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The mechanics of intermittent methane venting at South Hydrate Ridge inferred from 4D seismic surveying

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ABSTRACT

Sea floor methane vents and seeps direct methane generated by microbial and thermal decompositions of organic matter in sediment into the oceans and atmosphere. Methane vents contribute to ocean acidification, global warming, and providing a long-term (e.g. 500–4000 years; Powell et al., 1998) life-sustaining role for unique chemosynthetic biological communities. However, the role methane vents play in both climate change and chemosynthetic life remains controversial primarily because we do not understand long-term methane flux and the mechanisms that control it (Milkov et al., 2004; Shakhova et al., 2010; Van Dover, 2000). Vents are inherently dynamic and flux varies greatly in magnitude and even flow direction over short time periods (hours-to-days), often tidally-driven (Boles et al., 2001; Tryon et al., 1999). But, it remains unclear if flux changes at vents occur on the order of the life-cycle of various species within chemosynthetic communities (months, years, to decades Leifer et al., 2004; Torres et al., 2001) and thus impacts their sustainability. Here, using repeat high-resolution 3D seismic surveys acquired in 2000 and 2008, we demonstrate in 4D that Hydrate Ridge, a vent off the Oregon coast has undergone significant reduction of methane flow and complete interruption in just the past few years. In the subsurface, below a frozen methane hydrate layer, free gas appears to be migrating toward the vent, but currently there is accumulating gas that is unable to reach the seafloor through the gas hydrate layer. At the same time, abundant authigenic carbonates show that the system has been active for several thousands of years. Thus, it is likely that activity has been intermittent because gas hydrates clog the vertical flow pathways feeding the seafloor vent. Back pressure building in the subsurface will ultimately trigger hydrofracturing that will revive fluid-flow to the seafloor. The nature of this mechanism implies regular recurring flow interruptions and methane flux changes that threaten the viability of chemosynthetic life, but simultaneously and enigmatically sustains it.

1. Introduction

Understanding the long term methane flux through sea floor methane vent systems is critical for assessing its impact on the oceans, the atmosphere and especially the unique biological communities that feed directly on methane at vents (Milkov et al., 2004; Shakhova et al., 2010; Van Dover, 2000). Chemosynthetic communities that rely on methane vents for their survival are highly sensitive to methane flux. Slow or very rapid methane seeps support simple organisms of bacterial mats, while more complex communities require moderate methane flux rates to sustain a balanced level of microbial activity that supports their subsistence (Boetius and Suess, 2004; Roberts, 2001; Torres et al., 2002). Thus, they are highly sensitive to methane flux changes, especially long-term variations (years to decades), which is poorly known due to a lack of long-term monitoring. However, Powell et al. (1998) reported evidence of mussel and clam communities surviving in the same sites for 500–4000 years in the Gulf of Mexico, which implies long-term sustainability of chemosynthetic communities and steady methane flux rates.

A key element for the sustainability of chemosynthetic communities may be an underlying gas hydrate system. Carney (1994) noted that despite adequate methane and sulfide sources on the continental shelves, the abundant chemosynthetic communities in the Gulf of Mexico are restricted to water depths of >~400 m (a depth coincident with where gas hydrate becomes stable at the seafloor), and speculated that the methane storage capacity of methane hydrate has a stabilizing effect on methane supply to vents. Understanding long-term methane flux to assess the impact on oceans, atmosphere or chemosynthetic communities requires an understanding of the role of gas hydrates in the mechanisms of methane venting.

The mechanics of methane migration through vents with gas hydrates is complex. Not only does gas hydrate have the capacity to concentrate and store methane passing through vents, but methane migrating through deepwater hydrate systems involves a dynamic interaction between free gas and gas hydrate (Heeschen et al., 2003;

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Paull et al., 1995) that makes methane flow inherently unstable. In water depths greater than ~500 m, methane must pass through the methane hydrate stability zone to reach the seafloor (Gorman et al., 2002; Suess et al., 1999). Free methane gas migration through the gas hydrate stability zone (GHSZ) is problematic because if free methane mixes with water in this zone it forms solid methane hydrate, which along with authigenic carbonate formation near the seafloor can plug fluid-flow pathways (Tréhu et al., 2004b). In addition, gas hydrate fills pore space, reducing permeability so that upward migrating free gas can become trapped at the base of the hydrate stability zone, potentially resulting in gas overpressures (Dillon et al., 1980; Hornbach et al., 2004).

These observations raise an apparent paradox for methane flux: how does methane flow continue at vents and sustain vent communities, when gas hydrate formation should clog flow paths? One mechanism for free gas migration through the hydrate stability zone is the formation of gas hydrate pipes where hydrate forms along the outer walls of the conduit, isolating pore water and allowing gas to migrate vertical through the GHSZ to the seafloor without forming gas hydrate (Leifer and MacDonald, 2003; Riedel et al., 2006; Suess et al., 2001; Suess et al., 1999). Thus, gas hydrate appears to both enable and to impede free gas flow to seafloor vents. The nature of this dual role suggests that gas hydrate vent systems are unstable, and prone to dynamic changes from an effective conduit to an impermeable barrier.

Recent studies of marine gas hydrate systems have quantified and characterized the methane hydrate distribution in pore spaces and fractures in the host sediments within a few 100 m below the seafloor where methane hydrates are stable (Riedel et al., 2006; Tréhu et al., 2004a). These studies have shown that the highest concentrations of gas hydrates form near vents within porous, high-permeability sand and ash intervals and along vertical fractures, particularly near the base of the hydrate stability zone. This distribution offers a critical clue regarding the significance of high-permeability pathways for methane migration, but reveals little of the mechanisms of methane migration and dynamics between free gas and gas hydrates within vent systems. Pore-fluid chemistry (Torres et al., 2004) and pressure core samples (Milkov, et al., 2004) provide some clues to fluid, gas hydrate, and free gas interactions, but not on the time-scales of months to a year that shallow flux measurements imply (Boles et al., 2001; Tryon, et al., 1999). Addressing the dynamics of methane migration requires regular, repeated, observations that constrain flow not only at the shallow surface but to the source of the gas. In this paper we present the results of two collocated 3D seismic reflection surveys acquired in 2000 and 2008 that show how gas migrates through the south Hydrate Ridge vent system, and how the mechanics of methane migration impacts methane flux and the sustainability of chemosynthetic communities at methane vents.

2. Methods

We acquired the 2000 survey with the R/V Thompson using a portable seismic system that included a 600-m, 48-channel single streamer and two Generator-Injector (GI) airguns with 0.75/.075 l (45/45 in^3) chambers towed at 2 m depth. We shot 81 lines at 50 m spacing and covered a 4 × 11 km area (Fig. 1).

We used the P-Cable seismic system for the 2008 survey, which has 10 30-m-long streamers that stream behind the ship and parallel to each other with 12.5 m spacing. It was designed to improve spatial resolution by towing streamers with a narrow, 12.5 m line spacing, but sacrificed multiple traces for stacking to suppress noise. Stacking with the single channel streamers was only possible in areas of survey overlap or by enlarging bin size to greater than 12.5 m. We used an almost identical source to that of the 2000 survey, two-1.23/1.23 l (75/75 in^3) GI airguns towed at 2 m. The source signature frequency content is nearly identical in both data sets (Fig. 2) and no tuning is required to match sources. The surveys are not completely overlapping (Fig. 1), but they overlap completely at the vent site.

3. Results

With the two collocated 3D seismic reflection surveys from 2000 and 2008 (Fig. 1), we observe three simultaneous and spatially coincident changes in the south Hydrate Ridge vent system that imply a change in migration pathways through the GHSZ rather than changes in gas supply: we observe (1) free gas migration toward the south summit along Horizon A (Figs. 3 and 4), (2) the increasing amplitude of Horizon A beneath the vent (Figs. 4 and 5), and (3) cessation of seafloor venting (Fig. 3).

3.1. Gas migration updip toward the summit

In the subsurface, our 2000 3D seismic reflection data revealed that the main gas supply to the hydrate stability zone occurs along a well-defined, isolated high-permeability stratigraphic layer, Horizon A, that directs deeply sourced largely thermogenic gas to a closed structure beneath the seafloor vent at the summit of south Hydrate Ridge (Fig. 5). At the summit, Horizon A lies more than 150 m below, and subparallel to the seafloor beneath the gas hydrate layer. ODP Leg 204 penetrated Horizon A at five locations (Fig. 1) and recovered a 2–4 m thick interval of distinct high-permeability gas-filled ash and sands, bounded by low-permeability clays. It therefore makes an ideal stratigraphic conduit for gas migration.

In 2008, we conducted a repeat 3D survey across south Hydrate Ridge vent to improve resolution of vent conduits. The overlapping 3D surveys allow us to compare the changes in the seismic reflection of the critical gas migration pathway, Horizon A, between 2000 and 2008. The high porosity of Horizon A and the fact that gas occupies its pore-space results in a high seismic impedance contrast and reversed-polarity relative to the seafloor that is sensitive to free gas content. Horizon A increases in amplitude toward the summit of south Hydrate Ridge directly beneath the vent where the high gas content produces its maximum amplitude (Fig. 3). Comparison of relative amplitudes between 2000 and 2008 shows that free gas has moved > 100m up dip toward the summit along Horizon A.

3.2. Growing Horizon A reflection amplitude beneath the vent

Comparison of Horizon A from the 2000 to 2008 surveys also shows that free gas has accumulated directly below the vent. Specifically, in 2000 seismic reflection amplitudes at the summit are moderate, however, when we accurately match and scale amplitudes of the 2000 survey with the 2008 survey, Horizon A reflection amplitudes are substantially larger in 2008. Note that a scale factor of 10,000 results in similar BSR amplitude distributions for both surveys (Fig. 6). Furthermore, the distribution of differences between the 2000 and 2008 surveys is centered near zero and amplitudes are balanced between the two surveys. We attribute the higher Horizon A amplitude to gas accumulations directly below the vent during the past eight years (Fig. 4).

A critical concern with reflection amplitude comparison from these data is whether amplitude variations are a result of navigation errors, acquisition artifacts, and processing effects from the two acquisition systems. The best way to assure amplitude changes are real is by conducting a similar comparison with a seismic reflection similar to Horizon A that we do not expect to have detectable changes in 8 years.

The BSR is a seismic reflection that forms due to the seismic impedance contrast generated by the vertical transition across the gas hydrate stability zone phase boundary from frozen methane hydrate to free gas. Drilling data confirmed that this phase boundary is not out of equilibrium with current pressure and temperature conditions and we expect this boundary to change minimally in an eight year period.

The BSR amplitudes in the areas of overlap between the two surveys show only small differences (Fig. 6). The 2000 data have acquisition artifacts that appear as E–W oriented stripes on the