FINAL REPORT: DOE Three-Dimensional Structure and Physical Properties of a
Methane Hydrate Deposit and Gas Reservoir, Blake Ridge

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W. Steven Holbrook, University of Wyoming

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Submitted by:
Dept. of Geology and Geophysics
University of Wyoming
1000 E. University Ave
Dept. 3006
Laramie, WY 82071

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ABSTRACT

This report contains a summary of work conducted and results produced under the auspices of award DE-FC26-00NT40921, “DOE Three-Dimensional Structure and Physical Properties of a Methane Hydrate Deposit and Gas Reservoir, Blake Ridge.” This award supported acquisition, processing, and interpretation of two- and three-dimensional seismic reflection data over a large methane hydrate reservoir on the Blake Ridge, offshore South Carolina.

The work supported by this project has led to important new conclusions regarding (1) the use of seismic reflection data to directly detect methane hydrate, (2) the migration and possible escape of free gas through the hydrate stability zone, and (3) the mechanical controls on the maximum thickness of the free gas zone and gas escape.

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EXECUTIVE SUMMARY

The work supported by this project has led to important new conclusions regarding the distribution and quantities of methane gas and methane hydrate on the Blake Ridge. In particular, our data provided new insights on (1) the use of seismic reflection data to directly detect methane hydrate, (2) the migration and possible escape of free gas through the hydrate stability zone, and (3) the mechanical controls on the maximum thickness of the free gas zone and gas escape. Five peer-reviewed papers were published during the course of the project [*Gorman et al.*, 2002; *Holbrook et al.*, 2002a; *Holbrook et al.*, 2002b; *Hornbach et al.*, 2003; *Hornbach et al.*, 2004], and several more are in preparation.

Direct detection of methane hydrate is an important, but elusive, goal of seismic studies in hydrate provinces. Although the presence of hydrate can be inferred from a bottom-simulating reflection (BSR), the amplitude of the BSR is principally a function of the concentration of free gas beneath the hydrate stability zone rather than the concentration of hydrate [*Holbrook*, 2001; *Holbrook et al.*, 1996]. Detection of hydrate away from the BSR from seismic reflection data is difficult, since many factors other than hydrate can cause amplitude anomalies. One criterion that has been proposed is amplitude blanking, the suppression of reflection amplitudes by the preferential formation of hydrate in high-porosity (and thus low-velocity) layers [*Lee and Dillon*, 2001], but clear instances of blanking require amplitude changes to occur entirely in the hydrate stability zone, away from complicating effects of free gas [*Holbrook*, 2001]. Our data show three types of evidence for direct detection of hydrate: (1) unequivocal evidence for amplitude blanking above the BSR on the eroding flank of the Blake Ridge [*Holbrook et al.*, 2002a; *Hornbach et al.*, 2003], (2) seismic bright spots in the hydrate stability zone, spatially associated with disruptions in the BSR, that we interpret as layers of concentrated hydrate [*Gorman et al.*, 2002; *Holbrook et al.*, 2002a; *Hornbach et al.*, 2003], and (3) a paleo-BSR above the present-day BSR formed by erosion and downward migration of the hydrate/gas phase boundary [*Hornbach et al.*, 2003]. The zone of amplitude blanking on the Blake Ridge has anomalously high P-wave velocities, supporting the idea of enhanced hydrate concentrations (~13% bulk hydrate). This work shows the importance of using multiple criteria (e.g., amplitude blanking and elevated P-velocities) to directly detect hydrate with seismic methods.

One of the outstanding questions in methane hydrate research is the role, if any, played by hydrate in the global carbon cycle and climate change. Paleooceanographic evidence suggests that large quantities of methane from the hydrate reservoir have escaped and played a role in climate change during the late Paleocene and Quaternary [*Dickens et al.*, 1995; *Kennett et al.*, 2000]. However, the sites and mechanisms of hydrate/gas release remain poorly understood. The research sponsored by this project has produced several new results that bear on the interactions of the hydrate reservoir with the oceans (and, possibly, atmosphere). First, the results presented in *Gorman et al.* [2002] showed that methane gas can migrate vertically hundreds of meters through the hydrate stability zone, given a permeability pathway (such as a fault). Second, *Holbrook et al.* [2002b] showed evidence for escape of a significant quantity (0.6 Gt) of methane

gas through large-scale sediment waves on the Blake Ridge. The escape was apparently triggered when seafloor erosion removed a capping layer of young, impermeable sediments, thereby exposing faults connecting the free gas zone to the seafloor, enabling gas escape. These results indicate that mechanisms of tapping methane directly from the free-gas zone, such as widespread seafloor erosion, should be considered when seeking the causes of large-scale carbon isotope records in the paleoceanographic record.

Hornbach et al. [2004] explored this notion by comparing free gas zone thicknesses in the Blake Ridge and elsewhere on rifted margins to develop a model for the thickness of the free gas zone based on Mohr-Coulomb failure theory. Failure theory predicts that the thickness of the free gas (assuming a continuously interconnected gas column) cannot exceed the strength of the overlying sediments, or hydrofracture or fault reactivation will occur, thus allowing gas migration. The resulting “critical thickness” of the free gas zone is therefore a function of hydrate stability zone thickness – i.e., water depth. This model passes a critical test when applied to a global compilation of free gas zone thicknesses, which tend to follow, and do not exceed, the predicted maximum thickness. This model has two important implications. First, it allows the first estimation of the size of the global free gas reservoir. This has been elusive, because the base of the free gas zone, unlike the base of hydrate stability, is not a chemical phase boundary describable by simple P-T relationships. Second, the model provides a simple physical mechanism for the escape of large amounts (~2000 Gt) of methane during bottom-water warming events, such as the late Paleocene thermal maximum: thinning of the hydrate stability zone results in a super-critical free gas zone thickness, which thus causes hydrofracture and/or fault reactivation, thus providing pathways for upward migration of free gas into the oceans and, ultimately, the atmosphere.

EXPERIMENTAL

During the course of this work we used the following experimental methods.

1. Data Acquisition.

Seismic data acquisition was conducted on the R/V Maurice Ewing in September and October 2000, in both 2D and 3D geometries, according to standard practice. Details of data acquisition are given below.

Acquisition Parameters.

We used the Syntron streamer in several different configurations during the cruise. For the regional 2D lines we used 6000 m (480-channels) of the streamer; during the 3D shooting and the Blake Ridge diapir lines, we used 4000 m (324 channels); during the OBS shooting we used 600 m (36 channels). Group spacing was 12.5 m for all configurations, yielding a CMP spacing of 6.25 m.

We recorded at a sample rate of 0.002 s, with record lengths varying from 9-10 s.

Shooting was done on distance, with principal shot intervals of 37.5 m during 2D and 3D MCS shooting and 20 m when shooting to the OBS's.

Shooting on distance served two goals: (1) It effectively randomized shot times, to prevent coherent previous shot noise, and (2) it simplified assignment of geometry in MCS processing.

Acquisition System

Data were recorded with a Syntrak 480 acquisition system.

Airgun Array

We used two different source configurations: (1) a 6-gun, 1340 cu. in. (22 liter) airgun array throughout the cruise, with gun sizes ranging from 80 to 500 cu. in., and (2) a two-element GI (generator-injector) gun array, with GI guns configured at 105/105 cu.in. Guns were floated from Norwegian floats, with a nominal depth of 5 m for the 6-gun array, and either 2.5 m or 5 m (OBS only) for the GI guns. The airguns performed well throughout the cruise, with little maintenance needed, apart from occasional line tangles due to heavy seas. When functioning normal, the GI gun source is remarkably sharp and stable, with practically no bubble pulse (see Source Monitor Hydrophone section). However, through much of the cruise, a negative spike appeared on the blast phone monitor, which we believe produces a clear bubble pulse in the data (see figure below). The problem always occurred on the starboard gun.

Streamer Configuration

The full Syntron streamer consisted of 480 channels, 6000 m total of active sections, 40 active cans, and groups spaced at 12.5 m intervals. The offset of the near trace (channel #480) from the center of the gun array is 181.65 m (see setback diagram), and the offset of the far trace (channel #1) is 6169 m. Other configurations used fewer channels. Twenty-four birds (12 with compasses) were attached to the streamer. Towing depth varied from 2.5 m (when possible) to as deep as 7 m in heavy seas (4 m was the target depth during the 3D shoot).

We had many problems with streamer balance, as detailed in the recommendations section.

3D Survey Design

The design of a 3D survey is a difficult procedure in which many competing factors -- including geological targets, survey size, line spacing, temporal and spatial resolution, and survey time -- need to be balanced. We decided on the following parameters (all of which, in hindsight, have held up as sound decisions):

- The 3D box was approximately 6.5 km by 39 km in size (250 km²) and was shot (as planned) in 22 days. The location was selected to cover a combination of stable ridge crest, collapse structure, and eroding ridge flank, and to encompass several high-priority proposed drill sites. It would not have been possible to achieve all of those objectives if the box had been located over the existing Leg 164 drill sites, so we instead acquired high-quality 2D tie lines between each of the drill sites and the 3D box.
- The box was rotated from its original NE-SW orientation into a more E-W orientation, due to our observation of currents during the 2D shooting. The predominant current direction was NE-SW, which would have given us very little streamer feathering in the planned box, thus preventing us from filling cross-line bins.
- Line spacing was 75 m. This decision was based on our observation of streamer feathering during the 2D shooting, which gave us reasonable (and ultimately justified) confidence that we could fill in 12.5 m bins between the shot lines.
- 4 m streamer towing depth. A 2.5 m depth would have been preferable (to keep the source and streamer ghosts consistent), but we knew we couldn't count on the 3 weeks of solidly good weather we would have needed to keep the streamer at such a shallow depth. The 4 m depth turned out to be a good compromise between resolution, source character, and streamer stability and was a good decision.
- We used a 4-km streamer rather than the full 6-km streamer. This was a calculated risk -- although we would have preferred the full streamer (both for filling additional bins and for providing longer offsets), we were not confident that we would be able to keep the 6-km streamer stable at 4 m depth, given the greater spacing between birds. As it turned out, the 4-km streamer was just sufficient to fill in our bins at 75 m line spacing, and we were, by and large, able to tow it well at 4 m depth.

2. Data Analysis.

Detailed data analysis techniques are described in the individual published papers, which are included in the “Results and Discussion” section below. A brief description of general methods is included here for convenience.

2D Data Analysis

2D seismic images were created with to standard methods [Yilmaz, 1987], including digital filtering, common-midpoint gathering, stacking, and post-stack migration. We used the Sioseis (copyright Scripps Institution of Oceanography) and Focus (copyright Paradigm Geophysical) processing packages.

Waveform inversion was conducted on prestack data (supergathers of 6 adjacent common-midpoint gathers) using the technique of Korenaga et al. [1997], which is based on the code of Kormendi and Dietrich [1991] and Singh et al. [1994].

In Hornbach et al. [2003], detailed velocity analysis was performed using stacking velocities and the Dix equation (e.g., [Yilmaz, 1987]).

3D Data Analysis

Although 3D data analysis is not complete, principally due to several computer hardware failures, we did achieve an initial 3D stack using standard 3D processing methods and Paradigm Geophysical's Focus3D processing package.

3D data will be visualized using Paradigm's VoxelGeo package.

RESULTS AND DISCUSSION

INSIGHT I: *Migration of Methane Gas in Marine Sediments.*

Published paper: Gorman, A.R., W.S. Holbrook, M.J. Hornbach, K.L. Hackwith, D. Lizarralde, and I.A. Pecher, Migration of methane gas through the hydrate stability zone in a low-flux hydrate province, *Geology*, 30, 327–330, 2002.

Summary:

These results directly addresses the goals of Tasks 1.0, 2.0, and 3.0, particularly Subtasks 1.2, 2.2.3 and 3.2.3a. Gorman et al. (2002) showed that, even in a relatively simple geological environment such as the Blake Ridge, free gas can migrate vertically hundreds of meters through the hydrate stability zone before freezing into hydrate. The evidence for this comes from three spatially linked observations. First, disruptions in the BSR and free gas zone suggest missing gas and chimney-like migration pathways. Second, bright spots above and adjacent to the gas disruptions appear to be zones of concentrated hydrate, as evidenced by waveform inversions that show them to be thin, positive-velocity layers. Rock-physics models suggest that hydrate concentrations in the layers are as high as ~40% bulk concentration. Third, pervasive dewatering faults in the hydrate stability zone penetrate upward to an unfaulted cap of impermeable sediments. The hydrate bright spots have exactly the same vertical extent, suggesting that the faults provide the pathways for gas migration.

These results have several important implications. (1) Gas would easily escape into the ocean if the cap of impermeable sediments did not exist, or were removed. Even in a low-flux environment such as the Blake Ridge, therefore, the hydrate stability zone does not constitute a significant barrier to vertical gas migration. (2) Waveform “polarity” can be very misleading in a thin-bed reflection. The hydrate bright spots appear to the human eye to have “negative polarity,” and were interpreted shipboard as evidence for gas in the hydrate stability zone (similar to previous interpretations of the “stringer”, cf. Subtasks 1.2 and 3.2.3a). However, waveform inversion showed unequivocally that the bright reflection is the result of a thin, positive velocity anomaly. Interference of reflections from the top and bottom of a thin-bed reflector can cause a misleading appearance of a negative polarity.

Details:

Seismic Observations

Much of the Blake Ridge hydrate province is seismically characterized by relatively flat-lying strata of varying reflectivity with an easily-identifiable BSR overlying a high-amplitude gas-charged layer (Shipley et al., 1979; Holbrook et al., 1996; Dillon et al., 1998). In general, the younger and shallower strata appear undisturbed in seismic data (Figs. 2 and 3) whereas older strata are cut by small-offset normal faults. Because the ridge is not under tectonic extension (Dillon et al., 2001), these faults, which have dips between 50° and 55°, are likely the result of sediment compaction as older strata are buried by younger sediments. The uppermost, structurally undisturbed strata have greater reflectivity and are correlated to young sediments cored at Ocean Drilling

Project (ODP) Leg 164 drill sites 994, 995, and 997 (Paull et al., 1996). The base of these reflective sediments is a chronostratigraphic boundary dated at 2.25 Ma (Fig. 2). However, faulting is observed in some places to extend upward into strata just below the 0.95 Ma chronostratigraphic reflection (Fig. 2B). This simple lithology provides a clear background reflectance against which anomalous seismic observations can be readily interpreted in terms of free-gas and hydrate occurrence. In this paper we present two observations that suggest injection of gas into the HSZ.

The first example, located on line R37 ~10 km southeast of Site 997 (Figs. 1 and 2), shows vertically oriented regions of low reflectivity capped by moderately strong reflections that cannot be correlated to adjacent strata. These low-amplitude "chimneys" extend no higher than the 2.25 Ma reflection, suggesting that their occurrence is controlled by the physical properties of the normal-faulted part of the section. The BSR beneath the chimneys lies ~14 m shallower than in adjacent strata (determined by the waveform inversions discussed below; see also Fig. 3), implying an upward deflection of isotherms, probably by active fluid flow. Reflection amplitudes within the free-gas zone (FGZ) immediately underlying the chimneys are lower than in neighboring strata.

The second example, located in the newly acquired three-dimensional seismic grid (Figs. 1 and 2), shows several narrow high-amplitude reflections, or bright spots, within the HSZ that contrast strongly with neighboring low-amplitude strata. The bright spots often appear to be bounded on at least one side by normal faults and, as in the first example, extend upward only as far as the top of the faulting. The bright spots extend over an area of ~1000 m by 600 m within the survey grid, and individual events are up to 200 m in diameter. As in the first example, the BSR and the strata of the underlying FGZ are less reflective than in adjacent areas.

We propose that these observations indicate dynamic passage of free methane gas through the HSZ. Three lines of evidence support this hypothesis. (1) The observed low-amplitude "chimneys" bear a remarkable resemblance to similar features observed in high-flux regimes where methane gas is known to have migrated vertically through the HSZ (e.g., Riedel et al., 2001). (2) The bright spots and low-amplitude chimneys are vertically associated with zones of reduced amplitudes and (as will be shown in the next section) high velocities in the underlying free gas zone, strongly suggesting expulsion of methane from the FGZ into the HSZ. (3) The vertical extent of amplitude anomalies within the HSZ is limited to the faulted sediments, which suggests that gas migration occurs along preexisting faults or fractures.

Velocity Analysis

In order to examine short length-scale (2 - 4 m) vertical variations in P-wave velocity, we conducted one-dimensional full-waveform inversions on the new high-resolution (10 - 220 Hz) data. This method, which has been well established for wide-angle reflection data at the Blake Ridge (Korenaga et al., 1997; Holbrook, 2001), is based on minimizing the difference between observed seismic data and synthetic seismograms in the frequency-slowness (ω - p) domain (Kormendi and Dietrich, 1991; Minshull et al., 1994; Singh and Minshull, 1994). In order to reduce aliasing during transformation of the input data to the ω - p domain, one trace from every channel on the seismic streamer is used in an input supergather that is made up of data from six adjacent common midpoint (CMP) gathers; with a CMP spacing of 6.25 m, the resulting supergather footprint (31.25

m) is an order of magnitude less than the inversion targets. We generated a well-constrained, one-dimensional, long-wavelength starting velocity model using ray-theoretical traveltime inversion (Zelt and Smith, 1992) of prominent reflections (including the seafloor reflection and the BSR). These velocity profiles, composed of three or four homogeneous layers, were smoothed to remove first-order discontinuities at layer boundaries and to provide a slightly-positive velocity gradient corresponding to expected seafloor sediment compaction. Although these starting models (Fig. 3) are based on the average velocities of relatively thick units, their simple structure is representative of the uniform shaley lithology observed at the Blake Ridge (Paull et al., 1996). Additional considerations include: (1) selection of a source wavelet using the method of Korenaga et al. (1997) modified for the geometry of marine seismic reflection acquisition, (2) correcting for source-receiver directivity, (3) assumption of the Korenaga et al. (1997) relationships between P-wave velocity and other physical characteristics (S-wave velocity, density, P- and S-wave dispersion), and (4) selection of a frequency band of 20 – 150 Hz for the inversion; higher frequencies were avoided to reduce ringing in the inverted time-series. The remarkable agreement of the waveform inversion results in the upper 100 – 150 m of seafloor sediments, for each of the pair of inversions (Fig. 3), emphasizes the robustness of the method.

Inversions outside (Fig. 3A) and inside (Fig. 3B) the chimney (Fig. 2A) show contrasting P-wave velocity structure. The “outer” example has a high-velocity hydrate “wedge” at the BSR (Hyndman and Spence, 1992; Korenaga et al., 1997) with a maximum velocity of 2.2 km/s overlying a gas zone with velocities as low as 1.3 km/s. Using the rock-physics model of Helgerud et al. (1999) and assuming 54% porosity (Paull et al., 1996), a critical porosity of 37%, and an average of nine contacts per grain, the concentration of hydrate in the narrow layer above the BSR can be estimated to lie between bulk values of 13% (if pore-space hydrate strengthens the grain matrix) and 20% (if hydrate fills the pores without affecting the rigidity of the matrix). This range of concentrations is as high (Korenaga et al., 1997) or higher (Holbrook, 2001) than those estimated for “wedges” at other locations on Blake Ridge. The “inner” example shows a much smaller velocity contrast at the BSR, suggesting both that gas has been removed from the free-gas zone and that hydrate concentration in the “wedge” has been reduced. As would be expected, the lower 300 m of the HSZ within the chimney shows slightly less variation in velocity than outside where observed amplitudes are higher. Although this velocity response could be the result of amplitude “blanking” within the chimney, caused by the cementing of sediment pore space with hydrate (Lee et al., 1996), we prefer the explanation that rapid vertical migration of overpressured gas through these sediments resulted in the disruption of the stratal relationships that give the neighboring rock its reflective character (Wood and Gettrust, 2001). The absence of a hydrate wedge immediately above the BSR within the chimney can be explained by hydrate dissociation caused by a localized upward deflection in isotherms; the BSR is at 464 mbsf within the chimney but 478 mbsf outside the chimney (Fig. 3).

Waveform inversions through a bright spot (Fig. 3C) and an adjacent section (Fig. 3D) also show contrasting velocity structures. Reflectivity is subdued within the HSZ and FGZ in the inversion at the bright spot, similar to that seen within the chimney in the previous example. The prominent bright spot in the HSZ is caused by a 6- to 8-m-thick high-velocity layer with a peak velocity of 2.1 km/s (above a background velocity

of 1.9 km/s). Again by using the method of Helgerud et al. (1999) and assuming 60% porosity (Paull et al., 1996), a critical porosity of 37%, and an average of nine contacts per grain in the matrix, the concentration of hydrate in this layer can be estimated at 30% to 42% of the bulk volume. We conclude that this higher concentration resulted from the freezing of free gas into hydrate in a thin stratum of higher porosity adjacent to a migration pathway.

Conclusions

The vertical association of bright spots, BSR disruptions, increased seismic velocity in the HSZ and FGZ, and decreased reflectance in the FGZ clearly indicates migration of free gas from beneath the BSR upward 100s of meters into the HSZ. Gas transport into the HSZ on the Blake Ridge occurs by two mechanisms: (1) along vertical pathways resulting in a disruption of stratal geometries, and (2) along steeply dipping normal faults. In both cases, evidence for gas migration extends upward only as far as the young, unfaulted, shallow sediments. This finding suggests that gas-migration pathways – likely faults or fractures – are restricted to the deeper, faulted sediments; the overlying younger, unfaulted sediments form an impermeable barrier to gas migration. In places where the upper sediments can be penetrated, either by fracturing or alternative pathways, gas would escape into the ocean. For example, current observations of seismic data acquired at the nearby Blake Ridge Depression (Fig. 1) reveal evidence for gas escape where seafloor erosion exposes the older, faulted sediments (Holbrook et al., submitted to *Geology*). Recent seismic observations of the hydrate province on the northern Cascadia margin, off the coast of Vancouver Island (Hyndman et al., 2001; Riedel et al., 2001), show gas-escape signatures within the HSZ that in places extend right to the seafloor and are accompanied by observed methane seeps on the seafloor. There, no sedimentary cap is imaged, and faults are observed throughout the entire HSZ from the BSR to the seafloor.

The observations made here have important implications for understanding the interaction of subseafloor methane with the ocean. The passage of free gas through the HSZ has been demonstrated in "high-flux" regimes such as the Cascadia margin, but in "low-flux" regimes such as the Blake Ridge, the HSZ has been largely considered an impermeable barrier to the migration of free gas. The new high-resolution seismic data show that the BSR is commonly disrupted by gas injection into the HSZ. This observation implies that methane gas can be transported upward through the HSZ to a level limited only by the availability of permeable pathways. Models of hydrate and hydrosphere interaction must include mechanisms for directly tapping mobile free gas beneath the hydrate stability zone, regardless of the location of the hydrate province.

Figure Captions

Figure I-1. (a) Location of Blake Ridge extending approximately 400 km to the southeast of the continental margin of the USA. The white region delimits the approximate area of hydrate deposits. Bathymetric contour interval: 500 m. (b) Hydrosweep image of the seafloor bathymetry illuminated from the northeast. Locations of the 2-D lines (black) and the 3-D grid (outlined in white) acquired in 2000 and located within the map area are shown. ODP drill sites (white circles) are indicated. Locations of data examples used in this paper are annotated in black on line R37 and in the southwestern corner of the 3-D grid.

Figure I-2. Migrated seismic line R37. Low amplitude columns, capped by distinct reflections, disrupt otherwise continuous strata within the lower part of the hydrate stability zone. Character of underlying bottom simulating reflector (BSR) is disrupted. Amplitude of gas-charged strata beneath BSR is reduced. Locations of 1-D waveform inversions shown in Fig. 4 are indicated by labeled triangles. The seafloor reflection and BSR are annotated with black triangles. Chronostratigraphic boundaries that are age-correlated by core samples from Ocean Drilling Project Leg 164 (see text) are denoted by gray triangles. Vertical exaggeration ~8:1.

Figure I-3. Migrated seismic line 3D-03. Bright spots, associated with normal faulting, step up through the lower part of the hydrate stability zone. Seismic characters of underlying bottom simulating reflector (BSR) and gas charged strata are disrupted. Locations of 1-D waveform inversions shown in Fig. 5 are indicated by labeled triangles. The seafloor reflection and BSR are annotated with black triangles. Chronostratigraphic boundaries that are age-correlated by core samples from Ocean Drilling Project Leg 164 (see text) are denoted by gray triangles. Vertical exaggeration ~8:1.

Figure I-4. Waveform inversion results for line R37. (a) Supergather A (CMP gathers 31650 to 31655, location as shown in Fig. 2.) The tau-p transformed synthetic seismogram (thinner lines) is an almost perfect fit for the tau-p transform of the data in Fig. 2 (thicker lines). The enlargement of the response from the hydrate stability zone (HSZ) and BSR for a short range of slownesses shows excellent fit between real and synthetic data. The resultant velocity profile shows strata with highly variable velocities in the upper 200 m of overlying strata with weakly varying velocities in the lower part of the HSZ. A concentrated hydrate lens is interpreted at the base of the HSZ overlying a strongly charged gas layer. The starting model (gray), from which short wavelength variations were determined by the waveform inversion, underlies the resulting velocity profile (black). (b) Velocity profile (black) for Supergather B (CMP gathers 31540 to 31545, location as shown in Fig. 2.) Starting model shown in gray. The section above the BSR is similar to (a); however, the lower portion of the HSZ has less velocity variation. The response of the hydrate wedge and free gas layers are almost eliminated.

Figure I-5. Waveform inversion results (black lines) for line 3D-03. Starting models shown in gray. (a) Velocity profile from supergather C (CMP gathers 387250 to 387255, location as shown in Fig. 3) within bright spot field. Zone of concentrated hydrate at ~2.95 km. (b) Velocity profile from supergather D (CMP gathers 387180 TO 387185, location as shown in Fig. 3) external to bright spot field.

Figure I-1.

Figure I-2.

Figure I-3.

Figure I-4.

(a) Bright spot
location

(b) No bright
spot

Figure I-5.

INSIGHT II: *Direct Seismic Detection of Methane Hydrate.*

Published papers:

Holbrook, W.S., A.R. Gorman, M.J. Hornbach, K.L. Hackwith, J.W. Nealon, D. Lizarralde, and I.A. Pecher, Seismic detection of marine methane hydrate, *The Leading Edge*, 21, 686–689, 2002.

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

These results directly address the goals of Task 2.0, particularly Subtask 2.2.2.

Summary:

Holbrook et al. (2002) and Hornbach et al. (2003) showed that, under certain circumstances, seismic reflection data can directly detect hydrate in the hydrate stability zone (well above the BSR). Our data show three types of evidence for direct detection of hydrate: (1) unequivocal evidence for amplitude blanking above the BSR on the eroding flank of the Blake Ridge, (2) seismic bright spots in the hydrate stability zone, spatially associated with disruptions in the BSR, that we interpret as layers of concentrated hydrate, and (3) a paleo-BSR above the present-day BSR formed by erosion and downward migration of the hydrate/gas phase boundary. The zone of amplitude blanking on the Blake Ridge has anomalously high P-wave velocities, supporting the idea of enhanced hydrate concentrations (~13% bulk hydrate). This work shows the importance of using multiple criteria (e.g., amplitude blanking and elevated P-velocities) to directly detect hydrate with seismic methods.

Details:

Seismic lines R22 and 3D-03 both show evidence of direct seismic detection of methane hydrate. Data from the eastern portion of line R22 reveal the subsurface structure of the eroding eastern flank of the Blake Ridge (Figures 1,2). The BSR, a reflector crosscutting strata between 4.6 and 4.7 s two-way traveltimes, is bright on the western half of the section, but fades to the east, implying less gas accumulation. Scattered, deeper bright spots beneath the BSR and on the eastern half of the section represent other gas pockets. The strata below 4.4 s are relatively continuous with a maximum apparent western dip of 3.2°; the highly reflective, younger strata above an unconformity near 4.3s represent partially eroded sediment waves. A strong reflection crosscutting dipping strata within the GHSZ just above 4.6 s, extends from CMP ~28920 to ~29180--roughly 1.6 km (Figure 3). This unusual reflection overlies a zone of reduced reflectance that is bounded at its base by the present day BSR.

We believe the reflection at 4.6 s represents a paleo-BSR that formed when erosion of the eastern flank of the Blake Ridge resulted in the lowering of the hydrate/free-gas phase boundary. Significantly high concentrations of gas then crystalized into hydrate within a discrete, concentrated layer (figure 4). Because hydrate has nearly twice the P-wave velocity of the strata on the Blake Ridge, sediments with

high concentrations of hydrate can create strong impedance contrasts. If, therefore, sediment is eroded off the seafloor at a location that exhibits a strong BSR, the gas just beneath that BSR can crystalize into hydrate and produce a strong seismic reflection that will continue to crosscut strata (Figure 4). Furthermore, we believe that the reduced amplitude region found between the paleo-BSR and the BSR consists of sediments that contain high concentrations of hydrate. This low amplitude region is defined as “the lens” throughout the rest of the paper.

Line 3D-03 reveals isolated irregular strong reflections within the GHSZ found at 3.8-3.9 s from shot 64539 to 64559 (Figure 5), which we define as “bright spots” throughout the rest of the text. The BSR, which is strong and continuous elsewhere, is disrupted directly below and to the west of the bright spots, suggesting upward gas migration from the BSR into the hydrate stability zone. Disrupted low-amplitude strata immediately below the bright spots are interpreted as faulted channels for fluid migration (Gorman et al., 2002).

Velocity Analysis and Results

Because methane hydrate has a P-wave velocity of 3.3 km/s (Sloan, 1990) and strata on the Blake Ridge have velocities between 1.5-1.8 km/s (Holbrook et al., 1996), one way to verify and quantify methane hydrate within the lens of reduced reflectance and bright spots is to determine whether these strata have anomalously high interval velocities. We used the Dix equation to determine the interval velocity of the lens. Recognizing that interval velocities calculated from the Dix equation are highly sensitive to small errors in semblance picks, we chose a statistical approach in which many CMP gathers were analyzed in the three regions of interest and interval velocities were tabulated in histograms. We created 450 CMP gathers of line R22 and from these produced 150 semblance plots within the lens (CMPs 28950-29100) as well as 150 semblance plots both to the west (CMPs 29200-29350) and east (CMPs 28700-28850) of the lens. On each CMP gather, we picked RMS velocities at intervals of 0.1 s, from the seafloor to 0.6 second below. This approach enables comparison of velocities in intervals of consistent thickness and at common sub-seafloor depths. The lens lies between 0.4 and 0.5 s below the sea-floor. If no clear peak semblance existed at a 0.1 s interval, picks were interpolated between coherent semblance values above and below the pick. For example, CMP 29000 (Figure 6) shows numerous clear reflections and semblance peaks, including the seafloor (4.19 s), the paleo-BSR (4.58 s), and the BSR (~4.68 s); stacking velocity picks were made at regular 0.1 s intervals. Interval velocities were then calculated from RMS velocities using the Dix equation,

$$V_{int}^2 = (V_n^2 t_n - V_{n-1}^2 t_{n-1}) / (t_n - t_{n-1})$$

where V_{int} is the interval velocity from pick $n - 1$ to n , V_n is the RMS velocity at pick n , and t_n is the two-way traveltimes at pick n . For our example of CMP 29000 (Figure 6), interval velocity increases from 1770 m/s between 0.3-0.4 s to 1892 m/s in the lens, between 0.4-0.5 s. To determine velocities of the bright spots: Gorman et al. (2002) used traveltimes inversion (Zelt and Smith, 1992) followed by amplitude waveform inversion (Singh et al., 1993; Korenaga et al., 1997).

Interval velocities immediately beneath the paleo-BSR (0.4-0.5 s subbottom, Figure 1) exhibit an anomalously high mean value of 1910 m/s compared to interval velocities at adjacent locations outside the lens, which average 1819 m/s to the east and 1849 m/s to the west (Tables 1(a). and 1(b). Figures 7(d), 7(e), and 7(f)). The mean interval velocities at 0.3-0.4 s sub-bottom depth, however, are nearly identical to each other, at approximately 1790 m/s (Figures 7(a), 7(b), and 7(c)). The lowest mean interval velocity at both 0.3-0.4 s and 0.4-0.5 s is found in the oldest sediment to the east of the lens, where no BSR exists. Velocities outside the lens agree with results from vertical seismic profiles obtained during ODP leg 164, which showed velocities ranging from 1750-1850 m/s for times between 0.3-0.5 s (Holbrook et al., 1996).

To first order, velocity histograms of line R22 resemble normal distributions, so that Gaussian statistics can be used to derive velocity error. Within one standard deviation, the mean interval velocity of the lens from 0.4-0.5 s does not overlap with velocities outside the lens. Velocities at 0.3-0.4 s, in contrast, are statistically identical, with nearly complete overlap at one standard deviation (Table). Close inspection reveals a bimodal character for the velocity histograms within and west of the lens, resulting in a higher mean than mode velocity west of the lens and a lower mean than mode velocity within the lens. Stratigraphic dip fails to explain the anomalously high velocities within the lens, since the strata dip no more than 3.2° , resulting in less than a 0.2% increase in velocity (Table 1a, 1b) (e.g., Yilmaz, 1987). Moreover, stratigraphic dips are similar within and east of the lens. As a final validity test for our statistically derived velocities, we determined the interval velocity in the lens using a 2-D tomographic inversion code (Zelt and Smith, 1992). Velocities are 1790 m/s above the paleo-BSR and 1920 m/s between the paleo-BSR and BSR, consistent with our statistically derived Dix equation average velocity values in Figures 7(b) and 7(e) (Figure 8). We therefore conclude that our calculated velocities are accurate.

Amplitude waveform inversion results of Gorman et al. (2002) based on the method of Korenaga and Holbrook (1997) show that the bright spot imaged within the hydrate stability zone on line 3D-03 is caused by a thin high-velocity layer (Figure 5). The bright spot yields a P-wave-velocity of ~ 2100 m/s — 14% faster than the velocity of the overlying strata (~ 1800 m/s).

Hydrate Concentration in Lens

We conclude that the high interval velocities within the lens indicate the presence of methane hydrate. Vertical seismic profiles (VSPs) conducted at the Blake Ridge reveal that sediments 0.4-0.5 s below the seafloor have a velocity of 1750-1800 m/s when only 1% bulk hydrate exists in strata, significantly lower than 1910 m/s observed in the lens (Wood and Ruppel, 2000; Holbrook et al., 1996). Three possible explanations exist for the anomalously high interval velocities in the lens. Sediments in the lens may (1) have a different lithology than adjacent sediment, (2) be older and thus better lithified, or (3) contain higher concentrations of methane hydrate. We can rule out the first two explanations by recognizing that the strata are continuous throughout the area of interest, that velocities in the 0.3-0.4 s interval are constant across all three regions, and that the oldest sediments are east of the lens, where interval velocities are *lowest*. The higher velocities correspond to the lens and the region west of the lens, where a strong BSR

exists. We therefore conclude that methane hydrate is responsible for both the paleo-BSR and the high interval velocity in the lens.

The bimodal velocity distribution displayed in Figures 7(d) and 7(e) may be a result of methane hydrate distribution directly above the BSR. Though the paleo-BSR ends clearly around CMP 28920 to the east, it is unclear exactly how far the paleo-BSR extends westward, because strata there are parallel to the paleo-BSR. We speculate that the higher velocities creating the bimodal peak at roughly 1885 m/s in Figure 7(d) result from remnants of the methane hydrate lens existing just above the BSR in this region.

We can estimate the total amount of methane within the lens by determining its volume and average hydrate concentration. Regional and 3D seismic lines show that the lens occupies an area roughly 1.9×11 km and has an approximate thickness of 95 m. The total volume of the lens is therefore ~ 2 km³. Using the rock physics models of Helgerud et al. (1999), we can obtain end-member estimates for the concentration of hydrate in the lens. Maximum hydrate concentration estimates assume that hydrate fills pore space without affecting the elasticity of the sediment frame; minimum estimates assume hydrate cements grains, strengthening the sediment matrix. Assuming the average number of contacts per grain is 9, a critical porosity of 37%, and using porosity values obtained from ODP drill site 997, the bulk hydrate concentration within the lens region falls between 13 and 22% (Figure 9; Helgerud et al., 1999). Taking the conservative estimate of 13% hydrate and recognizing that 123 kg of methane exist per m³ of pure methane hydrate (Mathews and von Huene, 1985), then the 2 km³ lens contains 3.2×10^{10} kg, or 1.5 TCF (4.2×10^{10} m³) of methane. If, as suggested by Lee and Collett (2001) hydrate acts as a pore-filling substance, the resulting estimate of 22% bulk hydrate yields 2.5 TCF (7.2×10^{10} m³) of methane in the lens.

Hydrate Concentration in Bright Spots

The bright spots located in the methane hydrate stability zone are also the result of concentrated hydrate. Methane gas is not only unstable at the depth where the bright spots exist, but would create a low-velocity anomaly--not the ~ 2100 m/s high velocity peak we observe. Assuming 60% porosity (Paull et al., 1996), a critical porosity of 37%, and an average number of contacts per grain of 9, Helgerud et al. (1999) end-member estimates range from 30 to 42% bulk hydrate (50 to 70% of the pore space) within the bright spots. The hydrate bright spots likely contain 2-3 times the concentration of hydrate predicted in the lens.

Hydrate and Reflectance

The hydrate bright spots and lens show that hydrate can either enhance or suppress seismic reflectance depending on hydrate concentration. Both of these effects are modeled by Lee and Dillon (2001), who demonstrate that low concentrations of hydrate ($\sim < 20\%$ bulk) may produce amplitude blanking, while significantly higher concentrations of hydrate ($\sim > 35\%$ bulk) produce amplitude enhancement. Since subsurface impedance contrasts produce seismic reflections, the basic principle of amplitude blanking is that cementation of several sedimentary layers with high-velocity hydrate effectively reduces the impedance contrast of the sediments, thereby reducing the reflectance of these layers. Blanking theory predicts that hydrate causes decreased reflectivity if impedance contrasts are principally due to changes in porosity and hydrate

preferentially forms in high-porosity layers (Lee and Dillon, 2001, Dillon et al., 1993). Unfortunately, low reflectance is a non-unique indicator of increased methane hydrate concentration, since other factors, including homogenous lithology and sediment compaction can also suppress reflectance (Lee et al., 1996; Holbrook, 2001). Amplitude blanking has been frequently inferred by comparing the reflectivity of *different* strata, or more commonly, of strata above and below the BSR (e.g., Shipley et al., 1979; Lee and Dillon, 2001), which introduces the problem that the proposed “blanking” could also result from differences in lithology or simply gas-charged bright spots. The hydrate lens offers an ideal situation to study the blanking hypothesis because strata pass continuously from inside the lens, where reflectance is weak, to outside the lens, where reflectance is strong. Low reflectance can therefore be attributed to an increase in hydrate concentration, not variations in lithology. Strata passing through the lens exhibit a 40% reduction in amplitude (Figure 3). Though amplitude reduction in the lens shows that hydrate may legitimately instigate blanking, it remains difficult to use blanking as a means of quantifying methane hydrate concentrations because precise knowledge of sediment porosity is required (Lee and Dillon, 2001). We therefore conclude that blanking can be qualitatively used to determine where increased hydrate concentrations exist in specific cases where lateral contrasts in reflection amplitude occur above the BSR in sediments of the same lithology.

If hydrate concentration is great enough within a single sedimentary layer, however, it can also create bright spots. Our results reveal that bulk hydrate concentrations from 30-42% create hydrate bright spots on the Blake Ridge (Figure 5). Because hydrate has nearly the same density as water but twice the P-velocity, a major increase in hydrate concentration should result in a major velocity contrast with non-hydrate filled sediments, resulting in a strong reflection. Both our results and the model of Lee and Dillon (2001) imply that hydrate concentrations are much higher in bright spots than blanked regions, and hydrate concentration calculations suggest bright spots in the methane hydrate stability zone represent regions of the highest hydrate concentrations on the Blake Ridge.

Conclusions

Our results show methane hydrate can be directly detected in at least three ways: paleo-BSRs, highly reflective bright spots, and low-amplitude "blanked" strata. These observations provide important indicators of places where efforts to quantify hydrate deposits should be focused. Amplitude blanking may be useful as a method of detecting methane hydrate in *limited* cases where lateral contrasts in reflection amplitude occur above the BSR in sediments of the same lithology. The large number of variables affecting reflection amplitude between two different strata makes it difficult to use blanking as a means of accurately quantifying hydrate. Quantification of hydrate concentrations, therefore, is best performed through detailed velocity analysis and comparison to rock physics models. Velocity analysis reveals that the hydrate bright spot contains higher hydrate concentrations (30-42% bulk hydrate) than the blanked lens region (13-23% bulk hydrate). End member estimates of methane trapped within the lens fall between 1.5 and 2.5 TCF ($4.2\text{-}7.2 \times 10^{10} \text{ m}^3$). Ongoing research that emphasizes 3-D imaging and interpretation of the lens will offer even more accurate estimates of methane hydrate quantities on the Blake Ridge in the future.

Figure Captions

Table1. Mean velocities of the histograms before and after dip correction for (a) an interval between 0.3-0.4 s and (b) an interval between 0.4-0.5 s below the seafloor. We shot our data from east to west and the reflectors dip to the west; thus, the calculated interval velocity values for this region are actually slightly lower than the raw values.

Figure II-1. Stacked seismic reflection data of line R22 migrated with constant water velocity reveals a paleo-BSR just above 4.6 s between CMPs 29160 and 28920. The bright reflector cross-cutting strata between 4.6 and 4.7 s is the BSR. A region of low amplitude reflectance exists directly below the paleo-BSR and current BSR. Vertical exaggeration is approximately 3:1. The three regions marked by horizontal lines above and below show where interval velocities were calculated from 0.4-.05 s below the seafloor.

Figure II-2. Bathymetric location map of the Blake Ridge study area produced from hydrosweep data obtained during the 2000 cruise. The two thick solid lines represent R22 and R32--the two seismic lines discussed in this paper. A small section of line R22 extending from $\sim 75^{\circ} 24'$ to $75^{\circ} 18'$ longitude is shown in figure 1. The dashed arrows indicate the flow direction of the Western Boundary Undercurrent. White annotated circles denote Leg 164 drill sites. The thin gray box at the intersection of R22 and R32 shows the approximate extent of the lens.

Figure II-3. A true-amplitude variable-area wiggle trace enlargement of the lens. The amplitudes of strata passing into the lens decrease by an average of 40%. The paleo-BSR crosscuts strata at ~ 4.58 s; the BSR, located in the bottom left-hand corner, is the highest amplitude feature in the figure. Note the presence of other, weaker, paleo-BSRs running nearly horizontal between ~ 4.58 and ~ 4.65 s within the lens. Since our air guns produced virtually no bubble pulse, we believe these events are real, and therefore reveal how the gas at the BSR continuously crystalized into hydrate as the eastern flank of the ridge eroded.

Figure II-4. Cartoons showing how a paleo-BSR consisting of hydrate might form. (a) Initial situation: the white reflector cross-cutting strata represents the BSR. The lighter areas represent regions of high gas concentrations. Above the BSR methane hydrate is stable and no methane gas exists. (b) After erosion occurs on the ridge, the thermal gradient equilibrates, forcing the BSR downward. The region where the BSR used to exist has cooled, resulting in the formation of methane hydrate from free gas and water. The

localized high concentration of methane hydrate at the former BSR creates a high velocity hydrate lens that cross-cuts strata.

Figure II-5. A small section of Line 3D-03 which has been migrated with a constant velocity of 1.5 km/s (left panel). Results of an amplitude waveform inversion (right panel) performed at shot 64543 (location denoted by the triangle above the section) by Gorman et al. (2002) based on the method used by Korenaga and Holbrook (1997) reveal a high velocity spike at the bright spot location due to increased hydrate concentration and a 500 m/s drop in velocity at a depth where the BSR exists due to gas accumulation. The low velocity of ~1400 m/s at the seafloor, is not an artifact, but a value frequently observed across the Blake Ridge, using several different velocity analysis techniques.

Figure II-6. This figure gives an example of how we obtained interval velocities for our CMPs. Left panel: normal-moveout-corrected CMP gather 29000, which contains the hydrate lens and BSR. Center panel: semblance plot of CMP 29000. The crosses mark the location of each 0.1 pick, starting at the seafloor. Right panel: interval velocities for these picks.

Figure II-7. Histograms of interval velocities from .3 to .4 s and from .4 to .5 s beneath the seafloor for the lens, (b) and (e), and strata to the west, (a) and (d), and east, (c) and (f). Velocities are binned in 5m/s intervals. The dashed line on the left represents the average velocity found at 0.3 –0.4 s just above the lens [i.e., the average velocity of values in (b)],

and the dashed line on the right represents the average velocity found at 0.4 – 0.5 s sub-bottom within the lens [i.e., the average velocity of values in Fig. (e)].

Figure II-8. A 2D ray theoretical travel-time inversion model (Zelt and Smith, 1992) of CMP 29075 which passes through the middle of the lens: velocities are similar to the average velocities found using statistical methods shown in Figure 7(b) and 7(e).

Figure II-9. Hydrate predictions for strata below and above the paleo-BSR based on the model by Helgerud et al. (1999) assuming (a) hydrate only fills the pore space and fails to effect sediment matrix elasticity and (b) hydrate becomes part of the sedimentary matrix. The gray lines indicate the velocity we should see for a given hydrate concentration of 5%, 15%, and 25%. The fluctuations in gray lines are due to variations in porosity with depth (taken from ODP leg 164 Site 997 results).

Table 1.a	.3 to .4 s Raw Int. Vel. (m/s)	.3 to .4 s Dip Corrected Int. Vel. (m/s)	Std (m/s)
West of Lens	1798	1797	-29
Lens	1787	1785	-37
East of Lens	1780	1778	-40
Table 1.b	.4 to .5 s Raw Int. Vel. (m/s)	.4 to .5 s Dip Corrected Int. Vel. (m/s)	Std (m/s)
West of Lens	1850	1849	-26
Lens	1911	1910	-33
East of Lens	1821	1819	-37

Figure II-1.

Figure II-2.

Wiggle Trace True Amplitude Display of the Lens

Figure II-3.

Figure 4a.

Figure 4b.

Figure II-4.

Figure II-5.

Figure II-6

Histogram of interval velocities
from .3 to .4 seconds depth:

Histogram of interval velocities
from .4 to .5 seconds depth:

Figure II-7.

Figure II-8.

Figure II-9.

INSIGHT III: *Mechanical and Geological Controls on Escape of Methane Gas.*

Published papers:

Holbrook, W.S., D. Lizarralde, I.A. Pecher, A.R. Gorman, K.L. Hackwith, M. Hornbach, and D. Saffer, Methane gas escape through sediment waves in a large methane hydrate province, *Geology*, 30, 467–470, 2002.

Hornbach, M.J., D.M. Saffer, and W.S. Holbrook, Critically pressured free gas reservoirs below gas hydrate provinces, *Nature* (*in press, to appear Jan. 8, 2004*), 2004.

Summary:

These papers directly address the goals of Task 2.0, particularly Subtask 2.2.3. Holbrook et al. (2002) presented a new (and now widely accepted) interpretation of the “collapse” feature on the Blake Ridge, which had been proposed on the basis of single-channel seismic data as a site of massive seafloor failure and consequent escape of gas into the ocean/atmosphere system [Dillon, 1994; Dillon and Drury, 1996]. Our new, higher-resolution multichannel seismic data showed that the Blake Ridge “collapse” (which we renamed the Blake Ridge Depression, or BRD) is actually a sedimentary, rather than a structural, feature: the BRD is a large sediment wave field. Scarps previously interpreted as fault scarps are actually erosional scarps, as evidenced by the lack of structural disruptions extending into the sub-seafloor, and the extremely low dips (2-5°) of the scarps.

However, our data supported the ideas of Dillon and co-workers that significant quantities of free gas (~0.6 Gt) are missing from beneath the BRD. The re-interpretation of the origin of the BRD therefore required a new model for gas escape. By examining the relationships between faults and erosional scarps, and by using a simple hydrological model, we showed that gas could escape from the BRD when seafloor erosion removed the veneer of impermeable sediments, thereby unearthing faults that connected the free gas zone to the seafloor. These results thus imply that the role of the free gas zone may be more important than previously realized in effecting interactions of the hydrate/gas system with the oceans and atmosphere.

Hornbach et al. further explored the implications of Holbrook et al. [2002b] and Gorman et al. [2002] for the role of the free gas zone in transferring methane from the hydrate/gas system to the oceans during climate change events. We developed a model, based on Mohr-Coulomb failure theory, for the maximum thickness of the free gas zone in basin settings where the maximum principal stress is vertical. Failure theory predicts that the thickness of the free gas (assuming a continuously interconnected gas column) cannot exceed the strength of the overlying sediments, or hydrofracture or fault reactivation will occur, thus allowing gas migration. The resulting “critical thickness” of the free gas zone is therefore a function of hydrate stability zone thickness – i.e., water depth. This model passes a critical test when applied to a global compilation of free gas zone thicknesses, which tend to follow, and do not exceed, the predicted maximum thickness. This model has two important implications. First, it allows the first estimation of the size of the global free gas reservoir. This has been elusive, because the base of the free gas zone, unlike the base of hydrate stability, is not a chemical phase boundary

describable by simple P-T relationships. Second, the model provides a simple physical mechanism for the escape of large amounts (~2000 Gt) of methane during bottom-water warming events, such as the late Paleocene thermal maximum: thinning of the hydrate stability zone results in a super-critical free gas zone thickness, which thus causes hydrofracture and/or fault reactivation, thus providing pathways for upward migration of free gas into the oceans and, ultimately, the atmosphere.

Details:

Recent studies [Gorman *et al.*, 2002; Tryon *et al.*, 2002] demonstrate that free gas migration may occur at hydrate provinces via gas chimneys and along faults. Though fault slip can occur in sediment basins without gas overpressures, here we calculate the amount of free gas below the BSR necessary to instigate fault slip in the overlying hydrate-bearing sediments, which would briefly increase fault permeability, allowing gas to migrate out of the FGZ (Fig. 1). We first evaluate this scenario for the Blake Ridge, a sediment drift deposit located 300 km east of South Carolina, using constraints on FGZ thickness from sonic well logs. We then calculate the thickness of the free gas zone required for fault reactivation in ocean basins, as a function of BSR depth and sediment properties, and compare our results with measured gas column heights below BSRs worldwide. Though our model does not predict free gas zone thickness for hydrate provinces in tectonic settings where σ_1 is not vertical, we compare measured free gas zone thickness below passive basin regions and active tectonic regions, and note a systematic difference in free-gas thickness below the two populations. We use this information to estimate the global inventory of free gas below hydrate provinces.

We calculate the gas column height required for fault slip in marine basin settings. For passive basin settings we assume that $\sigma_1 = \sigma_v$ (vertical), and $\sigma_3 = \sigma_h$ (horizontal), as indicated by (1) low seafloor slopes and (2) conjugate faults dipping ~60° found throughout passive basin settings. The failure criterion is:

$$P_{\text{gas}} = (\sigma_v + \sigma_h)/2 + (\sigma_v - \sigma_h)/2 * (1 + \cos 2\theta - \sin 2\theta/\mu) + C/\mu - P_w$$

where P_{gas} is the gas pressure necessary for fault slip, σ_h is the least principle stress, P_w is water pressure, σ_v is overburden stress; θ is the fault dip angle, C is the sediment cohesive strength (assumed equal to zero for pre-existing faults), and μ is the coefficient of sliding friction on faults. We determined $\theta = 59^\circ$ for the Blake Ridge by measuring the dips of 150 normal faults from seismic data and calculated μ by: $\mu = \tan(90 - 2\theta) = 0.53$. We use a poroelastic formulation for the least principle (horizontal) stress, which accounts for changes in horizontal stresses due to both the Poisson's effect and pore pressure increase in a laterally confined basin [Engelder and Fischer, 1994]:

$$\sigma_v = \int_0^z \rho_s(z) * g * dz$$

$$\sigma_h = \sigma_v / (1 - \mu) * \sigma_v + \mu * (1 - 2\mu) / (1 - \mu) * (P_w + P_{\text{gas}})$$

where $\rho_s(z)$ is sediment bulk density; g is gravitational acceleration, ν is the Poisson's ratio of sediments at the BSR, β is the Biot coefficient of effective stress, and z is thickness of sediment above the BSR [Helgerud *et al.*, 1999]. In calculating overburden stress, we assume porosity decreases linearly with depth [Guerin *et al.*, 1999; Hamilton, 1979]. For calculations of critical gas pressure as a function of water (and BSR) depth, we allow β to vary from 0.41-0.45, in accordance with measured values for sediments at the Blake Ridge based on drilling results [Guerin *et al.*, 1999; Miller, 1996], and with typical values for marine sediments [Hamilton, 1979]. We allow ν , which we calculate directly from Blake Ridge sediment core analysis, to vary from 0.67-0.77—corresponding to 25% - 0% bulk hydrate in sediment, respectively [Helgerud *et al.*, 1999]. Values of β_h calculated using these parameters, and assuming no gas or water phase overpressures, correspond to a β_h/β_v ratio of ~ 0.75 . To calculate the FGZ height necessary to trigger brittle failure, we assume that all gas is methane and account for failure of the ideal gas law at high pressures by calculating the compressibility factor necessary for non-ideal compression of methane gas [Mattar and Brar, 1975].

Our results reveal that a critical gas column thickness exists below the Blake Ridge, suggesting that faults at the crest of the Blake Ridge are poised at the mechanical limit of failure (Fig. 2). Our model predicts that fault reactivation will occur when gas column thickness below the BSR exceeds 150-290 m for $\beta = 0.41\text{--}0.45$ —a range of Poisson ratio values consistent with those measured at the BSR on the Blake Ridge [Guerin *et al.*, 1999; Miller, 1996]. VSPs and well logs from two drill sites on the Blake Ridge, ODP sites 995 and 997, show that gas creates a 200- to 250-m-thick low velocity zone below the BSR [Holbrook *et al.*, 1996]. As long as this gas below the BSR forms an interconnected network, then the faults that intersect the BSR on the Blake Ridge are poised for reactivation. Changes in external conditions, such as pressure and temperature, therefore have the potential to release methane gas from beneath the BSR into the hydrate stability zone, and perhaps into the oceans and atmosphere.

To test the hypothesis that FGZ thickness is mechanically regulated globally, we calculate critical FGZ thickness as a function of BSR depth and compare our results to nine hydrate provinces where conjugate normal faults indicate a near vertical β_1 , and where the FGZ thickness is well constrained by seismic analysis or drilling (Fig. 3). Of these, seven have FGZ thickness at or near the critical value. Critical gas column thickness increases as a function of BSR (and hence water) depth, because overburden and β_h are correspondingly larger. This result implies that a free gas “wedge” of increasing thickness with BSR depth may occur in hydrate basins that are not limited by organic-poor sediments (where methane is less likely to form) (Fig. 3).

Observed gas columns thicken as BSR depths increase, as would be expected for a mechanical seal. No observed gas column thickness significantly exceeds the calculated critical value. These observations imply a mechanically regulated upper limit on FGZ thickness and support the idea that gas below hydrate basins forms an interconnected network, because vertically isolated gas pockets could occupy a zone much thicker than our predicted upper limit. We conclude for hydrates in passive basin settings that (1) the observed increase in gas column thickness as a function of BSR depth is consistent with a mechanically regulated FGZ thickness; (2) although available data are limited, critical gas columns required for mechanical failure appear common; and (3) a reservoir of

potentially mobile methane that is sensitive to changes in environmental conditions exists below the BSR.

A systematic difference in gas column thickness exists between hydrate provinces in basin settings where σ_1 is near-vertical (Fig. 3, blue points) and compressional settings where σ_1 is presumably near-horizontal (Fig. 3, red points). Unlike FGZs in basin hydrate provinces—which increase in thickness with BSR depth—FGZs in compressional settings are generally thinner and more constant in thickness, averaging ~35m thick, and typically not exceeding 50m regardless of BSR depth (Fig. 3, red points only) [Bangs *et al.*, 1993; Hovland *et al.*, 1997; Hyndman *et al.*, 2001; Minshull and White, 1989; Minshull *et al.*, 1994; Pecher *et al.*, 1996; Tinivella *et al.*, 1998]. One possible explanation for thin free-gas zones in active tectonic settings is that they are often characterized by water phase overpressures, even at shallow depths, which reduce the gas column height required to initiate slip [Karig, 1993].

The concept of a mechanical upper limit on FGZ thickness allows, for the first time, calculation of the global potential volume of free methane gas beneath hydrate provinces. Following Dickens' [Dickens, 2001] model for global hydrate volume calculation, we calculate the maximum FGZ thickness along a typical continental margin (Fig. 3 inset). To estimate an upper limit on volume of the global free gas reservoir below marine hydrate provinces we assume (1) that passive margins comprise 50% of all margins, (2) 30% of all passive margins have critical gas columns [Milkov, accepted], (3) sediment porosity averages 50%, (4) gas fills 4% of the underlying pore space [Hovland *et al.*, 1997; Pecher *et al.*, 1996], and (5) gas column height on active margins averages 35 m, as indicated by existing data. These assumptions yield a maximum total free gas inventory of ~1550 Gt, or ~1/6 to ~2/3 of the total methane trapped in hydrate, depending on which global estimate of hydrate volume is used [Kvenvolden, 1993; Milkov, accepted]. A reasonable lower limit of the global free gas inventory is ~130 Gt, assuming that only 10% of all passive margins have critical gas columns [Milkov, accepted] and that free gas fills only 1% of the pore space [Bangs *et al.*, 1993; Holbrook *et al.*, 1996]. Our best estimate of the mass of the global free gas reservoir in hydrate provinces, calculated assuming critical gas columns on 20% of passive margins and assuming 2% free gas saturation, is ~840 Gt.

Our model offers a simple physical mechanism to explain methane gas escape during bottom-water warming events, such as the Late-Paleocene Thermal Maximum (LPTM). Dickens [Dickens, 2001] demonstrates that a 5° C bottom water temperature increase results in the dissociation of ~2000 Gt of methane from hydrate—the amount necessary to explain the observed -3‰ $\delta^{13}\text{C}$ excursion during the LPTM. This model, however, assumes that the majority of the methane that escapes during the warming event comes from dissociation of the hydrate wedge—a narrow area on the continental slope where hydrates from the seafloor to the BSR would dissociate completely during the warming event (Fig. 3. inset). For the “hydrate wedge” to supply the methane necessary to drive the $\delta^{13}\text{C}$ excursion, hydrate would have to fill, on average, $\geq 15\%$ of the pore space—a value considered unreasonably high [Dickens, 2001; Holbrook *et al.*, 1996]. This suggests that significant quantities of dissociated free gas trapped below hydrate provinces must also escape to cause the LPTM $\delta^{13}\text{C}$ excursion [Dickens, 2001].

Using Dickens' [Dickens, 2001] model of BSR depths for bottom water temperatures of 0° and 5° C, we calculate the amount of free gas produced by hydrate

dissociation that must escape the free gas zone to keep gas pressures from exceeding critical values. The minimum amount of methane gas that must escape, calculated using our minimum free gas estimate and assuming that hydrate fills only 2% of sediment pore space above the BSR [Holbrook *et al.*, 1996]; is 250 Gt. An upper limit on gas escape, calculated using our maximum free gas estimate above and assuming that hydrate fills 10% of the sediment pore space [Pecher *et al.*, 1996], is 3800 Gt. The large difference between these estimates is due to the strong concentration of methane in hydrate. Our best estimate is that a 5° C bottom water temperature increase causes ~2000 Gt of methane gas to escape from the hydrate wedge and free gas zone into the hydrate stability zone, and perhaps the oceans and atmosphere, to keep gas column thickness just below critical (fig. 3 inset). This estimate is conservative, in that it does not include the possibility that gas overpressures could trigger submarine landslides, which would prompt complete gas evacuation [Paull *et al.*, 1996].

Figure Captions:

Fig III-1. Cross-section cartoon of a normal fault in a basin showing a thin free gas zone below the BSR (top left) versus a thick free gas zone below the BSR (top right) where gas overpressures below the BSR can cause fault-reactivation and gas escape. The arrows on the plot to the right indicate possible gas migration pathways during fault slip. Mohr diagram demonstrating the two scenarios (bottom). Because shallow submarine sediments are poorly consolidated, little difference exists between the cohesive strength of pre-existing faults and of unfaulted sediment, resulting in a Mohr circle diagram that appears appropriate for both a pre-existing fault and a new shear zone. Increased gas column thickness produces higher gas pressure at the BSR, reducing effective normal stress and moving the Mohr's circle to the left. Note that circle diameter decreases as it moves left due to poroelasticity.

Fig.III- 2. Gas column thickness required for fault reactivation (blue), at the Blake Ridge, for water depth of 3000 m and BSR depth of 400 m—the values for the location of the ODP Leg 164 Drill sites. The top boundaries are for an $\alpha=0.77$, corresponding to zero hydrate in the sediment matrix; the bottom boundaries are for $\alpha=.67$, corresponding to 25% bulk hydrate. Any increase in hydrate content above 25% would cause both of the envelopes to shift downward. Arrows indicate the amount failure thresholds will shift for 100 kpa of fault cohesion at the BSR (and assuming $T= C/3$), which might result from hydrate cementation. Box indicates range of Poisson ratios and gas column heights measured on the Blake Ridge^{14,17}.

Fig.III-3. Depth from seafloor to BSR (m) versus gas column thickness. The blue symbols (1-9) show gas column thickness below BSRs at several hydrate provinces in basin settings where σ_1 is vertical. The red symbols (10-19) show gas column thickness below BSRs at hydrate provinces in compressional settings where σ_1 is not vertical. Note that gas column thickness generally increases with depth for the blue points, but remains nearly constant for the red points. The gray area indicates gas required for fault reactivation. Top of the gray area corresponds to high-end values of $\alpha = 0.77$ (zero hydrate at the BSR) and $\nu = 0.45$; bottom of the gray area corresponds low end values of

$\alpha=0.67$ (25% bulk hydrate) and a v of 0.41. Point Locations: 1 = Barents Sea ²⁷; 2 = the Norwegian Margin ²⁸; 3= Bering Sea Basin ²⁹, 4,5 = Blake Ridge ¹⁷; 6= Beaufort Sea ¹⁸; 7, 8,9 = Basin in Makran Accretionary Prism that has experience rapid sedimentation ^{30,31}; 10 = Offshore Cascadia ¹⁹; 11 = Offshore Chile ²⁰, 12 = Niger Delta ²²; 13, 15 = Offshore Colombia ²¹; 14 = Gulf of Oman Anticline ²³; 16 = Offshore Peru ²⁴; 17 = S. Shetland Is. ²⁵; 18, 19= Oman Accretionary Toe ^{32,33}. Inset: change in BSR and base of gas depth for a 5° C temperature change at the seafloor, where solid black line is seafloor, solid blue line is current base of BSR, dashed blue line is base of free-gas, solid red line is base of BSR for 5° C temperature increase at seafloor, and dashed red-line base of free-gas for a 5° C temperature increase at seafloor. The gray “hydrate wedge” indicates the area where complete hydrate dissociation in the sediment occurs for a 5° C temperature increase at seafloor.

Figure III-1.

Figure III.2.

Pore-Pressure Vs. Depth for Sedimentary Basins

Figure III-3

CONCLUSION: SUMMARY OF PROJECT ACHIEVEMENTS

On balance, we consider this project to have been highly successful, although it was marked by several setbacks along the way. To date, this project has resulted in five published papers in peer-reviewed journals, one M.S. thesis, and numerous conference presentations. In addition, two PhD theses and several additional papers are in preparation using data acquired during this project.

Work is continuing, beyond the end of this project, on several of the original goals, particularly the 3D imaging. We fully anticipate successful completion of the goals of Task 2.0 using 3D data, although this will occur outside the duration of the DOE contract.

Successes to date include the following discoveries. (1) Seismic reflection data can, under certain circumstances, both directly detect methane hydrate and provide estimates of hydrate concentrations. (2) The Blake Ridge “collapse” is not a structural collapse but is rather a sediment wave field formed by mud-wave deposition and seafloor erosion. Significant amounts of gas did, however, escape from the structure, likely along pathways that link the free gas zone to the seafloor – especially faults and stratigraphic surfaces bounding sediment wave packages. (3) Even in a low-flux environment such as the Blake Ridge, free gas can migrate hundreds of meters vertically through the hydrate stability zone, given a suitable permeability pathway. The hydrate stability zone does not constitute a perfect “seal” on gas migration. (4) The thickness of the free gas zone on the Blake Ridge, and in other basins where the maximum principal stress is near vertical, appears to be controlled by the mechanical strength of the overlying sediments. The “mechanical seal” of the hydrate stability zone can be punctured when the underlying free gas zone exceeds a critical thickness governed by Mohr-Coulomb failure theory. This model has important implications for the release of methane from the free gas zone into the oceans during climate change events.

Looking forward, our results have several implications for future work and technologies. First, our results on direct seismic detection suggest that bright spots should be sought in seismic data as a possible indicator of concentrated hydrate, especially when the bright spots occur in close spatial proximity to disturbances in the BSR and underlying free gas zone. Our predictions of hydrate concentrations, however, have not yet been confirmed by drilling. A dedicated field sampling program to test seismic predictions of hydrate concentration in the marine environment would be desirable. Amplitude blanking can also be an indicator of hydrate, but should be viewed with skepticism unless blanked zones also correspond to high-velocity zones. Second, our waveform inversion results show that interpretations of the presence of hydrate or gas based solely on observations of waveform “polarity” can be quite deceiving. Such interpretations should always be followed by waveform inversion to verify that polarity has not been modified by interference from thin-bed reflections. Third, the role of the free gas zone in interactions between the hydrate/gas and ocean/atmosphere systems is probably much more important than previously realized. Models for the effects of the

hydrate system on climate should focus less on “melting” hydrate and more on understanding the causes and consequences of free gas migration.

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