1. INTRODUCTION¹

Shipboard Scientific Party²

INTRODUCTION

Gas hydrate is a solid phase composed of water and low molecular weight gases (predominantly methane) that form under conditions of low temperature, high pressure, and adequate gas concentrations conditions that are common in the upper few hundred meters of rapidly accumulated marine sediments (Claypool and Kaplan, 1974; Sloan, 1989). Although gas hydrate may be a common phase in the shallow geobiosphere, it is unstable under normal surface conditions, and thus surprisingly little is known about it in natural settings.

Enormous volumes of natural gas may be associated with gas hydrate-bearing sediments (Kvenvolden, 1988b). Large quantities of gas may be stored in gas hydrate-cemented sediments because as much as 164 times the saturation concentration of gas at standard temperature and pressure (STP) conditions exists in these solid phases per unit volume (Sloan, 1989). It is estimated that there are ~10⁴ Gt (Gt = 10^{15} gm) of carbon stored as gas hydrate in sediments, which is about two times the estimate for the carbon in all other fossil fuel deposits (Kvenvolden, 1988a). Moreover, there may be considerable volumes of both free gas trapped beneath the overlying solid gas hydrate-cemented zones that are associated with the bottomsimulating reflector (BSR) and dissolved gas in the pore fluids. However, at present we know too little about natural gas hydrate to be confident about these estimates (Kvenvolden, 1988a).

Ocean Drilling Program (ODP) Leg 164 was devoted to refining our understanding of the in situ characteristics and amounts of natural gas hydrate stored in sediments. The program involved drilling holes at three sites on the Blake Ridge to 750-m depths that extend through the zone where gas hydrate is stable and into the sedimentary section below. Short holes (50 m) were drilled at four sites on the crests of two diapirs on the Carolina Rise where the intrusion of diapirs has disturbed gas hydrate–bearing sedimentary sections. Because of the ephemeral nature of gas hydrate, we emphasized downhole measurements and sampling strategies that allowed the in situ conditions of gas hydrate to be reconstructed.

Seismic Detection of Marine Gas Hydrate

Gas hydrate is thought to be common in continental margin sediments because seismic reflection data have indicated its presence in every ocean basin (Kvenvolden and Barnard, 1982; Kvenvolden, 1988a, 1988b). Gas hydrate is usually detected in seismic reflection data because it produces a BSR. The BSR often cuts across sediment bedding planes, thus clearly distinguishing itself as an acoustic response to a diagenetic change rather than a depositional horizon. The BSR is thought to represent the base of the gas hydrate stability zone, which occurs at depths between ~200 and 600 m below seafloor (mbsf) on continental rises. The pore spaces of sediments above the BSR are thought to be partly filled with gas hydrate, which may increase the sediment density, whereas deeper sediments may contain free gas, resulting in a sharp contrast in acoustic impedance (density × velocity) and a strong reflector at the base of the gas hydrate stability zone. The Carolina Rise, particularly along the Blake Ridge, was one of the first areas where marine gas hydrate was first identified on the basis of a BSR. It is also an area where gas hydrate appears to be especially extensive (Fig. 1) (Markl et al., 1970; Tucholke et al., 1977; Shipley et al., 1979; Dillon et al., 1980; Paull and Dillon, 1981; Dillon and Paull, 1983; Markl and Bryan, 1983) and might be considered the "type section" for marine gas hydrate.

Where gas hydrate has been detected in seismic reflection data, the BSR is a very high-amplitude reflector that is associated with a phase reversal (Shipley et al., 1979; White, 1979). Phase reversals are diagnostic of a change from high acoustic impedance above to lower impedance below. This phase reversal may indicate that the upper sediments are extensively cemented with gas hydrate, whereas another zone exists at or beneath the BSR in which gas hydrate has decomposed and released free gas back into the sediment pore spaces and gas from below is trapped.

In seismic reflection data from some areas, there are zones of variable thickness above the BSR that have surprisingly low reflectivity. These low-reflectivity zones (or seismic blanking zones) may be produced by pervasive gas hydrate cementation that reduces the acoustic impedance contrasts (Lee et al., 1993).

Sampling of Natural Gas Hydrate

Direct sampling of natural gas hydrate is much less common than its detection based on geophysical data. However, gas hydrate has



Figure 1. Map of the general area where gas hydrate occurrence has been mapped on the basis of BSRs on the southeastern North American continental margin (from Dillon and Paull, 1983). Contours are in meters.

¹Paull, C.K., Matsumoto, R., Wallace, P.J., et al., 1996. Proc. ODP, Init. Repts., 164: College Station, TX (Ocean Drilling Program).

²Shipboard Scientific Party is given in the list of participants that precedes the Table of Contents.

been drilled in permafrost regions (e.g., Makogon, 1981; Kvenvolden and Grantz, 1990; Collett, 1994; Dallimore and Collett, 1995) as well as at Deep Sea Drilling Program (DSDP) and ODP sites (i.e., Legs 67, 68, 76, 84, 96, 112, 127, and 146). Gas hydrate also has been recovered from piston cores (e.g., Yefremova and Zhizhchenko, 1975; Brooks et al., 1984; Brooks et al., 1991), gravity cores (Ginsburg et al., 1993) and off the seafloor with submersibles (MacDonald et al., 1994).

An attempt to drill a strong BSR was made on DSDP Leg 11 on the Blake Ridge. At the time, the origin of the BSR was a mystery. Very gassy sediments that self-extruded from their core liners were recovered at Sites 102, 103, and 104. The conclusion at the time was that the level of the BSR had been penetrated and it corresponded with a hard layer at the base of the hole (Shipboard Scientific Party, 1972).

Site 533 of DSDP Leg 76 was successfully drilled on the flanks of the Blake Ridge to sample gas hydrate-bearing sediments (Gradstein et al., 1983). Some gas hydrate was encountered at Site 533 (Kvenvolden et al., 1983). Site 533 was intentionally located on the periphery of the major gas hydrate accumulation, and drilling there did not penetrate into sediments associated with significant seismic blanking that is potentially indicative of more extensive gas hydrate formation. Thus, estimates of the amount of gas hydrate in the entire section could not be made.

IMPORTANCE OF GAS HYDRATE Resource Potential

The resource potential of marine gas hydrate is unknown, but considering the possibility of enormous gas reservoirs, gas hydrate will continue to attract attention until its development potential is established.

Role in Continental Margin Sediment Instability

One explanation for some of the major slumps on continental rises relates to the instability of sediments caused by the breakdown of gas hydrate (Summerhayes et al., 1979; Embley, 1980; Carpenter, 1981; Cashman and Popenoe, 1985; Prior et al., 1989; Kayen and Lee, 1991; Popenoe et al., 1993). Seismic data near some slump areas show that there are numerous normal faults that sole out at or near the BSR (e.g., Popenoe et al., 1993). If gas hydrate comprises a significant portion of the volume of rise prism sediments above the BSR (Heling, 1970; Harrison and Curiale, 1982), then the physical properties of the sediments would change dramatically when gas hydrate decomposes. Solid gas hydrate decomposes to water plus (overpressured?) gas (Kayen, 1988). Sediment instability and failure are likely to be concentrated along this horizon because of its low shear strength. Gas hydrate may play an important role in sediment tectonics, strengthening the sediments above and weakening the sediments at the base of the gas hydrate stability zone. Thus, the potential for physical property changes that significantly alter the mechanical strength of the margin is best understood by establishing the extent of gas hydrate formation in the overlying sediments and the physical characteristics of the sediments both at and beneath the BSR.

ENVIRONMENTAL IMPACT

Pressure and temperature affect the stability of continental rise gas hydrate. The former is associated with substantial sea-level changes; the later, by the bottom-water temperature. During the Pleistocene glaciations, sea level was more than 100 m lower than it is today, and the associated pressure change would cause the lower limit of gas hydrate stability to rise ~20 m (Paull et al., 1991). This may have created a weak "lubricated" zone along the rise at the base of the gas hydrate stability zone that could have resulted in frequent sediment failures. Thus, when sea level drops, large volumes of methane (a greenhouse gas) may be released. Conversely, when sea level rises, the lower limit of gas hydrate stability migrates downward and may trap more gas.

Temperature changes of the bottom seawater also may affect the stability of marine gas hydrate. If the temperature increased by 5°C, the base of gas hydrate stability would be raised by a hundred meters or more, resulting in a massive decomposition of gas hydrate. If the bottom-water temperatures increase, huge amounts of methane could be released to the atmosphere-ocean system.

The effects of changes in sea level and bottom-water temperature on the stability of marine gas hydrate must be assessed. Past changes in the stability field will change the size of the marine gas hydrate reservoir by a few percent. Given that there are ~3.6 Gt of methane carbon in the modern atmosphere, a release of one-tenth of 1% of the carbon from the estimated current gas hydrate reservoir would be equivalent to the anthropogenic inputs of the last century! Scenarios can be constructed in which the exchange between the gas hydrate reservoir and the atmosphere may determine the limits of glaciation (Nisbet, 1990; MacDonald, 1990; Paull et al., 1991) or accelerate global warming through the positive feedback effects of gas hydrate decomposition (Matsumoto, 1995). Simple mass balance calculations suggest that release of even a small portion of marine gas hydrate could cause a dramatic negative excursion in δ^{13} C of dissolved inorganic carbon of the ocean (Erwin, 1993; Dickens et al., 1995; Matsumoto, 1995). Unfortunately, neither the volumes of gas that are involved nor their dynamics are well enough understood to assess whether, or to what degree, marine gas hydrate acts as a buffer or accentuator to climatic change and ocean environment.

Role in Sediment Diagenesis

The formation of gas hydrate within sediment pores may significantly alter the mechanical properties and diagenetic history of the sediment in a number of ways: (1) hydrate formation and decomposition alters the porosity and, presumably, the permeability structure of the sediments and thus alters fluid- and gas-migration patterns, (2) the authigenic addition of gas hydrate changes the mechanical properties and consolidation pathways of the sediments, and (3) hydrate formation changes chemical and isotopic composition of the interstitial waters. Understanding the effects of gas hydrate formation and decomposition in recent sediments may provide valuable insight toward interpreting the ancient rock record.

PHYSICAL AND GEOCHEMICAL EFFECTS OF GAS HYDRATE

Seismic Velocity Estimates

Published velocity measurements in sediments from the Blake Ridge indicate very low (<1500 m/s) V_p velocities just below the BSR. These low velocities have been attributed to gas-charged sediments (Dillon et al., 1980), such as those that have been found beneath BSRs elsewhere (Bangs et al., 1993; MacKay et al., 1994). Velocity estimates for the sediment section directly above the BSR are variable, with some relatively high (\geq 2200 m/s) estimates (Dillon and Paull, 1983; Rowe and Gettrust, 1993a) and other more modest (\geq 2000 m/s) estimates (Wood et al., 1994; Katzman et al., 1994). Moreover, unusual V_s velocity structures have been inferred (Ecker and Lumley, 1993). Clearly, the relationship between acoustic velocity and gas hydrate amount still is not well calibrated.

By measuring the acoustic velocities of gas hydrate-bearing sediments, it may be possible to assess the amount of gas hydrate that exists in the subsurface. The inferred occurrence of gas hydrate in the sediment is adequate to increase the sediment interval velocities by \sim 25% in some places, which suggests the amount of gas hydrate must be extensive. However, the consequences of adding high-velocity material to the sediment column are difficult to predict, especially without knowing whether gas hydrate can be best thought of as a pervasive cement or as discrete nodules in otherwise unaltered sediments (Toksöz et al., 1976).

Various elastic wave velocities have been reported for experimentally grown gas hydrate. The velocities range from 2.4 to 3.8 km/s (Stoll et al., 1971; Stoll and Bryan, 1979; Davidson et al., 1983; Pandit and King, 1982). However, all these measurements have been made on systems containing pure propane and ethane gas hydrates (structure II), which may not be representative of methane gas hydrate amounts and sediment velocities needs to be calibrated in situ.

The addition of gas hydrate to sediments may be analogous to cementation of the sediments and is thought to decrease the impedance contrast between the sediment layers above the BSR and to produce the amplitude-blanking zone that is observed above the BSR. These changes in the acoustic impedance have been used to model the amount of gas hydrate that is in the sediments (Miller et al., 1991; Lee et al., 1993). Modeling estimates indicate that large amounts of gas hydrate are required to produce the observed acoustic blanking in the sediment, especially in the Blake Ridge–Carolina Rise area (Lee et al., 1993).

Determining the in situ sediment velocities in areas of extensive gas hydrate requires special care to collect and integrate data from the different techniques for velocity measurement. Well-log data provide accurate information on the velocity structure that occurs within a few meters of the hole. Vertical seismic profiles (VSPs) can provide data on the interval velocities (Hardage, 1985; Shipboard Scientific Party, 1990). Thus, differences between the averaged values of the VSPs and the well-log velocities indicate how typical the core site is of the surrounding sediments. In addition, shipboard physical properties measurements are done after gas hydrate has started to decompose or is completely decomposed. Comparisons with velocity-log data and velocimeter measurements may provide insight into velocity changes associated with gas hydrate decomposition.

Spatial Variation and In Situ Fabric of Gas Hydrate Development

To date, most studies on the distribution and occurrence of gas hydrate have been directed at regional distribution patterns inferred from BSR characteristics. However, seismic reflection profiles also show that there is an enormous amount of local lateral variability in the strength of the BSR and the extent of the acoustically blank zone above the BSR within individual gas hydrate–containing regions. The causes of these variations are not understood and merit further study via the drilling of closely spaced holes.

The physical characteristics of gas hydrate that has been sampled from marine sediments also suggest that gas hydrate distribution is quite patchy in a vertical sense. At present, little is known about the effects of either grain size or lithology on gas hydrate formation. Hydrate may form as either veins or lenses that have some horizontal continuity or as isolated gas hydrate nodules within the sediment matrix. If they are, in fact, laterally continuous layers, they may control the local permeability and velocity structure. In some gas hydratecontaining cores, gas hydrate forms layers as much as several centimeters thick, particularly in coarser grained sediments, suggesting an association with more permeable conduits. The relative importance of finely disseminated gas hydrate as compared to the abundance of larger hydrate nodules is difficult to assess. Finely disseminated gas hydrate may be undersampled because it is not visually detected and leaves only slight chemical signatures in core samples obtained using conventional recovery techniques. More and better fabric data on gas hydrate occurrences are needed to improve the quality of gas hydrate volume estimates and to understand the effects of gas hydrate on the structure of the sediments.

Modification of Fluids

Methane and saline fluids may be expelled from abyssal sediments as a consequence of gas hydrate formation and deterioration. In the process of gas hydrate formation, water and low molecular weight gases (i.e., methane) form a crystalline solid that cements the sediment, leaving the remaining pore fluids enriched in salts (Hesse and Harrison, 1981; Harrison and Curiale, 1982; Ussler and Paull, 1995). At greater depths, gas hydrate breaks down and adds methane and freshwater back into the pore waters, decreasing the salinity and increasing the methane concentration. Gas hydrate decomposition leaves a porous zone that is charged with methane beneath the gas hydrate stability zone. If gas hydrate formation is extensive, it may exert a strong influence on the composition of continental margin pore fluids.

Sources of Gas: In Situ Production or Upward Migration

We are interested in assessing whether the gas hydrate system is sustained by in situ production or requires gas to migrate. To have gas hydrate formation, saturation by methane or another gas hydrate– forming gas is required. Because the existing isotopic and compositional data on the Blake Ridge suggest that this gas is microbial methane (Brooks et al., 1983; Galimov and Kvenvolden, 1983), it is frequently assumed that the gas is produced locally beneath surficial, sulfate-reducing sediment. Thus, between the zone of sulfate depletion and the BSR, the onset of gas hydrate formation (~100 mM CH₄ concentrations under in situ pressure/temperature conditions) must occur. Depth-concentration profiles of microbial byproducts indicate whether there have been adequate amounts of local microbial gas production (Claypool and Kaplan, 1974) to account for the observed methane concentrations.

Conversely, if the in situ production of methane and other gases is not adequate to generate saturation at shallow depths, then there must be addition of gas from below (Hyndman and Davis, 1992). Microbial gas may accumulate as a result of the recycling of gas at the base of the gas hydrate stability zone. As continental rise sediments are progressively buried, they experience an increase in temperature associated with the geothermal gradient. At some point, the sediments leave the zone of gas hydrate stability. Gas bubbles produced by gas hydrate decomposition would be expected to move upward and reenter the gas hydrate field above (Paull et al., 1994). If there is a perfectly efficient recapture of the gas that is mobilized into the overlying sediments by the gas hydrate, the gas will never get out of the system. Thus, the gas in gas hydrate that is above the BSR may have been produced at any time in the history of the rise. The gas hydrate that forms the ~6-m-thick layer in the Middle America Trench (Kvenvolden and McDonald, 1985) almost certainly formed in a flow conduit.

Physical Properties Changes in Sediments

Changes in the velocity structure of gas hydrate-bearing sediments suggest that either the volumes of gas hydrate are very high or that gas hydrate is very efficient at binding the sediments to produce a high-velocity medium. At present, we do not know whether gas hydrate preferentially grows in the voids or at grain contacts or how effective it is at binding sediment. However, the growth of gas hydrate in sediment pore spaces inevitably affects the sediment's compaction history. Thus, samples that contain abundant gas hydrate and subsequently pass out of the gas hydrate stability zone should be underconsolidated and mechanically weak, especially if the pore spaces are now gas charged. The potential change in physical properties related to gas hydrate decomposition needs to be assessed as a mechanism for causing slope failure (Kayen, 1988; Paull et al., 1991).

Very few data are available on the porosity structure of gas hydrate-bearing sediments. Shipboard physical properties data suggest that normal porosity reduction may not have taken place because of gas hydrate infilling. For example, data collected at DSDP Site 533 indicate that to the base of the hole (399 m) the porosity remains near 57%, which is surprisingly high for silty claystones (Gregory, 1977).

The thermal conductivity of gas hydrate is lower than that of the pore waters it replaces (Stoll and Bryan, 1979; Sloan, 1989), and the thermal conductivity of free gas layers is relatively low. Thus, areas that contain any appreciable volumes of gas hydrate (above the BSR) and gas (at or beneath the BSR) may act as thermal insulators within continental margin sediments. Lateral variations in the thermal characteristics of sediment may occur because zones of extensive gas hydrate–bearing sediment are better insulated than areas that contain less hydrate. Heat may be refracted toward sediment zones with less abundant gas hydrate. If lateral thermal gradients exist, then they may stimulate fluid circulation.

Isotopic Fractionation and Signature of Pore-Water Sources

During the formation of gas hydrate, the heavy molecules of water $(H_2^{18}O \text{ or } DH^{16}O)$ preferentially concentrate in the gas hydrate lattice while the isotopically lighter molecules of water $(H_2^{16}O)$ remain in the residual water (Davidson et al., 1983). This phenomenon has been employed to explain (1) deep-sea sediment cores that contain water with higher $\delta^{18}O$ content and lower salinities than seawater as having been generated by the recent breakdown of gas hydrate (Hesse and Harrison, 1981; Harrison and Curiale, 1982; Matsumoto, 1989; Ussler and Paull, 1995) and (2) other pore waters from deeper cores that are isotopically light and saline as resulting from the expulsion of fluids during gas hydrate formation (Kvenvolden and Kastner, 1990).

Hydrologic Circulation Within Sections of Gas Hydrate–Bearing Sediment

Sediments associated with extensive gas hydrate formation may have undergone a significant porosity reduction. As a consequence, the gas hydrate-cemented sediments in the Blake Ridge-Carolina Rise gas hydrate field may act as a barrier for pore-water exchange between the continental margin sediments and the adjacent ocean waters. Any fluid flow that is in response to regional gradients will concentrate into breaks in the gas hydrate seal. Moreover, local circulation systems might be stimulated as a consequence of gas hydrate formation or decomposition because (1) saline fluids in the gas hydrate-bearing zone are heavy and tend to sink or, conversely, waters associated with the natural breakdown of gas hydrate in the subsurface are buoyant with respect to seawater and, thus, rise, (2) the lower thermal conductivity of the free gas beneath gas hydrate refracts heat away from areas that contain abundant gas hydrate toward areas that contain less hydrate and stimulates small circulation systems (Kohout, 1967), and (3) compactive expulsion of pore waters from sediments (Shi and Wang, 1986) may occur either above or below gas hydrate. Compactive expulsion may be particularly active underneath gas hydrate as the sediments undergo a porosity and pore-fluid pressure increase as a consequence of gas hydrate dissociation and the release of gas (Kayen, 1988). Fluids may migrate laterally to escape upward at breaks in the overlying seal (Rowe and Gettrust, 1993a, 1993b; Paull et al., 1995).

If there are circulation cells within gas hydrate-bearing sediments, their internal characteristics may be indicated by patterns of velocity variations in the sediment, pore-water composition, and heat-flow gradients that overlie these cells. A close relationship among sediment physical properties, pore-water advection, and porewater chemistry that may exist in gas hydrate-bearing sediments along continental margins requires closely spaced sites that are carefully positioned with respect to lateral changes in reflection characteristics.

Carbonate Diagenesis and Gas Hydrate

At present, we do not have techniques to indicate whether gas hydrates were once developed in ancient sediments. However, there is a largely unassessed potential for significant diagenetic changes to occur as a consequence of gas hydrate formation and decomposition. For example, the oxygen isotope ratios in diagenetic siderite found on the Blake Ridge and those contained in the Miocene siliceous sediments of northern Japan are thought to be related to gas hydrate decomposition (Matsumoto and Matsuda, 1987; Matsumoto, 1989). Thus, these materials may contain a record of paleo-BSR positions, which in turn could be related to sea-level and/or bottom-water temperatures. To evaluate these materials, we need more sampling from sedimentary units that have experienced the diagenetic changes associated with extensive gas hydrate formation.

Recently, carbonate crusts have been found on continental margin seafloors in association with methane-bearing cold-water seepages (e.g., Hovland et al., 1987; Grant et al., 1986) and are suspected of being related to the dissociation of marine gas hydrate (Matsumoto, 1990). Carbonate lenses encountered within sedimentary sequences may indicate methane seepage to the seafloor in response to massive decomposition of gas hydrate.

Crystallographic Studies of Natural Gas Hydrate

Gas hydrate can occur with several different crystal structures. Natural gas hydrate, which is associated with microbial methane, is generally considered to be a structure I gas hydrate. It forms cubic crystals with internal cages (cavity radius = 3.91-4.33 Å) that can efficiently accommodate methane molecules. When the cages of a structure I hydrate are largely occupied with methane, the mole ratio of H₂O to CH₄ (hydration number) is between 6 and 7, and the STP volume of gas in the gas hydrate is estimated to be 150 to 170 times as large as the gas hydrate crystal. However, experimental and theoretical studies suggest that methane hydrate could form a structure II hydrate if the gas contains a few percent nitrogen, oxygen, or higher molecular weight hydrocarbon gases (Sloan, 1989). In fact, compositional and nuclear magnetic-resonance data show that structure II hydrate, as well as a hexagonal hydrate (structure H), occur on the seafloor in the Gulf of Mexico (Brooks et al, 1984; Davidson et al., 1986; Sassen and MacDonald, 1994). Because the water/gas ratio of structure II and structure H hydrates is greater than in structure I, the volume of gas would be reduced in structure II hydrates. Therefore, it is crucial to determine the crystal structure of natural gas hydrate to assess the amount of gas trapped in gas hydrate-bearing sediments.

Currently, little is known about the crystallographic structure of natural gas hydrate in marine sediments. Laser Raman spectroscopic studies of air hydrate in the Greenland ice cores have been conducted (e.g., Hondoh et al., 1990). Similar measurements of the crystallographic structure of natural marine gas hydrate by means of Raman spectroscopy should provide critical and basic information concerning the amount of gas in sediments as well as the relation between composition and structure of marine gas hydrate.

Calibrating the BSR as a Temperature-Pressure-Composition Indicator

The BSR pins the boundary at which three phases (hydrate-gaswater) coexist. Thus, in theory, if one knows the chemical composi-



Figure 2. Physiography of the continental margin off southeastern North America. Location of Leg 164 sites and previous DSDP sites are indicated (map from Gradstein and Sheridan, 1983). Contours are in meters. Box indicates area covered in Figure 4.

tion and the BSR depth, one can calculate the temperature from gas hydrate phase-stability data and use the BSR as a tracer of sediment temperatures. Unfortunately, gas hydrate phase equilibria is very sensitive to the composition of pore fluids, gases, and trace levels of various microbial or thermogenic gases (e.g., H₂S, CO₂, CH₄, and C₂H₆) and ions (e.g., Cl⁻) that shift the phase boundaries (Deaton and Frost, 1946; Kobayashi et al., 1951; de Roo et al., 1983). Because the ionic concentration of pore fluids increases as gas hydrate formation proceeds, the hydrate-gases-water phase boundary shifts toward higher pressure and lower temperature. Ultimately, the best way to unequivocally establish the position and conditions at the base of the gas hydrate stability zone is by drilling in areas where the influence of hydrate is most dramatic.

REGIONAL SETTING

All the drill sites for Leg 164 are on the eastern end of the Blake Ridge and southernmost Carolina Continental Rise (Fig. 2). The Carolina Rise sites overlie the Carolina Trough, whereas the Blake Ridge sites overlie old oceanic crust (Klitgord and Behrendt, 1979; Hutchinson et al., 1982).

The closest drill sites to the Leg 164 sites are DSDP Sites 102, 103, 104, and 533 on the Blake Ridge (Figs. 1, 2). These sites show that the Blake Ridge is a major Neogene and Quaternary sediment drift (Tucholke et al., 1977) that consists of hemipelagic silt and clay-

rich contourite deposits. The lithologies of the sediments drilled during Leg 164 are similar to the previous sites on the Blake Ridge.

It appears that the dominant sediment source for the Blake Ridge is from the north. The Western Boundary Undercurrent carried clastic materials that occur on this portion of the rise southward along the continental margin (Shipboard Scientific Party, 1972). During Leg 11, it was determined that some of the clay minerals had unique origins that could be traced to Labrador.

One significant aspect of the seafloor morphology of the southern Carolina Rise is that it lacks submarine canyons (Fig. 2). This is markedly different from the continental rise north of Cape Hatteras. Apparently, little sediment makes it across the continental shelf, under the Gulf Stream, across the Blake Plateau, and out to the Carolina Rise.

The Carolina Rise Diapirs are thought to originate from the base of the Carolina Trough to as much as 12 km below sea level (Dillon et al., 1982) (Fig. 3). The diapirs form a linear array along the eastern margin of the Carolina Trough. Although many investigators think that the diapirs are probably salt cored, no direct sampling has confirmed this inference (Paull et al., 1989).

The Carolina Rise Diapirs breech the seafloor only within the scar of the Cape Fear Slide (Figs. 3, 4). The Cape Fear Slide is one of the largest and best documented continental margin slide features in the world (Popenoe et al., 1993). Its headwall scarp is more than 50 km wide and 120 m high and encircles the Cape Fear Diapir. Deposits from this slide extend downslope at least 400 km (Popenoe et al.,



Figure 3. Map showing basement contours that outline the Carolina Trough, the position of the Carolina Trough diapirs ("salt domes" on legend), and the headwall scarp of the Cape Fear Slide (from Dillon et al., 1982). Arrows indicate location of the Cape Fear Diapir (CFD) and Blake Ridge Diapir (BRD). Contours are in meters.



Figure 4. Map showing detailed bathymetry of region where ODP Leg 164 drilling occurred. The location of Cape Fear Slide scar is indicated (from EEZ Scan 87 Scientific Staff, 1991).

1993). Whether the diapir caused the slide or whether gas hydrate is involved in the sediment failure is unknown, but much discussed (Popenoe et al., 1993; Schmuck, 1993).

Although large amounts of microbial gas were encountered at the previous DSDP drill sites on the Blake Ridge, no indications of thermogenic hydrocarbons were noted in these holes (Brooks et al., 1983; Claypool and Threlkeld, 1983; Galimov and Kvenvolden, 1983). More than 80 piston cores, from which dissolved gases were collected, have been taken from the Carolina Rise and Blake Ridge (Paull et al., 1994). The methane/ethane ratios were uniformly high (>1000:1) in the cores that penetrated to a great enough depth (>10 m) to contain microbial methane. Carbon isotopic values are low (-100% to -75% [PDB]) (Borowski et al., 1995). One active methane-bearing seafloor seep has been identified in this area (Paull et al., 1995). Existing data on molecular and isotopic compositions all indicate that the gas is of microbial rather than thermogenic origin.

OBJECTIVES

The objectives of Leg 164 include (1) assessing the amounts of gas trapped in gas hydrate-bearing sediments, (2) contributing to an understanding of the lateral variability in the extent of gas hydrate development, (3) refining the understanding of the relationship between bottom-simulating reflectors and gas hydrate development, (4) investigating the distribution and in situ fabric of gas hydrate within sediments, (5) establishing the changes in the physical properties (e.g., porosity, permeability, velocity, and thermal conductivity) associated with gas hydrate formation and decomposition in continental margin sediments, (6) determining whether the gas captured in gas hy-

drate is produced locally or has migrated from elsewhere, (7) investigating the role of gas hydrate in the formation of authigenic carbonates, (8) refining our understanding of chemical and isotopic compositions of gas hydrates, (9) determining the gas compositions, hydration numbers, and crystal structures of natural gas hydrates, (10) determining the role of gas hydrate in stimulating or modifying fluid circulation, (11) investigating the potential connection between major slumps and the breakdown of gas hydrate, and (12) establishing the influence of the Carolina Rise Diapirs on gas hydrate as well as the origin of the diapirs themselves.

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