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Marine gas hydrates in thin sand layers that soak up microbial methane

Alberto Malinverno

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA

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ABSTRACT

At Site U1325 (IODP Exp. 311, Cascadia margin), gas hydrates occupy 20–60% of pore space in thin sand layers (<5 cm) surrounded by fine-grained intervals (2.5 m thick on average) that contain little or no hydrate. This is a common occurrence in gas hydrate-bearing marine sequences, and it has been related to the inhibition of hydrate formation in the small pores of fine-grained sediments. This paper applies a mass balance model to gas hydrate formation in a stack of alternating fine- and coarse-grained sediment layers. The only source of methane considered is in situ microbial conversion of a small amount of organic carbon (<0.5% dry weight fraction). The results show that in a sequence such as that at Site U1325 the methane concentration never reaches the supersaturation needed to form gas hydrates in the fine-grained layers. Methane generated in these layers is transported by diffusion into the coarse-grained layers where it forms concentrated gas hydrate deposits. The vertical distribution and amount of gas hydrate observed at Site U1325 can be explained by in situ microbial methane generation, and a deep methane source is not necessary.

1. Introduction

Natural gas hydrates, ice-like compounds of water and natural gas (mostly methane), are widely found in continental margin sediments (Kvenvolden, 1993; Buffett, 2000). These deposits store large amounts of carbon: recent global inventory estimates are 500–2500 Gt (Milkov, 2004) and 1600–2000 Gt (Archer et al., 2008) of carbon. Marine gas hydrates are stable within the sediment column in a depth interval (the gas hydrate stability zone, or GHSZ) of low temperature and high pressure. Changes in sea level and ocean temperature can shrink the GHSZ and cause dissociation of the hydrates, which in turn may result in submarine sliding (e.g., McIver, 1982) and massive methane emissions in the ocean-atmosphere system. Methane emissions from gas hydrates have been proposed as the cause of major climatic excursions in the geological past (e.g., Dickens et al., 1995) and have the potential to affect climate in the future (Archer et al., 2008; Reagan and Moridis, 2008). Methane in gas hydrates is also a potential energy resource (Collett, 2002; Max et al., 2006).

Gas hydrates are not uniformly distributed in the sediments of the GHSZ, which complicates estimating their global inventory, predicting the effects of their dissociation, and assessing their resource potential. Two end-member gas hydrate systems result in different distributions of gas hydrate (Milkov and Sassen, 2002; Claypool et al., 2006; Tréhu et al., 2006). In focused gas hydrate systems, methane is transported into the GHSZ by localized fluid flow (e.g., along faults or permeable layers), and gas hydrates accumulate at high concentrations at vent sites near the seafloor. This paper concentrates on the distributed gas hydrate systems found in most of the GHSZ, where gas hydrates are dispersed within the sediment column. In these systems, sediment grain size is a major control on the heterogeneous distribution of gas hydrates. Gas hydrates are often found concentrated in coarse-grained layers next to fine-grained sediments that contain little or no hydrate. Examples include gas hydrate-bearing sand layers on the Cascadia margin (Weinberger et al., 2005; Torres et al., 2008) and on the eastern continental margin of India (Collett et al., 2008), and volcanic ash layers on the Costa Rica margin (Kimura et al., 1997; Lorenson, 2000) and in the Andaman Sea (Collett et al., 2008). As the formation of gas hydrates is inhibited in the small pores of fine-grained sediments, Henry et al. (1999) proposed that gas hydrates may form preferentially in coarse-grained layers if molecular diffusion homogenizes the concentration of dissolved methane. This mechanism, however, has not been studied in depth.

Gas hydrate formation requires a source of methane, which is generated ubiquitously in situ by methanogenic microbes (Claypool and Kaplan, 1974; Kvenvolden and Barnard, 1983; Claypool et al., 2006; Pohlman et al., 2009). Methane produced below the GHSZ and transported upward by fluid flow has also been proposed as a source, especially on accretionary margins (Hyndman and Davis, 1992; Ruppel and Kinoshita, 2000). Methane transport into the GHSZ is usually called for because in situ microbial methane generation is thought to be insufficient to produce the observed amounts of gas hydrate (e.g., Paull et al., 1994; Tréhu et al., 2006).

The aim of this paper is to test two ideas: (1) whether diffusion of dissolved methane can lead to gas hydrate accumulating in the

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E-mail address: alberto@ldeo.columbia.edu.

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coarse-grained layers of a mud–sand sequence and (2) whether in situ microbial methane generation is enough to explain the observed amounts of gas hydrate. The test will compare mass balance modeling predictions to the detailed observations made at IODP Site U1325 (Cascadia margin) by Torres et al. (2008). Modeling will be applied first to a case where lithology is uniform, as previously done (Xu and Ruppel, 1999; Davie and Buffett, 2001, 2003b; Bhatnagar et al., 2007). While most recent studies used numerical approaches, this paper derives new simple analytical expressions for the methane concentration and gas hydrate content (assuming steady-state conditions, constant porosity, and no fluid advection). It is also shown that the accounting of microbial methane generation generally used in the literature underestimates the methane produced from a given amount of organic carbon. The main new contribution of this paper is the modeling of gas hydrate formation in a sedimentary sequence composed of alternating thick layers of fine-grained mud and thin layers of sand. The results show that microbial methane generated in the mud layers (where gas hydrate formation is inhibited) is transported by diffusion into the thin sands where it forms concentrated gas hydrate deposits.

2. Gas hydrates in thin sands at Site U1325

Site U1325 was drilled during IODP Expedition 311 near the deformation front of the Cascadia accretionary wedge west of Vancouver Island (Fig. 1A). Site U1325 is located in a slope basin containing horizontally stratified sediments (Riedel et al., 2006), an environment suitable to the one-dimensional modeling presented here. Estimates of gas hydrate content from downhole logging and pore water chemistry are summarized in Fig. 1B (Malinverno et al., 2008). Gas hydrates are present from a shallowest occurrence at 73 m below seafloor (mbsf) down to the base of the GHSZ.

Detailed core observations show that gas hydrates occupy 20–60% of pore space in thin sand layers, while adjacent fine-grained marine muds contain little or no gas hydrate; at Site U1325, about 90% of the variance in gas hydrate content can be explained by the sand content of the host sediment (Torres et al., 2008). Most of the cored sand layers are <5 cm thick, except for two thicker beds (9 and 23 cm). These thin sand beds are separated by much thicker (2.5 m on average) fine-grained mud layers. Infrared core images display the gas hydrate-bearing sand layers as anomalously cold intervals due to endothermic dissociation (Riedel et al., 2006).

The organic carbon content in sediments at Site U1325 seems to decrease with depth from about 1% (dry weight fraction) near the seafloor to about half as much at depths below the base of the GHSZ (Fig. 1C). These organic carbon measurements constrain the amount of carbon available for microbial methane generation.

3. Modeling gas hydrate formation in uniform lithology

3.1. Mass balance of methane

Gas hydrate formation can be quantitatively modeled by balancing the mass of methane that is generated and transported in the sediment column. Fig. 2 shows the components of a unit volume of sediment with a porosity ϕ. Methane is microbially produced from organic matter, and is found either dissolved in the pore water with a concentration c (kg/m^3 of pore water) or in solid gas hydrate that occupies a fraction h of the pore volume.

If we follow this unit volume as it is buried by sedimentation, it will start near the seafloor with no gas hydrate and a concentration of dissolved methane that is extremely low, matching that of undersaturated ocean waters (a few nM; Reeburgh, 2007). The methane concentration will remain very low (<0.1 mM) in a depth interval where

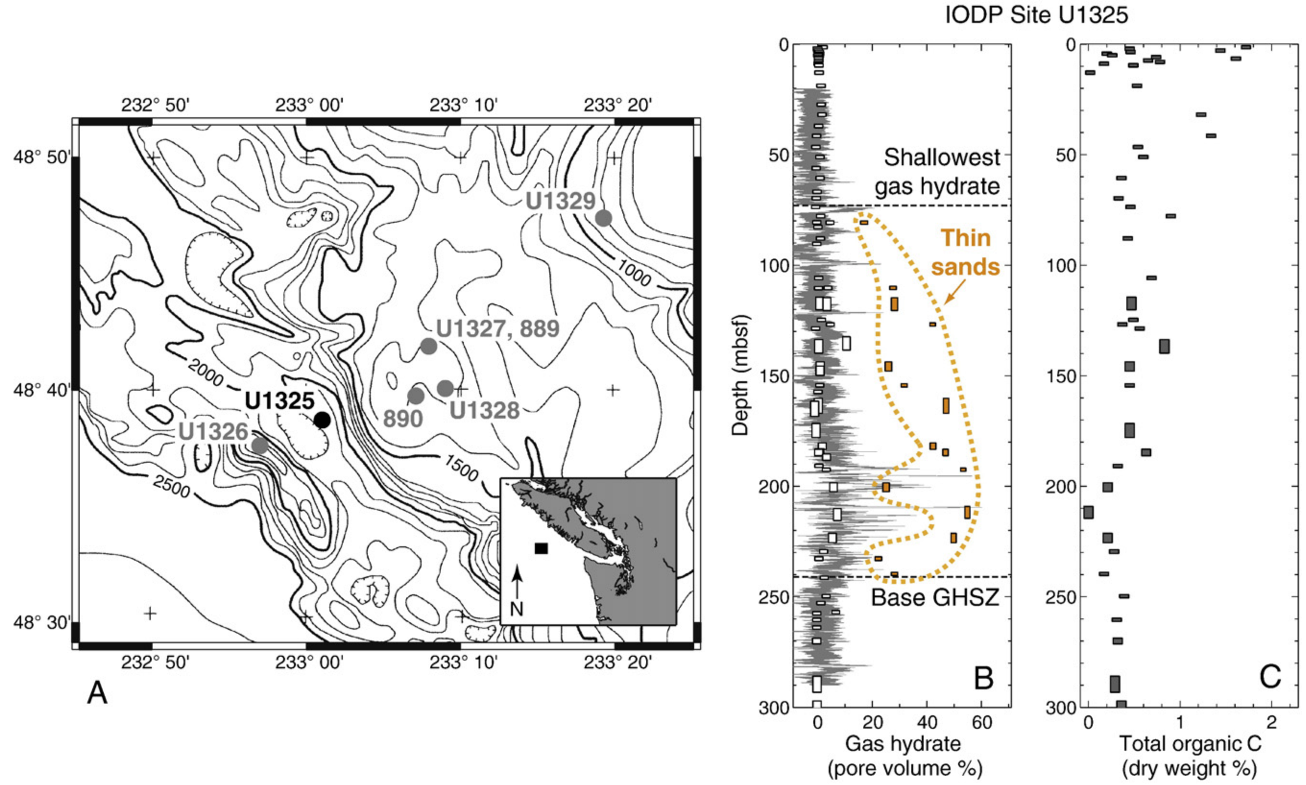

Fig. 1. A. Location map of Sites 889 and 890 (ODP Leg 146; Westbrook et al., 1994) and Sites U1325-U1329 (IODP Exp. 311; Riedel et al., 2006). Bathymetry after Westbrook et al. (1994); depths are in meters below sea level, contour interval is 100 m, and bathymetric lows are shown by ticks pointing downslope. B. Gas hydrate content in sediments of IODP Site U1325, from downhole resistivity and porosity logs (gray band) and from pore chemistry data (rectangles). The width of the gray band spans the uncertainty in the estimated gas hydrate content and the height of the rectangles is the sample depth uncertainty due to incomplete core recovery (after Malinverno et al., 2008). C. Organic carbon content (dry weight %) of IODP Site U1325 samples (Riedel et al., 2006); the height of the rectangles is the sample depth uncertainty.