# Detecting hydrate and fluid flow from bottom simulating reflector depth anomalies

Matthew J. Hornbach[1]*, Nathan L. Bangs[2], and Christian Berndt[3]
[1]Southern Methodist University, Huffington Department of Earth Sciences, Dallas, Texas 75275-0395, USA
[2]University of Texas Institute for Geophysics, John A. and Katherine G. Jackson School of Geosciences, Austin, Texas 78758-4445, USA
[3]Leibniz-Institute for Marine Sciences, IFM-GEOMAR, Gebäude Ostufer, Wischhofstraße 1-3, 24148 Kiel, Germany

## ABSTRACT

**Methane hydrates, ice-like compounds that consist of water and methane, represent a potentially enormous unconventional methane resource that may play a critical role in climate change and ocean acidification; however, it remains unclear how much hydrate exists. Here, using a newly developed three-dimensional (3-D) thermal technique, we reveal a novel method for detecting and quantifying methane hydrate. The analysis reveals where fluids migrate in three dimensions across a continental margin and is used to quantify hydrate with meter-scale horizontal resolution. Our study, located at Hydrate Ridge, offshore Oregon (United States), suggests that heat flow and hydrate concentrations are coupled and that 3-D thermal analysis can be used to constrain hydrate and fluid flow in 3-D seismic data. Hydrate estimates using this technique are consistent with 1-D drilling results, but reveal large, previously unrecognized swaths of hydrate-rich sediments that have gone undetected due to spatially limited drilling and sampling techniques used in past studies. The 3-D analysis suggests that previous hydrate estimates based on drilling at this site are low by a factor of approximately three.**

## INTRODUCTION

For decades, researchers have attempted to detect and quantify gas hydrates to assess their potential as an unconventional hydrocarbon resource, their role in climate change, and, more recently, their role in ocean acidification (Biastoch et al., 2011; Collett, 1988; Dickens et al., 1997; Holbrook et al., 1996; Kvenvolden, 1993; Milkov et al., 2003). Standard techniques for quantifying methane hydrate include direct methods via geochemical analysis of sediments (Dickens et al., 1997; Milkov et al., 2003) and indirect geophysical analysis, including seismic velocity modeling (Bunz et al., 2005; Holbrook et al., 1996), downhole logging (Collett, 2001), or electrical resistivity measurements (Weitemeyer et al., 2010). When drilling or seismic velocities are unavailable, hydrates are also sometimes indirectly inferred using seismic data by the presence of a bottom simulating reflector (BSR) (Kvenvolden, 1993).

The BSR is a negative impedance seismic reflection that indicates the base of the hydrate stability zone. In deep-water environments where methane is present, methane hydrate stability depends primarily on temperature (e.g., Dickens and Quinby-Hunt, 1994). The BSR therefore indicates the depth at which temperatures are too high for hydrate formation: above the BSR temperatures are cooler and hydrate formation is possible; below the BSR, temperatures are too warm for hydrate formation, resulting in methane gas and water. The BSR therefore acts to first-order as a temperature gauge in deep-water environments (Yamano et al., 1992; Dickens and Quinby-Hunt, 1994; Kvenvolden, 1993; Minshull and Keddie, 2010). In the absence of significant (e.g., millimeters per year) erosion, a BSR will appear anomalously shallow if upward fluid advection exists (Hornbach et al., 2008; Martin et al., 2004).

Here, using two recently acquired three-dimensional (3-D) seismic reflection data sets collected at Hydrate Ridge, offshore Oregon (United States) (Fig. 1), we demonstrate a new high-resolution approach that uses 3-D thermal analysis and BSR depth to determine where fluid flow exists and hydrate concentrations are elevated. The first 3-D survey was acquired in 2000 using a 600 m, 48 channel single streamer and two generator-injector (GI) airguns with 0.75/0.75 L chambers. The second 3-D survey was acquired in 2008 using the P-Cable seismic system, which consists of ten 30-m-long streamers spaced 12.5 m apart and two GI airguns with 1.23/1.23 L chambers as a source. The 2008 survey has much higher lateral resolution (12.5 × 12.5 m vs. 12.5 × 50 m) than the 2000 survey. Combining 3-D seismic data with drilling results, our approach takes advantage of the observation that heat flow and hydrate concentrations across south Hydrate Ridge appear coupled. Comparisons between heat-flow and hydrate concentrations estimated at nine drill sites indicate that a correlation exists between heat flow and hydrate. Specifically, where higher heat flow exists at Hydrate Ridge, higher hydrate concentrations also generally exist (Tréhu et al., 2006, 2004b) (Fig. 2). One logical explanation for this local correlation is that upward fluid flow generates both higher regional heat flow and higher hydrate concentrations by supplying more methane-rich fluids from the subsurface.

## NEW 3-D METHOD FOR HYDRATE AND FLUID FLOW DETECTION

We use the BSR imaged in seismic data combined with a 3-D steady-state heat-flow model to determine where elevated heat flow and therefore elevated hydrate concentrations exist across the region. Specifically, we develop a high-resolution 3-D thermal model to determine the depth where the BSR should exist if steady-state diffusive heat flow exists across the 3-D data (Fig. 3). To our knowledge, this repre-

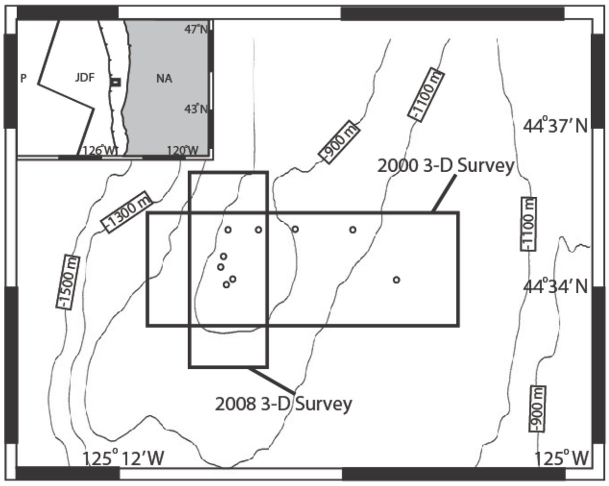


**Figure 1. Map view of study area. Inset shows location of study area with respect to regional tectonics. P—Pacific plate; JDF—Juan de Fuca plate; NA—North America plate. Black box in inset shows location of main figure. Black boxes in main figure show locations of 2000 and 2008 three-dimensional (3-D) seismic data sets collected at south Hydrate Ridge (offshore Oregon, United States). Circles represent locations of Ocean Drilling Program Leg 204 drill sites.**

*E-mail: mhornbach@smu.edu.


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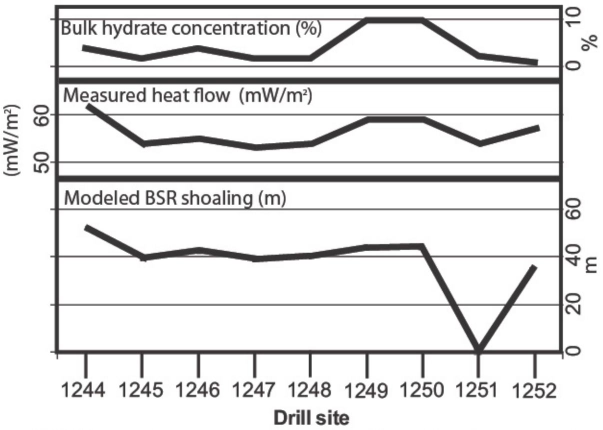


**Figure 2. Hydrate concentration, heat flow, and modeled bottom simulating reflector (BSR) shoaling at Hydrate Ridge drill sites. The *x* axis represents values measured at nine drill sites at Hydrate Ridge (locations shown in Fig. 1). Top: Measured mean hydrate concentration (based on Tréhu et al., 2004b). Center: Measured heat flow at drill sites based on Tréhu et al. (2003, 2006). Bottom: Normalized BSR shoaling modeled at each of the sites. Note that heat flow, hydrate concentration, and BSR shoaling appear coupled: as heat flow increases, hydrate concentration and BSR shoaling also generally increase; where heat flow decreases, hydrate concentration and BSR shoaling generally decrease. This effect cannot be explained by thermal conductivity of hydrate, since hydrate has lower thermal conductivity than surrounding sediments (Cook and Leaist, 1983).**

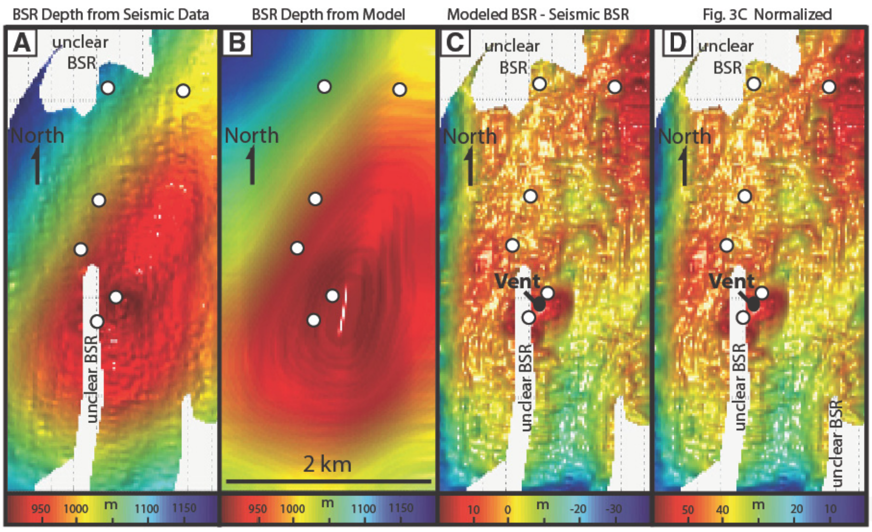


**Figure 3. Observed versus modeled bottom simulating reflector (BSR) depth for 2008 three-dimensional (3-D) seismic data. A: Depth of BSR (meters below sea level) picked across 3-D seismic volume, assuming mean seismic velocity of 1550 m/s in sediment. B: Modeled 3-D steady-state BSR depth (meters below seafloor) across 2008 seismic volume. C: Difference between modeled steady-state BSR depth (B) and observed BSR depth (A). Note clear shoaling (red) of BSR near known seafloor vent site, as well as significant shoaling along northeast corner of the volume where no seafloor venting is currently observed. White dots show drilling locations. Shoaling at several drill sites is near zero, such that modeled BSR depths match BSR depths measured both in seismic data and from drilling. This indicates that seismic velocity and heat-flow models we use are accurate. D: Normalized BSR shoaling in which we set most negative BSR anomaly at zero. As much as 60 m of variability exists between BSR anomalies, significantly more than model BSR depth uncertainty of ±15 m.**

sents the first hydrate stability model that fully accounts for thermal refraction effects in three dimensions, allowing prediction of steady-state BSR depths using 3-D seismic data with meter-scale resolution. To generate a 3-D steady-state temperature profile at Hydrate Ridge, we use a 3-D finite-difference diffusive thermal model that utilizes 3-D seismic data and drilling results at Hydrate Ridge to constrain the geometric shape, thermal conductivity, and heat flow across the region. Model resolution is 12.5 m in the horizontal and 6.25 m in the vertical direction, consistent with seismic resolution for the 3-D seismic surveys. We use a background thermal gradient consistent with mean heat flow and thermal conductivity values measured at the nine well sites (Tréhu et al., 2006, 2004b). Temperature increases with depth at all of the 9 drill sites, indicating an average heat flow of 57.4 mW/m² with a standard deviation of ~8%, consistent with BSR-derived heat flow estimates across the ridge using seismic data (e.g., Yamano et al., 1982). Lithology at the nine drill sites is generally uniform, and as a result, thermal conductivity also remains generally constant across the site, averaging 0.97 W/(m · K) (Tréhu et al., 2006, 2004b). From these values, we estimate an average thermal gradient of 55.6 ± 3.8 °C/km. The 3-D model has Dirichlet boundary conditions, with temperature increasing linearly with depth below the seafloor at side boundaries, and constant temperature at the bottom boundary that assumes a linear increase in temperature with depth. Seafloor temperature is held constant in time but is variable in depth, consistent with measured temperature-depth profiles in this region (Tréhu et al., 2003). Once we generate the steady-state 3-D temperature-depth profile across the 3-D data sets, we estimate the depth of the BSR using standard gas hydrate phase boundary methods, where we assume hydrostatic pressures, salt water as the pore fluid, and pure methane forming hydrate (e.g., Sloan, 1998).

We estimate that error to 1σ in model-predicted BSR depths averages ±15 m due to uncertainty in several model parameters. These uncertainties include differences between hydrostatic versus lithostatic pressure regimes that result in average BSR depths uncertainties of ±7 m, seismic velocity model errors that result in BSR depth uncertainties of as much as 10 m, and heat-flow estimate errors that may result in ±12 m of BSR uncertainty. Analysis of model results indicates that thermal refraction effects are significant at some locations on south Hydrate Ridge (~5–10 m), and should therefore be accounted for in hydrate thermal models where complex topography and meter-scale seismic resolution exists.

## ANALYSIS AND DISCUSSION

### Link Between Diffusive Flow and Hydrate Concentrations

Subtracting modeled steady-state BSR depths from seismically imaged BSR depth at Hydrate Ridge reveals clear BSR depth anomalies across the site (Fig. 3). The analysis shows anomalously shallow BSRs near the crests of ridges, and anomalously deep BSRs near the flanks, implying that heat flow is generally higher along regional anticlines (Fig. 3). The fact that significant negative BSR anomalies also exist implies that heat-flow estimates at drill sites are likely biased, with most data acquired near higher heat-flow regions, as recent studies demonstrate (Harris et al., 2011). Considering this, we normalize the data to show that net differences between predicted and actual BSR depths vary by as much as 55 m, well beyond the ±15 m uncertainty of our model (Fig. 3D). Model results indicate that anomalously shallow BSRs exist directly below the only known seafloor methane vent site in the region, as we might expect given the clear evidence of upward fluid flow at the vent (Torres et al., 2004) (Fig. 3D). Nonetheless, our analysis indicates that shallow BSR depth anomalies are widespread and extend broadly away from both vent and drill sites (Figs. 3 and 4). In particular, BSR shoaling is pronounced in regions where sediments above the BSR are fractured, folded, and contain discontinuous high-amplitude reflections above, but show no evidence for seafloor venting (Tréhu et al., 2004a, 2004b) (Figs. 4C and 4D).

Upward fluid advection or inaccurate seismic velocities models above the BSR offer two possible explanations for anomalously shallow BSRs. High concentrations of hydrate above BSRs can lead to unexpectedly high seismic velocities. If hydrate-related high velocities are unaccounted for in the seismic velocity model, they can cause apparent BSR shoaling (see the GSA Data Repository[1]). Therefore, upward fluid flow, the presence of hydrate, or a combination of both might explain anomalously shallow BSRs in the seismic data. Drilling results have no significant depth uncertainties and indicate that shallow BSRs generally occur where both elevated heat flow and elevated hydrate concentrations exist (Fig. 2). The correlation between hydrate concentrations and heat-flow measurements at the nine well sites suggests a link between diffusive upward flow and hydrate concentrations.

### Rich 3-D Picture of Hydrate

With BSR shoaling indicative of higher methane hydrate accumulations, the analysis suggests that a rich and complex system of fluid flow and hydrate accumulation extends across the region. In particular, our study suggests that significant quantities of hydrate exist in broad regions away from drill sites (Fig. 4). Most of the areas where BSR shoaling occurs are along regional anticlines, and our analysis confirms that methane migration and accumulation focuses along these zones. Anticlines like those at Hydrate Ridge therefore act as along-strike propagators of methane and as migration corridors for chemosynthetic communities in which methane accumulates and eventually releases along these features as seafloor methane vents (Tréhu et al., 2004a) (Figs. 4A and 4B).

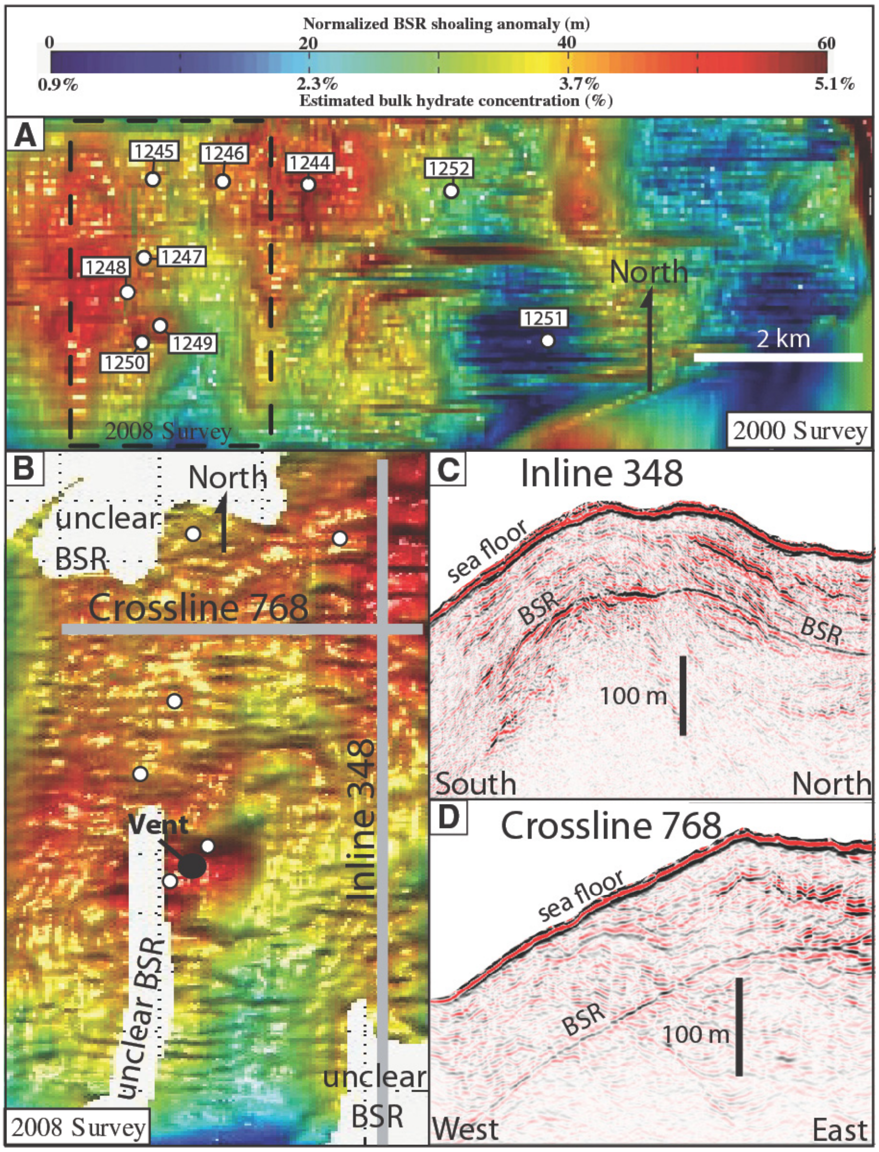


**Figure 4. Bottom simulating reflector (BSR) depth anomalies across both 2000 and 2008 three-dimensional (3-D) seismic data sets. Red in A and B indicate where most pronounced BSR shoaling occurs and where highest hydrate concentrations likely exist. A: BSR depth anomaly in 2000 survey. White dots represent locations of drill sites. Dashed box indicates where higher-resolution 2008 survey overlaps. B: BSR depth anomaly in 2008 survey. Despite different shooting parameters and survey design, BSR anomaly in A and B is consistent across 3-D data sets. C: Seismic inline 348. D: Seismic crossline 768. Locations of C and D are shown in B. At crossline 768, seafloor gets deeper to east, yet BSR continues to shoal. High-amplitude reflections above BSR and faulting are coincident with areas where most significant BSR shoaling occurs.**

### Implications for Hydrate Quantification

To estimate the total amount of hydrate present below the 3-D data, we calibrate heat flow with estimated hydrate concentrations at the nine drill sites (Tréhu et al., 2004b; Milkov et al., 2003). As a simple first-order calibration, we fit a linear trend to assess hydrate concentrations versus heat flow (see the Data Repository). Although the linear fit is weak, it is consistent with previous observations: areas with little or no normalized BSR shoaling have bulk hydrate concentrations of <1% (Fig. 4) (Milkov et al., 2003; Tréhu et al., 2004b). Likewise, areas with significant BSR shoaling have hydrate concentrations of a few percent (Milkov et al., 2003; Tréhu et al., 2004b). The analysis implies a bulk hydrate concentration increase of an average

[1]GSA Data Repository item 2012057, Figure DR1 (controls on the depth of the gas hydrate stability zone) and Figure DR2 (hydrate concentration vs. heat flow), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

0.54% for every 1 $mW/m^2$ increase in heat flow at Hydrate Ridge. This is equivalent to a 0.07% increase in bulk hydrate concentration per meter of BSR shoaling. The mean normalized BSR shoaling across the 2000 3-D data set at Hydrate Ridge is 23 m (Fig. 4). This suggests a mean hydrate concentration of ~2.5% at Hydrate Ridge. Our linear fit is likely conservative, since it underestimates the amount of hydrate at several key drill sites where significant quantities of hydrate (~10% bulk) exist (Milkov et al., 2003; Tréhu et al., 2004b). Despite this, our mean background estimate of 2.5% bulk hydrate is ~3 times higher than previous hydrate estimates at this site that are based on extrapolation of 1-D drilling results (Milkov et al., 2003).

Our hydrate estimate is higher because it accounts for broad zones of previously undetected hydrate across the region (Fig. 4); however, it is notably consistent with more recent mean hydrate estimates of 2%–4% to the north, offshore Cascadia (Hobro et al., 2005; Torres et al., 2008). Global hydrate estimates based on drilling results at Hydrate Ridge are likely too low by a factor of three because they fail to account accurately for 3-D variability of hydrate (e.g., Milkov et al., 2003). The 3-D analysis presented here therefore offers a unique, high-resolution 3-D method for a spatially more complete assessment of hydrate and fluid flow and shows the importance of accounting for 3-D variability when quantifying hydrate.

## FUTURE WORK

Several large 3-D seismic data sets now exist across gas hydrate provinces (Bangs et al., 2010; Hornbach et al., 2008; Minshull and Keddie, 2010; Petersen et al., 2010; Riedel, 2007). Applying this approach to more 3-D data sets will ultimately constrain hydrate accumulations more accurately and reveal with meter-scale detail where subsurface accumulations of hydrate and fluid-flow occur along continental margins. Future analysis of other 3-D data using this technique combined with calibration from drilling will substantially improve both global hydrates estimates and our understanding of 3-D fluid flow along continental margins.


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