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Shallow Seabed Methane Gas Could Pose Coastal Hazard

By A. I. Best, M. D. Richardson, B. P. Boudreau, A. G. Judd, I. Leifer, A. P. Lyons, C. S. Martens, D. L. Orange, and S. J. Wheeler

Abnormally high levels of methane gas in seafloor sediments could pose a major hazard to coastal populations within the next 100 years through their impact on climate change and sea level rise. Marine scientists have known for many years that biogenic methane (CH_4) is generated in shallow seabed sediments on continental margins, especially in rapidly deposited muddy sediments with high organic matter content (see Methane Flux Control in Ocean Margin Sediments (METROL) project in *Mienert et al.*, [2004]).

Gassy sediments are found in river deltas, estuaries, and harbors, but also in deeper waters on continental shelves and slopes. Human activities can accelerate natural seafloor gas generation by increasing the supply of sediments and organic matter from rivers through deforestation and intensive farming, and also by the disposal of human waste at sea. When this extra organic matter becomes buried to about one meter beneath the seabed, biogeochemical processes start to convert it to CH_4 [*Floodgate and Judd*, 1992]. The impact of this extra CH_4 could be felt within the next 100 years, assuming a one-centimeter-per-year sediment accumulation rate.

Shallow gassy marine sediments deserve immediate attention because significant amounts of seabed CH_4 (a potent greenhouse gas) are leaking into the atmosphere, enough to contribute to global warming and sea level rise [*Judd*, 2003]. Gassy sediments can also destabilize seabed slopes close to shore. Trigger events, such as earthquakes, increased rainfall, and even human activities, can then initiate slope failures with disastrous consequences for coastal populations [e.g., *Longva et al.*, 2003].

Gassy sediments also pose hazards to offshore drilling operations and the siting of seabed structures (e.g., wind farms, hydrocarbon industry installations, pipelines, and power and communications cables).

Another reason to examine gassy sediments is that seafloor gas seeps and heightened gas concentrations in the water column are also associated with little-studied, highly specialized habitats for chemosynthetic organisms [see *Weaver et al.*, 2004]. These habitats are important for aquaculture, fishing and bioprotein production. Shallow gassy sediments could even provide a way to quantify and monitor the impact of human activities on global climate change through studies of the rates of sediment accumulation and CH_4 production.

To assess hazards from these sediments and to quantify their use as a monitor of anthropogenic climate change, data are needed on the amount of gas stored in the sediments, vented into the water column, and released into the atmosphere, and the rate of gas flux. The required knowledge base for such studies is multidisciplinary, and will draw on expertise from fields such as biogeochemistry, geology, geophysics, geotechnical engineering, and underwater acoustics.

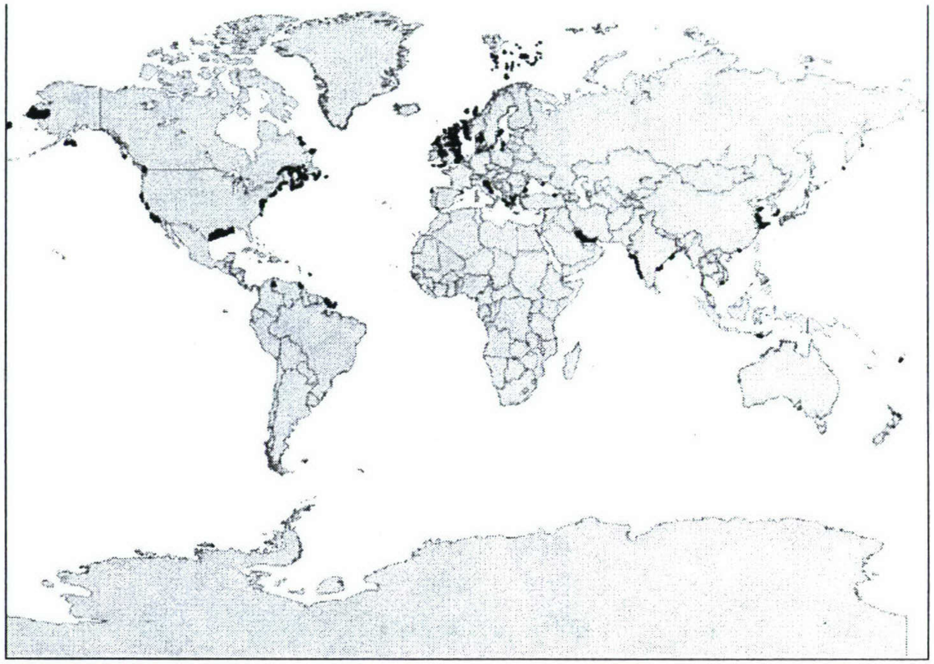

Fig. 1. Global distribution of methane gas in marine sediments (indicated by dark shading) from a compilation of published data [after Fleischer et al., *2001].*

How Much Seabed Gas Is There?

Acoustic survey methods currently allow seabed gas and gas rising through the water column to be detected, and are the most common form of evidence for shallow seabed gas [e.g., *Fleischer et al.*, 2001]. In fact, shallow gas has been found on continental margins worldwide, although there are data gaps in the tropics and polar regions (see Figure 1). Other means of detecting seabed gas include cameras, geochemical probes, and sediment coring, while sea surface gas emissions can be studied using satellite or airborne laser fluorescence (ALF) methods.

Recent estimates suggest that about 20 teragrams of CH_4 per year (~3% of global CH_4 emissions) escape from the seabed into the atmosphere [*Kvenvolden et al.*, 2001]. However, these estimates are uncertain, and much more effort is needed to quantify and monitor global seabed gas emissions. This will require some predictive capabilities best addressed through the development of

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reliable models of seafloor gas generation and gas flux processes, and the collection of reliable model input data (sediment accumulation rates, organic matter concentrations, amount of gas present, sediment shear strength, and so forth) through improved seafloor measurement and remote sensing technologies such as underwater acoustics.

Acoustic methods still offer the most practical means of efficiently surveying large areas of seabed and estimating sediment gas content. The geoacoustic response of a gassy sediment is related to the number of gas bubbles present, their size and shape, and the geotechnical properties of the host sediment (compressibility, shear strength, and so forth). There is increasing evidence that gas bubbles in marine sediments resonate in a fashion similar to gas bubbles in water when subjected to a passing acoustic wave [*Best et al.*, 2004; *Lyons et al.*, 1996]. This resonance phenomenon leads to strong shifts in sound speed and attenuation with measurement frequency that could be exploited by new acoustic survey tools.

Although there is some theoretical understanding of the likely acoustic response mechanisms, there are few well-constrained experimental data sets to validate and improve these models. Ultimately, reliable theoretical models are needed to interpret acoustic data in terms of seafloor gas content. The next step is to relate gas content to other environmental factors that can be modeled.

Microbial CH_4 Generation

Significant progress has been made on the modeling of microbial CH_4 generation [*Martens et al.*, 1998]. Geographically referenced data sets such as water column organic matter from satellite ocean color observations, hydrodynamic particle transport and settling rates, and water depth variations, together with knowledge of biogeochemical processes, allows modeling of sediment gas generation on kilometer-scale grids at sites such as estuaries, deltas, and embayments. However, finer-scale studies are needed to test biogeochemical models and controls on bubble growth.

Also, other forms of shallow microbial gas production need to be considered, such as photosynthetic oxygen generation in sandy sediments. Conventional geoacoustic survey methods cannot distinguish gas types (only the presence or absence of gas), but they could give information on bubble size and shape that influences the geotechnical properties of the sediment.

Geotechnical Properties

Bubbles can be classified into three types [*Anderson et al.*, 1998]: type I bubbles that form wholly within the void spaces between mineral grains; type II bubbles that encompass several adjacent void spaces (i.e., patchy gas saturation); and type III bubbles that actually deform the surrounding water-saturated sediment as they grow. Type I and II bubbles are associated with coarse-grained sediments such as sands and gravels that can behave as gas reservoirs, whereas type III bubbles are thought to be the dominant form in muds.

These ideas are supported by recent observations of X-ray computerized tomography scans of natural gas bubbles in pressure-sealed cores showing type II bubbles in sand, and crack-like (ellipsoidal) type III bubbles in mud [*Best et al.*, 2004]. Type III bubbles can significantly lower the shear strength of mud [*Wheeler*, 1988] with implications for slope stability. Crack-like bubbles also suggest a method by which bubbles are likely to form and migrate to the seabed.

Gas Migration

The way in which gas migrates to the seabed through apparently impermeable mud has been a mystery until recently. The buoyancy of typical (less than 1 centimeter diameter) spherical or ellipsoidal type III gas bubbles is insufficient to overcome the shear strength of the surrounding mud, and so gas bubbles should remain static within the mud where they form. Possible gas migration mechanisms include small bubbles moving slowly through the connected void spaces in the mud, or slow molecular diffusion of gas dissolved in the water filling the voids, or rapid gas movements through existing cracks in the mud.

Recent laboratory simulations of gas bubble growth in gelatin and mud provided convincing evidence for another gas migration mechanism called linear elastic-fracture [*Boudreau et al.*, 2005]. A bubble will form and grow as gas is injected into the mud until a critical pressure is reached that depends upon the intrinsic strength of the mud. The mud then fractures, expanding the crack-like bubble and lowering the gas pressure. This process can repeat as long as there is a sufficient supply of gas.

Linear elastic-fracture bubbles tend to form flat, cornflake-shaped voids with their long axes aligned in the direction of maximum stress (usually subvertical in seabed sediments) and migrate upward (see Figure 2). This novel result leads to the prediction that seabed gassy muds should be riddled with subvertical fractures, some open and some closed at any given moment, providing conduits for gas to escape from the seabed.

Shallow gas in marine sediments to date has received relatively little attention from governmental research agencies, although it is a topic of increasing concern due to its impact on global climate change and coastal zones. Once the current high levels of human organic matter reaching the seabed become buried by about one meter, possibly within the next 100 years, there will be a dramatic increase in seabed CH_4 production, resulting in continental slope instability and possibly resulting in elevated atmospheric greenhouse gas concentrations, the latter occurring as CH_4 is released from the seabed.

The activities of international experts need to be coordinated to tackle the key research questions central to understanding this phenomenon, and to provide pragmatic models and technologies for quantifying shallow gas in marine sediments. In addition to academic researchers, these experts should involve representatives from industry, such as hydrocarbon exploration companies and offshore geotechnical survey companies that have accumulated a large volume of data useful to seabed gas studies and are familiar with the challenges posed by gassy sediments.

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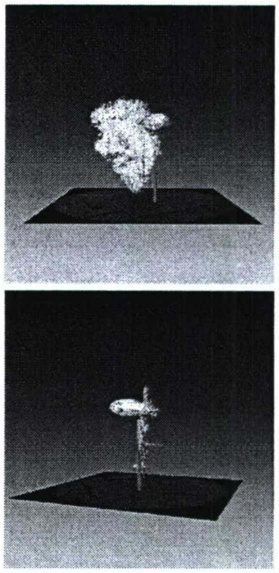

Fig. 2. High-resolution X-ray computerized tomography images of a cornflake-shaped gas bubble (cross-sectional and plan views), which was injected into a sample of mud from Cole Harbor, Nova Scotia, Canada. The golden yellow false-color represents the gas (air), red indicates the glass injection capillary, and silver is a mussel shell. The sediment has been made transparent, and the base of the core is indicated by the dark gray circle on the black square. The bubble is roughly a very eccentric oblate spheroid; the top diagram offers a view of the 'flat side' of the bubble, while the bottom view shows a cross-section. The bubble is about 20 millimeters across and one millimeter thick. The golden spike out from the bubble in the bottom diagram results from gas moving into a cavity created by a piece of decaying seagrass. Gaps in the bubble may be real areas without gas, or simply below the resolution of the image. Note that the gas goes around the surface of the shell. (Images provided by Chris Algar and Mark Barry at Dalhousie University, Halifax, Nova Scotia, Canada, and Alan Reed at Naval Research Laboratory, Stennis Space Center, Miss.)

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