may ultimately lead to soil collapse and triggering of submarine slope failures. This paper will summarize the properties of gas hydrates and highlight their role in submarine slope instability.

RESUME

Les hydrates de gaz sont des substances semblables à de la glace composées de molécules d'eau qui encapsulent des molécules de gaz naturel en une forme très compacte. De vastes quantités d'hydrates de gaz naturel sont présentes entre le sol et la roche dans des régions à pergélisol ou dans des régions off-shore. Le risque naturel lié aux hydrates de gaz met les installations off-shore, les structures ou les câbles dans un grand risque de dommages. Des preuves concluantes ont montré le lien entre les effondrements importants du plancher océanique et la présence d'hydrates de gaz. Les analyses de cas reportés de glissements de terrain sous-marins survenus dans des régions à pente douce ont montré que la location des glissements de terrain est située soit au top ou à la base d'une couche d'hydrates. De plus, des analyses théoriques et en laboratoire ont montré que le sol va encourir une forte réduction de sa résistance au cisaillement due à la dissociation des hydrates de gaz, ce qui entraînera, dans une étape ultérieure, à des glissements de terrain sous-marins. Ce papier résumera les propriétés des hydrates de gaz et présentera leur rôle dans les instabilités du sol sous-marin.

1. INTRODUCTION

Gas hydrates are ice-like materials composed of water molecules that encapsulate natural gas molecules in a very compact form. Immense quantities of gas hydrates exist in permafrost and offshore regions around the world. Figure 1 illustrates the distribution of the world's onshore and offshore naturally occurring gas hydrate deposits.

Judge et al. (1994) have mapped the locations of natural gas hydrate deposits in Canada. Onshore deposits have been identified in the Canadian Arctic, trapped within the permafrost soils of the Yukon, Northwest Territories, and the Mackenzie Delta. Offshore Canadian deposits are located in the Beaufort Sea, off Vancouver Island, and off the coast of Newfoundland and Labrador. These deposits exist both on the seabed and more commonly trapped within the seabed sediments.

Gas hydrates came into awareness in the 1930s when hydrate formations were discovered to be the cause of pipeline blockage during the transmission of natural gas. Sloan (1998) summarizes the history of gas hydrate research and includes reference to the first observations of naturally occurring hydrates found in permafrost regions in 1965. By the 1970s, it was recognized that gas hydrates occur naturally in the sediments underlying 'deep' water (Claypool & Kaplan 1974). Interest in hydrates has continued in the last 30 years during which

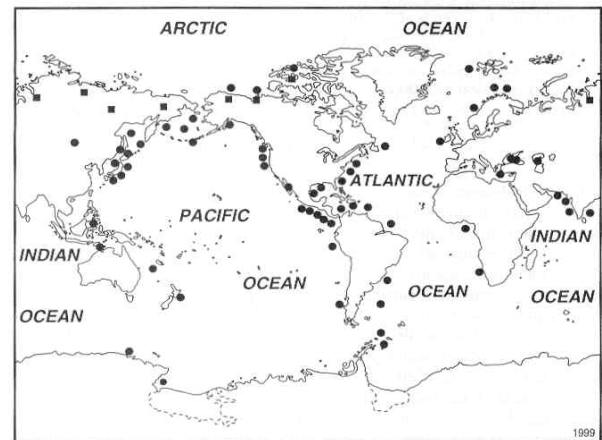


Figure 1. Map showing worldwide locations of known and inferred gas hydrate deposits (Kvenvolden 2000).

time it has been identified that hydrates affect humans in three distinct ways: (1) as a potential energy resource, (2) as a factor in global climate change, and (3) as a submarine geohazard (Kvenvolden 1993).

There are many examples of a possible connection between gas hydrates and submarine slope failures. Kvenvolden (1993; 1999) summarized slope failures on

the continental slope and rise of the west coast of Africa, on the US Atlantic continental slope, on the Norwegian continental margin, in the fjords of British Columbia, and on the Alaskan Beaufort Sea continental margin. Sloan (1998) indicates that there is substantial observational evidence that links major seafloor collapses, submarine slides, and drilling hazards to the presence of hydrates. This paper summarizes the properties of gas hydrates and highlights their role in submarine slope failures.

2. GAS HYDRATE PROPERTIES

2.1 Structure

Natural gas hydrates belong to a class of solids known as clathrates. Several different structures of clathrates exist which accommodate guest molecules of different sizes. The hydrate forming gases include light alkanes, carbon dioxide, hydrogen sulphide, nitrogen and oxygen. Methane gas, the most common clathrate, forms a Structure-I hydrate in which one volume of water will encathrate (adsorb) 207 volumes of methane gas. This translates to 1 m³ of hydrate containing 0.9 m³ of water and 164.5 m³ of methane gas, at standard conditions, or 1.1 m³ of methane gas at 1000 m water depth and 2 °C.

2.2 Acoustic properties

Acoustic properties (P and S waves) provide important information on the soil structure. Knowledge of the material occupying the pore space and the consolidation stress is critical to understanding the implications of the velocity measurements (Winters et al. 1999). Table 1 summarizes some published acoustic properties (based on Anderson 1992).

Table 1. Summary of acoustic properties of gas hydrates (from Anderson 1992).

Parameter	Pure hydrates	Water-saturated sediments	Hydrate-sediment mixture
Compression wave V_p (km/sec)	3.25-3.6	1.6-2.5	2.05-4.5
Shear wave V_s (km/sec)	1.65	0.38-0.39	0.14-1.56
Bulk density ρ (g/cm ³)	-	1.26-2.42	1.15-2.4

Winters et al. (1999) performed studies on the properties of hydrate-sediment mixtures using core samples obtained from the Mallik well. Their investigation into the acoustic properties indicated that the P-wave velocity of specimens containing hydrates decreased at least 25% after dissociation. Booth et al. (1998) presented a correlation between the change in compression wave velocity and the presence of hydrates.

2.3 Electrical resistivity

Gas hydrate formation is accompanied by a sharp increase in the electrical resistivity (Makogon et al. 1997; Booth et al. 1998). The resistivity of hydrate-saturated sediments varies from approximately 10³ to 10⁶ Ohm-m (Tzirita 1994). Water has a resistivity of approximately 10 Ohm-m, sand approximately 10²-10³ Ohm-m, and ice about 10⁵ to 10⁶ Ohm-m. Electrical properties have been used to estimate hydrate content (Buffet & Zatsepina 2000; Booth et al. 1998) but further work on the electrical resistivity of hydrate-sediment mixtures is required.

2.4 Density

The density of pure methane gas hydrates ranges from 0.895 g/cm³ at 1 MPa to 1.053 g/cm³ at 1000 MPa (Makogon et al. 1997). The density of hydrate-sediment mixtures will depend on the density of the sediment and the percentage of the void spaces occupied by hydrates.

2.5 Strength properties

The strength of hydrate and hydrate sediment mixtures is influenced by a number of factors including strain rate, temperature, confining pressure, grain size, density, and hydrate cage occupancy. Studies on the strength of hydrates and hydrate saturated porous media have been performed by Parameswaran et al. (1989), Cameron and Handa (1990), Jeanjean and Briaud (1990), and Winters et al. (1999). Results indicate that specimens containing gas hydrates have undrained shear strengths in the order of three times greater than similar specimens without hydrates. The strength of hydrate bearing sand is in the same range as the strength of ice bearing sand. Although the hydrates will increase the strength of the soils, it is essential to consider the significant strength loss if dissociation of the hydrates occurred.

2.6 Hydraulic conductivity

There is considerable variation in the hydraulic conductivity of hydrate-sediment mixtures (Winters et al. 1999). Factors affecting the in situ hydraulic conductivity will include grain size, porosity, structure, discontinuities, tortuosity of the sediments and viscosity of the fluids.

3. HYDRATE STABILITY

Gas hydrates form under specific conditions of low temperature and high pressure. Oceanic hydrates are stable in a zone extending downward from the seafloor in water depths greater than 400 m. The hydrate stability zone is a function of the water depth, seafloor temperature, and geothermal gradient. For offshore conditions, the pressure-temperature correlation shown in Figure 2 can be used to determine the hydrate stability zone in pure water (Kamath et al. 1987). For hydrates in seawater, the temperature is shifted approximately -1.5°C, i.e. salt water inhibits hydrate formation to a certain extent (Dickens and Quinsby-Hunt 1994).

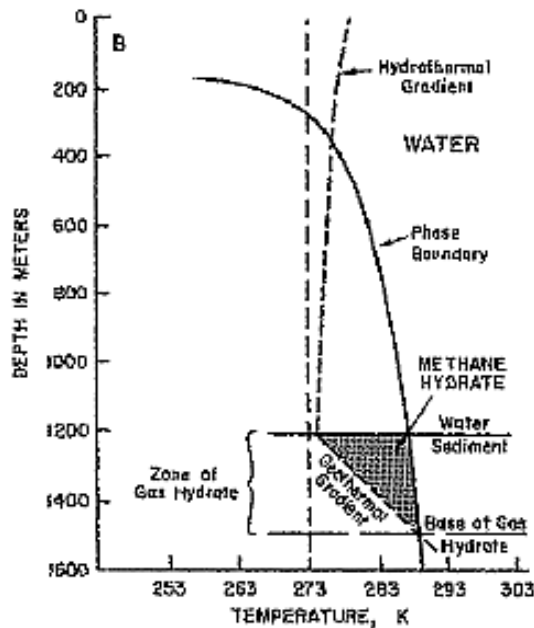


Figure 2. Hydrate stability diagram in ocean sediments (Kvenvolden 1993). The shaded area indicates the zone in which methane gas hydrates would be stable.

At pressure and temperature conditions outside the stability range, dissociation or melting of gas hydrates will occur. Pressure decreases may occur due to sea level variations or removal of mass by slumping or sliding. Temperature increases may develop due to increased seawater temperatures, due to sedimentation, or due to heat from producing wells.

4. FORMATION/DISSOCIATION OF GAS HYDRATES

4.1 Formation of hydrates

Natural gas hydrates are formed from both biogenic and thermogenic gas sources. Biogenic gas is the product of anaerobic bacterial activity and is found in areas where there is a rapid accumulation of organic matter and sediments. Thermogenic gas, the product of organic precursors at high temperature and pressure, is found along faults, vents and seeps. Most scientists believe that most natural gas hydrates are formed from biogenic methane gas. In general, biogenic hydrates are more evenly distributed throughout the sediment except when the organic matter has been concentrated or the methane gas has migrated to the bottom of a less permeable layer. Thermogenic hydrates are likely to be more concentrated and can often mound on the seafloor near the fault. Figure 3 shows a gas hydrate 'glacier' located off the west coast of Canada.

Gas hydrates have been observed in coarse sediments, such as sand and sandstone; fine-grained sediments, such as clays; deep-sea ooze and mudstones; and also



Figure 3. A methane hydrate 'glacier', approximately 4 m high by 10 m wide, on the seafloor, 850 m below the surface, near Ucluelet, B.C. (www.uvic.ca).

filling in fractures within sediments (Kvenvolden 1993; Ginsburg and Soloviev 1998; Makogon 1981). The tendency for hydrates to form in sediments of higher porosity has been observed but a clear-cut relationship does not exist. Clennel et al. (2000) have investigated how pore size and capillary action affect hydrate stability and determined that hydrate growth is inhibited within fine-grained sediments. Clennel and co-workers also developed a model to predict hydrate distribution within sediments from the microscale to mesoscale. The geologic history will also affect the formation of hydrates within sediments. Hydrate layers may melt and reform. Seasonal or climatic fluctuations will affect the stability of hydrates as will earthquakes or other mechanical disturbances. Hydrates may form caps, which seal off faults or they may fill in sediment pore spaces effectively sealing them (Rowe and Gettrust 1993).

4.2 Dissociation of gas hydrates

At pressures and temperatures outside the hydrate stability range, dissociation (melting) of gas hydrates will occur. Dissociation will result in the release of water and methane gas but requires heat input through heat flow. Makogon et al. (1997) gives an expression for calculating the heat of formation/dissociation from natural gases. Complicating the dissociation process are the effects of time dependency, soil permeability, and diffusion.

As dissociation occurs, the released gas and water creates a volume expansion that, depending on the drainage conditions, can cause an increase in the pore fluid (gas and water) pressures and a resulting decrease in the effective stress. The following discussion on the effect of methane hydrate on the soil response to temperature and total stress changes is based on Grozic & Kvalstad (2001).

Dissociation of gas hydrate will release gas and generate a volume expansion. If the temperature/heat transport and the pressure change processes are fast compared

with pore pressure dissipation processes, the excess pore pressure and reduction in effective stress can be estimated as follows:

$$-0.13 \cdot n \cdot (1 - S_w) + \frac{164.6 \cdot n \cdot (1 - S_w) \cdot 1 \text{ atm} \cdot T_{eq}}{298.15 K \cdot p_{eq}} = - \frac{\Delta \sigma'}{M(\sigma')}$$

where n is the soil porosity, S_w is the degree of water saturation, $(1 - S_w)$ is the degree of saturation of gas hydrates assuming no free gas in the hydrate stability zone, T_{eq} is the equilibrium temperature of gas hydrate in K, p_{eq} is the equilibrium pressure of gas hydrate in atm, $\Delta \sigma'$ is the change in effective stress caused by melting of gas hydrate, and M is the confined compression modulus of soil. The first term represents the difference between the hydrate volume and melted water volume ($1.0 \text{ m}^3 - 0.87 \text{ m}^3$), the second term represents the volume of released gas at equilibrium temperature and pressure and the final term represents the volume change of the soil.

The effect of hydrate dissociation has been predicted using the above equation. Figure 4 shows a plot of hydrate content (percentage of voids occupied by hydrates) versus the normalized effective stress. This figure illustrates that if even as little as 10% hydrates occupy the soil voids, changes in equilibrium leading to dissociated could bring about soil failure.

A few laboratory studies have investigated the soil response to hydrate dissociation. Grozic and Kvalstad (2001) investigated the response of clay soil to hydrate dissociation in the laboratory. The results indicate that the specimen will undergo an increase in pore fluid (water and gas) pressures during dissociation which results in a decrease in effective stress and a loss of shear strength. Comparison of the theoretical results predicted using the theory presented above and observed test results showed a correspondence, however considerable uncertainty existed regarding estimates of the hydrate content in the laboratory and further testing was recommended. Wright et al. (1999) formed and dissociated gas hydrates within fine sand to investigate the pressure temperature conditions and kinetics of hydrate formation/dissociation. They noted a small but measurable shift in the pressure – temperature equilibrium threshold during hydrate dissociation which may be related to weakly bound water in association with soil particles surfaces in unsaturated fine sands. Mikami et al. (2000) used granular core samples, containing natural gas hydrates within the pore spaces, from the Mallik 2L-38 well drilled in the Mackenzie Delta. They warmed the samples while they were contained within a computerized tomography scanner. Dissociation of the hydrates was controlled through controlled pressure reductions to bring the samples out of the hydrate stability range. The important conclusion from this experiment was that dissociation was initiated nearly simultaneously within the interior of the sample and at the sample surface, although this could be

due to the pore spaces not being completely filled with hydrate.

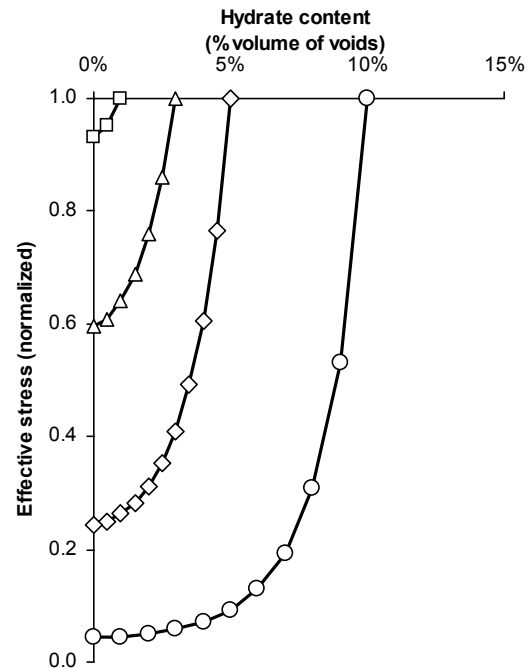


Figure 4. Theoretical stress change with hydrate dissociation (Grozic & Kvalstad 2001).

5. ROLE OF GAS HYDRATES IN SUBMARINE SLOPE INSTABILITY

Observational evidence suggests that gas hydrates have a role in the failure of submarine slopes. Kvenvolden (1993; 1999) present several cases where hydrates are believed to play a role in the failure of submarine sediments. Many of these slides are on gentle slopes which should be stable.

Submarine sliding can occur due to an increase in the applied shear stress or a reduction in the soil strength. When gas hydrates dissociate they release water and gas which will have the net effect of either increasing the pore water pressures (if the sediments are sealed or the decomposition is rapid) or increasing the volume (if dissipation of the fluid pressures is allowed). The increase in fluid pressure, dilation of the sediments, and the development of gas bubbles all have the potential to weaken the sediment (Prior and Coleman 1984). The results of theoretical and laboratory programs have confirmed that the soil will experience a dramatic reduction in effective stress and an associated reduction in shear strength due to hydrate dissociation. The dissociation may come about due to pressure reductions such as sea level changes, localized sliding and slumping, or temperature increases such as global warming, sedimentation, or reservoir production. Figure 5

illustrates how a drop in sea level could initiate slumping or sliding.

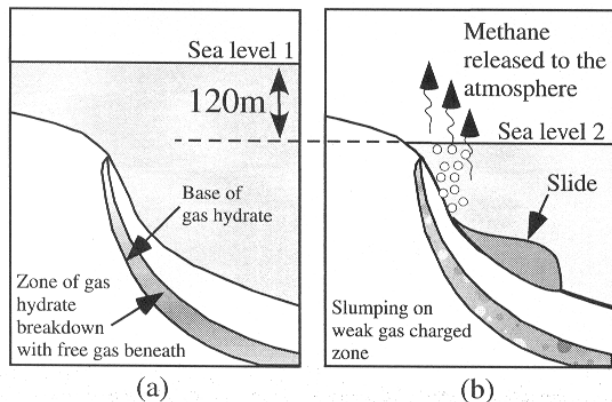


Figure 5. The role of gas hydrates on slope instability as a result of sea level lowering. (a) Time of high sea level with the base of solid hydrates close to the surface of the sediments. (b) Lower sea level resulting in reduction in confining pressure and release of gas hydrates (Locat and Lee 2002; Dillon and Max 2000).

The inference that gas hydrates are associated with submarine slope failures is often based on observational evidence from bottom simulating reflectors (BSR), which is the only commonly available remote detection indicator for the presence of gas hydrates (Paull et al. 2000). Authors such as Summerhayes et al. (1979), Embley (1980), Carpenter (1981), Cashman and Popenoe (1985), Paull et al. (1991), Rothwell et al. (1998), Nisbet and Piper (1998), and Cherkis et al. (1999) have related submarine slides to the instability of sediments due to the dissociation of gas hydrates through BSR profiles.

The BSR is a contrast in velocity created by the hydrate-cemented zone which is seen as a reflection in seismic profiles as illustrated in Figure 6. A lower velocity is observed below the hydrate zone, in the water saturated sediments, due to the lower velocity of water or trapped gas. This produces a well-defined seismic reflection from the base of the hydrate zone which roughly parallels the sea floor. Gas hydrates are also interpreted from blanking in seismic profiles (Figure 6), which is the reduction of the amplitude of the seismic reflection that is caused by the cementation of the hydrate. The blanking occurs throughout the hydrate zone and is used to estimate the amount of gas hydrate present.

Paull et al. (2000), with reference to Figure 7, explain how sediments in the up-dip limit (i.e. up slope limit of the seaward thickening prism of hydrate stability zone) of the gas hydrate occurrence have the greatest potential to be altered by short term pressure and temperature changes. The hydrates in this area will also produce the largest net volume and/or pressure change (see Figure 7). If gas hydrates play a large role in submarine failures, then the frequency of failures should be focused on sediments at or just below the up-dip limit of the gas hydrate stability

zone (Paull et al. 2000). This phenomenon is illustrated in the following case history.

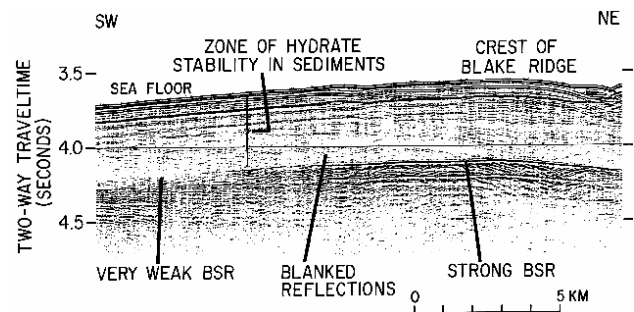


Figure 6. Interpreted seismic profile illustrating bottom simulating reflection (BSR) which is interpreted as the base of the hydrate stability zone and blanking which is used to interpret the quantity of gas hydrates (USGS 2003).

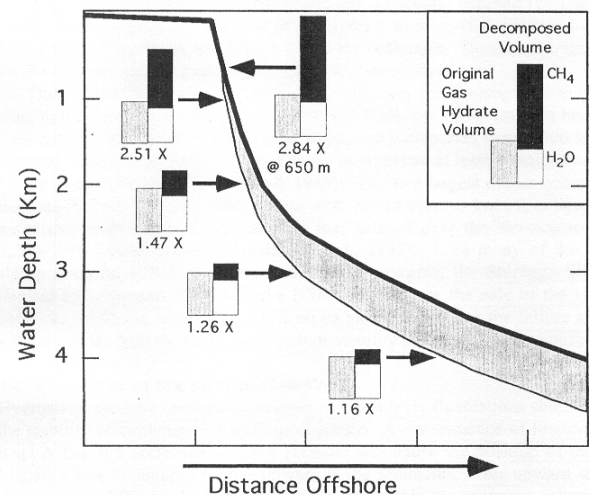


Figure 7. Diagram showing the distribution of gas hydrate stability beneath the ocean floor. The dark line indicates the seafloor and the lighter line is the position of the gas hydrate phase boundary (which is presumably coincident with the BSR if one is present). The shaded area between the two lines indicates that region where gas hydrate is stable within the sediments. Boxes show the relative volume change associated with a fixed volume of gas hydrate decomposing into water and methane gas. Note that the relative volume change decreases with increasing water depth (Paull et al. 2000).

5.1 U.S. Atlantic margin failures

Along the U.S. Atlantic margin over 200 slump scars have been mapped using seismic methods (Booth et al. 1994). This intensive mapping has shown that intermittent BSR's occur along the entire margin, indicating that gas hydrates are common within the sediments. When the distribution

of the slides scars were analyzed, they were neither randomly distributed nor were they strongly associated with steep slopes (Paull et al. 2000); Instead they were strongly associated with the current up-dip limit of gas hydrate stability. Figure 8 illustrates that the majority of the slide scar headwalls occur in the 500-700 m ocean depth range which is consistent with the distribution of sliding that would be predicted if gas hydrate decomposition played a significant role in causing these failures.

Carpenter (1981) investigated the relationship between gas hydrate decomposition and two major slump complexes on the U.S. Atlantic continental slope. The results of this work indicate that the two slumps are underlain by hydrates and that there is a cause and effect relationship between the failures and the presence of hydrates. They postulate that the upward migration of gas from hydrate decomposition, due to water temperature increases and sea level changes at the time, caused weakening of the overlying sediments to the point of failure thus resulting in the slumps.

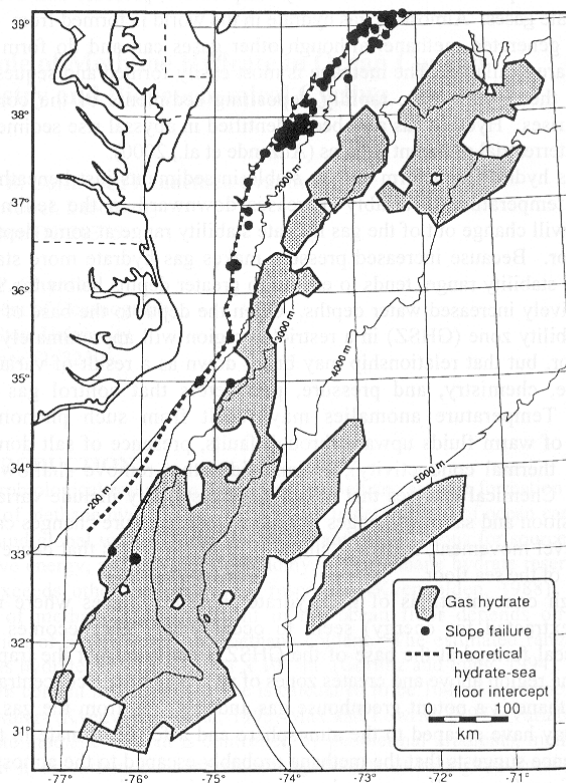


Figure 8. Map showing locations of the tops of slide scars on the U.S. Atlantic continental margin compared to the depth of the theoretical upper limit of gas hydrate stability (Booth et al. 1994). Clustering of slope failures within the zone of gas hydrate stability, just below the upper limit, is considered to be circumstantial evidence for a relation between slumps and gas hydrate processes (Dillon and Max 2000).

Analysis of these failures on the Atlantic continental margin indicates that the slide scars are near the top of the hydrate zone and that there is less hydrate in the sediment beneath the slide scars. Failures on the continental margin seem to occur at the base of the hydrate layer where the hydrates tend to break down and free methane is found (Dillon 1992). Similar links between seafloor failures and the presence of gas hydrates have been found in the Gulf of Mexico (Twichell et al. 2000; Cooper et al. 2000).

5.2 The Storegga Slide

The Storegga slide is one of the largest known submarine slides in the world. The slide occurred approximately 7300 years ago on the Norwegian Continental margin (see Figure 9). The slide scar covers an area of approximately 34,000 km² with a headwall 290 km long, sediment run-out distances in the order of 800 km, and involved over 5,500 km³ of material (Bugge et al. 1987; 1988). Evidence of a tsunami generated by this slide has been found along the coast of Norway, Scotland and the Faeroe Islands.



Figure 9. Outline of the Storegga Slide scar located off the coast of Norway.

Seismic results (BSR) show that gas hydrates are present in the area surrounding the slide scar but that no hydrates have been shown to be present within the slide area. The disturbed sediments of the slide scar lie at the depth of the pre-slide gas hydrate stability zone which has lead researchers (Berndt et al. 2002; Bouriak et al. 2000) to suggest that gas hydrate dissociation played a role in triggering or contributing to the slope failure.

The Storegga Slide has been extensively investigated in recent years due to the proposed development of the Ormen Lange gas field which lies within the slide scar. Analyses of triggering mechanisms suggest that although gas hydrates may have played a role in the slide

propagation, they did not initiate the slide (Kvalstad, personal communications 2002).

5.3 Discussion

It has been demonstrated that dissociation of gas hydrates will induce high fluid pressures and can ultimately result in the loss of strength and collapse of seabed sediments. Observational evidence suggests a link between dissociation of gas hydrates and submarine slope failures; however, most of this evidence is based on bottom simulating reflectors (BSR). At the current state of knowledge, the circumstantial evidence supports the concept that gas hydrate breakdown is often instrumental in triggering sediment mass movement on the sea floor (Paull et al. 2000) but clearly more research is required to add support to this hypothesis.

It has been a major advance in our understanding of submarine slope failures to recognize the role of gas hydrates in the development of slope instabilities yet it remains a major challenge to integrate the role of hydrates into the analyses and prediction of submarine slope failures (Locat and Lee 2002). Sloan (1998) identified four underlying areas where research on gas hydrates and the role they play in submarine slope instability and the other human-interest areas is needed: a) distribution, occurrence, and concentration of gas hydrates; b) detection, sampling, transport, and handling of hydrates; c) sediment properties including strength and deformation properties of hydrate-sediment mixtures; and d) hydrate controls such as dynamics of hydrate equilibrium and their response to fluxes. Clearly there remains much work to be done before a quantitative understanding of the role of gas hydrates in the initiation and failure of submarine slopes can be developed.

6. CONCLUSIONS

Gas hydrates represent a potentially vast energy resource yet also a significant geohazard. In addition, they may play an important role in global climate change. The physical properties of gas hydrates are relatively well studied yet much research is still required on the properties of gas hydrates in porous media. It is understood that dissociation of gas hydrates will result in increased fluid pressure, dilation of the sediments, and the development of gas bubbles all which will have the effect of substantially weakening the sediments. This mechanism could be responsible for the triggering of submarine slope failures. Observational evidence from seismic profiles show a correlation between dissociation of gas hydrates and submarine slope failures thus supporting the concept that gas hydrate breakdown is instrumental in triggering sediment mass movement on the sea floor. Clearly more research is required before a quantitative understanding of the role of gas hydrates in the initiation and progression of submarine slope failures can be developed. It is suggested that fundamental research is required in the areas of 1) the behavioural properties of gas hydrate-sediment mixtures; 2) the

dynamic equilibrium of gas hydrate-sediment mixtures including the effects of perturbations to this system; 3) in situ detection and distribution of gas hydrates.

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