INTRODUCTION AND BACKGROUND

The application of geophysical methods to the study of methane hydrates is motivated by the need to characterize physical parameters or processes that may control or be affected by the distribution of gas hydrate and free gas. Although drilling provides direct samples of gas, hydrate, and sediment, geophysical methods have the capacity to estimate the distribution of free gas and gas hydrate both laterally and vertically, quickly and remotely over large areas. A particular strength of Leg 164 was the combination of direct sampling (coring) with the acquisition of in situ and laboratory geophysical data from which the elastic, thermal, electrical, magnetic, and porous media properties of the sediments and gas hydrate reservoir can be estimated.

Previous geophysical studies in the Ocean Drilling Program (ODP) Leg 164 study area have focused primarily on characterizing thermal (Ruppel et al., 1995) conditions or elastic properties that are either directly or indirectly related to the occurrence of gas hydrates. The Blake Ridge was among the earliest marine provinces recognized as a significant gas hydrate area (Markl et al., 1970), and initial single-channel seismic (SCS) and multichannel seismic (MCS) studies (Shippley et al., 1979; Paull and Dillon, 1981) focused on determining the nature and extent of the bottom-simulating reflector (BSR). Attempts to quantify the amount of gas hydrate present in this area have been made on the basis of seismic velocity analyses (Rowe and Gettrust, 1994), waveform inversion (Wood et al., 1994; Korenaga et al., 1997), and SCS reflection amplitudes (Lee et al., 1993). Other seismic data have been used to interpret connections between geologic structures (faults and slumps) and gas hydrate/free-gas deposits (Dillon et al., 1994; Dillon, Danforth et al., 1996; Dillon, Hutchinson et al., 1996). High-resolution seismic surveys (both surface and deep towed) have revealed finer scale structural features, including complex fault systems cutting through the BSR and overlying sediment and a BSR that appears broken and discontinuous over length scales of meters to tens of meters (Rowe and Gettrust, 1993a, 1993b; Dillon et al., 1994).

ODP Leg 164 greatly enhanced the existing geophysical data sets for gas hydrate provinces through the acquisition of zero offset and walk-away vertical seismic profiles (ZVSPs and WVSPs, respectively) and closely spaced (30–50 m) downhole temperature data at three sites located along a transect on the Blake Ridge. This paper first reviews the major results to emerge from the analysis of Leg 164 geophysical and ancillary data sets. We then discuss the implications of the geophysical results for certain phenomena (e.g., seismic blanking); for interpretation of the base of gas hydrate stability, the base of the zone of gas hydrate occurrence, and the top of the free gas zone; and for the microscale (centimeters to meters) distribution of gas hydrate. Throughout this synthesis, we incorporate results from Leg 164 geochemical and sedimentological analyses as appropriate.

Geologic Setting

The Inner Blake Ridge, a major physiographic feature on the southeastern U.S. passive margin, is a sediment drift deposit formed by erosion of the Blake Plateau at the confluence of the late Oligocene (Tucholke and Mountain, 1986) or early Miocene Gulf Stream (Markl and Bryan, 1983; Dillon and Poponoe, 1988). The Blake Ridge has several distinct advantages for the study of the distribution of gas hy-
hydrate and free gas and of the processes related to evolution of gas hydrate provinces. First, the vertical and lateral homogeneity of Blake Ridge sediments and sedimentary processes implies that any major changes detected in seismic stratigraphy and seismic velocity structure might be directly attributable to the presence of free gas or gas hydrate. Second, the Blake Ridge lies in a tectonically quiescent setting, proximal to the passive margin. This implies that the Blake Ridge should not be significantly affected by major late Cenozoic tectonic activity or by large-scale fluid flow along major faults in the basement or sedimentary column, factors that have complicated analyses in other gas hydrate provinces (e.g., Cascadia; Westbrook, Carson, Musgrave, et al., 1994). Finally, the Blake Ridge BSR is among the best studied on Earth’s continental margins and may be considered the archetypal BSR (Shipley et al., 1979), due to its conspicuous crosscutting relationship to strata being eroded on the ridge’s northeastern flank. A consistent and intriguing aspect of the Blake Ridge sediments is low reflectivity between the seafloor and the BSR (Fig. 1).

Despite the quiescent tectonic regime and uniform sedimentology of the Blake Ridge, both Leg 164 and ancillary studies have yielded results that partially challenge assumptions about the simplicity of this setting for the study of gas hydrate problems. For example, various seismic studies have revealed the presence of a large-scale collapse structure near the principal drilling transect (Dillon, Danforth, et al., 1996) and pervasive small offset normal faults rooted within the gas hydrate–bearing zone (Rowe and Gettrust 1993a, 1993b; Wood and Gettrust 1998) coincident with the transect. Just off the transect, SCS Line 16 reveals a complicated pattern of sedimentation, slumping, reflectivity, and disrupted BSRs (W.S. Holbrook, pers. comm., 1998). These observations suggest processes more sophisticated than a laterally uniform zone of high-velocity, hydrate-laden sediment immediately above a zone of gas-charged sediment.

### SUMMARY OF FINDINGS FROM SEISMIC MEASUREMENTS

#### Compressional Wave Velocity ($V_p$) Analysis

The most time consuming, but also most direct, geophysical technique employed on Leg 164 was vertical seismic profiling (both WVSP and ZVSP) at Sites 994, 995, and 997 using air-gun and water-gun sources. Details of the VSP experiments can be found in Paull, Matsumoto, Wallace, et al. (1996). In addition to very accurate estimates of depth to the BSR (440 ± 10 m at Site 995, and 464 ± 8 m at Site 997), the ZVSP results (Figs. 2, 3) suggest the presence of a thick low-velocity zone ($V_p < 1550$ m/s) below the BSR. Holbrook et al. (1996) attribute the sharp drop in velocity to gas-charged sediments, the upper limit of which is marked by bright, reversed polarity reflections in the SCS data (Figs. 1, 3). However, at Site 994 this bright reflector is not continuous with the strong BSR observed at Sites 995 (440 mbsf) and 997 (464 mbsf). Instead, the Site 994 reflector lies at a depth of ~560 mbsf. As it is traced across the ridge, this reflector parallels the BSR at Sites 995 and 997 and even appears to lie above the BSR several kilometers to the northeast (Dillon, Hutchinson, et al., 1996). Although the ~560 mbsf reflector almost certainly corresponds to the top of free gas at Site 994, in a more regional sense the reflector appears to be coincident with the top of a series of gas-charged sediments. The change in depth of the top of gas may be due to a lower methane flux at Site 994 than at Sites 995 and 997 (Xu and Ruppel, 1999).

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Figure 1. Line 31 (from Katzman et al., 1994) is shown here unmigrated and converted to depth using interpolated and extrapolated velocities determined from the VSPs at Sites 994, 995, and 997. The section is displayed to accentuate the fine-scale faulting (discontinuous reflections) throughout the gas hydrate–stability zone. The high-amplitude events below 3300 m correspond to gas-charged sediments at Site 994, and continue below the BSR at Sites 995 and 997. The change in depth of the top of gas may be due to a lower methane flux at Site 994 than at Sites 995 and 997 (Xu and Ruppel, 1999).
buried faults seen in some seismic sections. At Sites 995 and 997, the coincidence of the BSR in the SCS data and the top of the free-gas zone as constrained by the VSP data confirms earlier interpretations of the BSR as a reversed polarity reflector that marks the top of the free-gas zone (Shipley et al. 1979; Paull and Dillon, 1981). The seismic velocities determined from the ZVSP data were confirmed by a WVSP study that revealed ~10% anisotropy in $V_P$ at Site 995 (Pecher et al., 1997). Although this result may have some implications for quantifying the concentration and distribution of gas hydrate (e.g., evenly disseminated vs. as cement in layers), such values of anisotropy are not unusual in fine, layered sediments (Levin, 1979) and may not necessarily reflect the presence of gas hydrate.

The velocities within the GHZ determined from the ZVSPs were also somewhat lower than velocities derived from other measurements in the area (Fig. 2). Using wide angle ocean bottom hydrophone (OBH) data from this location, Katzman et al. (1994) estimate that the velocity of the sediments ~200 m above the BSR is 1900 m/s, similar to the result obtained by Wood et al. (1994) using MCS data acquired with a 6-km-long, surface-towed streamer. The highest velocities reported for GHZ sediments in the area are as high as 2450 m/s and are determined from deep-towed MCS data acquired on the flank of the ridge ~160 km to the south and in 4000 m of water (Rowe and Gettrust, 1993b). The anisotropy discussed earlier may explain the lower velocities determined on the basis of the ZVSPs. The energy recorded by the ZVSPs travels in the vertical, slow direction, whereas the other analyses are based on energy traveling with some horizontal component, resulting in higher estimates of velocity. However, anisotropy of 10% is insufficient to explain the velocity discrepancy between the ridge crest and flank, which are presumably lithologically similar. The difference in velocities might be better explained by higher gas hydrate concentrations on the flank than on the crest of the ridge. As discussed below, higher concentrations of gas hydrate may reflect more vigorous fluid flux. Greater concentrations of gas hydrate on the ridge flank might be expected if the highly disrupted nature of the BSR (Rowe and Gettrust, 1993a) is either a cause or effect of increased fluid flux.

Another assessment of $V_P$ values in the study area has been made by Tinivella and Lodolo (Chap. 28, this volume) based on tomographic inversion of surface-towed MCS data. The results are generally consistent with those obtained from the VSP data but have poorer vertical resolution due to the geometry of the data acquisition.

**Shear-Wave Velocity ($V_S$) Analysis**

In marine settings, shear-wave velocity measurements with a surface source may only be obtained from seismic energy that has been converted from $P$- to $S$-waves. This requires large incidence angles, or equivalently, large offsets, which were obtained on Leg 164 using a walk-away VSP (WVSP) data collected with borehole geophones operated from the JOIDES Resolution at Sites 994 and 995. The data were acquired using a 150-in$^3$ generator-injector air-gun source towed behind a second ship (R/V Cape Hatteras) at offsets up to ~5 km, allowing incidence angles of up to 45°. A better signal to noise ratio was obtained at Site 995 than at Site 994 because of operational and mechanical issues (Paull, Matsumoto, Wallace, et al., 1996). Most analyses have therefore concentrated on the Site 995 data. At Site 995, additional wide-angle data were also obtained through the deployment of a three-component ocean-bottom seismometer.

To date, the analyses of the WVSP data collected on Leg 164 have revealed the first known $P$-to-$S$ conversions from a BSR (Pecher et al., 1996, 1997), an effect attributed to a sharp change in $V_S$ at the reflector. Other converted shear waves in the data set came from within the GHZ itself, but accurate determinations of the depths of these conversions requires extensive inverse modeling. For the specific geometry of the WVSP experiments, Pecher et al. (1997) show that if the shear modulus changes across a given interface, then a significant $V_S$ impedance contrast can exist without a significant $V_P$ impedance contrast. Thus, if small amounts of gas hydrate cement mostly affect the shear modulus of sediments (Dvorkin and Nur, 1993), then the re-
Figure 3. At each of Sites (A) 994, (B) 995, and (C) 997, a suite of geophysical measurements is compared with the Cl– and CaCO3 profiles. The minima in the Cl– profile (left, circles) are the most direct measure of hydrate concentration available and show roughly the same pattern of variation throughout the GHSZ (200–450 mbsf) at all three sites. At each site note the strong correlation between the peaks in CaCO3 (center left) and high seismic reflectivity (center right) in the upper ~100 m of the sediment column. Note also low Vp (bold curve, left panel) associated with the high seismic reflectivity lower in the section, between 450 and 600 mbsf. These effects accentuate the appearance of weak reflectivity from 100 to 450 mbsf. The intersection of the extrapolated temperature profile (right panel) with the phase equilibrium curve for 3.3% seawater (dashed curve) and fresh water (solid curve) at Sites 995 and 997 lies significantly deeper than the base of gas hydrate stability inferred from the seismic data, (redrawn from Paull, Matsumoto, Wallace, et al., 1996; Holbrook et al. 1996; and Ruppel, 1997).
results of Pecher et al. (1997) suggest that seismically based determinations of the concentration and distribution of gas hydrate may require the use of wide angle data.

Attenuation Analysis

The attenuation of $P$-waves through Blake Ridge sediments has been investigated by Wood et al. (Chap. 27, this volume) using SCS data acquired at the sea surface on a transect coincident with the drill sites (Fig. 1, Line 31; Katzman et al., 1994). The analysis was based on the change in frequency content of the normal incident signal with depth, and the principal results are shown in Wood et al. (Fig. 2B of Chapter 27, this volume). Although detailed investigations of $Q$ in fine-grained sediments are rare, Wood et al. (Chap. 27, this volume) suggest that gas hydrate concentrations on the order of a few percent by volume have little or no effect on $P$-wave attenuation. Values of $Q = 100$–400 determined within the gas hydrate–stability zone (GH-SZ) are not unexpected for fine-grained sediments lacking gas hydrate (Bowles, 1997). Below the GH-SZ, the analysis revealed significantly higher attenuation ($Q$ values as low as $\sim$5), consistent with gas charged sediments (Toksoz et al., 1979). This corroborates the results of other seismic studies that indicate the presence of free gas at this depth (Holbrook et al., 1996).

Seismic Constraints on Fault-Controlled Gas Hydrate Deposition

Leg 164 also provided sample, logging, and paleontological data critical to the interpretation of seismic images that reveal high-angle faulting of Blake Ridge sediments. Figure 4A shows surface-towed, 10- to 240-Hz SCS data collected in the vicinity of Site 997 as part of Line 31 (Katzman et al., 1994). These data are very mildly filtered (cosine ramp from 0 to 1 between 5 and 10 Hz and from 1 to 0 between 200 and 240 Hz) and have not been migrated, because such processing may blur higher frequency waveforms. The image shows faulting (lateral discontinuities) throughout the GH-SZ and underlying sediments. However, it is difficult to trace individual faults or determine which, if any, fault or faults may have been intersected during drilling.

Evidence that a fault plane was intersected at Site 997 comes from the composite paleontological record (Fig. 4D) to a depth of 424 mbsf in Hole 997A and from 416 to 750 mbsf in Hole 997B (Paull, Matsumoto, Wallace, et al., 1996). A temporal hiatus between 360 and 375 mbsf (arrow in Fig. 4D) corresponds to $\sim$14 m of missing section. There is no indication in the seismic data of an exceptionally strong reflector or truncated reflectors corresponding to an erosional surface at this depth. Normal faulting, which is seen in seismic data and which can account for missing section, is the more likely explanation.

A higher resolution image of this type of faulting was acquired in 1993 at a location $\sim$1 km to the southeast of the drilling transect using the Naval Research Laboratory’s deep-towed acoustics geophysics system (DTAGS, Gettrust et al., 1991). The small sample of unmigrated data shown in Figure 5 is of the same vertical and horizontal dimension as the SCS data in Figure 3. The 24-channel vertical array DTAGS data were moved out, median stacked, and shifted to make the seafloor horizontal; depth converted using velocities obtained at Site 997 by Holbrook et al. (1996); and gained with a linear ramp of slope 0.08 m$^{-1}$ beginning at 80 mbsf. The DTAGS data exhibit clear images of individual faults and show that the faults are spaced tens to hundreds of meters apart, frequently penetrate the BSR, and are quite
prevalent on the ridge crest (Rowe et al., 1995; Wood and Gettrust, 1998). Displacement across the faults, which the DTAGS section clearly shows to be syndepositional, is ~14 m at 340 mbsf but less than vertical resolution of the data at ~30 mbsf. This amount of displacement is consistent with the thickness of missing section estimated from the paleontological results. That the perturbation of the BSR at the location of the faults is significantly smaller than the displacement on the fault might be partially attributed to a small pressure change across the fault (Rowe and Gettrust, 1993a). The faults have normal sense displacement and associated minor antithetic faults that produce small grabens.

The significance of the faulting is clear when viewed in the context of other Leg 164 geophysical data. A massive section of hydrate ~20 cm long (pure hydrate, from which virtually all sediment has been excluded) was recovered at 330 mbsf at Hole 997A but not at Hole 997B, located only 20 m away to the northwest (Fig. 4A). Subsequent logging of Hole 997B revealed a thin (less than a few meters thick) zone of anomalously high acoustic velocity and resistivity at 365 mbsf (Figs. 4B and 4C, respectively), interpreted as an indicator of localized concentrations of methane hydrate (Paull, Matsumoto, Wallace, et al., 1996). The velocity and resistivity anomalies in Hole 997B occurred 35 m deeper than the massive hydrate in Hole 997A and were inferred to indicate the presence of gas hydrate in ~23% of pore volume (Paull, Matsumoto, Wallace, et al., 1996).

Highly localized concentrations of gas hydrate like those discovered in Hole 997A are consistent with hydrate accumulation controlled by strong fluid advection (Xu and Ruppel, 1999), probably in a high-permeability zone represented by a single high-angle fault crossing both holes. If gas hydrate concentration was instead primarily controlled by sediment stratigraphy, two holes separated by only 20 m might be expected to exhibit sediment anomalously rich in hydrate at nearly identical depths. Although the paleontologically determined intersection of a possible fault and the two holes is inexplicably reported 30–40 m deeper than the level that yielded the massive hydrate, it seems fairly certain that at least one fault was intersected and that this fault likely promotes fluid advection and gas hydrate formation.

**SUMMARY OF FINDINGS FROM TEMPERATURE MEASUREMENTS**

Three downhole tools were used to acquire temperature data at a nominal vertical spacing of 30–50 m to depths as great as ~415 mbsf at Sites 994, 995, and 997. The deepest measurements at both Sites 995 and 997 were to within 55 m above the BSR and provide an unprecedented constraint on temperatures deep within a thick GHZ. Details of the data acquisition and preliminary analysis can be found in
Three independent estimates of temperature at the BSR can be obtained from Leg 164 and peripheral data sets (C. Ruppel, unpubl. data). The simplest method uses the technique described by Yamano et al. (1982) to determine the BSR temperature by combining the gas hydrate phase equilibria and constraints on the depth of the BSR below the seafloor. Assuming that pressure in the sediments is hydrostatic, the BSR temperatures estimated using this method are 21.6°C–22.7°C at Sites 995 and 997 for stability boundaries based on the Brown et al. (1996) fit to the Dickens and Quinby-Hunt (1994) results for 3.3% NaCl water and on Sloan (1998) for freshwater. The second estimate can be derived from downward extrapolation of the shallow thermal gradients measured by Ruppel et al. (1995) to the depth of the BSR. This calculation yields BSR temperature estimates of ~24°C and ~25.5°C at Sites 995 and 997, respectively. The third and probably most accurate estimate is based on downward projection of the Leg 164 in situ temperature data and yields BSR temperatures of 17.4°C–18.8°C and 19.8°C–21.1°C at Sites 995 and 997, respectively (Ruppel, 1997).

The disparities between these BSR temperature estimates highlight several problems with using data other than those collected in deep boreholes to constrain the thermal state of sediments within a GHZ. First, if the in situ data acquired on Leg 164 are presumed to provide the most accurate constraint on BSR temperatures, then even very high quality traditional heat flow data may yield an overestimate of actual BSR temperatures (C. Ruppel, unpubl. data). It is striking that this result was obtained in a low advective flux setting (Egeberg and Dickens, 1999) in a sediment drift deposit near a tectonically qui-

Figure 5. Deep-towed, high-frequency vertical array data clearly show not only the position, but also the displacement on faults that penetrate the BSR. This is a small sample of a larger data set that reveals fault spacing at tens to hundreds of meters (from Wood and Gettrust, 1998).

Paull, Matsumoto, Wallace, et al. (1996), and Ruppel (1997). The Leg 164 temperature data can be used to constrain the conductive and advective components of heat flux, to evaluate disparities between traditional heat flow data (Ruppel et al., 1995) and in situ measurements, and to determine temperatures at the BSR.
escent continental margin. BSR temperature estimates based on downward extrapolation of surface heat flow may be even more inaccurate in active margin gas hydrate provinces characterized by high fluid-flux rates, variated sediments, and tectonic deformation. Second, the method of Yamano et al. (1982) only provides a rough measure of the thermal gradient in the sediments above the BSR if the approximate BWT is known and if sediments can be assumed to be in thermal equilibrium with the bottom water. Third, the BSR temperatures at Sites 995 and 997 lie 2.9°C (Ruppel, 1997) below those predicted at the base of the GHSZ using presently accepted stability curves (Dickens and Quinby-Hunt, 1994; Sloan, 1997).

Several physical and chemical processes have been invoked to explain low temperatures at the Blake Ridge BSR. Capillary forces in the fine-grained sediments (e.g., Clennell et al., in press) or controversial third-surface effects associated with the high concentration of clay minerals (Cha et al., 1988; Kotkoskie et al., 1990) may inhibit gas hydrate stability. Alternately, the phase equilibria for systems at these pressures (~32.2 MPa) may still be too poorly known to draw reliable conclusions about the significance of the apparently cold temperatures measured deep within the GHZ, close to the BSR. Indeed, new theoretical curves emerging from statistical thermodynamics calculations (Tobih, et al., 1997) yield dissociation temperatures much closer to those determined for the Blake Ridge BSR although capillary effects may still need to be invoked to explain the full magnitude of the apparent temperature deficit at the BSR (Clennell et al., in press).

**DISCUSSION**

**Blanking**

The relatively lower reflection amplitudes of some sediments within the Blake Ridge GHSZ compared to sediments below the GHSZ have been previously interpreted as reduction of impedance contrast and reflectivity due to cementation of sediment by gas hydrate (Lee et al., 1993). Holbrook et al. (1996) did not find the anomalously high velocities one would expect for frozen sediment, and they attributed the lack of impedance contrasts within the GHSZ to the homogeneity of the sediments at this location, which may only be reflective below the GHSZ because of the presence of free gas within preferentially porous strata. Although the velocities determined from the VSPs suggest minimal cementation on a scale of tens to hundreds of meters, the relative amplitude reduction (or blanking) may involve factors other than merely sediment homogeneity.

In some highly localized zones, particularly near faults, the Leg 164 sampling and logging results imply that gas hydrate concentrations may be high enough to fill a significant portion of pore space and to affect seismic velocity at submeter- to meter-length scales. Dillon et al. (1994) describe “fingers” of blanking that extend upward into the GHSZ from faults below the BSR. Such blanking zones may continue to even shallower depths in the section along unresolved faults. Cementation from high concentrations of gas hydrate are more likely in fault zones than in adjacent, unfaulted sediments characterized by presumably lower fluid flux. However, these potentially cemented fault zones are not oriented horizontally, may be quite irregular in shape and impedance, and may thus be more efficient in scattering energy outward rather than directly upward to the receivers. Thus, a “blank” zone in seismic data may imply a paucity of nearly horizontal reflectors, not necessarily a lack of impedance contrasts. The kind of scattering described here typically exhibits strong frequency dependence (e.g. Clay and Medwin, 1977) and would likely yield different results when studied with seismic systems of different frequencies.

Another phenomenon that may be responsible for blanking at larger scales is the increasing throw with depth on the syndepositional faults imaged in the DTAGS seismic data (Fig. 5). A spherical, spreading seismic wave has a finite lateral resolution that decreases with decreasing frequency and increasing distance from the reflector. Inhomogeneities that are below the resolution are averaged, and, due to scattering, generally result in lower reflectivity being recorded by the receivers (Clay and Medwin, 1977). For wavelengths greater than ~30 m, (less than ~60 Hz), a 15-m displacement in a reflector creates destructive interference, and the observed reflectivity is diminished. For data of this frequency, we would therefore expect a decrease in observed reflectivity with depth, because the lateral heterogeneity increases due to increasing fault throw. Destructive interference will increase with the distance from the source as more heterogeneity is incorporated into the first Fresnel zone. This may explain why the high-frequency, deep-tow data shown in Figure 5 (250–650 Hz, at 750 m above the BSR) does not show as great a discrepancy between reflectors just above and just below the top of gas as seen in the surface-tow data of Figure 1 (10–240 Hz, 3250 m above the BSR). The lateral heterogeneity of the faulted sediments, combined with the nonhorizontal distribution of hydrate, leads us to believe that the reduced reflectivity is more likely due to scattering and destructive interference than to reduced impedance contrasts from sediment cementation.

**Phase Equilibria and Seismically Important Boundaries in the Reservoir**

Theoretical modeling of the steady-state methane gas hydrate system in porous marine sediments (Xu and Ruppel, 1999) reveals several misconceptions about the significance of the BSR relative to the base of the GHSZ and GHZ. Although the intersection of the temperature profile with the phase boundary does mark the lower limit of gas hydrate stability (base of GHSZ) and the potential upper limit for the top of free gas, several factors control where gas hydrate (GHZ) and free gas actually occur. Most notably, the GHZ can only extend as deep as the base of the stability zone/top of the free-gas zone if the rate of methane supply exceeds a critical rate whose value depends on fluid-flux rate, energy flux, and other parameters. Furthermore, under certain conditions, the top of the free-gas zone may be separated from the base of the GHSZ by a layer of sediments lacking both free gas and gas hydrate.

Xu and Ruppel (1999) note that these results have particular significance for interpreting seismic data and other observations made on ODP Leg 164. At Site 994, where a strong BSR continuous with those at the adjacent sites is lacking, Holbrook et al. (1996) inferred the presence of free gas at ~560 mbsf. Chloride anomalies between 196 and 456 mbsf at this site (Paull, Matsumoto, Wallace, et al., 1996) are consistent with pore-water freshening (Hesse and Harrison, 1981) and the in situ occurrence of gas hydrate. Thus, the top of the free-gas zone at Site 994 appears to lie significantly below the base of the actual zone of gas hydrate occurrence (GHZ), consistent with models in which the methane supply rate is less than the critical value. At Sites 995 and 997 (strong BSR), the top of the free-gas zone and the base of the GHZ are effectively coincident, which implies that the methane supply rate at these sites exceeds the critical value. Thus, if all other physical parameters at Sites 994 and 995 are approximately equivalent, the 3-km distance that separates the two sites may mark a transition from precritical to critical methane supply rates (C. Ruppel, unpubl. data). This transition in methane supply rates is accompanied by a transition from noncoincidence to coincidence of the top of free gas and the base of the GHZ/GHSZ and a consequent change from no BSR (Site 994) to a strong BSR (Site 995). If all methane were supplied by biogenic processes occurring below the GHSZ, then the observed coincidence between the top of free gas and the base of the GHZ can be used to determine the critical rate of methane supply and the potential size of the methanogenic bacterial population (Xu and Ruppel, 1999).

Figure 6 shows the predicted depths of different boundaries within the Blake Ridge gas hydrate system and the relationship between methane supply rate and the depth to the top of the free-gas zone, de-
determined using the Xu and Ruppel (1999) analytical model. Note that the base of the GHSZ in these plots lies closer to the actual observed depth of the BSR at Site 995 than would be predicted based on traditional stability curves and the measured geotherm (Ruppel, 1997). Two factors combine to explain the close agreement of the observed BSR depth (~440 mbsf) and the predicted depth to the top of free gas and base of the GHSZ/GHZ in Figure 6. First, the adopted value for constant energy flux (combination of advective and conductive components) is 40 mW/m², which is at the high end of the range of values (36.2–39.9 mW/m²) determined at Site 995 (C. Ruppel, unpubl. data). Second, the phase equilibria used in the Xu and Ruppel (1999) model are based on state-of-the-art statistical thermodynamics calculations by Tohidi et al. (1995) for methane hydrate and 3.5% seawater. These predicted phase equilibria yield somewhat lower temperatures at the base of the GHZ and a predicted BSR (where the top of free gas is in coincidence with the base of the GHZ/GHSZ) at a depth closer to that observed from seismic methods.

**Microscale Hydrate Distribution**

Large amounts of visible hydrate were not recovered at Sites 994, 995, and 997, except for the single 20-cm-long massive piece recovered at 330 mbsf in Hole 997A, probably at the intersection of a fault and the borehole. The overall lack of visible hydrate deposits, coupled with catwalk temperature measurements made immediately upon core recovery (Paull, Matsumoto, Wallace, et al., 1996), suggests that much of the gas hydrate in the section probably is finely disseminated. Independent analyses based on pore-water chloride anomalies, (Paull, Matsumoto, Wallace, et al., 1996), resistivity logs (Paull, Matsumoto, Wallace, et al., 1996), and seismic data (Holbrook et al., 1996) yield an estimate of 2%–3% gas hydrate throughout the GHZ.

If disseminated gas hydrate forms at grain contacts, it may act as a cement, effectively freezing the sediment. Dvorkin and Nur (1993) have shown that for cementation at an idealized spherical grain contact, both $V_p$ and $V_s$ reach ~90% of their saturation values when the cement occupies only ~3% of the total volume. However, the VSP data reveal only modest increases in velocity and do not support the cementation hypothesis on the scale of tens to hundreds of meters. Conversely, theoretical considerations and laboratory experiments (e.g., Handa and Stupin, 1992; Clennell et al., in press) suggest that capillary forces arising in fine-grained sediments like those on the Blake Ridge may inhibit gas hydrate stability, leading to an inference of initial formation in pore spaces away from grain boundaries (Clennell et al., in press). Ecker et al. (1998) used a model of gas hydrate formation away from grain contacts to explain MCS amplitude vs. offset results from the Blake Ridge. For seismic waves on the scale of meters or larger, the medium is a continuum, and gas hydrate in pore spaces would likely affect the $V_p$ of the sediment in a time-averaged sense, based on the fractional volume of gas hydrate present

![Figure 6](image_url)  
**Figure 6.** Relationship between the GHSZ, the GHZ, and the free-gas zone as determined from the theoretical, one-dimensional, steady-state model of Xu and Ruppel (1999). Based on parameters approximately appropriate for the Blake Ridge. These calculations use the observed BWT of 3°C and water depth of ~2800 m and assume constant porosity of 0.5. Mass flux is taken as 0.3 mm/yr, similar to the advection rate determined by Egeberg and Dickens (1999), and values of 40 mW/m² and 10–14 m² are adopted for energy flux and permeability, respectively. Solubility constraints are from Zatsepina and Buffett (1997). For the crude physical parameters chosen here, the predicted top of the free-gas zone lies at ~350 mbsf for a methane supply rate of 52.5 mol/m²/k.y. at Site 994. The bottom of the stability zone is at 453 mbsf, and gas hydrate is predicted to occur in a zone between 124 and 398 mbsf. The predicted base of the GHZ is shallower than the depth to which Cl⁻ anomalies extend (Fig. 3A). At Sites 995 and 997, where the BSR is strong, the top of the free-gas zone is predicted to be in coincidence with both the base of the stability zone and the base of the zone of actual gas hydrate occurrence. The critical methane supply rate must exceed 61 mol/m²/k.y. to produce coincidence of the base of the GHSZ/GHZ and the top of the free-gas zone at Site 995 for this set of adopted physical parameters. The transition from the subcritical to critical methane flux rate occurs over a narrow range of values. The model results shown here correspond to only one physical process that may explain the differences between Sites 994 and 995.
A small (2%–3%) concentration of hydrate would thus have only a small effect on elastic properties, a result consistent with the observed ZVSP velocities.

WVSP data are also affected by the microscale distribution of hydrate. The converted $S$-waves that arise within the GHZ occur at horizons where shear modulus changes abruptly, possibly due to gas hydrate forming at grain contacts over zones that are hundreds of meters thick. However, it is difficult to unambiguously ascribe changes in shear moduli to the presence of gas hydrate or the cementation of sediments by gas hydrate. Whether the contrasts in shear moduli are more significant than would be expected for compacting sediment lacking gas hydrate remains to be determined. Although $V_p$, $V_s$, and Q measurements from Leg 164 do not clearly resolve the microscale distribution of gas hydrate, current analyses suggest that the elastic effects from 2% to 3% gas hydrate by volume are small.

**Faults**

The Leg 164 geophysical data are consistent with increased concentration of gas hydrate near faults of the type shown in the seismic images of Figures 1 and 5. Such features were previously suspected to be possible conduits for advective flux (Wood et al., 1997) and the escape of methane gas (Rowe et al., 1995). As shown quantitatively by Xu and Ruppel (1999), large concentrations of gas hydrate or high accumulation rates are almost unequivocally linked to high rates of fluid flux and methane supply to porous sediments within the stability zone. At present, we lack a detailed high-resolution image that can precisely constrain the angle at which the boreholes may have intersected a fault. Furthermore, the degree of variability in gas hydrate concentration (Paull, Matsumoto, Wallace, et al., 1996) between Holes 997A (up to 100% at 330 mbsf) and 997B (23% at 365 mbsf) and sparse lateral sampling render simple interpretations impossible, particularly if the holes intersect the same fault. Quantitative calculations on a one-dimensional system indicate that gas hydrate accumulations in homogeneous porous media should be either relatively uniform with depth or more concentrated near the base of the zone (~450 mbsf), depending on the rate of mass flux through advection-dominated systems (Xu and Ruppel, 1999). If a fault represents a zone of effectively 100% porosity and Holes 997A and 997B intersect the same fault, then the inferred pattern of gas hydrate concentrations in both the vertical and lateral directions does not conform to the pattern predicted by simple models. More extensive modeling using more realistic parameters based on better field constraints on the lateral and vertical distribution of gas hydrate will be necessary to address the issue of gas hydrate distribution along conduits.

The thermal data do not reveal a significant advective component at any of the sites, but the slightly elevated thermal gradient at Site 997 is consistent with the intuitive notion that gas hydrate near a fluid conduit (fault) lies closer to the stability boundary than gas hydrate in the surrounding sediments and at adjacent sites. The fault zone provides an obvious escape pathway for warmer than in situ methane-laden fluids produced through dissociation of gas hydrate. Gas hydrate in and near such fault zones may represent a less stable, more mobile subreservoir whose dissociation might be triggered by relatively small bottom-water temperature increases or sea-level falls (possibly accompanying climate change; Paull et al., 1991; Dickens et al., 1995, 1997) or even episodes of rapid sedimentation (e.g., Pecher et al., 1998).

The potential high concentration of gas hydrate along faults may also affect seafloor stability. Dissociation of gas hydrates has long been linked to large mass-wasting phenomena produced when sediments presumably liquefy during gas hydrate dissociation (Kayen and Lee, 1991). If the more volatile (more mobile and less stable) gas hydrate deposits are concentrated along sites of previous strain (faults), then initial dissociation zones should be more localized. Thus, there is an even greater potential for the initiation of mass-wasting events at existing faults than would be expected in areas with no gas hydrate.

**CONCLUSIONS**

The geophysical data acquired on Leg 164 have contributed substantially to our understanding of methane hydrate distribution, formation, and dissociation on the Blake Ridge with implications for other areas. The data clearly show that a significant portion of the total methane exists as free gas below the base of gas hydrate stability and that large deposits of gas hydrate may be most closely associated with fluid flux along faults. Thus, even in this setting close to a passive margin, high rates of localized advective flux appear to be critical to the development of massive gas hydrates, a result confirmed by recent quantitative modeling. The possible localization of gas hydrate on fault planes within the Blake Ridge may have important implications for seafloor stability and for the volatility of the gas hydrate reservoir during even minor climate change or sedimentological events.

Preliminary analyses of wide-angle seismic data have revealed $P$-wave anisotropy and a significant shear modulus contrast within the GHSZ on the Blake Ridge. The Leg 164 results have also pointed to a more sophisticated potential cause of seismic blanking than cementation by hydrate, challenging the use of blanking as a means of estimating hydrate concentrations in marine sediments. Wide-angle seismic data and the analysis of $P$-to-$S$ conversions seem to hold more promise for remotely quantifying rock physical properties and the small amounts of gas hydrate present.

Thermal data acquired on the Blake Ridge imply that temperatures at the BSR are lower than the predicted temperature of dissociation at Sites 995 and 997. At present, this observation can only be explained by the inhibition of gas hydrate stability due to a physical or chemical process or by failure of the accepted phase equilibria to properly represent in situ conditions for the primarily methane system at 32.2 MPa pressure. The ODP Leg 164 temperature data loosely confirm the interpretation that Site 997 may be characterized by enhanced advection along buried faults.

Recent theoretical modeling offers one explanation for the different relationships between the free-gas zone and the base of the GHZ at Sites 994 and 995/997. The occurrence of the free-gas zone tens of meters deeper than the GHZ and the theoretical base of GHSZ at Site 994 may imply that the methane flux at this site is less than a critical value. At Sites 995 and 997, the apparent coincidence between the base of the GHZ, the base of the GHSZ, and the top of the free-gas zone produces a strong BSR and may imply that the critical methane supply rate has been exceeded.

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