Overview of gas hydrates in submarine slopes

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ABSTRACT
Interest in methane gas production from hydrate deposits has increased dramatically in the last decade. Gas hydrates are linked to large submarine slides, in part because hydrate dissociation results in loss of solid material, production of free gas, and increased fluid pressures; all which have the effect of reducing sediment strength. This paper presents recent results and advances on the intersection of gas hydrates and submarine slope stability, exploring the role of gas hydrates in triggering and/or propagating submarine mass movements.

RÉSUMÉ
L'intérêt pour la production de gaz méthane à partir des gisements d'hydrate a augmenté considérablement ces dix dernières années. Les hydrates de gaz sont liés aux larges glissements sous-marins, en partie parce que la dissociation des hydrates se traduit par une perte de matières solides, la production de gaz libre, et l'augmentation des pressions de fluide; ce qui a pour effet de réduire la résistance des sédiments. Cet article présente les derniers résultats et avances sur la relation entre les hydrates de gaz et la stabilité des pentes sous-marines, explorant le rôle des hydrates dans le déclenchement et/ou la propagation des mouvements de masse sous-marins.

1 INTRODUCTION

Circumstantial evidence suggests that weakening of hydrate bearing sediments have triggered large underwater landslides along the continental margins (e.g., Booth et al. 1994). Submarine landslides have the potential to destroy offshore equipment, jeopardize safety of personnel, and generate tsunamis which can impact coastal regions located hundreds of kilometers away (e.g., Locat and Lee 2002).

Gas hydrates are solid crystalline compounds comprised of hydrogen-bonded water molecules forming a rigid crystal lattice stabilized by encaged gas molecules, also known scientifically as clathrate (Max and Dillon 2000; Kvenvolden 2000). Gas hydrate stability is confined to a low-temperature, high-pressure regime where thermodynamic principles govern the kinetics of formation and dissociation. These conditions are found in permafrost regions and under the seafloor on continental slopes around the world. In-situ natural gas hydrate deposits are generally located in marine sediments at temperatures above freezing, commonly around 5 °C to 10 °C. The critical factors influencing hydrate formation and stability are pressure, temperature, gas composition, volume of bulk free water, salinity, gas availability, sediment type, presence of catalysts or inhibitors (Makogon and Holditch 2001; Kvenvolden 1988). Oceanic gas hydrates are capable of existing at water depths greater than roughly 400 m, where the maximum subsurface extent of gas hydrate is constrained by the geothermal gradient, as illustrated in Figure 1.

2 STRESS CHANGES IN HYDRATE BEARING LAYERS

The strength of intact pure hydrate can be 20 times that of pure ice (Durham et al. 2003). When contained within sediments, laboratory results show an increase in strength of hydrate bearing sediments over hydrate free sediments (Masui et al. 2008; Ebinuma et al. 2005), with hydrate and ice bearing sediments having similar strengths (Winters et al. 2004). The strength of hydrate bearing sediments will be a function of the strain rate, temperature, consolidation stress, grain size, density, and cage occupancy (Winters et al. 2004). How the hydrate and sediment interact also affects bulk sediment strength. As gas hydrate forms within sediment, three main pore habits are possible: pore filling, load bearing, and cementing. Pore filling contributes to an increase in the

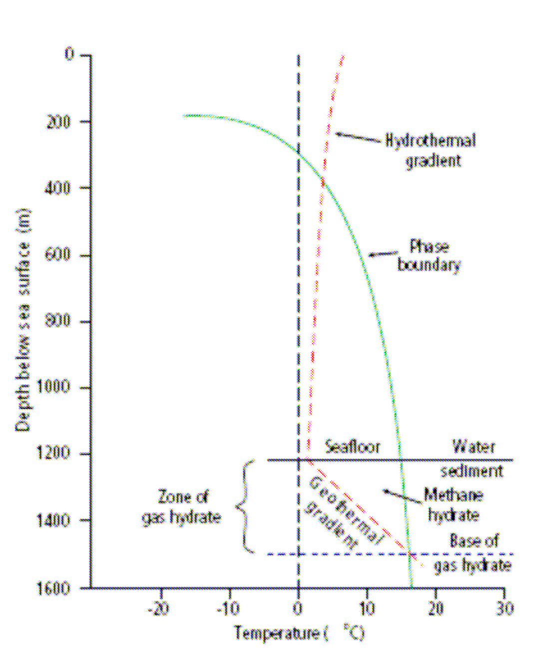

Figure 1. Hydrate stability zones for offshore conditions (after Collett 2002).

bulk stiffness and load bearing and cementing increase the sediment shear strength as well as the bulk stiffness (Waite et al. 2009).

When perturbations to the thermodynamic equilibrium of the gas hydrate system occur, hydrate can be pushed out of the stability zone and dissociation occurs. Dissociation releases water and methane gas, but as an endothermic reaction, requires heat input. If the heat transport fueling dissociation and the pressure increase due to methane gas release occur rapidly compared with pore pressure dissipation processes, excess pore pressure and reduction in effective stress ensues.

Both laboratory and theoretical studies have confirmed that gas hydrates dissociation produces excess pore pressures. The magnitude of the pressure generation is highly dependent on the flow boundary conditions, in particular, the host sediment permeability or the presence of a low permeability seal. Gas hydrate is least stable at the base of hydrate stability, where it can be overlain by a low permeability hydrate cap. It is therefore not unreasonable that significant pore pressures could develop with the effect of reducing effective stress and sediment strength.

3 STABILITY OF HYDRATE BEARING LAYERS

The link between gas hydrate dissociation and submarine slope failures was first postulated in a conceptual model by McIver (1982). Sea level lowering or continuing sedimentation are cited as factors which could induce dissociation at the base of the hydrate layer resulting in loss of cementation, gas production, and overpressurization. The result would be a glide plane along which massive wedges of hydrate cemented sediment would slide (Figure 2).

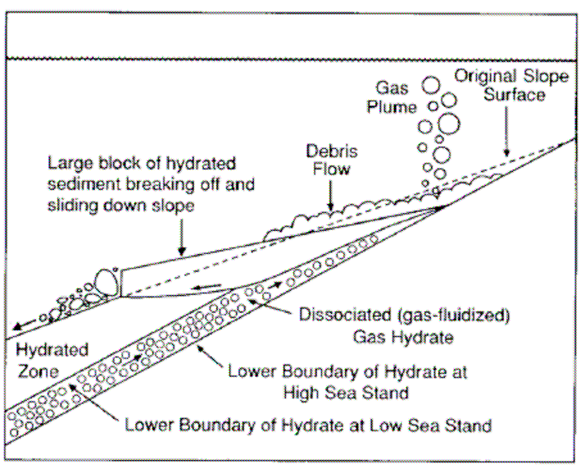

Figure 2. Conceptual model of mass movement on a slope face by slippage of a solid block along a hydrate-decomposition glide plane (after McIver 1982).

As shown in Figure 1, the gas hydrate stability zone thickness is controlled by the water depth and geothermal gradient in marine settings. As the water shallows, the base of the gas hydrate approaches the seafloor, pinching out the hydrate stability zone at approximately 400 m water depth. The pinch-out is referred to as the up-dip limit of the gas hydrate stability zone. It is in this feather edge of stability that hydrates experience the greatest impact from water bottom temperature fluctuations. It is also these surficial sediments that have the greatest potential for pressure generation associated with hydrate dissociation simply because ambient pressure controls the relative volume of gas that will be generated from the hydrate. Surficial sediments tend to be only lightly consolidated, thus relatively little change in pressure is required to surpass the lithostatic stress of these weak sediments. Paull et al. (2000) postulate that hydrate-related sediment failures should be most frequent at or just below the up-dip limit as this zone has the greatest potential for instabilities.

It is difficult to draw precise conclusions about the environmental controls on hydrate stability and its affect on seafloor instability. Sediment properties and hydrate characteristics are highly variable, even on local scales, and the time scales and amplitudes of sea level change and ocean bottom water temperatures can also vary significantly (Leynaud et al. 2008). Pressure changes are assumed to translate through the sediment's interconnected pores affecting hydrate stability immediately, while temperature changes penetrate progressively through the sediments, where it can take thousands of years for oceanic hydrate stability to be affected (Fyke and Weaver 2006; Hatzikiriakos and Englezos 1993). Detailed site specific information is required before conclusions can be drawn and landsliding attributed solely to hydrate dissociation.

Very few quantitative slope stability models have incorporated the effects of gas hydrate cementation and/or dissociation. Agreement that hydrate related landslides occur most frequently at shallow water depths has been observed (Xu and Germanovich 2006; Paull et al. 2000; Mienert et al. 2005; Sultan et al. 2004).

Further details of stress changes and stability of hydrate bearing layers can be found in Grozic (2009).

4 FIELD OBSERVATIONS

In order for gas hydrates to be the cause of a slope failure, three conditions must be met (Booth et al. 1994): 1) gas hydrates must be present and widespread; 2) the slide scar must intersect the boundaries of the hydrate layer; and 3) a low permeability material (sediment or hydrate-bearing sediments) must be common at the base of the hydrate stability zone. There are a number of cases where these conditions have been met and gas hydrates have been suggested, circumstantially, to have played a role in submarine slope failures. Examples of the connection between gas hydrates and submarine slope failures are found throughout the literature and have been summarized by Kvenvolden (1993; 1999) on the continental slope and rise of the west coast of Africa, on the US Atlantic continental slope, in the fjords of British Columbia, and on the Alaskan Beaufort sea continental margin. A few of instances where hydrates could have initiated submarine sliding are described below.

In the US Atlantic margin, the Cape Fear slide shows indications, on seismic profiles, of the presence of gas hydrate and underlying free gas coincident with the slip plane (Popenoe et al. 1993; Schmuck and Paull 1993). The area is also active seismically and with diapirism and the slide occurred during a period of sea-level rise (Lee 2008), thus the triggering mechanism cannot be attributed to hydrate dissociation alone.

Along the continental slope of Alaska, underlying the Beaufort Sea, are a string of almost continuous submarine landslides (Grantz and Dinter 1980). Gas hydrate deposits are coincident with the slide features (Kayen and Lee 1991) and the majority of the hydrate deposits are contained within low permeability sediments. Theoretical calculations of excess pore pressures indicate that hydrate dissociation would be sufficient to initiate seafloor sliding (Nixon and Grozic 2007; Kayen and Lee 1991); however, there is also evidence of seismic activity in the region.

A number of large submarine slides in the Amazon fan are indicated on seismic records (Piper et al. 1997). Although the timing of the slides is not certain, the failures seemed to have occurred during a period of lower sea level, which combined with the presence of gas and gas hydrates, points to a correlation between hydrate dissociation and failure.

The Storegga slide off the western coast of Norway is a well analyzed case history, due in part to its immense size, but perhaps more notable, is that the underlying Ormen Lange gas field is the second largest gas reserve in Norway. Triggering mechanisms considered have included high sedimentation rates, gas charged sediments, gas hydrate dissociation, diapirism and earthquakes (Bryn et al. 2005). Gas hydrates have been inferred from the seismic profile both inside and outside the slide scar (Bouriak et al. 2000) and careful consideration has been given to the possibility that gas hydrate dissociation triggered the Storegga slide (Mienert et al. 2005; Jung and Vogt 2004; Vogt and Jung 2002; Sultan et al. 2004). Bryn et al. (2005) conclude that the failure was earthquake triggered; Mienert et al. (2005) illustrate how gas hydrate dissociation in the shallower waters could have preconditioned the slope for the retrogressive failures that were observed.

Although instances of submarine slope failure potentially involving gas hydrates have been reported, the author is unaware of any slide that can be definitively attributed to gas hydrate dissociation as the singular triggering mechanism. Knowledge of well-scale failures as a result of gas hydrate dissociation is also mostly anecdotal and related to drilling and/or production operations (e.g., Nimblett et al. 2005).

5 CONCLUDING REMARKS

Slope failure due to hydrate dissociation is possible and circumstantial evidence from the field shows coincidence between observed slide scars and the base of the gas hydrate layer. Certainly the conclusion that hydrate dissociation can precondition a sediment mass for failure, both by loss of sediment strength and generation of excess pore pressures, can be drawn. Likewise, if failure is triggered through another mechanism, such as earthquake loading, gas hydrate dissociation may play a role in the propagation of the submarine failure. In moving forward, slope failure, particularly the genesis of localized failures, still needs to be carefully considered. This is in part because of our current lack of quantitative data, models, and methodologies for adequately assessing slope stability in hydrate bearing sediments.

The complexities of gas hydrates and their interactions with the host sediment, combined with the high cost of laboratory and field investigations, have sufficiently limited our knowledge to the extent that we still cannot obtain a definitive answer to the question “do gas hydrates cause submarine slope failures”. However, the increasing interest in gas hydrates, along with the growing number of hydrate researchers, imparts every indication that we are indeed moving forward. We are improving our fundamental knowledge and progressing toward being able to quantitatively assess the probability of gas hydrate dissociation triggering submarine mass movements.

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