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Marine Geology 164 (2000) 79–89

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.nl/locate/margeo

# Trapping and migration of methane associated with the gas hydrate stability zone at the Blake Ridge Diapir: new insights from seismic data

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Received 2 May 1999; accepted 6 October 1999

## Abstract

The Blake Ridge Diapir is the southernmost of a line of salt diapirs along the Carolina trough. Diapirs cause faulting of the superjacent sediments, creating pathways for migration of fluids and gas to the seafloor. We analyzed reflection seismic data from the Blake Ridge Diapir, which is located in a region with known abundant gas hydrate occurrence. A striking feature in these data is a significant shallowing of the base of gas hydrate stability (BGHS) over the center of the diapir: The seafloor is warped up by about 100 m above the diapir, from about 2300 m to about 2200 m. The BGHS, as indicated by a bottom simulating reflection (BSR), is about 4.5 s off the flanks of the diapir, rising to about 4.15 s at the center. Above the diapir, a fault system appears to rise vertically from the BGHS to about 0.05 s below the seafloor (40–50 m); it then diverges into several steeply dipping faults that breach the seafloor and cover an area ~700 m in diameter. Other secondary faults diverge from the main fault or emerge directly from the BGHS near the crest of the diapir. Gas and other fluids may migrate upward through the faults. We performed complex trace analysis to compare the reflection strength and instantaneous frequency along individual reflections. A low-frequency anomaly over the center of the diapir indicates high seismic attenuation. This is interpreted to be caused by migration of fluids (probably methane) along fault pathways. The migration of gas (i.e. probably mainly methane) through the gas hydrate stability zone is not yet understood. We speculate that pore fluids in the faults may be too warm and too salty to form gas hydrate, even at depths where gas hydrate is stable away from the diapir. Alternatively, gas hydrates may seal the fault walls such that water supply is too low to transform all the gas into gas hydrates. The shallowing of the BSR may reflect increased heatflow above the diapir either caused by the high thermal conductivity of the underlying salt or by advective heat transport along with fluids. High pore water salinity shifts the gas hydrate stability to lower temperatures and may also play a significant role in BSR shallowing. We, therefore, investigated the possible effect of pore water salinity on shallowing of the BSR. We found that BSR shallowing may theoretically be entirely caused by increased salinity over the diapir, although geologically this would not be reasonable. This observation demonstrates the potential importance of pore water salinity for lateral variations of BSR depths, in particular, above salt structures. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords*: Blake Ridge; Gas-hydrates; Salt diapirs; Trace attributes

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PII: S0025-3227(99)00128-0

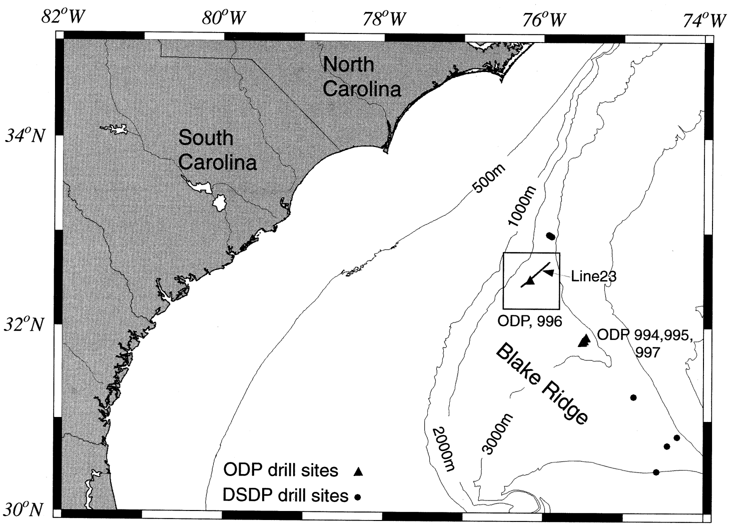


Fig. 1. Regional map illustrating location of the study area. The Blake Ridge Diapir is located northwest of the Blake Ridge. Box delimits bounds of the seismic line used in the study. Black triangles and dots represent ODP and DSDP drill hole locations, respectively.

## 1. Introduction

Gas hydrates are crystalline solids formed of water molecules, with gas, commonly methane, encaged in a crystal lattice (Sloan, 1990). They appear similar to ice. Gas hydrates form when pore fluids are saturated with respect to methane and appropriate low temperature and high pressure conditions are present, commonly within sediments below the seafloor at water depths exceeding ~500 m. Bottom simulating reflections (BSRs), reflections that are sub-parallel to the seafloor and that are mostly associated with free gas beneath the base of gas hydrate stability (BGHS), are probably the most common indicators for marine gas hydrates. At the Blake Ridge Diapir offshore South Carolina (Fig. 1), prominent BSRs indicate the presence of gas hydrates.

Methane-based chemosynthetic communities, which were found at the Blake Ridge Diapir during previous studies, also indicate the release of free gas at the seafloor (Paull et al., 1995; Paull et al., 1996). In addition, plumes and pockmarks associated with gas seeps have also been documented (Paull et al., 1995). However, the migration of methane through the hydrate stability zone (HSZ) is not yet well understood, nor is the effect of pore-water chemistry on the migration of fluids through the HSZ. There are indications that free gas migrates along faults at the Blake Ridge southeast of the Blake Ridge Diapir (Dillon et al., 1996), but this is not yet well constrained.

In late 1995, a seismic reflection experiment dedicated to the study of gas hydrates was conducted over the Blake Ridge Diapir and the Blake Ridge during Ocean Drilling Program (ODP) Leg 164. In this study, we will describe results from an attribute analysis of seismic reflection data from Line 23 over the Blake Ridge Diapir. We also investigate the observed shallowing of the BSR above the Blake Ridge Diapir (Fig. 2).

## 2. Geologic setting

The Blake Ridge Diapir is the southernmost of a linear array of at least 25 diapirs that extends northeastward along the seaward side of the Carolina Trough (Dillon et al., 1983; Dillon and Popenoe, 1988). The Carolina Trough is a long, narrow (about 450 km × 40 km) basin, one of the four principal continental margin basins formed by the initial rifting of the Atlantic margin of the US. Salt remaining in the basin occurs at great depth, approximately 11 km, but much has flowed seaward under the load of basin fill and generated the diapirs that rise along the seaward limit of the deep basin, marked by the East Coast

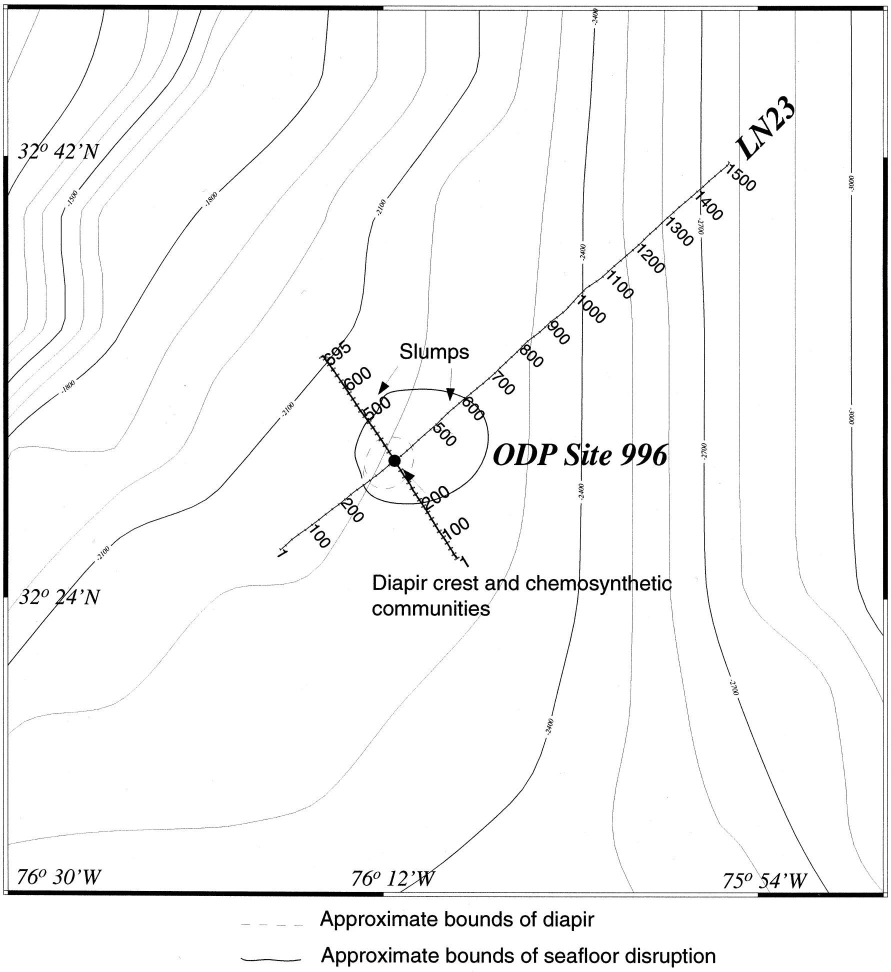


Fig. 2. Shot point location map for Line 23. Areas of seafloor disruption and areal extent of the Blake Ridge Diapir are outlined.

Magnetic Anomaly. Subsidence due to the salt migration has created a series of still-active growth faults along the landward side of the deepest part of the basin.

The diapir rises near the landward end of the Blake Ridge, an actively accreting and migrating sediment drift deposit that occurs in the transition between the carbonate platform of the Blake Plateau/Bahamas and the clastic-dominated US eastern continental margin (Dillon and Popenoe, 1988). The diapir is interpreted to result from salt rising from deep in the Carolina Trough, on the basis of high chloride concentrations in samples of interstitial waters from sediments above the diapir (Dillon et al., 1983; Paull et al., 1996). Photographs taken at the crest of the Blake Ridge Diapir document the presence of chemosynthetic communities, as well as authigenic carbonates probably formed by the oxidation of methane by seawater (Esikov and Pashkina, 1990; Paull et al., 1996). High-resolution seismic profiles display plumes rising into the water column originating from pockmarks at the seafloor (Paull et al., 1995). In addition, Egeberg (2000) analyzed interstitial waters from ODP Drillsite 996 (Paull et al., 1996), and utilizing transport equations for pore-water $Cl^-$ and $\delta^2H$, found that high concentrations of hydrate near the seafloor, are best explained by a transport-dominated system.

Gas hydrates, carbonate accumulations and hydrocarbon seeps similar to those at ODP Site 996, have been observed at many locations along continental margins, in regions where methane-rich fluids are venting onto the seafloor (Holvland and Judd, 1988; Esikov and Pashkina 1990; Hovland, 1992; Paull et al., 1996; Ginsburg and Soloviev, 1997; Soloviev and Ginsburg, 1997).

## 3. Methods

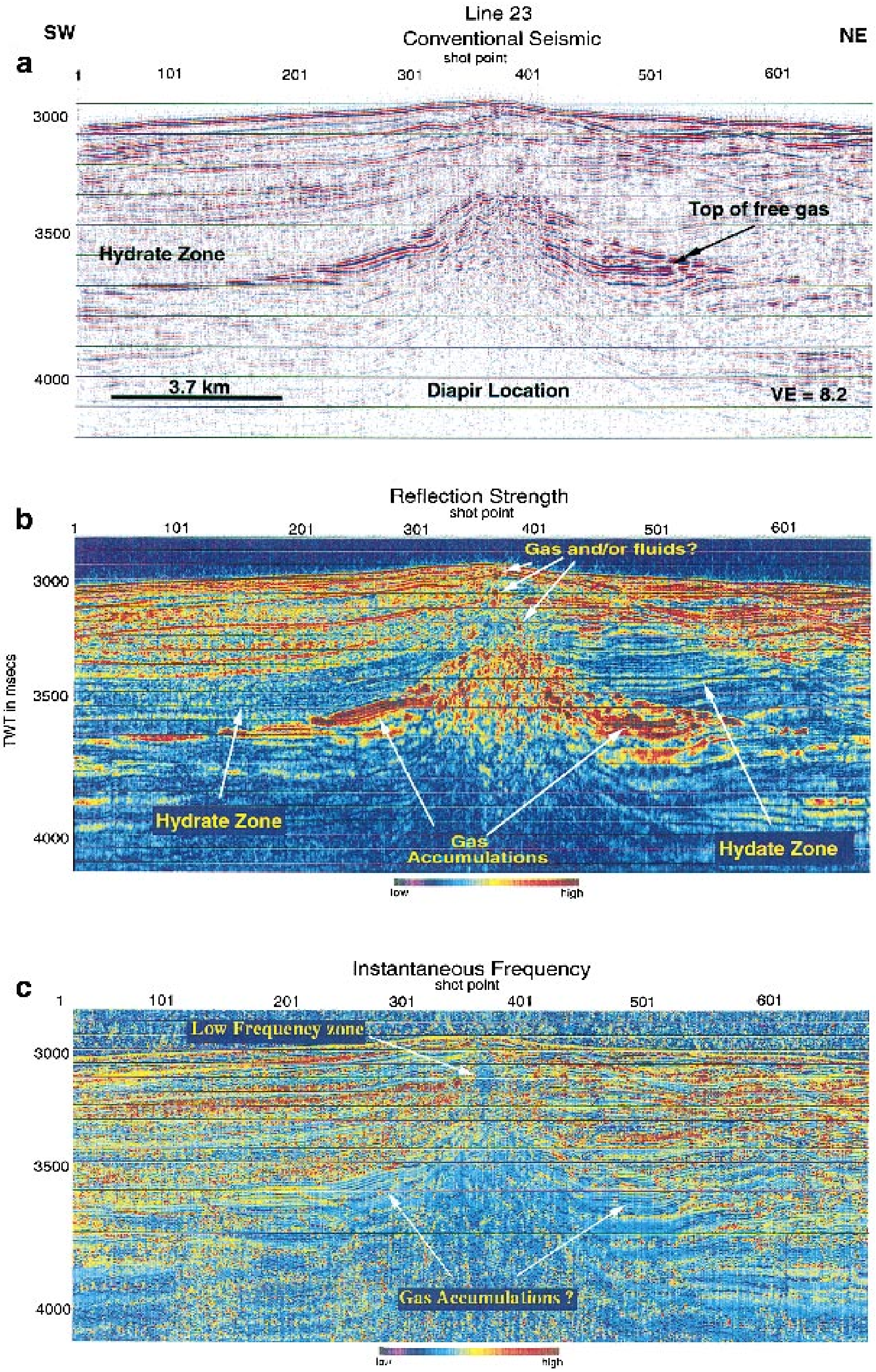
The seismic profile analyzed in this study was collected using a generator/injector (GI) gun (® Seismic Systems Inc.) as a seismic source. The GI gun consists of two independent airgun chambers (105 in.$^3$ each for this study). The first chamber (generator) produces the primary pulse. The second chamber (injector) is fired with a slight delay to suppress the bubble pulse from the first chamber. The result is an almost bubble-free source signature that enhances resolution. The main frequency of this source wavelet was about 50–75 Hz. The data were recorded with a 2-channel streamer and digitized at a 0.5-ms sampling rate. With this system, we achieved penetration below the base of the gas hydrate stability zone (BGHS), while maintaining the highest possible resolution.

Seismic reflection strength and instantaneous frequency were determined by using a series of trace transforms. The raw data were frequency-filtered with a broad bandpass filter (3 dB points at 5 and 100 Hz with 48-dB/octave rolloff at the low end and 128-dB/octave rolloff at the high end). We performed Memory-Stolt migration with water velocity to move the reflections to their true subsurface positions, thus improving the image of the structure, while preserving the frequency and amplitude of the wavelet (Taner et al., 1979; Yilmaz, 1987). A shift of the seismic wavelet to zero-phase using a phase deconvolution was applied to each seismic trace in order to increase resolution of the data and reliability of interpretation (Yilmaz, 1987). Finally, we performed a Hilbert transform to obtain the complex seismic trace and determine its seismic attributes (Taner et al., 1979). Instantaneous frequency and reflection strength were finally displayed with color encoding.

Reflection strength depends on contrasts of seismic impedance (i.e. velocity multiplied by density). Only a few percent of free gas in the pore space of sediments decrease seismic compressional (P-) wave velocity drastically (Domenico, 1977). Therefore, layers that contain trapped free gas often generate strong reflections (“bright spots”). Free gas is also known to highly attenuate seismic P-waves. Instantaneous frequency enables us to detect regions of high attenuation (by attenuation we mainly mean absorption of seismic energy due to internal friction). The amplitude decrease of a seismic wave depends on the number of wave cycles along its travel path. For a particular region of high attenuation, shorter wavelength (i.e. high frequency) energy will, therefore, be preferentially attenuated. This results in a shift towards lower frequencies of reflection arrivals from below regions of high attenuation (for an overview over seismic attribute analysis refer to Yilmaz (1987)).

The effect of gas hydrates on seismic attenuation has not been studied in detail, yet. Wood et al. (1996) saw indications of an increase of attenuation in the gas hydrate zone on the Blake Ridge. However, seismic data from gas hydrate regions worldwide suggest that attenuation of hydrate-bearing sediments is not nearly as high as that of gas-bearing sediments. Otherwise, penetration of signals beneath hydrate-regions would be severely limited. Seismic attribute analysis therefore helps to distinguish between impedance contrasts caused by the presence of low-velocity free gas, from

Fig. 3. (a) Plot of conventional seismic profile without application of trace transforms. Interpretation is more difficult resulting in less than accurate results. However, areas associated with hydrate accumulations are observed. (b) Reflection strength plot for line 23. High and low reflection strength represented by browns and blues, respectively. Notice prominent gas reservoir below BGHS and enhanced reflection elements above the diapir. The hydrate stability zone is apparent; notice cross-cutting relationship at northeast section of the line near shotpoint 550, ~3.25 s TWTT. Slumps northeast of the diapir are also observed to NE. (c) Plot of instantaneous frequency for line 23. Attenuation of higher frequencies results in the vertical low frequency anomaly near shotpoint 380, coincident with vertically positioned enhanced reflection elements in (b). Low frequency shadows also occur below reflection with high reflection strength values (BSR), between shot points 1–300 and 450–600.


Line 23
Conventional Seismic
SW
NE
a
shot point
1
101
201
301
401
501
601
3000
3500
4000
Hydrate Zone
Top of free gas
3.7 km
Diapir Location
VE = 8.2
Reflection Strength
b
shot point
TWT in msecs
Gas and/or fluids?
Hydrate Zone
Gas Accumulations
Hydate Zone
low
high
Instantaneous Frequency
c
shot point
Low Frequency zone
Gas Accumulations ?
low
high

reflections of similar strength associated with higher-velocity, hydrate bearing sediments and/or sediments lacking free gas accumulations.

## 4. Reflection characteristics associated with gas hydrate

The effect of gas hydrates on seismic sediment properties is not yet understood. Solid gas hydrates have a P-wave velocity of about 3.27 km/s (Waite et al., 1998) compared to 1.5 km/s of water. It is, therefore, commonly assumed that a replacement of part of the pore water by gas hydrates increases the seismic velocity of the bulk sediment, but to what degree it depends on the microscopic distribution of gas hydrates within the sediment pores (Dvorkin and Nur, 1993; Lee et al., 1993).

Gas hydrate zones are commonly underlain by a reflection that approximately parallels the seafloor, the "bottom simulating reflection" (BSR). BSRs are characterized by a reversed polarity compared to the seafloor reflection indicating a downward reduction of seismic impedance and hence, most likely, seismic velocity. VSPs acquired during ODP Leg 146 at the Cascadia Margin (Mackay et al., 1994) and ODP Leg 164 on the Blake Ridge (Holbrook et al., 1996) indicate that low velocities associated with free gas are the cause for the BSRs in both study areas. The free gas zone beneath the BGHS on the Blake Ridge was found to be at least 200 m thick. It appears to coincide with a zone of high reflectivity in seismic reflection profiles. In sediments that contain gas at low concentrations, the P-wave velocity is very sensitive to gas saturation. The high reflectivity may, therefore, be explained by slight variations in gas concentration (Holbrook et al., 1996) across layer boundaries generating strong P-wave velocity contrasts and hence, strong reflection coefficients. When gas-charged strata dip relative to the BGHS, BSRs may display a shingled appearance in high-resolution seismic profiles. This image is created if high reflectivity in the gas zone that is caused by slight variation of gas concentration across stratal boundaries that terminate against the BGHS. At lower frequencies, and hence larger Fresnel zones, these shingled reflections may appear as a continuous reflection.

There is some confusion about the proper use of the term BSR. In this paper, we refer to it as the top of the highly reflective gas zone beneath the BGHS, even where it does not exactly parallel (simulate) the bottom. We are aware that this is a slight deviation from the original definition of the BSR.

It has been suggested that a preferential accumulation of gas hydrate in higher-porosity (i.e. mostly lower-velocity) strata increases the velocity of these strata resulting in a reduction of the velocity contrast between two layers of low and high porosities. This would effectively reduce the reflection amplitude in hydrate bearing sediment sections ("amplitude blanking"; Lee et al., 1993). Holbrook et al. (1996), however, found from vertical seismic profiles (VSPs) that a uniform sedimentary section above the zone of highly reflective gas layers may be the reason for the relatively low reflectivity in the gas hydrate zone at ODP sites 994, 995, and 997 on the Blake Ridge.

## 5. Interpretation of seismic data

### 5.1. Seismic structure

Seismic reflection profiles (Fig. 3a and c) disclose localized doming and faults that extend up to the seafloor in an area of ~7 km$^2$ above the crest of the diapir. Sedimentation is active in this region, so these disruptions suggest that the diapir is undergoing contemporary deformation. Slumps downslope (northeast) of the diapir reach the seafloor at shotpoints ~390 and 560; they appear as gravity gliding, syndepositional features with slight antithetic rotation of the sliding block. Between shots 1–300 of line 23, the BSR displays a shingled appearance suggesting that strata dip through the BGHS. Northeast of shotpoint 400, the BSR is defined by the presence of SW dipping stratal terminations that we infer to be a result of gas-charged strata sealed at the updip end by hydrate-bearing sediments.

Above the Blake Ridge Diapir, the BSR is locally elevated toward the seafloor reflecting a shallowing of the BGHS. This may be caused by increased heatflow above the diapir because of the high thermal conductivity of salt or advective heatflow along with fluid expulsion. Alternatively, a possible increase of

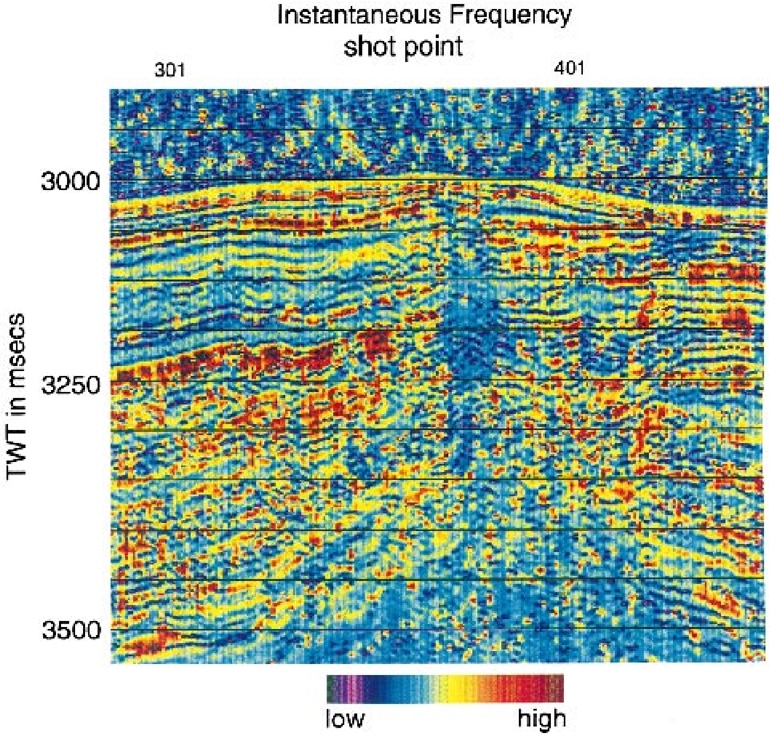


Fig. 4. Enlarged view of the low frequency anomaly above the crest of the diapir in Fig. 3c. A vertical decrease in frequency values is visible in the processed data.

salinity within interstitial waters above the diapir may act as a gas hydrate inhibitor and shift the phase boundary of gas hydrates towards lower temperatures (Sloan, 1990) and hence, the BGHS towards shallower depths (Dillon et al., 1993).

### 5.2. Reflection strength

The reflection strength plot (Fig. 3b) displays amplitude anomalies, enhanced in color, with high and low amplitudes corresponding to dark reds and blues, respectively. To the southwest of the diapir, a region of reduced amplitudes (enhanced in blue) extends from the BSR up to a stratigraphic horizon, but to the northeast, the top of the region of low amplitudes cuts across the strata. Below the BGHS a set of very strong reflections probably defines prominent gas accumulations. Above these probable gas accumulations, enhanced reflections (strong reflections marked by dark reds) occur in a vertical trend originating at the BGHS and extend to the seafloor in a discontinuous fashion. Abrupt changes in impedance values define these anomalies, suggesting enhanced density and/or velocity contrasts.

These density/velocity contrasts may be related to small-scale gas accumulations caused by strong fluid expulsion. Reflection-strength anomalies correlate well with regions of active faulting visible in the data. We, therefore, speculate that the sub-vertical faults contain gas and are acting as fluid conduits. The presence of gas conduits is to be expected, considering the previous observations of benthic chemosynthetic communities, vents and pockmarks on the seafloor above the diapir (Paull et al., 1995; Paull et al., 1996).

However, other phenomena such as high-velocity authigenic carbonate accumulations related to the oxidation of methane by seawater, thin high-velocity layers with elevated gas hydrate concentration, or enhanced porosity contrasts by trapped, overpressured fluids may also cause elevated reflection strength. An analysis of reflection polarity to discriminate between low- and high-velocity material as the cause of high

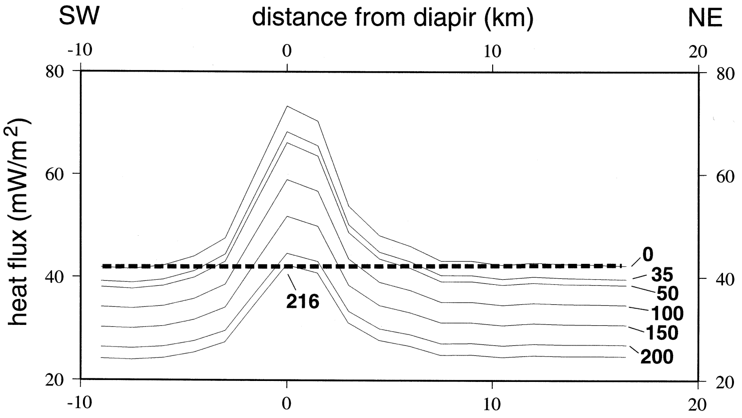


Fig. 5. Heat flux over the Blake Ridge Diapir for different salinities computed from the depth of the BSR along line 23 (solid lines). Numbers indicate salinity in g/l. A change of salinity from 0 to 216 g/l would be required to explain the shallowing of the BSR solely by increased salinity over the diapir (dashed line). See text for more details and assumptions.

reflectivity is not feasible because the layers may be thinner than a seismic wavelength which leads to interference of reflections from the top and base of these layers and hides the reflection polarity of individual layer boundaries.

### *5.3. Instantaneous frequency*

The instantaneous frequency plot of seismic data for line 23 (Figs. 3c and 4) displays high and low frequencies represented by reds and blues, respectively. A shift to lower frequency (blue) occurs beneath the BSR. Low frequency “shadows” indicate high absorption in the overlying layers. Gas-charged layers cause high absorption in addition to a sharp drop in P-wave velocity. Low frequency “shadows” are, therefore, commonly associated with free gas if they occur beneath highly reflective layers indicating strong velocity contrasts (Taner et al., 1979; Yilmaz, 1987). We suggest that the shift to lower frequencies beneath the BSR is associated with free gas. Above the diapir, between shotpoints 300–400, a vertical, narrow, low frequency anomaly extends from the BSR to the seafloor, with a lateral shift to higher frequencies adjacent to the anomaly along individual reflections, and a decrease in frequency values with depth. This low frequency anomaly correlates with high reflection strength anomalies. This observation is consistent with the suspected presence of free gas accumulations within the fault system, whereas authigenic carbonate accumulations, highly concentrated gas hydrate deposits, or enhanced porosity contrasts would generate high reflectivity, but would not be expected to cause high absorption. We caution, however, that the effect of gas hydrates on absorption of seismic waves has yet to be studied. Three-dimensional scattering and internal multiples from small-scale velocity anomalies may in theory also lead to a preferred attenuation of higher frequencies and hence, a shift of the seismic signal toward lower frequencies. For this, the sizes of the small-scale velocity anomalies that cause scattering or the thickness of the layers that cause internal multiples would have to be non-negligible at the high-frequency (short-wavelength) end of the spectrum of the seismic source signal and considerably less negligible at the low-frequency end.

## 6. What causes the shallowing of the BGHS?

The Blake Ridge Diapir is an example of an area actively undergoing forced advection of methane rich fluids and/or gas that is escaping to the seafloor from a trap that is sealed by the BGHS. A shallowing of the BSR as observed over the Blake Ridge Diapir is commonly associated with elevated heatflow. An increase in heatflow is expected above salt diapirs because the thermal conductivity of salt is several times higher than that of sediments and because of possible advective heatflow along with fluid expulsion (for a discussion of heatflow above salt diapirs see (Nagihara et al. (1992)). BSR shallowing, however, could also be caused by the inhibition effect of pore water salinity on gas hydrate stability. Increased salinity compared to that of seawater has been observed in the ODP Site 996 boreholes above the diapir. This would lead to a shift of the BGHS towards lower temperatures and hence, upward. We computed heatflow from the depth of the BSR and estimated the salinity changes that would be required to cause such a pronounced shallowing of the BSR (Fig. 5). These calculations are not intended to be an accurate heatflow study over the diapir. They should merely emphasize the significant effect of pore water salinity on the depth of the BGHS.

We assumed: (1) a pure methane/water system; (2) the phase equation of Brown (1996), including their approach to account for salinity; (3) a velocity of 1.6 km/s in the sediment above the BSR; (4) water temperature of 3.5°C at the seafloor (ODP Sites 994, 995, and 997; (Paull et al., 1996)); (5) a constant thermal conductivity of 1W/(m K) as an average of ODP Sites 994, 995, and 997 (thermal conductivity at Site 996 was only measured at 10 locations and was found to be in the range between 0.9 and 1.4; (Paull et al., 1996)); (6) thermal equilibrium (i.e. constant thermal gradient); and (7) hydrostatic pressure.

The method of calculating heatflow on the basis of depth to the BSR is currently being debated because of observations made during ODP Leg 164. Observed temperatures at the BSR at ODP Sites 994, 995, and 997 were as much as 2.9°C lower than temperatures that would be expected from the theoretical phase boundary for pure methane hydrate in fresh water (Ruppel, 1997). However, for our discussion only relative heatflow changes are important. We assume that a possible discrepancy between observed and theoretical BSR temperature is constant along the line.

Assuming a constant salinity of 35 g/l, heatflow would be predicted to increase from about 40–70 mW/m$^2$. This is roughly in agreement with results from a conventional heatflow study over a diapir further north (Ruppel et al., 1995), where heatflow increased from about 45–67 mW/m$^2$. The similarity of the “background” heatflow away from the diapir demonstrates that we used realistic estimates as input values for our calculations. Maximum heatflow above salt diapirs depends largely on their depths beneath the seafloor. The similarity of values from our calculations and from conventional measurements at a different diapir is, therefore, a mere coincidence.

We found that the salinity would have to change from 0 to 216 g/l over the diapir to explain the shallowing of the BSR by a change in salt concentration with constant heatflow (Fig. 5). Salinity of seawater is 35 g/l; salinity at the bottom of Site 996 (about 60 mbsf) was about 50 g/l. Therefore, 216 g/l seems to be an unreasonably high salt concentration. However, during DSDP Leg 23, salt concentration above a salt diapir in the Red Sea had been measured up to over 250 g/l (i.e. near saturation) (Mannheim, 1974). Salinities at about 50 mbsf at these sites were only between about 30 and 80 mg/l, similar to the concentrations at Site 996. The shallowing of the BSR could, therefore, theoretically be solely caused by an increase of salinity. Geologically this would not be a reasonable assumption since increased heatflow would be expected above salt diapirs as pointed out above. A combination of both increased salinity and heatflow is, therefore, likely to cause the shallowing of the BSR. Additional conventional heatflow measurements would be necessary to quantify the contributions from both processes. Our calculations, however, emphasize how strong an effect salinity can have on lateral variations of the BGHS and BSR. This may be important for gas hydrate studies in regions that are underlain by salt like the Gulf of Mexico.

## 7. Conclusions

We find strong indications of free gas that is trapped beneath the updomed BGHS above the Blake Ridge Diapir. Although, we cannot ultimately rule out other processes that may lead to similar seismic signatures, we suggest that this gas is escaping upward through the HSZ along faults. Evidence supporting this interpretation includes: (1) Seismic data showing “enhanced reflections”, anomalous strong reflection events, that correlate well with fault pathways above the diapir and that may result from reflections from strong acoustic impedance contrasts generated at gas pockets. (2) Attenuation of higher frequencies along faults above the Blake Ridge Diapir, resulting in vertically decreasing values for frequency anomalies, consistent with the presence of gas and/or fluids. (3) Seafloor photographs of chemosynthetic communities, authigenic carbonates and rafted hydrate deposits (?) concentrated above the crest of the diapir, and which are proximal to seafloor pockmarks within the zone of seafloor disruption (Paull et al., 1995; Paull et al., 1996).

We have quantified the effect that pore water salinity would have on the phase stability of methane hydrate, and conclude that the shallowing of the BGHS could theoretically be explained by an increase of pore water salinity. It is, therefore, not possible to predict whether increased pore water salinity or enhanced heatflow is the dominant process behind the shallowing of the BGHS. Conventional heatflow measurements and/or pore water compositions at the BGHS would have to be obtained to quantify the effects of both processes on the shallowing of the BSR.

## Acknowledgements

The US Department of Energy, Office of Naval Research and the National Science Foundation provided funding for ship operations. We would like to thank Charles K. Paull for enlightening discussions on the geology, biology and chemistry associated with the Blake Ridge Diapir and Myung Lee for helpful discussions on the subject of trace attributes. Helpful reviews by Dr Anne Tréhu and Dr Ingo Grevemeyer greatly improved the quality of the manuscript.

## References

Brown, K.M., 1996. The nature, distribution, and origin of gas hydrate in the Chile Triple Junction region. Earth Planet. Sci. Lett. 139, 471–483.

Dillon, W.P., Popenoe, P., 1988. The Blake Plateau Basin and Carolina Trough. In: Sheridan, R.E., Grow, J.A. (Eds.). The Geology of North America, The Atlantic Continental Margin, vols. 1/2, pp. 291–328.

Dillon, W.P., Popenoe, P., Grow, J.A., Klitgord, K.D., Swift, B.A., Paull, C.K., Cashman, K., 1983. Growth faulting and salt diapirism: their relationship and control in the Carolina Trough, eastern North America. Studies Continent Margin Geol. 34, 21–46.

Dillon, W.P., Lee, M.W., Fehlaber, K., Coleman, D., 1993. Gas Hydrates on the Atlantic Continental Margin of the United States-Controls on Concentration, The Future of Energy Gases. USGS Prof. Paper 1570, 313–330.

Dillon, W.P., Hutchinson, D.R., Lee, M.W., Drury, R.M., 1996, Seismic reflection profiles on the Blake Ridge near sites 994, 995 and 997, Proceedings of the Ocean Drilling Program, Initial Reports, vol. 164, pp. 47–56.

Domenico, S.N., 1977. Elastic properties of unconsolidated porous sand reservoirs. Geophysics 42, 1339–1368.

Dvorkin, J., Nur, A., 1993. Rock Physics for the characterization of gas hydrates, The Future of Energy Gases. USGS Prof. Paper 1570, 293–298.

Egeberg, P.K., 2000. Hydrates associated with fluid flow above salt diapirs (site 996), in press.

Esikov, A.D., Pashkina, V., 1990. A study of the process of joint formation of methane gas-hydrate and authigenic carbonates in bottom sediments in the Sea of Okhosk. Natl Geophys. 4 (1), 135–141.

Ginsburg, G.D., Soloviev, V.A., 1997. Methane Migration within the submarine gas-hydrate stability zone under deep-water conditions. Mar. Geol. 137, 49–57.

Holbrook, W.S., Hoskins, H., Wood, W.T., Stephen, R.A., Lizarralde, D., Leg 164 Science Party, 1996. Methane hydrate and free gas on the blake ridge from vertical seismic profiling. Science 273, 1840–1843.

Holvland, M.H., Judd, A.G., 1988. Seabed Pockmarks and Seepages: Impact on Geology, Biology and the Marine Environment, Graham and Trotman, London, 293 pp.

Hovland, M.H., 1992. Hydrocarbon seeps in northern marine waters—their occurrence and effects. Palios 7, 376–382.

Lee, M.W., Hutchinson, D.R., Dillon, W.P., Miller, J., Agena, W.F., Swift, B.A., 1993. Method of estimating the amount of in situ gas hydrates in deep marine sediments. Marine Petrol. Geol. 10 (5), 493–506.

Macay, M., Westbrook, G., Hyndman, R., ODP Leg 146 Scientific Party, 1994. Origin of bottom simulating reflectors: geophysical evidence from the Cascadia accretionary prism. Geology 22, 459–462.

Mannheim, F.T., 1974. Red Sea geochemistry. In: Whitmarsh, R.B., Weser, O.E., Ross, D.A. (Eds.). Initial Rep. Deep Sea Drill. Proj., vol. 23. US Printing Office, Washington, DC, pp. 975–995.

Nagihara, S., Sclater, J.G., Beckley, L.M., Behrens, E.W., Lawver, L.A., 1992. High heatflow anomalies over salt structures on the Texas continental slope, Gulf of Mexico. Geophys. Res. Lett. 19, 1687–1690.

Paull, C.K., Spiess, F.N., Ussler III, W., Borowski, W.S., 1995. Methane-rich plumes on the Carolina continental rise: associations with gas hydrates. Geology 23, 89–92.

Paull, C.K., Matsumoto, R., Wallace, P.J., 1996. Proceedings of the Ocean Drilling Program, Initial Reports vol. 164, 1–623.

Ruppel, C., 1997. Anomalously cold temperatures observed at the base of the gas hydrate stability zone on the US Atlantic passive margin. Geology 25, 699–702.

Ruppel, C., von Herzan, R.P., Bonneville, A., 1995. Heat flux through an old (~275 Ma) passive margin: offshore southeastern United States. J. Geophys. Res. 100, 20 037–20 057.

Sloan, E.D., 1990. Clatherate Hydrates of Natural Gases, Marcel Dekker, New York, pp. 1–641.

Soloviev, V.A., Ginsburg, G.D., 1997. Water segregation in the course of gas hydrate formation and accumulation in submarine gas-seepage fields. Mar. Geol. 137, 59–68.

Taner, M.T., Koehler, F., Sheriff, R.E., 1979. Complex trace analysis. Geophysics 44 (6), 1041–1063.

Waite, W.F., Helgerud, M.B., Nur, A., Pinkston, J., Stern, L.A., Kirby, S.H., Durham, W.B., 1998. EOS Transactions, vol. 79(45). American Geophysical Union, p. 463.

ODP Leg 164 Science Party, Wood, W., Holbrook, W.S., Hoskins, H., Rowe, M.M., Gettrust, J., 1996. EOS Transactions, vol. 77(46). American Geophysical Union, p. 322.

Yilmaz, O., 1987. Seismic Data Processing; Investigations in Geophysics. Society of Exploration Geophysicists. Tulsa, vol. 2, 526 pp.