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1. Agency Use Only (Leave blank)		2. Report Type and Dates Covered.	
September 1993		Final - Journal Article	
4. Title and Subtitle. Faulted structure of the bottom simulating reflector on the Blake Ridge, western North Atlantic		5. Funding Numbers. Program Element No 0602435N Project No 03502 Task No JOB Accession No DN259007 Work Unit No 574515303	
6. Author(s). M. M. Rowe and J. F. Gettrust		8. Performing Organization Report Number. NRL/JA/7432--93-0008	
7. Performing Organization Name(s) and Address(es). Naval Research Laboratory Seafloor Sciences Branch Stennis Space Center, MS 39529-5004		9. Sponsoring/Monitoring Agency Name(s) and Address(es). Naval Research Laboratory Ocean Acoustics Branch Stennis Space Center, MS 39529-5004	
11. Supplementary Notes. Published in Geology.		10. Sponsoring/Monitoring Agency Report Number. NRL/JA/7432--93-0008 Justification	
12a. Distribution/Availability Statement. Approved for public release; distribution is unlimited.		12b. Distribution Codes Avail and/or Dist Special A-1 20	
13. Abstract (Maximum 200 words). <p>High-resolution multichannel seismic data collected from the Blake Ridge in the western North Atlantic by the Naval Research Laboratory's Deep Towed Acoustics/Geophysics System (DTAGS) show that the bottom simulating reflector (BSR) in this area is the reflection from the interface between an ~440-m-thick section of hydrate bearing sediment overlying and ~5-m-thick layer of methane gas-rich sediment. The high resolution attainable by the deep-tow seismic system reveals normal fault offsets of ~20 m in the BSR. These growth faults may provide a path for vertical migration of methane initially concentrated beneath the hydrate-bearing sediment, enabling hydrate to form throughout sediment above the BSR. Because the BSR represents a methane gas-methane hydrate phase boundary rather than a lithologic or diagenetic horizon, the observed offset of the BSR itself reflects discontinuities in the pressure-temperature field across the fault zones where they intersect the BSR.</p> <p>Original contains color plates; All DTIC reproductions will be in black and white.</p>			
14. Subject Terms. Directional ambient noise, bottom scattering, deep-towed array geophysical system, ocean bottom seismometer, towed array		15. Number of Pages. 4	
17. Security Classification of Report. Unclassified		16. Price Code.	
18. Security Classification of This Page. Unclassified		19. Security Classification of Abstract. Unclassified	
20. Limitation of Abstract. SAR			

Faulted structure of the bottom simulating reflector on the Blake Ridge, western North Atlantic

M. M. Rowe }
J. F. Gettrust } Naval Research Laboratory, Stennis Space Center, Mississippi, 39529-5004

ABSTRACT

High-resolution multichannel seismic data collected from the Blake Ridge in the western North Atlantic by the Naval Research Laboratory's Deep Towed Acoustics/Geophysics System (DTAGS) show that the bottom simulating reflector (BSR) in this area is the reflection from the interface between an ~440-m-thick section of hydrate-bearing sediment overlying an ~5-m-thick layer of methane gas-rich sediment. The high resolution attainable by the deep-tow seismic system reveals normal-fault offsets of ~20 m in the BSR. These growth faults may provide a path for vertical migration of methane initially concentrated beneath the hydrate-bearing sediment, enabling hydrate to form throughout sediment above the BSR. Because the BSR represents a methane gas-methane hydrate phase boundary rather than a lithologic or diagenetic horizon, the observed offset of the BSR itself reflects discontinuities in the pressure-temperature field across the fault zones where they intersect the BSR.

INTRODUCTION

Methane hydrate, an icelike solid that contains high concentrations of methane, is found within sediments where low temperatures and high pressures are such that methane hydrate is the stable phase of a water-methane mixture. In 1989, the Naval Oceanographic and Atmospheric Research Laboratory (now part of the Naval Research Laboratory [NRL]) recorded high-resolution, deep-tow, multichannel seismic data over an area on the Blake Ridge, in the western North Atlantic, where the presence of methane hydrate had been inferred from conventional, surface-tow, seismic-reflection data and from the drilling results from Deep Sea Drilling Project (DSDP) Sites 102, 103, 104, and 533 (Hollister et al., 1972; Sheridan et al., 1983). Evidence for the presence of significant amounts of methane hydrate from surface-tow seismic data include a bottom simulating reflector (BSR), an unusually high amplitude reflection horizon that follows sea-floor topography (Shipley et al., 1979), unusually high compressional velocities within the sediment (Dillon and Paull, 1983), and anomalous low-reflectivity zones (Dillon et al., 1991). These characteristics and evidence of normal faults penetrating the BSR are shown by NRL's high-resolution, multichannel seismic data collected on the northwestern slope of the Blake Ridge (Fig. 1). The Blake Ridge is a thick accumulation of organic-rich Miocene to Holocene terrigenous sediments, deposited by contour currents (Markl and Bryan, 1983), in which the upper ~660 m of sediment consists of uniform hemipelagic silty clay interspersed with thin (<1 m) beds and lenses of silty to sandy clay and calcareous mud (Hollister et al., 1972; Sheridan et al., 1983).

HIGH-RESOLUTION MULTICHANNEL SEISMIC MEASUREMENTS

The Deep Towed Acoustics/Geophysics System (DTAGS) is a unique multichannel

seismic system in which the source, a Helmholtz transducer that generates a chirp from 250 to 650 Hz, and linear receiving array are both towed 300 to 500 m above the sea floor at full ocean depths (Gettrust and Ross, 1990). The array contains 24 elements 21.0 m apart offset 137–620 m behind the source. Shots are fired at ~21 m (30 s) intervals. The high-frequency source and close proximity of the system to the sea floor enable the system to resolve subbottom structural features on a scale of ~5 m vertically and ~21 m horizontally (Rowe and Gettrust, 1993), greater than the resolution possible from surface-tow multichannel seismic systems. Normal-moveout-based semblance analysis techniques were applied to the common

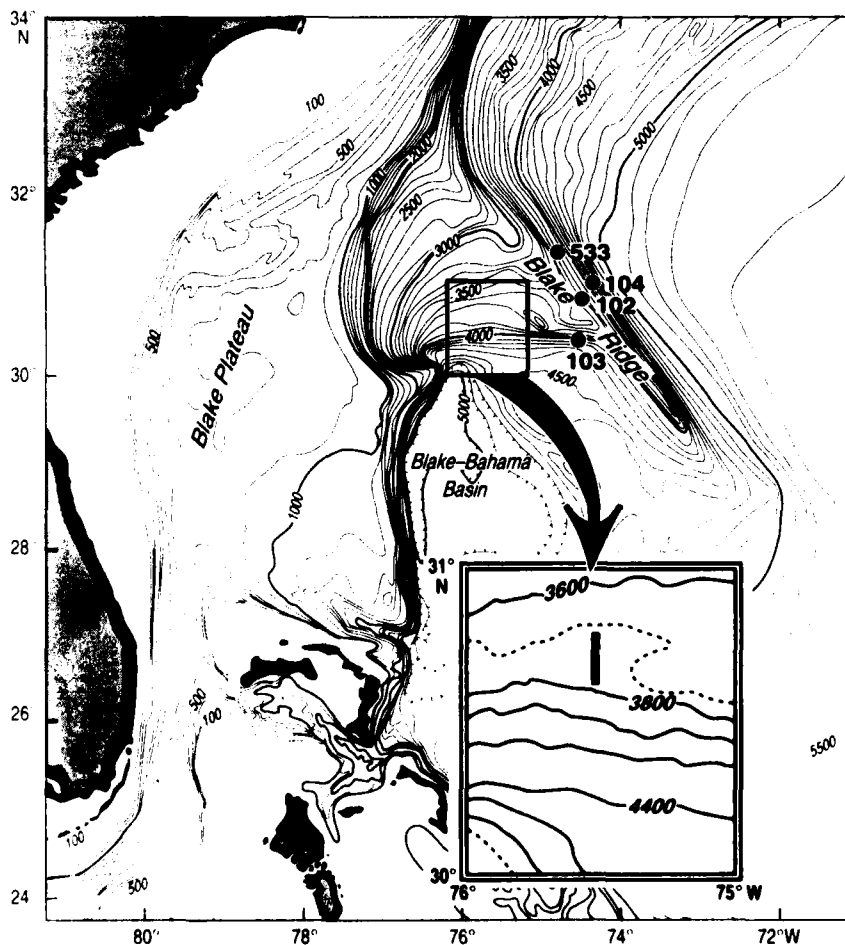


Figure 1. Map showing location of 2.5 km DTAGS multichannel seismic line from Blake Ridge. Contours indicate depths in metres; circles indicate DSDP sites.

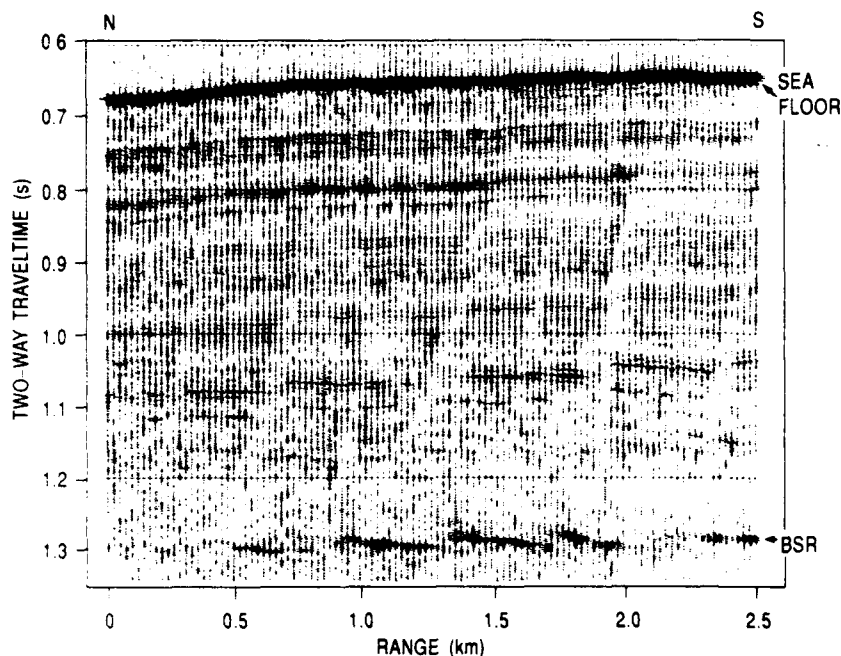
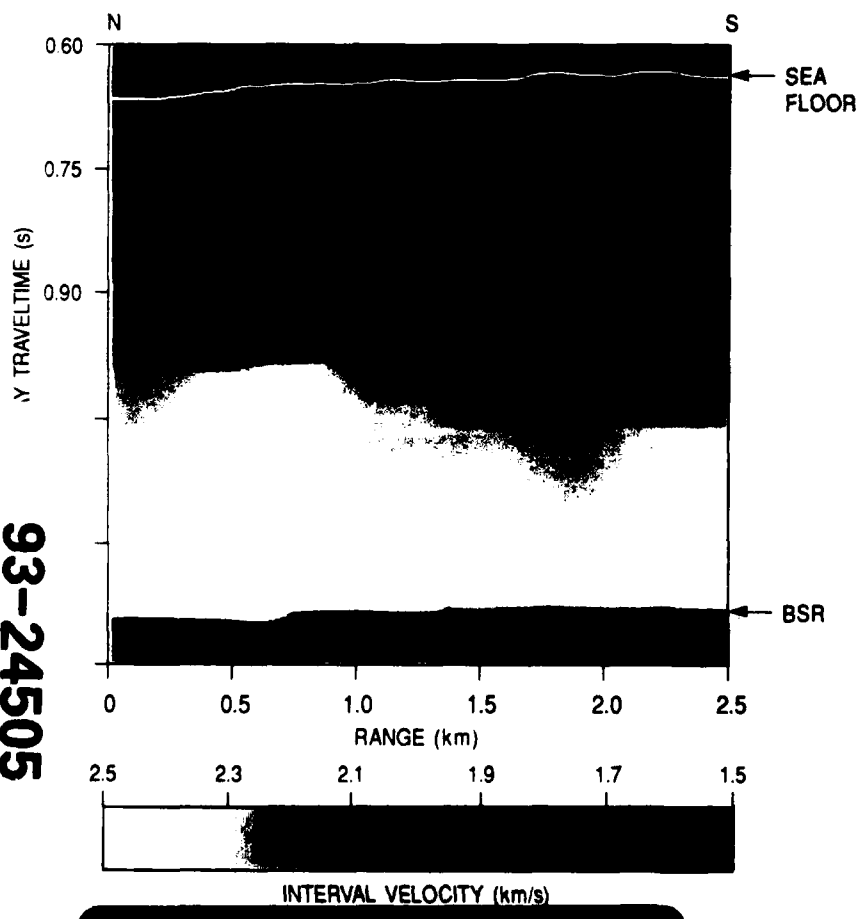


Figure 2. Seismic section recorded on Blake Ridge compiled from 137 m offset trace from each shot gather. Bottom simulating reflector (BSR), ~ 0.63 s below sea floor, marks base of methane-hydrate stability zone. Two-way traveltimes are referenced to DTAGS tow depth, ~ 500 m above sea floor.



shot gather data to obtain high-resolution (~ 25 m vertically, ~ 100 m horizontally) estimates of the compressional velocity within the sediment as a function of range along the ship track and depth below the sea floor (Rowe and Gettrust, 1993).

The seismic data discussed in this paper were collected along a 2.5-km-long line perpendicular to the ridge slope in water depths between 3700 and 3800 m (Fig. 1). The common offset (137 m) seismic section (Fig. 2) shows numerous closely spaced, flat-lying reflection horizons caused by the thin (< 4 m) layers of silty to sandy sediment and calcareous clay observed in cores (Hollister et al., 1972; Sheridan et al., 1983). Below ~ 0.2 s (all times given are two-way traveltimes) below the sea floor (bsf), reflection amplitudes decrease relative to the reflection amplitudes from the shallower reflectors, because of the decrease in impedance mismatch across sediment layers in regions where hydrate has formed within the sediment (Dillon et al., 1991). Normal faults dipping downslope offset reflection horizons from the sea floor through the BSR that is ~ 0.64 s bsf.

Compressional velocity estimates obtained from the deep-tow multichannel data (Fig. 3) show that there is almost zero velocity gradient between the sea floor and 0.17 s bsf, typical of shallow, fine-grained marine sediment (Gettrust et al., 1988). Between ~ 0.17 and ~ 0.18 s bsf, the compressional velocity increases sharply, from ~ 1.65 to > 2.00 km/s (Fig. 3). Below this depth, velocity continues to increase, reaching 2.45–2.70 km/s at the BSR. These unusually high velocities have been measured in fine-grained marine sediments buried < 600 m deep in areas in which the fractures and pore space are partially filled with methane hydrate (Mathews and von Huene, 1985). Although the top of this high-velocity gradient zone is at approximately the same depth across the section, comparison of Figure 2 and 3 shows that it does not coincide with a specific reflection horizon, suggesting that the upper boundary of the hydrate-bearing sediment is gradational, as suggested by Tucholke et al. (1977). The increase in compressional velocity with depth reflects the increasing percentage of sediment pore space that contains methane hydrate. Lateral variability of the compressional velocity within the high-velocity zone (Fig. 3) is consistent

Figure 3. Two-dimensional interval velocity model derived from DTAGS data. Black area at base of model marks maximum depth for which there are reflection horizons to determine velocities. Two-way traveltimes are referenced to DTAGS tow depth. BSR = bottom simulating reflector.

with lateral variability in the sediment hydrate content.

The reflection horizon that is 0.64–0.65 s bsf (Fig. 2), has the high amplitude and inverted polarity characteristic of a methane hydrate-related BSR (Shipley et al., 1979). This two-way traveltime is consistent with that of the BSR observed from surface-tow seismic data acquired in this area (Tucholke et al., 1977; Dillon and Paull, 1983). The deep-tow seismic data reveal that this BSR is a reflecting horizon composed of reflections from the top and bottom of a layer having a thickness of ~1–2 wavelengths (Fig. 4A; Rowe and Gettrust, 1993). Al-

though this layer is too thin for estimates of the compressional velocity within this layer to be made from the multichannel data, the distinct inversion in the phase of the reflection observed at the top of the BSR, at ~1.29 s (Fig. 4A), and lack of corresponding density decrease (Hollister et al., 1972) indicate that the compressional velocity of the material immediately beneath the top of the BSR is significantly lower than the compressional velocity of the overlying sediment. The reflection data at the BSR were synthesized (Fig. 4B) using the full-wavefield model SAFARI (Schmidt, 1984). The best fit to the shape and amplitude of the BSR

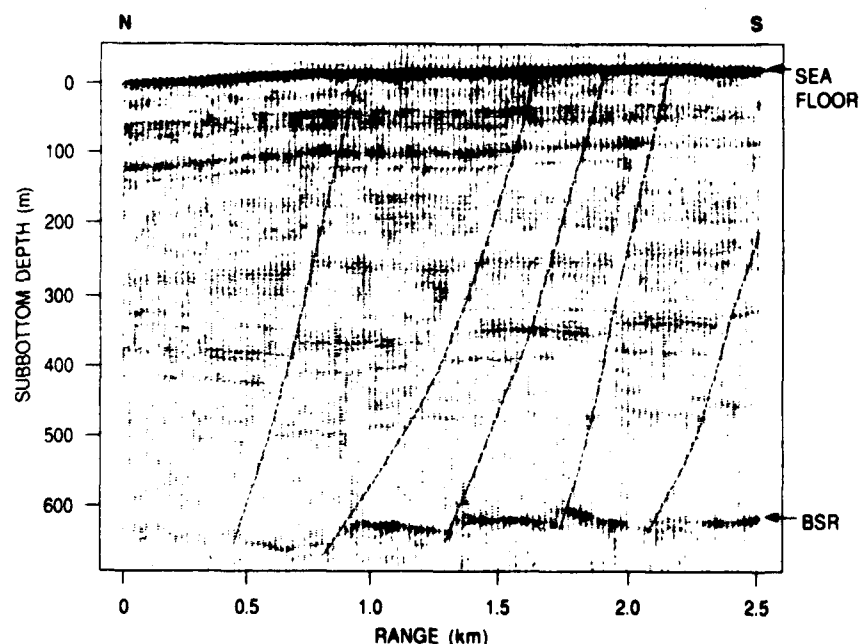
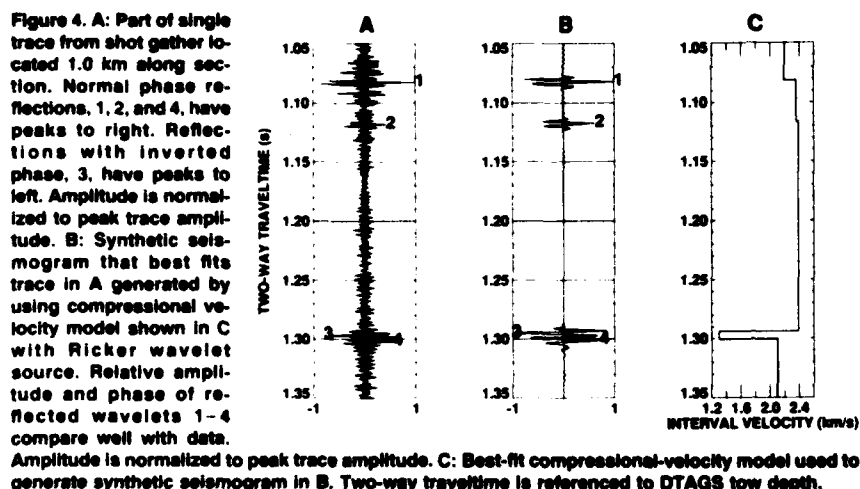
reflection was obtained using a model (Fig. 4C) consisting of a 4-m-thick, low-velocity (1.3 km/s) layer beneath high-velocity (2.4 km/s) material and underlain by another higher velocity (2.1 km/s) layer. Sediment compressional velocities as low as 1.3 km/s may be found in sediment in which pore spaces contain free gas (Miller et al., 1991).

Conversion of the seismic data from time to depth (Fig. 5), computed by using the interval compressional velocities derived from these data (Fig. 3), shows that the thin layer causing the BSR reflection lies 640–660 m bsf and is 3.5–7.0 m thick. The high compressional-velocity gradient zone that coincides with the top of the zone of low reflectivity, inferred to mark the top of the hydrate-bearing sediment, is ~210 m bsf. This hydrate-bearing interval (~210–650 m bsf) coincides with the depths at which high concentrations of methane were observed in core samples from nearby DSDP sites (Hollister et al., 1972; Sheridan et al., 1983).

FAULT CONTROLS ON METHANE DISTRIBUTION

For methane hydrate to form within this ~440-m-thick layer of methane-bearing sediment, large quantities of methane must be available throughout the region. Below the BSR, the thick sediment section contains large amounts of rapidly buried organic material (Markl and Bryan, 1983), a large potential methane source. Sufficient quantities of methane for hydrate formation may be concentrated at the base of the zone of hydrate stability, marked by the BSR, by upward migration of free methane gas or methane-rich pore fluid, driven by high pore pressures developed as methane is evolved (Hyndman and Davis, 1992). As methane enters the hydrate stability zone, it forms hydrate, filling sediment fractures and pore spaces at the base of this zone. The continuous BSR and unusually high compressional velocities throughout the sediment at the BSR are evidence that sufficient hydrate has formed within the sediment to create an impermeable layer that inhibits migration of methane into the overlying sediments. Methane that has continued to migrate from deeper sediment is trapped at the BSR. This trapped gas may form a reservoir beneath the impermeable hydrate-bearing sediment layer, as suggested by the full-waveform model.

The normal faults resolved by these seismic data extend into this methane-rich sediment layer (Fig. 5). Slope failure on the Blake Ridge, which may be occurring along this weak, gassy sediment layer (Dillon et al., 1983) or within the non-hydrate-bearing sediment below the hydrate stability zone, is accommodated in the overlying, more rigid,



hydrate-bearing sediments along these normal faults (Fig. 5). The dip angle of these faults, 44° to 60°, becoming shallower at depth, and the increasing offset with depth are consistent with the morphology of growth faults. Periodic rupture along these faults may provide avenues for migration of large quantities of methane past the impermeable hydrate-bearing sediment near the base of the hydrate stability zone (Reed et al., 1990). During the time the faults are inactive, hydrate seals the faults at the BSR depth, preventing methane gas from migrating. Movement along these faults causes the hydrate within the fault zones to dissociate, due to the pressure decrease and frictional heating caused by the fault movement. At this time, methane from the reservoir beneath the hydrate-bearing sediment is able to migrate upward along the fault zone into overlying non-hydrate-bearing sediment lying within the hydrate stability zone. Repeated fault rupture enables hydrate to form throughout a region extending several hundred metres above the BSR.

BSR FAULT OFFSETS

If the BSR represents a phase boundary, how are the observed vertical offsets (Fig. 5) in the BSR itself maintained? It has been suggested that the BSR might be caused by precipitation of carbonate minerals in a thin sediment layer at the base of the zone of hydrate stability (Lancelot and Ewing, 1972). However, the observed inverted phase of the BSR reflection requires a negative impedance contrast between the sediments above the BSR and the thin layer at the BSR. A negative change in impedance requires a decrease in compressional velocity or density across the interface, which is not true of the carbonate layers found at these depths (Lancelot and Ewing, 1972).

The abrupt discontinuities along the BSR, coincident with the fault zones, may be maintained by discontinuities in the temperature-pressure field which exist across the faults. Stress is higher on the downthrown side of a normal fault than on the upthrown side (Hafner, 1951). Under the higher pressure, the region in which hydrate is stable would extend deeper, into warmer sediments, causing a downward shift in the depth of the BSR across the fault. The observed ~20 m offset is equivalent to a pressure difference of ~200 kPa (~2 bar) across the faults, which enables hydrate to be stable at temperatures ~1 °C higher. A discontinuity in the isotherm across the fault caused by the downward shift of colder, shallower sediment on the downthrown side, adjacent to the deeper, warmer sediment, would further enhance the apparent offset. MacLeod (1982) estimated that sev-

eral thousand years are required for this isotherm to regain equilibrium.

CONCLUSIONS

Evidence from compressional velocities, reflection amplitude, and reflection character indicate that the BSR on the Blake Ridge is the reflection from the interface between an ~440-m-thick hydrate-bearing sediment layer, which formed within the zone of hydrate stability, and an ~4-m-thick layer of sediment containing free methane gas immediately beneath it. Although hydrate forming in the sediment at the base of the hydrate stability zone acts as a cap, preventing upward migration of methane and restricting hydrate formation to the base of the hydrate stability zone, the faults observed in these data provide a mechanism in this region for migration of methane gas above the BSR. Methane generated deeper within the thick, organic-rich Blake Ridge sediment may migrate upward through the sediment until it enters the hydrate stability zone, where it forms methane hydrate, inhibiting methane from migrating farther upward and causing it to pool at the base of the hydrate-bearing layer. As sediment continues to be deposited on the ridge flanks, the added weight causes slope failure, which is accommodated within the overlying rigid, hydrate-bearing sediment along the normal faults resolved by the seismic data. Rupture along these faults causes the dissociation of the methane hydrate within the fault zones, enabling significant amounts of methane to migrate out of the gas-rich layer and to form hydrate within an interval extending several hundred metres above the BSR.

ACKNOWLEDGMENTS

Supported by the Office of Naval Technology, program element 0602435N, and the Office of Naval Research, program element 0601153N. We thank Pete Fleischer and Fred Bowles for reviewing this manuscript. Naval Research Laboratory contribution JA/7432-93-0008.

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Manuscript received February 25, 1993
Revised manuscript received June 8, 1993
Manuscript accepted June 15, 1993