Geology

Massive methane release triggered by seafloor erosion offshore southwestern Japan

N.L. Bangs, M.J. Hornbach, G.F. Moore and J.-O. Park

Geology 2010;38;1019-1022
doi: 10.1130/G31491.1

Notes

Massive methane release triggered by seafloor erosion offshore southwestern Japan

N.L. Bangs[1*], M.J. Hornbach[1], G.F. Moore[2,3], and J.-O. Park[3,4]

[1]University of Texas Institute for Geophysics, J.J. Pickle Research Campus, Building 196, 10100 Burnet Road, Austin, Texas 78758-4445, USA

[2]Department of Geology and Geophysics, University of Hawaii, Honolulu, Hawaii 96822, USA

[3]Institute for Frontier Research on Earth Evolution, Japan Marine Science and Technology Center, 3173-25 Showa-machi, Yokohama 236-0001, Japan

[4]Ocean Research Institute, University of Tokyo, 1-15-1 Minamidai, Nakano-ku, Tokyo 164-8639, Japan

ABSTRACT

Vast amounts of methane hydrate exist beneath continental margins, but whether this methane releases from sediment on a large scale and affects the oceans and atmosphere remains unclear. Analysis of newly acquired three-dimensional seismic images and drilling data from a large gas hydrate province reveal a recently eroded v-shaped depression. The depression sharply cuts through a relic bottom simulating reflection (BSR) and hydrate-laden sediments. The shape of the relic BSR indicates that the seafloor depression was once a large anticline that has recently been eroded and released an estimated 1.51×10^{11} m^3 of methane. We hypothesize that erosion of the seafloor via bottom-water currents unroofed buoyant hydrate-laden sediments and subhydrate overpressured free gas zones beneath the anticline. Once triggered, gas-driven erosion created a positive feedback mechanism, releasing gas and eroding hydrate-bearing sediment. We suggest that erosive currents in deep-water methane hydrate provinces act as hair triggers, destabilizing kilometer-scale swaths of the seafloor where large concentrations of underlying overpressured methane exist. Our analysis suggests that kilometer-scale degassing events are widespread, and that deep-water hydrate reservoirs can rapidly release methane in massive quantities.

INTRODUCTION

Huge volumes of methane gas and frozen methane (hydrate) exist beneath the seafloor along continental margins (e.g., Milkov, 2004). Many studies postulate that these methane reservoirs are unstable and that slight changes in temperature or pressure may trigger hydrate dissociation and methane venting (e.g., Westbrook et al., 2009) or cause catastrophic seafloor failure and massive (gigaton scale) methane release into the oceans and atmosphere (e.g., Dillon et al., 1980; Paull et al., 2003; Kennett et al., 2000). However, the mobility of methane released from hydrate dissociation or trapped beneath hydrates is unknown because release mechanisms remain poorly understood. It is therefore unclear if methane in gas hydrate provinces is largely immobile, releases steadily from vent systems, or releases catastrophically.

Most mechanisms for large-scale methane release at hydrate provinces involve gas migration along focused vent systems (e.g., Westbrook et al., 2009) where gas flows through narrow conduits that leave sediment little changed and form small (meter-scale) pockmarks at the seafloor (e.g., Paull et al., 1995), implying small-scale release. Other larger-scale mechanisms involve landslides or seafloor erosion that disrupt the hydrate and unroof underlying free gas (Paull et al., 2003), with notable examples of massive methane release like Blake Ridge (offshore southeastern United States) (Holbrook et al., 2002).

In 2006, we acquired a three-dimensional (3-D) seismic reflection data volume across the Nankai margin in the vicinity of the Kii Peninsula, Japan (Fig. 1). These data were acquired by Petroleum Geo-Services with four 4500 m streamers towed with 150 m spacing and a 50 L (3090 in^3) well-tuned airgun array (Moore et al., 2007). Analysis of the data reveals strong evidence for a major seafloor erosion event that mobilized huge quantities of methane.

As a greenhouse gas, methane is 25 times more effective at raising temperature within the atmosphere than CO_2, and some carbon isotope studies suggest massive methane release from hydrates as a cause of a major global warming event at the end of the Paleocene (Dickens et al., 1995). Methane released relatively slowly as plumes in the deep oceans (>500 m depth) is oxidized in the water column and does not escape into the atmosphere (McGinnis et al., 2006), but sufficiently large, rapid methane release can affect atmospheric methane (Yamamoto et al., 2009). In any case, methane release at large scale is important for ocean acidification and deoxygenation and global redistribution of carbon. Our analysis, combined with other recent 3-D studies (Holbrook, et al., 2002; Rocha-Legorreta, 2009), suggests that erosion-driven methane release along continental margins is a global phenomenon that releases huge quantities of carbon.

DATA AND OBSERVATIONS

Notch

A deep depression extends along the seaward edge of the Kumano forearc basin (Fig. 1).

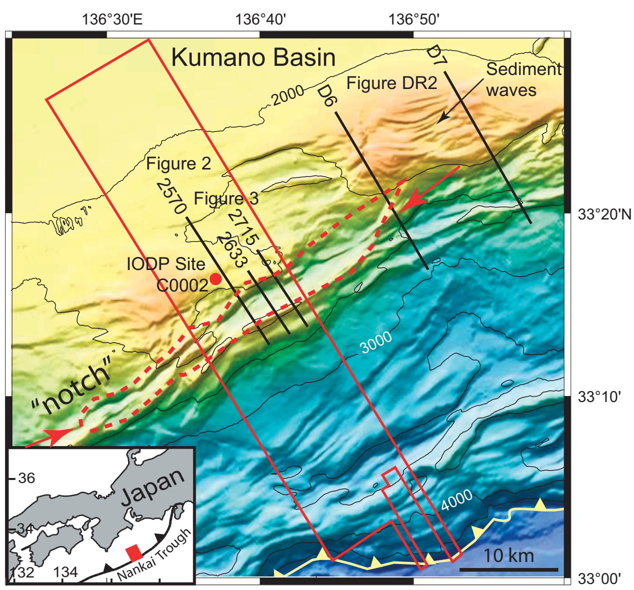

Figure 1. Location map with bathymetry across Nankai Trough to Kumano Basin showing broad scale of "notch" (area within dashed lines and between red arrows). Red outline is the three-dimensional survey area and black lines are individual profiles shown in Figures 2, 3, and 4. Ruffled seafloor between lines D6 and D7 are interpreted as reworked sediment waves and not deformational structures. Yellow line is the deformation front of the accretionary wedge. Contours in meters. Inset regional map shows extent of larger map (red rectangle). IODP—Integrated Ocean Drilling Program.

*E-mail: nathan@ig.utexas.edu.

The depression, referred to as the "notch," has a width of 3–4 km, is 300–400 m deep, and extends ~35 km in length with a v-shaped profile across most of the 3-D volume. A series of seafloor undulations, interpreted as sediment waves, is present along the northeast end of the depression (Fig. 1; see Figs. DR1 and DR2 in the GSA Data Repository[1]).

On the landward (northwest) flank of the notch, stratigraphic horizons clearly truncate at the seafloor along the steep walls of the depression (Figs. 2 and 3). Little if any sediment infill exists in the depression (<50 m) despite locally steep slopes. On the seaward flank, complex deformational structures exist below the seafloor; however, the few identifiable stratigraphic horizons in this region also truncate at the seafloor.

Multiple BSRs and Missing Hydrate

A bottom simulating reflection (BSR) extends across both flanks of the notch. BSRs are recognized by their seafloor-parallel position that crosscut strata (Fig. 2). Heat-flow analysis (see following) and drilling results confirm that the BSR depth is near steady state and represents a typical hydrate BSR with free gas below the reflection and methane hydrate stable above, resulting in a reverse polarity reflection (Bangs et al., 1993). An unusual feature in these data is other weaker-amplitude BSRs that also crosscut stratigraphy. These reflections, called paleo-BSRs and positive-polarity anomalous reflections (PPARs) (Figs. 2 and 3), are above and below the hydrate BSR, respectively. Unlike the BSR, these reflections generally have the same polarity as the seafloor.

Integrated Ocean Drilling Program (IODP) Leg 314 (Tobin et al., 2009) drilled through hydrate-rich sediment to 1000 m below the BSR near this site (Fig. 1). The resistivity log (Fig. 2) shows a pattern typical of hydrate provinces, with elevated resistivity above the BSR. Resistivity generally increases from the seafloor to the BSR, with local resistivity spikes generally associated with hydrate formation within sandier and more permeable turbidite intervals. Hydrate concentrations were estimated from these logs at ~15%, on average, and as high as 80% of pore space in the sandy turbidite intervals (Miyakawa et al., 2008). Sonic logs reveal a 200-m-thick low seismic velocity zone below the BSR, indicative of gas-charged sediments with a thickness equivalent to other thick sub-BSR gas intervals (Holbrook et al., 1996). The high-amplitude strata reflections beneath the BSR and the PPARs correlate with the 200 m sub-BSR low-velocity zone at the drill site. They also extend to the notch, suggesting that free gas also extends across this zone (blue shading in Figs. 2 and 3).

The paleo-BSR is within the current hydrate stability zone and has sufficient seismic impedance contrast, most likely due to hydrates,

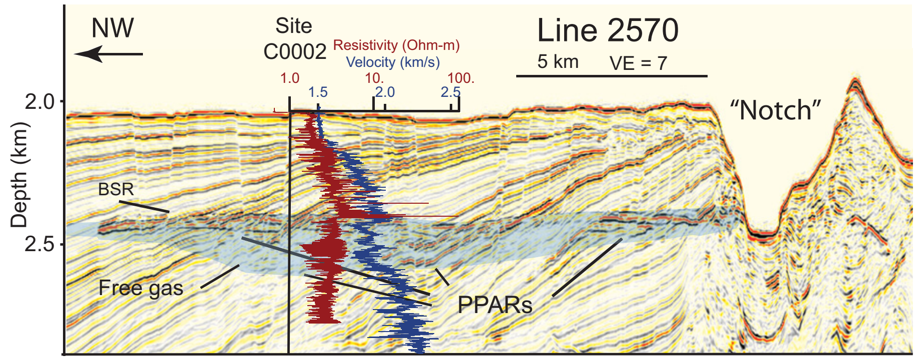

Figure 2. Line 2570 (see Fig. 1 for location) through "notch" and near Integrated Ocean Drilling Program (IODP) Site C0002. Red line is resistivity log and blue line is *P*-wave velocity log. Positive-polarity anomalous reflections (PPARs) are bottom simulating reflections below bottom simulating reflection (BSR). These and other anomalous reflections are believed to be caused by free gas and are used to infer lateral extent from Site C0002 (blue shaded area). VE—vertical exaggeration.

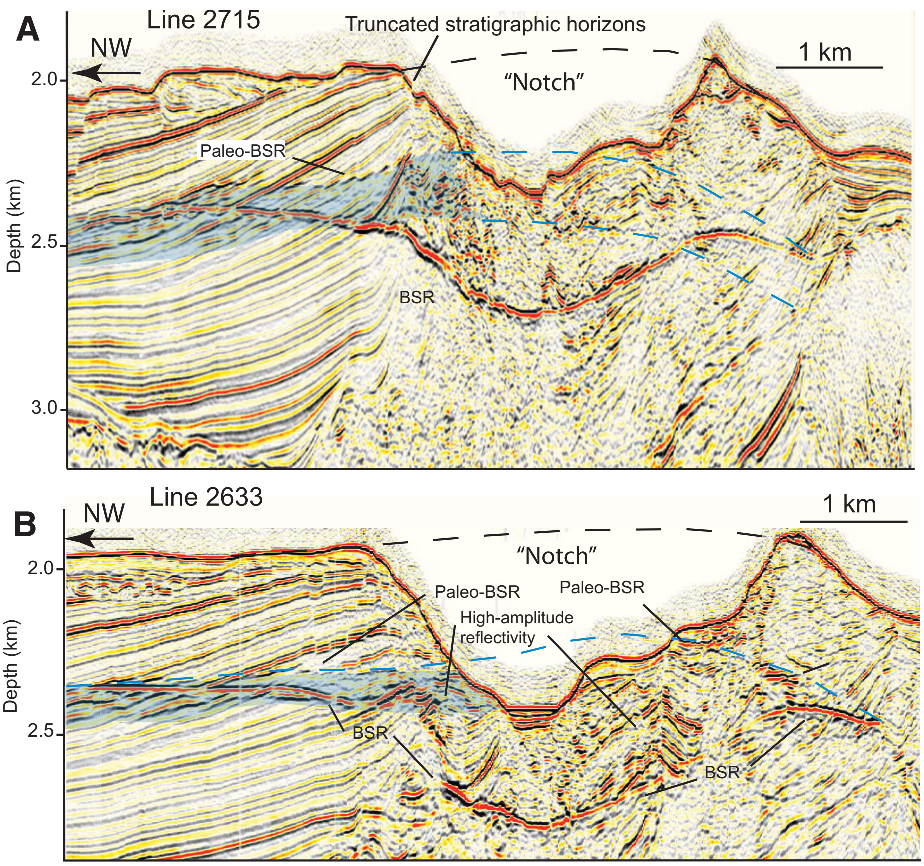

Figure 3. Lines from three-dimensional volume across deep depression known as "notch" (see Fig. 1 for location). A: Line 2715. B: Line 2633. Note that Kumano Basin strata are truncated at notch in both profiles. A reversed-polarity bottom simulating reflection (BSR) follows seafloor beneath notch; however, a weaker BSR (paleo-BSR) follows subparallel to seafloor where it is truncated by notch. Anomalously high amplitude reflections outline a paleo–free gas zone (blue shading) below the paleo-BSR, intersected by current BSR. Dashed lines show anticline that is inferred to have been removed as notch formed.

[1]GSA Data Repository item 2010282, supplemental material on seafloor erosion as a triggering mechanism and a numerical heat-flow model of the bottom simulating reflections, and Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

to produce the reflection. The paleo-BSR indicates a recent (within the past 40–50 k.y.; see the Data Repository), rapid downward shift of the hydrate stability boundary followed by conversion of methane gas to hydrate (Hornbach et al., 2003). The paleo-BSR closely parallels the seafloor away from the notch; near the notch, however, it follows a much smoother path than the present-day BSR (Fig. 3). By mapping the shape of the paleo-BSR in the 3-D volume, we infer the original shape of the seafloor in the region of the notch before erosion occurred. This map suggests that the paleo-BSR once was 50–100 m above the current base of the depression, and that before erosion began, the depression was actually an elongate dome-shaped structural high where focused flow likely led to free gas accumulation (Fig. 4).

Bulk estimates of hydrate concentration (~15% hydrate in pore space at 40% porosity between 200 and 400 m below seafloor) and free gas layer thicknesses (~200 m) at IODP Site C0002 provide a basis for an estimate of methane loss during notch formation. Hydrate distribution is known to be patchy and hydrate concentrations are substantially higher in coarse turbidite beds (Tobin et al., 2009), but 15% is a reasonable bulk average. We assumed free gas concentrations of ~2%, comparable to other thick free gas zones below BSRs (e.g., Holbrook et al., 2002). From this, methane release from hydrates and free gas at the notch alone is 1.51×10^{11} m^3 (0.14 Gt) at standard pressure-temperature conditions, or ~3% of the total methane currently in the atmosphere (assuming 15% hydrate in pore space, 40% porosity between 100 and 400 m below seafloor, and a gas column 200 m thick below the paleo-BSR across the notch.) This massive, recently active megavent may have released significant amounts of carbon into the oceans and possibly into the atmosphere.

MECHANISM FOR VIGOROUS METHANE VENTING

Seafloor erosion is clearly evident at the notch and is a viable mechanism for unroofing overpressured gas reservoirs (Paull et al., 2003). Slip along faults mapped beneath the notch (Martin et al., 2010) could also instantaneously lower stress and form pathways for venting gas; however, possible evidence for such a trigger has been eroded. Assessing a possible fault-related trigger requires future work. There is evidence for strong erosive ocean-bottom currents running counter to the Kuroshio Current (see Fig. DR1). Bottom currents are known to erode tens of meters of sediment in deep water, sometimes forming sediment waves (e.g., Holbrook et al., 2002). Analysis of seismic images indicates that bottom currents also likely eroded a few tens of meters of the ridge adjacent to the Kumano Basin between lines D6 and D7, where sediment waves exist (Fig. DR2). Bottom currents could also be responsible for the 400-m-deep (~2.5×10^{10} m^3) notch; however, the notch is an isolated, anomalous feature along the seafloor that contrasts sharply with other nearby sediment waves. Unlike smooth, sinuous, and interwoven sigmoidal shapes of traditional sediment waves, the notch is a single, well-defined individual feature consisting of steep, sharp edges. It seems unlikely that bottom-water currents would erode such a sharp, well-defined zone. The shape of the notch therefore indicates that it formed by a different mechanism than just bottom-water current erosion and deposition.

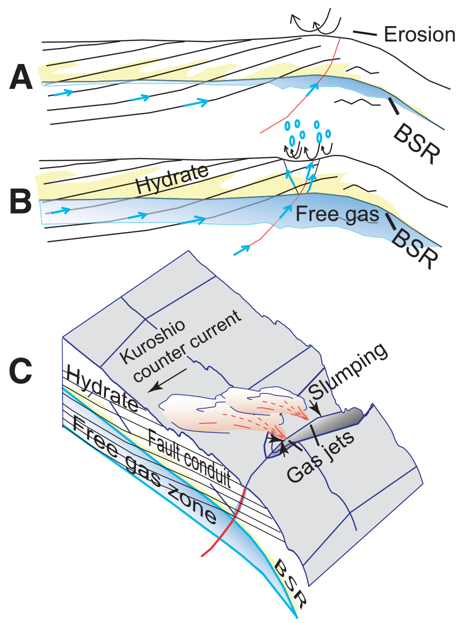

Figure 4. Model of gas release mechanism. A: Continuous anticline across seaward flank of Kumano Basin where seafloor erosion is beginning. Free gas (arrows) migrating along strata and faults (red line) forms hydrate (yellow) and restricts upward gas flow. BSR—bottom simulating reflection. B: Accumulating gas at anticline and further seafloor erosion, which continues until unroofing reduces lithostatic pressure enough to activate vigorous venting. C: Three-dimensional perspective view of vigorous gas venting; once initiated, it further erodes and unroofs adjacent areas and migrates laterally along anticline driven by venting gas. We speculate that sea bottom currents disperse eroded material.

Erosion of a few tens of meters of seafloor could be enough to unroof overpressured gas and buoyant hydrate-laden sediment accumulations beneath the seafloor, triggering rapid release of gas, hydrate, and hydrate-laden sediment (Fig. 4). Gas is known to accumulate beneath hydrate zones and build pressures to near lithostatic levels, and these pressures may ultimately result in fault activation, hydrofracture, and gas venting (Hornbach et al., 2004; Flemings et al., 2003; Tréhu et al., 2004). Columns as thin as 100 m may be sufficient for this mechanism with typical overburden (Hornbach et al., 2004). Free gas is currently observed to 200 m below the BSR at Site C0002. This observation implies potential for significant gas pressure below the notch and confirms the viability of a mechanism of gas release from hydrofracture and venting.

Lithostatic or near-lithostatic gas pressures have the potential for rapid, vigorous erosion or even catastrophic sediment eruption (Prior et al., 1989). If venting is sufficiently vigorous to erode overburden, gas overpressure will continue to exceed lithostatic pressure and cause further erosion and gas venting; this will finally terminate when gas pressure is insufficient to sustain this feedback effect. A similar erosion mechanism related to gas-induced overpressure has been operating on a smaller scale at Rock Garden, offshore New Zealand (Crutchley et al., 2010), and sediment eruptions between 50 and 250 m deep have been linked to catastrophic events within hydrate and free gas–bearing sediments (Rocha-Legorreta, 2009; Prior et al., 1989). We suggest that at Nankai this mechanism exists at a colossal (>30 km^3) scale.

Time of Notch Formation

Erosion of the notch will alter the pressure and temperature conditions, and therefore hydrate stability. Pressure changes will occur immediately as overburden is removed, resulting in destabilization of hydrate below. Temperature changes caused by erosion, however, will occur gradually over a few thousand years (Fig. DR3). We present a numerical diffusive heat-flow model of BSR positions following instantaneous formation of the notch (see the Data Repository). Most of the downward shift in the BSR occurs within 10 k.y., and equilibrium is reached to within the uncertainty of the model fit to the BSR in ~40–50 k.y. We believe that the notch formed ~50 k.y. ago, but more accurate estimates require further constraints on thermal properties, initial geometry, and erosion rates. Nonetheless, this is a modern process that could be easily activated in other locations today.

Is This Rare?

Both stratigraphic and structural controls on gas migration are often found in marine hydrate provinces. Drilling results near IODP Site C0002 revealed sandy turbidite layers that make ideal high-permeability conduits for gas migration below the BSR and are excellent hosts for hydrate (Tréhu et al., 2004). The gentle dip of these strata toward the notch focuses gas migration toward the site. In addition, faults identified by Martin et al. (2010) are common gas migration conduits, which here may direct gas to the base of the notch, focusing gas at the crest of the anticline for long distances along strike.

Bottom-water current–driven seafloor erosion is also common, and western boundary currents like the Kuroshio can generate strong bottom currents that erode and redistribute bottom sediments, resulting in constantly changing temperature-pressure conditions at the site. A particularly extreme example occurs along the Blake Ridge (Holbrook et al., 2002), where bottom currents have generated large sediment waves and caused massive methane release. Such strong bottom currents routinely exist where strong surface currents (like the Gulf Stream and Circum-Antarctic Current) are present.

Earthquakes and coseismic slip are additional mechanisms for destabilizing free gas beneath the notch and triggering venting, as proposed for the cause of large pockmarks observed in the vicinity of the Hellenic Trench (Hasiotis et al., 2002). The Nankai Trough has regular Mw 8+ earthquakes. This additional triggering mechanism further broadens the possible settings for massive methane release.

CONCLUSIONS

The Nankai data presented here reveal a clear example of massive methane mobilization likely instigated by erosion and gas overpressures. Small amounts of seafloor erosion may be a hair trigger for hydrate destabilization, vigorous venting, further seafloor erosion, and large volumes of methane mobilization. Identification of past vent features at this scale from 2-D seismic stratigraphy is difficult, as gas venting systems are inherently 3-D (Tréhu et al., 2004; Cole et al., 2000). Nonetheless, recent academic 3-D seismic surveys clearly indicate their prevalence. While we are only just beginning to realize how prevalent these features may be, it is evident that there is a mechanism that has released globally significant quantities of methane from deep-water hydrates. Our analysis, combined with other studies, indicates that the critical elements for massive methane release are (1) free gas accumulations beneath the BSR, and (2) a trigger to initiate venting, both of which are very common along continental margins. Mechanisms that destabilize hydrate include bottom-water warming along the seafloor, lowering sea level, or, as presented here, slight changes in seafloor erosion and sedimentation patterns that change the thermal and pressure regime below the seafloor.

ACKNOWLEDGMENTS

We thank Bob Hardage for discussions that led to this manuscript, and the anonymous reviewers for helpful reviews. We thank Paradigm for three-dimensional data processing software used for processing and interpretation.This work was supported by National Science Foundation grant OCE-0452340. This is University of Texas Institute for Geophysics contribution 2272.

REFERENCES CITED

Bangs, N.L.B., Sawyer, D.S., and Golovchenko, X., 1993, Free gas at the base of the gas hydrate zone in the vicinity of the Chile Triple Junction: Geology, v. 21, p. 905–908, doi: 10.1130/0091-7613(1993)021<0905:FGATBO>2.3.CO;2.

Cole, D., Stewart, S., and Cartwright, J., 2000, Giant irregular pockmark craters in the Paleogene of the Outer Moray Firth Basin, UK: North Sea Marine Petroleum Geology, v. 17, p. 563–577, doi: 10.1016/S0264-8172(00)00013-1.

Crutchley, G.J., Geiger, S., Pecher, I.A., Gorman, A.R., Zhu, H., and Henrys, S.A., 2010, The potential influence of shallow gas and gas hydrates on sea floor erosion of Rock Garden, an uplifted ridge offshore of New Zealand: Geo-Marine Letters, v. 30, no. 3–4, doi: 10.1007/s00367-010-0186-y.

Dickens, G.R., O'Neil, J.R., Rea, D.K., and Owen, R.M., 1995, Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene: Paleoceanography, v. 10, p. 965–971, doi: 10.1029/95PA02087.

Dillon, W.P., Grow, J.A., and Paull, C.K., 1980, Unconventional gas hydrate seals may trap gas off the southeastern U.S: Oil & Gas Journal, v. 78, p. 124–130.

Flemings, P.B., Liu, X., and Winters, W.J., 2003, Critical pressure and multiphase flow in Blake Ridge gas hydrates: Geology, v. 31, p. 1057–1060, doi: 10.1130/G19863.1.

Hasiotis, T., Papatheodorou, G., Bouckovalas, G., Corbau, C., and Ferentinos, G., 2002, Earthquake-induced coastal sediment instabilities in the western Gulf of Corinth, Greece: Marine Geology, v. 186, p. 319–335, doi: 10.1016/S0025-3227(02)00240-2.

Holbrook, W.S., Hoskins, H., Wood, W.T., Stephen, R.A., Lizzarralde, D., and Party, L.S., 1996, Methane gas-hydrate and free gas on the Blake Ridge from vertical seismic profiling: Science, v. 273, p. 1840–1843, doi: 10.1126/science.273.5283.1840.

Holbrook, W.S., Lizarralde, D., Pecher, I.A., Gorman, A.R., Hackwith, K.L., Hornbach, M., and Saffer, D., 2002, Escape of methane gas through sediment waves in a large methane hydrate province: Geology, v. 30, p. 467–470, doi: 10.1130/0091-7613(2002)030<0467:EOMGTS>2.0.CO;2.

Hornbach, M.J., Holbrook, S.W., Gorman, A.R., Hackwith, K.L., Lizarralde, D., and Pecher, I.A., 2003, Direct seismic detection of methane hydrate on the Blake Ridge: Geophysics, v. 68, p. 92–100, doi: 10.1190/1.1543196.

Hornbach, M.J., Saffer, D.M., and Holbrook, W.S., 2004, Critically pressured free-gas reservoirs below gas hydrate provinces: Nature, v. 427, p. 142–144, doi: 10.1038/nature02172.

Kennett, J.P., Cannariato, K.G., Hendy, I.L., and Behl, R.J., 2000, Carbon isotopic evidence for methane hydrate instability during Quaternary interstadials: Science, v. 288, p. 128–133, doi: 10.1126/science.288.5463.128.

Martin, K., Gulick, S.P.S., Bangs, N.L.B., Moore, G.F., Ashi, J., Park, J.-O., Kuramoto, S., and Taira, A., 2010, Possible strain partitioning structure between the Kumano fore-arc basin and the slope of the Nankai Trough accretionary prism: Geochemisty Geophysics Geosystems, v. 11, Q0AD02, 15 p., doi: 10.1029/2009GC002668.

McGinnis, D.F., Greinert, J., Artemov, Y., Beaubien, S.E., and Wüest, A., 2006, Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere?: Journal of Geophysical Research, v. 111, C09007, doi: 10.1029/2005JC003183.

Milkov, A.V., 2004, Global estimates of hydrate-bound gas in marine sediments: How much is really out there?: Earth-Science Reviews, v. 66, p. 183–197, doi: 10.1016/j.earscirev.2003.11.002.

Miyakawa, A., Yamada, Y., Saito, S., Bourlange, S., Chang, C., Conin, M., Tomaru, H., Kinoshita, M., Tobin, H., and Expedition 314/315/316 Scientists, 2008, Estimation of gas hydrate saturation with temperature calculated from hydrate threshold at C0002 during IODP NanTroSEIZE Stage 1 expeditions in the Nankai Trough: Eos (Transactions, American Geophysical Union), Fall meeting, abs. T31B–198.

Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S., Pangborn, E., and Tobin, H.J., 2007, Three-dimensional splay fault geometry and implications for tsunami generation: Science, v. 318, p. 1128–1131, doi: 10.1126/science.1147195.

Paull, C.K., Ussler, W., Borowski, W.S., and Spiess, F.N., 1995, Methane-rich plumes on the Carolina continental rise: Associations with hydrates: Geology, v. 23, p. 89–92, doi: 10.1130/0091-7613(1995)023<0089:MRPOTC>2.3.CO;2.

Paull, C.K., Brewer, P.G., Ussler, W., Peltzer, E.T., Rehder, G., and Clague, D., 2003, An experiment demonstrating that marine slumping is a mechanism to transfer methane from seafloor gas-hydrate deposits into the upper ocean and atmosphere: Geo-Marine Letters, v. 22, p. 198–203, doi: 10.1007/s00367-002-0113-y.

Prior, D.B., Doyle, E.E., and Kaluza, M.J., 1989, Evidence for sediment eruption on deep sea floor: Gulf of Mexico Science, v. 243, p. 517–519.

Rocha-Legorreta, F.J., 2009, Seismic evidence and geologic distinctiveness related to gas hydrates in Mexico: Leading Edge, v. 28, p. 714–717, doi: 10.1190/1.3148414.

Tobin, H., Kinoshita, M., Ashi, J., Lallemant, S., Kimura, G., Screaton, E., Moe, K.T., Masago, H., and Curewitz, D., and the Expedition 314/315/316 Scientists, 2009, NanTroSEIZE Stage 1 expeditions: Introduction and synthesis of key results, *in* Kinoshita, M., et al., eds., Proceedings of the Integrated Ocean Drilling Program, 314/315/316: Washington, D.C., Integrated Ocean Drilling Program Management International, Inc., doi: 10.2204/iodp.proc.314315316.101.2009.

Tréhu, A.M., Flemings, P.B., Bangs, N.L., Chevallier, J., Gràcia, E., Johnson, J.E., Liu, C.-S., Liu, X., Riedel, M., and Torres, M.E., 2004, Feeding methane vents and gas hydrate deposits at south Hydrate Ridge: Geophysical Research Letters, v. 31, L23310, doi: 10.1029/2004GL021286.

Westbrook, G.K., and 18 others, 2009, Escape of methane gas from the seabed along the West Spitsbergen continental margin: Geophysical Research Letters, v. 36, L15608, doi: 10.1029/2009GL039191.

Yamamoto, A., Yamanaka, Y., and Tajika, E., 2009, Modeling of methane bubbles released from large sea-floor area: Condition required for methane emission to the atmosphere: Earth and Planetary Science Letters, v. 284, p. 590–598, doi: 10.1016/j.epsl.2009.05.026.

Manuscript received 21 June 2010
Revised manuscript received --
Manuscript accepted 22 June 2010

Printed in USA