OCEAN DRILLING PROGRAM

LEG 164 SCIENTIFIC PROSPECTUS

GAS HYDRATE SAMPLING ON THE BLAKE RIDGE AND CAROLINA RISE

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June 1995

Scientific Prospectus No. 64
First Printing 1995

Distribution

Copies of this publication may be obtained from the Director, Ocean Drilling Program, Texas A&M University Research Park, 1000 Discovery Drive, College Station, Texas 77845-9547, U.S.A. Orders for copies may require payment for postage and handling.

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Canada/Australia Consortium for the Ocean Drilling Program
Deutsche Forschungsgemeinschaft (Federal Republic of Germany)
Institut Français de Recherche pour l'Exploitation de la Mer (France)
Ocean Research Institute of the University of Tokyo (Japan)
National Science Foundation (United States)
Natural Environment Research Council (United Kingdom)
European Science Foundation Consortium for the Ocean Drilling Program (Belgium, Denmark, Finland, Iceland, Italy, Greece, The Netherlands, Norway, Spain, Sweden, Switzerland, and Turkey)

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ABSTRACT

ODP Leg 164 will be devoted to refining our understanding of the *in situ* characteristics of natural gas hydrates. The program involves drilling four sites to 750-m depths on the Blake Ridge that extend down through the zone where gas hydrates are stable and into the sedimentary section below. Short holes (50 m) will also be drilled at three sites on the crests of two diapirs on the Carolina Rise where gas hydrate-bearing sedimentary sections have been disturbed by the intrusion of diapirs. Because of the ephemeral nature of the gas hydrates, emphasis will be placed on downhole measurements and sampling strategies that allow the *in situ* conditions of the gas hydrates to be reconstructed.

The objectives of Leg 164 include 1) assessing the amounts of gas trapped in extensively hydrated 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 hydrates within sediments, 5) establishing the changes in the physical properties (porosity, permeability, velocity, thermal conductivity, etc.) associated with gas hydrate formation and decomposition in continental margin sediments, 6) determining whether the gas captured in gas hydrates is produced locally or has migrated from elsewhere, 7) investigating the role of gas hydrates in the formation of authigenic carbonate nodules, 8) refining our understanding of chemical and isotopic composition of gas hydrates, 9) determining the gas composition, hydration number, and crystal structure of natural gas hydrates, 10) determining the role of gas hydrates 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 the gas hydrates as well as the origin of the diapirs themselves.

BACKGROUND

Gas hydrates are a solid phase composed of water and low-molecular-weight gases (predominantly methane) which 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 hydrates may be a common phase in the shallow geobiosphere, they are unstable under normal surface conditions, and thus surprisingly little is known about them in natural settings.

Enormous volumes of natural gas may be associated with gas hydrated sediments (Kvenvolden and Barnard, 1983; Kvenvolden, 1988a). Large quantities of gas may be stored in the gas hydrate-cemented sediments, because up to 164 times the saturation concentration of gas at STP condition exists in these solid phases per unit volume (Sloan, 1989). It is estimated that about 10^4 Gt (Gt = 10^{15} gm) of carbon is stored in gas hydrates, which is about 2 times the estimate for the carbon in all other fossil fuel deposits (Kvenvolden 1988b). Moreover, there may be considerable volumes of both free gas trapped beneath the overlying solid gas hydrate-cemented zones that are associated with the BSR and dissolved gas in the pore fluids. However, at present we know too little about natural gas hydrates to be confident about these estimates (Kvenvolden, 1988b).

Seismic Detection of Marine Gas Hydrates

Gas hydrates are believed to be common in continental margin sediments, because seismic reflection data have indicated their presence in every ocean basin (Kvenvolden and Barnard, 1983; Kvenvolden, 1988a, b). Gas hydrates are usually detected in seismic reflection data, because they produce a bottom-simulating reflector (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 believed to represent the base of the gas hydrate stability zone, which occurs between about 200- and 600-m depths below the seafloor on continental rises. The pore spaces of sediments above the BSR are partly filled with gas hydrates, which may increase the sediment density, while deeper sediments may contain free gas. The Carolina Rise, particularly along the Blake Ridge, was the area where marine gas hydrates were first identified on the basis of a BSR and is an area where gas hydrates appear to be especially extensive (Fig. 1) (Markl et al., 1970; Tucholke et al., 1977; Shipley et al., 1979; Paull and Dillon, 1981; Dillon and Paull, 1983; Markl and Bryan, 1983) and might be considered the "type section" for marine gas hydrates.

Where gas hydrates have 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 (density × velocity) above to lower impedance below. This phase reversal may indicate that the upper sediments are extensively cemented with gas hydrates, while another zone exists at or beneath the BSR where the gas hydrates have decomposed (or trapped gas from below) and released free gas back into the sediment pore spaces.

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

Sampling of Natural Gas Hydrates

Direct sampling of natural gas hydrates is much less common than their detection based on geophysical data. However, gas hydrates have been drilled in permafrost regions (e.g., Makogon, 1981; Kvenvolden and Grantz, 1991; Collett, 1994) as well as at DSDP and ODP sites (i.e., Legs 67, 68, 76, 84, 96, 112, and 146). Gas hydrates also have been recovered from piston cores (e.g., Yefremova and Zhizhchenko, 1975; Brooks et al., 1984; Brooks et al., 1991) 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. Although 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 (Hollister, Ewing, et al., 1972), this interpretation was based on estimates of sediment velocity that are lower than those that actually occur at this site, on the basis of subsequent work. Therefore, we question whether DSDP Leg 11 actually penetrated to the level of the BSR.

DSDP Site 533 was successfully drilled on the flanks of the Blake Ridge to sample hydrated sediments. 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 field, and did not penetrate into sediments associated with significant seismic blanking that is indicative of more extensive hydrate formation. Thus, estimates of the amount of gas hydrate in the entire section could not be made.

Importance of Gas Hydrates

The resource potential of marine gas hydrates is currently unknown, but considering the possibility of enormous gas reservoirs, gas hydrates will continue to attract attention until they are development targets or it is demonstrated that they do not have resource value.

Role in Continental Margin Sediment Instability

One explanation for some of the major slumps on continental rises relates to instability of the sediments caused by the breakdown of gas hydrates (Summerhayes et al., 1979; Embley, 1980; Carpenter, 1981; Cashman and Popenoe, 1985; Prior et al., 1989). Seismic data near some slump areas show numerous normal faults that sole-out at or near the BSR (Popenoe et al., 1993). If gas hydrates make up a significant part of the volume of rise prism sediments above the BSR (Heling, 1970; Harrison and Curiale, 1982), the physical properties of sediments will change dramatically when gas hydrates decompose. Solid gas hydrates decompose to water plus (over-pressured?) gas (Kayen, 1988). Sediment instability and failure are likely to be concentrated along this lubricated horizon. The gas hydrates may play an important role in sediment tectonics, strengthening the sediments above and weakening the sediments at and below the BSR. Thus, the potential for physical property changes that significantly alter the mechanical strength of the margin will best be understood by establishing the extent of the gas hydrate formation in the overlying sediments and the physical characteristics of the sediments both at and beneath the BSR.

Storage of a Greenhouse Gas

The stability of continental rise gas hydrates will be affected by the change in pressure that is associated with substantial sea-level changes. During the Pleistocene glaciations, sea level was more than 100 m lower than it is today, and the associated pressure change would have caused the lower limit of gas hydrate stability to rise about 20 m. This may have created a weak "lubricated" zone along the rise at the base of the BSR 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 will migrate downward and may trap more gas. These changes in the stability field will change the size of the marine gas hydrate reservoir by a few percentage points. Given that there are about 3.6 Gt of methane carbon in the modern atmosphere, a release of one tenth of one percent of the carbon from the gas hydrate reservoir would be equivalent to the anthropogenic inputs of the last century! Scenarios can be constructed that suggest that the exchange between the gas hydrate reservoir and the atmosphere may determine the limits of glaciation (Nisbet, 1990; MacDonald, 1990; Paull et al., 1991). 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 hydrates act as a buffer or accentuator to climatic change.

Role in Sediment Diagenesis

The formation of gas hydrates within sediment pores may significantly alter the mechanical properties and diagenetic history of the sediment in a number of ways: 1) the pore volume will be decreased by authigenic mineral (hydrate and carbonate) formation; 2) the authigenic addition of the gas hydrate will also change the mechanical properties and consolidation pathways of the sediments; and 3) hydrate formation and decomposition will alter the porosity and presumably the permeability structure of the sediments and thus alter fluid and gas migration patterns. 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 Hydrates

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), as 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 (>2200 m/s) estimates (Dillon and Paull, 1983; Rowe and Gettrust, 1993) and other more modest (>2000 m/s) estimates (Katzman et al., 1994). Moreover, unusual V_s velocity structures have also been inferred (Ecker and Lumley, 1993). Clearly, the relationship between acoustic velocity and gas hydrate amount is still not well calibrated.

By measuring the acoustic velocities of hydrated 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 ~25% in some places, which suggests that 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 the gas hydrates can be best thought of as a pervasive cement or as discrete nodules in otherwise unaltered sediments (Toksoz et al., 1976).

Various elastic wave velocities have been reported for experimentally grown gas hydrates that 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, these measurements have all been made on systems containing pure propane and ethane gas hydrates (type II), which may not be representative of the methane gas hydrates (type I). Thus, the relationship between gas hydrate amounts and sediment velocities needs to be calibrated *in situ*.

The addition of gas hydrates to sediments may be analogous to cementation of the sediments and is believed to decrease the impedance contrast between the sediment layers above the BSR and 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 hydrates that are 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 Carolina Rise Blake Ridge area (Lee et al., 1993).

Determining the *in situ* sediment velocities in areas of extensive gas hydrates will require 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 (VSP) can provide data on the interval velocities (Hardage, 1985; Shipboard Scientific Party, 1990). Thus, differences between the averaged values (VSP) and the well-log velocities will indicate how typical the core site is of the surrounding sediments. Shipboard physical property measurements are frequently done after the gas hydrates have started to decompose or are completely decomposed. Comparisons with velocity-log data and velocimeter measurements may provide insight into the velocity change 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 hydrates have been directed at regional distribution patterns that are 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 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 the gas hydrates that have 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. Hydrates 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 hydrate-containing cores, the gas hydrates form layers up to several centimeters in thickness, particularly in coarser grained sediments, suggesting an association with more permeable conduits. The relative importance of finely disseminated gas hydrates in terms of the size of the hydrate pool is difficult to assess.

Finely disseminated gas hydrates may be under-sampled because they are not visually detected and leave 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 the gas hydrates on the structure of the sediments, which will require detailed sampling and *in situ* experiments in different settings.

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 hydrates break down and add methane and fresh water 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 stable gas hydrate zone. If gas hydrate formation is extensive, it may be exerting a strong influence on the composition of continental margin pore fluids.

Sources of the 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 from elsewhere. In order to have gas hydrate formation, saturation by methane or another hydrate-forming gas is required. Because the existing isotopic and compositional data for 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 CH_4 concentrations under *in situ* P/T conditions) must occur. Depth-concentration profiles of microbial byproducts will 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 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 will 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 the recapture of the gas that is mobilized into the sediments above by the gas hydrates is perfectly efficient, 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 hydrates that form the ~3-m-thick layer in the Middle America Trench (Kvenvolden and McDonald, 1985) almost certainly formed in a flow conduit.

Another approach to discriminate between locally produced gas and migrated gas may come from the depth distribution of gas hydrates. If the gas hydrates are produced locally in favorable lithologies, there should be a gradual increase in the amount of gas hydrate with depth. However, if the gas is advected up from below, gas-hydrate amounts will increase dramatically near the base of their stability field (i.e., near the BSR).

Physical Property Changes in the Sediments

Changes in the velocity structure of hydrated sediments suggest that either the volumes of gas hydrate are very high or the gas hydrates are very efficient at binding the sediments together to produce a high velocity medium. At present we do not know whether the gas hydrates preferentially grow in the voids or at grain contacts or how effective they are at binding sediment together. However, the growth of gas hydrates in the sediment pores will inevitably affect the sediment's compaction history. Thus, samples that were extensively hydrated, but have passed out of the gas-hydrate stability zone, should be under-consolidated 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 little data are available on the porosity structure of hydrated sediments. Shipboard physical property data suggest that the normal porosity reduction may have taken place by gas hydrate in filling. For example, data collected by DSDP at Site 533 indicate that the porosity remains near 57% right to the base of the hole (399 m), which is surprisingly high for silty claystones (Gregory, 1977).

The thermal conductivity of gas hydrates is lower than that of the pore waters they replace (Stoll and Bryan, 1979; Sloan, 1989) and the thermal conductivity of free gas layers is also relatively low. Thus, areas where there is any appreciable volume of gas hydrate (above the BSR) and gas (at or beneath the BSR) may act as a thermal insulator within continental margin sediments. Lateral variations in the thermal characteristics of sediment may occur, because zones of extensively hydrated sediment will be better insulated than less hydrated areas. Heat may be refracted toward less extensively hydrated sediments. If lateral thermal gradients exist, they may stimulate fluid circulation.

Isotopic Fractionation and Signature of the Pore Water Sources

During the formation of gas hydrates, the heavy molecules of water ($H_2{}^{18}O$ or $DH^{16}O$) are preferentially concentrated in the gas hydrate lattice, while the isotopically lighter molecules of water ($H_2{}^{16}O$) are left in the residual water (Davidson et al., 1983). This phenomenon has been employed to explain deep-sea sediment cores that contain water with higher $H_2{}^{18}O$ content and lower salinity than seawater as having been generated by the recent breakdown of gas hydrates (Hesse and Harrison, 1981; Harrison and Curiale, 1982; Ussler and Paull, 1995), and 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, 1989).

Hydrologic Circulation within Gas Hydrated Sediment Sections

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 be concentrated into breaks in the gas hydrate seal. Moreover, local circulation systems might be stimulated as a consequence of hydration processes because 1) saline fluids in the hydrated zone will be heavy and will tend to sink, or conversely, waters associated with the natural breakdown of gas hydrates in the subsurface will be buoyant with respect to seawater and thus will rise; 2) the lower thermal conductivity of the free gas beneath the gas hydrates will refract heat away from areas that are extensively hydrated toward areas that are less hydrated and stimulate small circulation systems (Kohout, 1967); and 3) compactive expulsion of pore waters from sediments (Shi and Wang, 1986) may occur either above or below the gas hydrates. Compactive expulsion may be particularly active underneath the gas hydrates 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, 1993; Paull et al., 1995).

If there are circulation cells within the hydrated 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 between sediment physical properties and pore-water advection may exist in hydrated regions of continental margins, which will require closely spaced sites that are carefully sited with respect to known lateral changes in reflection characteristics.

Solid-Phase Records

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 believed 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. To evaluate these materials, we need more sampling from sedimentary units that have experienced the diagenetic changes associated with extensive gas hydrate formation.

Crystallographic Studies of Natural Gas Hydrates

Gas hydrates can occur with several different types of crystal structures. Natural gas hydrates that are associated with microbial methane are generally believed to be a type I hydrate. Type I hydrates form cubic crystals that have an internal cage of a size (10 Å) that can efficiently accommodate methane molecules. When the cages of a type I hydrate are largely occupied with methane, the mole ratio of H_2O to CH_4 (hydration number) is between 6 and 7, and the STP volume of gas in gas hydrates 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 type II hydrates when it also contains a few percentage points of nitrogen, oxygen, or hydrocarbon gas (Sloan, 1989). In fact, compositional and nuclear magnetic resonance data show that type II hydrates, 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). As the water/gas ratio of type II and structure H hydrates are greater than those of type I, the volume of gas would be reduced in type II hydrates. Therefore, it is crucial to determine the crystal structure of natural gas hydrates to assess the amount of gas trapped in hydrated sediments.

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

Calibrating the BSR As a Temperature-Pressure-Composition Indicator

The BSR pins the boundary at which three phases (hydrate-gas-water) coexist. Thus, in theory, if one knows the chemical composition and the BSR depth, one can calculate the temperature from gas hydrate phase data and use the BSR as a tracer of sediment temperatures. Unfortunately the gas hydrate phase equilibria are very sensitive to the composition of the pore fluids and gases and trace levels of various microbial or thermogenic gases (e.g., H_2S, CO_2, CH_4, C_2H_6) 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-gas-water phase boundary will shift 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 is by drilling in areas where the influence of hydrates is most dramatic.

DRILLING AREA

The sites proposed for gas hydrate drilling on Leg 164 are all 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).

The closest drill sites to the proposed Leg 164 sites are DSDP Sites 102, 103, 104, and 533 on the Blake Ridge (Figs. 1 and 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. We expect that the lithologies of the sediments to be drilled on Leg 164 will be similar to those of the previous sites on the Blake Ridge.

The dominant sediment source for the Blake Ridge is believed to be from the north. The clastic materials that occur on this portion of the rise have been carried southward along the continental margin by the Western Boundary Undercurrent (Hollister, Ewing et al., 1972). During Leg 11, it was determined that some of the clay minerals had origins that could be uniquely 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 believed to originate from the base of the Carolina Trough, to a depth of 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. While many investigators believe 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 and 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 it encircles the Cape Fear Diapir. Deposits from this slide extend downslope at least 400 km (Popenoe et al., 1993). Whether the diapir caused the slide, or whether the gas hydrates are involved in the sediment failure, is unknown but much discussed (Popenoe et al., 1993; Schmuck and Paull, 1993).

Although large amounts of microbial gas were encountered in 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). During the last few years, over 80 piston cores have been taken from the Carolina Rise and Blake Ridge from which dissolved gases were collected (Paull et al., 1994). The methane-to-ethane ratios in the cores, which penetrated to an adequate depth (>10 m) to contain microbial methane, were uniformly high (>1000:1). Carbon isotopic values are low (-100 to -75 ^{o}/oo [PDB]). One active methane-bearing seafloor seep has been identified in this area (Paull et al., 1995). The molecular and isotopic indicators all indicate that this gas is of microbial, not thermogenic, origin.

MEASUREMENT STRATEGY

The most important objectives of Leg 164 are to determine the amount of gas hydrate that occurs in these continental margin sediments, to establish chemical and physical property changes associated with gas hydrate formation and decomposition, and to investigate the distribution and fabric of gas hydrate within the sediments. The ephemeral nature of the hydrates under surface conditions will make the achievement of these objectives more difficult. Therefore, emphasis onLeg 164 will be placed on sampling and downhole measurements, which assist in determining the *in situ* physical parameters in these boreholes. A higher priority will be placed on assuring that each site is well characterized rather than maximizing the amount of core that is recovered.

Downhole Measurements

Vertical seismic profiles (VSP) will be run in at least three of the deep holes. The VSPs will be coupled with walkaway shooting in two of the holes. Results from an offset VSP would also show velocity changes below hydrates, particularly if free gas is present. Walkaway shooting will provide a unique understanding of the lateral variations in the acoustic structure (both V_p and V_s) that are in turn related to the extent, fabric, and distribution of gas hydrate development.

Three standard logging runs (Quad, Geochem, and FMS) are planned for each of the 750-m drilling sites on the Blake Ridge. Runs of a fourth logging tool, the shear-dipole logging tool (a third-party tool of the BRG-LDEO) are also planned in at least two holes. Acoustic-velocity logs (along with the VSPs) are critical in determining the velocity structure associated with the BSR. Depth-to-seismic ties will also be accomplished by means of synthetic seismograms computed from density and sonic logs. This correlation can be made using standard logs to measure the density, porosity and compressional velocity of the sediments. A dipole shear-wave log is also planned, because the V_p/V_s ratio could be used to identify the spatial distribution of free gas below the hydrates. Sediment permeability may be estimated by temperature gradient and heat-flow changes by running temperature, porosity, and resistivity (DIT) logs. The geochemical logs will be important in studying sedimentary, diagenetic, and paleoceanographic processes, and formation microscanner (FMS) images can indicate thin beds and fractures in hydrated sediments (e.g., sediment fabric).

Special efforts will be devoted to running the WSTP (water sampling temperature probe), PCS (pressure core sampler), and ADARA tools. The WSTP has two roles: 1) the chlorinities of *in situ* sampled pore waters when coupled with the shipboard pore-water measurements will be critical to establishing how much hydrate decomposed in the cores after recovery; 2) precise data on the temperature gradient through the sediment column will be important for refining our understanding of physical conditions at the gas hydrate phase boundary or BSR. During runs of the advanced piston corer (APC) tool, additional thermal data will be collected with the ADARA tool.

The PCS has the potential of providing the best data on the *in situ* gas concentrations associated with these gas hydrate-bearing sections. It also has the potential of providing samples that have not experienced gas hydrate decomposition during the sampling process. Multiple PCS runs are planned in every APC hole.

Pore-Water and Physical Properties Sampling

Four exceptions to the routine ODP sampling policy are required to meet the cruise objectives:

1. Rapid sampling of some sections of core that are believed to contain pieces of gas hydrate will be needed. Because of the ephemeral nature of the hydrates, the time delay involved in the normal flow of core through the sediment lab would result in the loss of the hydrates. Thus, with the consent of the co-chiefs, whole-round sections of core that are suspected of containing massive hydrate or hydrate nodules will be cut off on the catwalk and dissected as quickly as possible. Samples from these cores will provide solid hydrates for experiments on the nature and composition of the hydrate crystals. Some of these experiments involve placing gas hydrates into sample chambers that allow decomposition of the hydrate under controlled conditions or

allow samples to be restabilized and preserved for shore-based studies. Other pieces of hydrate will be needed for quick measurement of their physical properties (e.g., XRD and microscopy).

2. Close spacing of whole-round sections for interstitial-water sampling will be required in two intervals. Establishing very detailed pore-water gradients in the upper 50 m will be essential. It is believed that the diffusive flux of methane out of the sedimentary section is balanced by the flux of sulfate into the sediments from the overlying seawater (Borowski et al., 1995). The amount of methane diffusing upward out of the methane-charged sediment section can be calculated from detailed sulfate and methane gradients through the zone of sulfate reduction and into the upper parts of the methane-bearing section below. Establishing these gradients will require pore-water samples that are spaced as little as 2 m apart through the upper 50 m. Characterizing the changes in pore-water composition also will be particularly important near the base of the gas hydrate stability zone and well into the underlying gas hydrate-free zone below. Thus, interstitial pore-water samples may be required from every core for 100 m above and 100 m below the estimated depth of the base of gas hydrate stability.
3. Physical properties testing will require taking about 25 8-cm-long whole-round core sections for shore-based shear and consolidation tests. The sampling strategy will concentrate on denser sampling of an individual site that is characteristic of a particular region. These measurements will help in evaluating the stress history, permeability, and strength of fine-grained "plastic" sediment, especially with respect to gas hydrates.
4. The normal flow of the cores will be altered to assess whether gases are being evolved from the core and to quantify the amount. After the cores are cut into the routine 1.5-m sections on the catwalk, one section of each core will be placed into a sealed chamber (instead of the normal core rack) while it comes into thermal equilibrium and while it is awaiting normal processing. These chambers consist of pipes that are slightly larger than the core liners with gas-tight seals on their ends. Thus, any gas that is evolved from the core will be captured, and its composition and volume can be measured. Simultaneously, temperature probes will be placed into these core sections and automatically logged. Since gas hydrate decomposition is endothermic (Sloan, 1989), unusual temperature equilibration paths (especially temperature decreases) will be indicative of gas hydrate presence. Except for the small holes associated with the thermal probes, this process is nondestructive of the core materials.

DRILLING STRATEGY

Leg 164 Transect Summary

ODP drilling is proposed along transects in four areas of the Blake Ridge - Carolina Rise gas hydrate field during Leg 164 (Fig. 1; Tables 1 and 2). Most of this program involves drilling four 750-m-deep holes along a transect on the Blake Ridge [BRH- 4, 5, 6, and 1a] where the geology and topography are relatively simple. This simplicity will give us an opportunity to assess the basic properties of the hydrated sediments and to understand their natural spatial variability. The Blake Ridge transect has been selected because it is an area where the patterns of variations in the development of the BSR and seismic blanking are especially distinct. Rapid lateral changes occur along the proposed transect from areas where the BSRs are extremely well developed to areas where there is no indication of BSR development from seismic reflection data.

Drilling is also proposed on the crest and flanks of two diapirs (Cape Fear Diapir and Blake Ridge Diapir) where formerly or currently gas hydrate-bearing sediments have been disturbed. Three 50-m-deep sites around the Cape Fear Diapir (CFD - 5, 6, and 7) are planned for penetrating the sole of an enormous slide scar (Cape Fear Slide) and to sample materials pushed up by the diapir. Here the process of re-equilibration after a significant section of the rise has been removed can be assessed. Three short (<50-m), closely spaced holes are proposed on the crest of the Blake Ridge Diapir (BRD-1 a to c). The objective at this site is to investigate methane migration and gas hydrate formation in a fault zone where methane is leaking out of the rise, presumably derived from gas hydrates below.

Schedule and Sequence of Drilling
Leg 164 is scheduled to proceed from Newfoundland to Miami. Thus, the Carolina Rise - Blake Ridge area will be approached from the north. To minimize transit time (~5.5 days), three sites on the Cape Fear Diapir (CFD-5, CFD-6, and CFD-7) will be drilled first. Since the drill string does not need to be pulled between sites, this transect is estimated to take only ~2 days. The transit times to the remaining sites are 6 hours or less. The BRD-1 site will take less than 1 day with the transit. The diapir sites will be followed by the Blake Ridge Transect (BRH-4, BRH-5, BRH-6, and BRH-1a). It is estimated that these four sites will take ~40 days, including the inter-site transits. The transit to Miami will be ~1.5 days, which will complete the 54 days allotted for Leg 164.

The cruise schedule has been estimated assuming that the APC/XCB will not be capable of reaching 750-m depths and that a B hole (using the RCB) will be needed at each of the Blake Ridge sites. However, if the APC/XCB is capable of reaching to 750-m depths at these sites, an appreciable amount of time will be saved. In the event that additional time remains after the Blake Ridge transect is completed, the drilling options will be reassessed in light of our drilling experience at the others sites. Sufficient time could remain to drill both of the Carolina Rise sites (CRH-1 and CRH-2). However, the drilling of the CRH-2 site is required before CRH-1 is attempted. Other options include drilling another of the approved sites on the Blake Ridge (BRH-2a or BRH-3a) and/or finishing the Cape Fear Diapir Transect with CFD-8a.

PROPOSED DRILL SITES

Primary Sites

Cape Fear Diapir and Slide Transect
The Cape Fear Diapir transect is on the upper rise around 33˚00'N, 75˚55'W, in ~2550 to 2700 m of water (Figs. 4, 5, and 6). A transect (CFD-5, CFD-6, and CFD-7) of shallow drill sites

(50 m deep) on the flank of the Cape Fear Diapir is planned. The sites are all located within the scar of the Cape Fear Slide near the exhumed crest of the Cape Fear Diapir. The transect extends from near the topographic crest of the diapir and across the area where jointed, allochthonous materials of diverse Tertiary ages are exposed on the seafloor. The continuity of the BSR is lost on the flanks of the diapir (Fig. 6). Thus, the diapir apparently produced a “hole” in the regional gas hydrate field that is suspected to be related to slumping and/or the emplacement of the diapir.

The objectives of this transect are 1) to establish the tectonic, thermal, and hydrologic influence of the diapir on gas hydrates; 2) to obtain samples from a structural transect that crosses sediments beneath the sole of a major slump and materials transported upward by the diapir; these sediments probably have been exposed to differing degrees of hydrate formation and decomposition; shallow samples from the crest of this diapir will provide information on the conditions deeper in the rise; 3) to examine the nature of fluid and gas transport through the sole of this major sediment scar; the zone of deformed sediments that rims this diapir may provide a conduit for fluid flow from deeper in the sediment column, including fluids from beneath the zone of hydrate stability; 4) to examine the geochemical re-equilibration associated with the slumping; these strata were buried more than 140 m before being exhumed by slumping; thus, when the slide occurred, methane-bearing sediments were exposed on the seafloor; with time, sulfate will diffuse back into these sediments and oxidize the pore-water methane; evaluating the process of re-equilibration to new shallower conditions may provide great insight into the sensitivity of hydrated sediment to changes in the physical conditions and to the dynamics of gas hydrate venting; and 5) to establish the nature of the diapir's core material. Although Carolina Trough diapirs are believed to be salt structures, the existence of salt has not been documented, and previous sampling on top of these structures has not produced data to confirm this assumption.

Blake Ridge Diapir Site

The drilling of three holes (BRD-1a, b, and c) up to 50 m in length is planned along a short transect (~100 m in length) at 32˚29.629'N, 76˚11.480'W, in ~2167 m water depth (Figs. 4, 7 & 8). Here, there is a small fault in the Quaternary sediment cover on the crest of the Blake Ridge Diapir. Fluids and/or gases are escaping along this fault (Paull et al., 1995). The fault is believed to connect the base of the gas hydrate stability zone (BGHS) with the seafloor. The intention is to drill these shallow holes across the area where the fault intersects the seafloor to sample the migrating fluids and/or gases. This site offers the potential to establish the influences of these fluids on the host sediments and to investigate the nature of the plumbing.

Blake Ridge Hydrate Transect

Four drill sites are planned on the Blake Ridge (BRH-4, BRH-5, BRH-6, and BRH-1a). The bathymetry of the area, the distribution of the BSR, and structure contours on the BSR surface are shown in Figure 9. BRH-2a and BRH-3a are optional sites. All the Blake Ridge sites are located along seismic profile CH-06-92 line 31 (Fig. 10). The *in situ* characteristics of gas-hydrated sediments can best be studied by drilling where gas hydrates are as extensive as possible and their influence on sediment properties are largest. The Blake Ridge is an excellent area for a gas hydrate drilling program because it is associated with sediments that exhibit distinct reflection characteristics, including a well-developed BSR.

Sites BRH-4, BRH-5, and BRH-6 make up a transect of holes that will penetrate below the base of gas hydrate stability within the same stratigraphic interval over a relatively short distance (3.5 km). A BSR is not observed at BRH-4, a modest BSR occurs at BRH-5, and a strong BSR is seen at BRH-6. Establishing the cause of this variation in BSR development is a major objective. This transect will enable the assessment of lateral hydrate variations caused by local lithologic, chemical, and hydrologic factors.

BRH-1a is located on the crest of the Blake Ridge (CH-06-92, line 31, 31˚50.59'N, 75˚28.12'W) in 2722 m of water. Here, a well-developed BSR is at 0.547 s sub-bottom. Hydrate development may be at an extreme in this hole.

Because all the sites on the Blake Ridge will penetrate below the base of gas hydrate stability they will provide critical information on the amounts of gas and gas hydrate in the sediments and the nature of the BSR. At these sites, special effort will be devoted to determining the *in situ* properties of the hydrates by 1) extensive well logging, 2) VSPs at all sites, 3) walkaway expanded spread shooting to the VSP tool using a second ship (at two sites), 4) closely spaced runs of the WSTP and ADARA tool to obtain detailed thermal measurements and pore-water samples, and 5) very closely spaced pore-water sampling from the cores, and repeated runs of the PCS.

Alternative Sites

Carolina Rise Hydrate Transect

An alternate transect of two sites (CRH-1 and CRH-2) is proposed on the upper Carolina Rise (Figs. 4, 11, and 12) if time is available. This transect was selected because 1) it is on a typical section of the rise rather than a sediment drift (i.e., the Blake Ridge); 2) it overlies an extremely well-developed BSR that is crossed by stratal reflectors making the lithologic control identifiable (Figs. 11 and 12); 3) it is about the topographically smoothest area on the rise and is not associated with diapirs or slump scarps; and 4) the potential for migration of gas through various layers will be examined. This area overlies the thickest section of the Carolina Trough, which is composed of rift-stage crust, overlain with ~8 km of continental shelf strata, and capped by modern rise sediments (Hutchinson et al., 1982). As a consequence, the Carolina Rise sites may have different fluid sources than the Blake Ridge sites.

At the Carolina Rise sites, the sedimentary layers slope upward toward the seafloor through the zone of hydrate stability. Beneath the BSR, an appreciable thickness of highly reflective layers is observed on seismic reflection profiles (Fig. 12). These reflective layers are interpreted as sediment beds of variable porosity and grain size. Where these beds cross the BSR they lose their reflectivity in the transparent zone, but again they become clearly traceable in the section a few hundred meters above the blank zone. Here the same layers can be penetrated and cored over a short lateral distance. Thus, the physical properties of individual sediment layers can be compared between closely spaced drill sites where geophysical data indicate a lateral transition from non-hydrated to hydrated sediment.

Additional Sites on the Blake Ridge

Proposed site BRH-2a is located on the upper flank of the Blake Ridge (on CH-06-92 line 31; 31˚52.84'N, 75˚25.11'W) in 2828 m of water. The BSR is not evident at this site, although strong BSRs exist at the up- and downslope sites, BRH-1a (strong) and BRH-3a (weak). Thus, a "hole" in the BSR's surface exists at BRH-2a (Fig. 10). However, a series of strong reflectors that are apparently related to stratigraphic horizons beneath the predicted level of the BSR (~0.53 s sub-bottom as projected up- and downslope) occurs here. Drilling at proposed site BRH-2a should penetrate well below the level of gas hydrate stability into these reflective sediments. With a range of sediment velocities between 1850 and 2500 m/s, the inferred base of the hydrate stability zone would lie between 492 and 665 m respectively. To be sure that the inferred level for the BSR is penetrated, the site's proposed depth is 800 m.

Proposed site BRH-3a is located on the flank of the Blake Ridge (on CH-06-92 line 31; 31˚54.40'N, 75˚23.02'W) in 2965 m of water. Here, a weak BSR occurs at 0.585 s subsurface. If a relatively high velocity of 2500 m/s is assumed, the BSR would be at 731 m sub-bottom. This site is intended to obtain a direct comparison of the same stratigraphic horizons above the BSR that were sampled below the projected level of the BSR at BRH-2a. The horizons that extend to the shallower depths from site BRH-2a to site BRH-3a are acoustically transparent at BRH-3a but reflective at BRH-2a.

Additional Site on the Cape Fear Diapir Transect

Site CFD-8a is located at 32˚55.46'N, 75˚ 50.27'W, in 2988 m of water, well downslope of the core of the Cape Fear Diapir. A 75-m hole drilled at this site would pass through the sole of the Cape Fear Slide into the underlying sediments. The objective of this site is to characterize the pore-water and solid-phase alteration caused by the fluids and gases that are and have been in these sediments before and after the overburden was removed, without the potential complications associated with proximity to the diapir.

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Table 1:

Table 1 Cont.

Table 2

FIGURES

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

Figure 2. Physiography of the continental margin off southeastern North America where ODP drilling is proposed. Locations of proposed sites and previous DSDP sites are indicated (map from Gradstein and Sheridan, 1983). Contours are in meters.

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

Figure 4. Map showing bathymetry of region proposed for drilling during ODP Leg 164 and the location of Cape Fear Slide scar (from GLORIA Atlas, 1991). Lines within the Cape Fear Slide scar indicate internal boundaries. The areas covered in the detailed maps shown in Figures 5, 7, 9, and 11 are outlined.

Figure 5. Map showing the bathymetry (in meters) of the Cape Fear Diapir with respect to the Cape Fear Diapir drilling transect. Both the location of the original CFD sites and the new CFD sites (CFD-5, CFD-6, CFD-7, and CFD-8a) are shown. Location of CH-07-88 line 19, which passes over this transect of sites, is also indicated. Contours are in meters.

Figure 6. Seismic profile CH-07-88 line 19, along which the Cape Fear Diapir drilling transect is proposed. While there are several high-quality digital seismic reflection profiles across the diapir, this older analog record lies on the most effective transect for drilling.

Figure 7. Map showing the bathymetry over the Blake Ridge Diapir with respect to the BRD-1 site (indicated with "bull's-eye"). The area where the diapir occurs in the subsurface is indicated with the large, dot-filled circle. Location of CH-06-92 line 37 (Fig. 8), which passes near this site, is indicated by the dashed line. The small fault along which seepage occurs is indicated by the short line through the drill site. Small circles are piston core locations. Contours are in meters.

Figure 8. Seismic profile CH-06-92 line 37 immediately north of Site BRD-1. Fault along which venting is occurring is indicated.

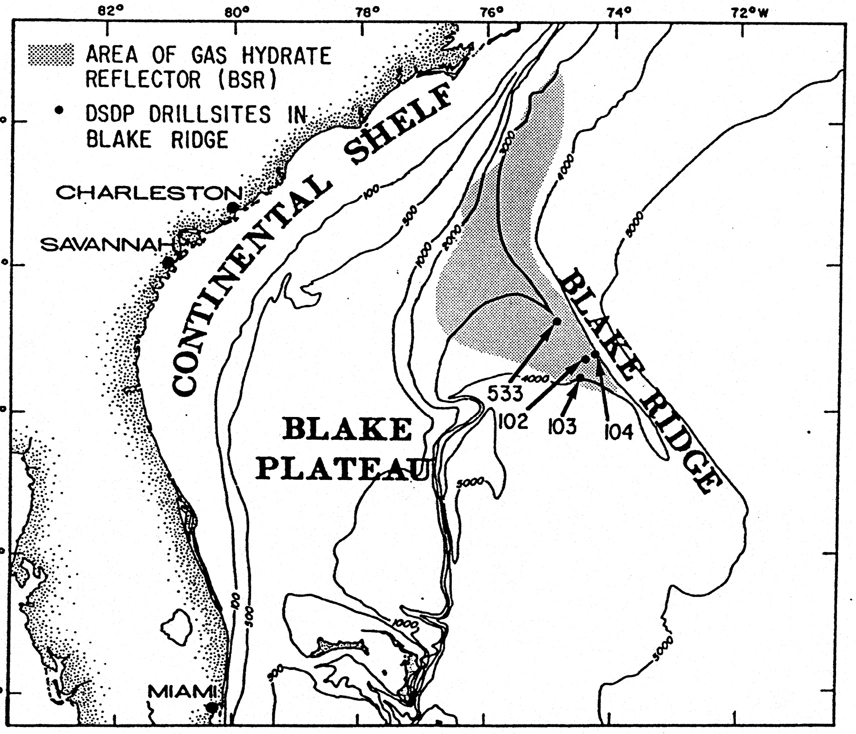
Figure 9. Map showing detailed bathymetry, distribution of BSR, depth to the BSR surface (assuming a velocity of 1875 m/s), and position of seismic profile CH-06-92 line 31 (shown in

Fig. 10) in the area where the Blake Ridge hydrate transect (BRH-1a, BRH-2a, and BRH-3a or BRH-4, BRH-5, and BRH-6) is proposed. The patchy distribution of the BSR suggests stratal control. Contours are in meters.

Figure 10. Seismic reflection profile CH-06-92 line 31. The profile is located on the Blake Ridge drilling transect and crosses perpendicular to the Blake Ridge. Vertical scale is in seconds of two-way traveltime. The penetration of proposed sites BRH-1a, BRH-2a, BRH-3a, BRH-4, BRH-5, and BRH-6 for ODP Leg 163 are projected, assuming a velocity of 2000 m/s.

Figure 11. Map showing detailed bathymetry, distribution of the BSR, depth to the BSR surface (assuming a velocity of 1875 m/s), and position of seismic profile CH-06-92 line 41 (shown in Fig. 12) in the area where the Carolina Rise hydrate transect (CRH-1 and CRH-2) is proposed. Note the banded distribution pattern of the BSR, suggesting stratal control. Contours are in meters.

Figure 12. Seismic profile CH-06-92 line 41, along which the Carolina Rise drilling transect is proposed. Vertical scale is in seconds of two-way traveltime. Holes are projected assuming a velocity of 2000 m/s.



82°
80°
78°
76°
74°
72°W
34°
32°
30°
28°
26°
▨ AREA OF GAS HYDRATE REFLECTOR (BSR)
● DSDP DRILLSITES IN BLAKE RIDGE
CHARLESTON
SAVANNAH
MIAMI
CONTINENTAL SHELF
BLAKE PLATEAU
BLAKE RIDGE
533
102
103
104
100
500
1000
2000
3000
4000
5000

Figure 1

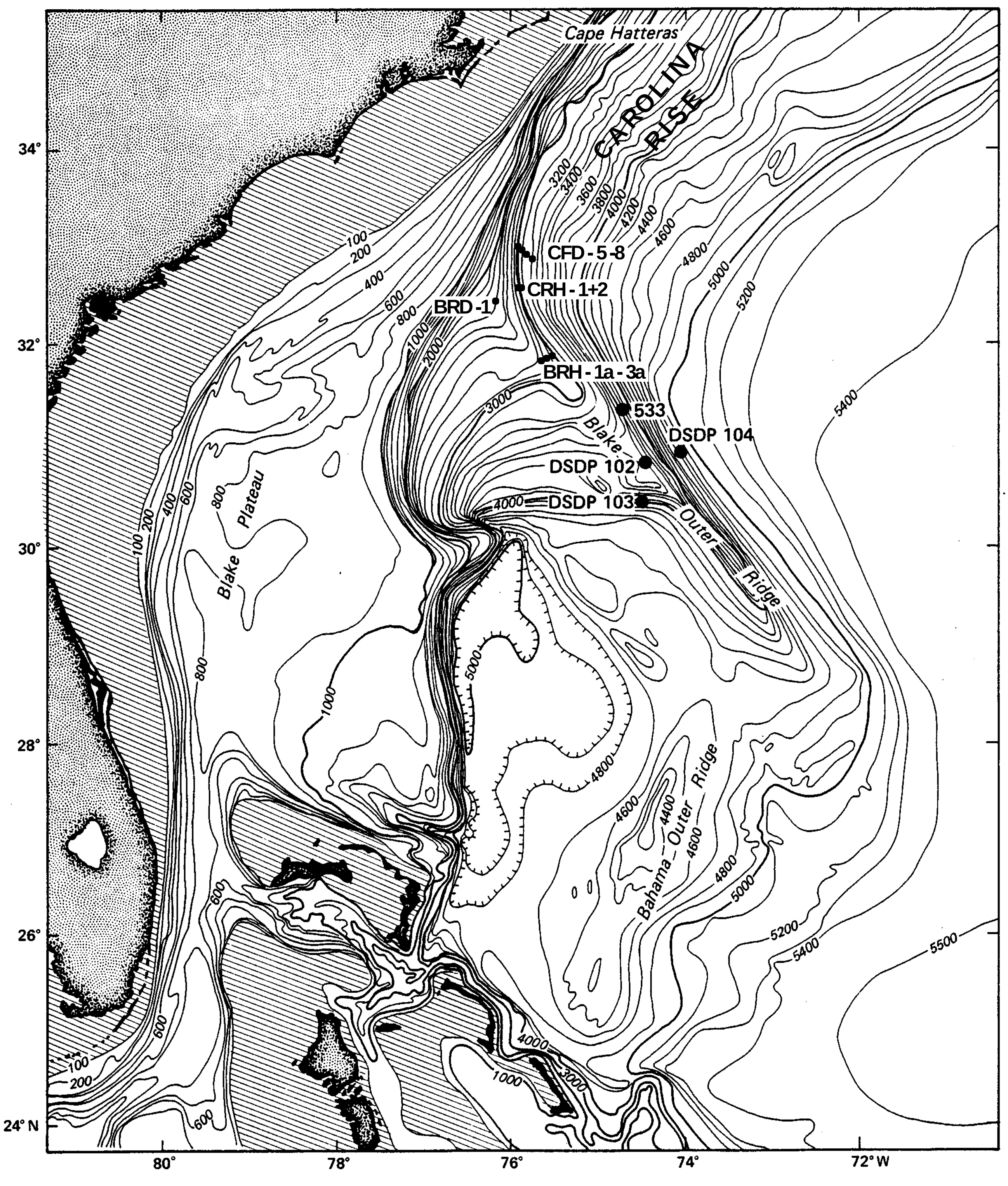


Figure 2. Physiography of the continental margin off southeastern North America where ODP drilling is proposed. Locations of proposed sites and previous DSDP sites are indicated (map from Gradstein and Sheridan, 1983). Contours are in meters.

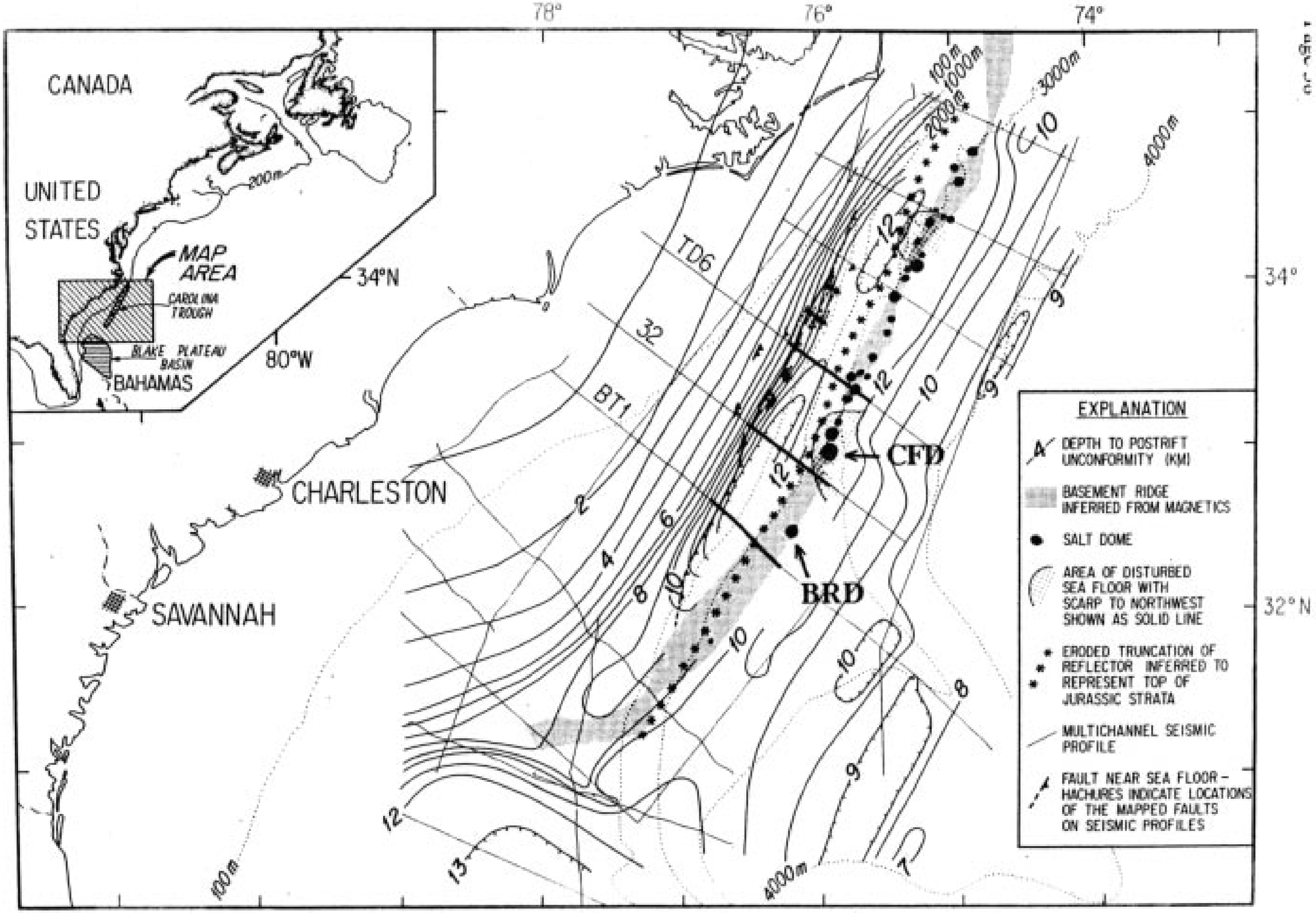

78°
76°
74°
34°
32° N
CANADA
UNITED
STATES
200m
MAP
AREA
34°N
CAROLINA
TROUGH
80°W
BLAKE PLATEAU
BASIN
BAHAMAS
CHARLESTON
SAVANNAH
TD6
32
BT1
2
4
6
8
10
12
13
100m
1000m
2000m
3000m
4000m
9
8
7
CFD
BRD
EXPLANATION
DEPTH TO POSTRIFT UNCONFORMITY (KM)
BASEMENT RIDGE INFERRED FROM MAGNETICS
SALT DOME
AREA OF DISTURBED SEA FLOOR WITH SCARP TO NORTHWEST SHOWN AS SOLID LINE
ERODED TRUNCATION OF REFLECTOR INFERRED TO REPRESENT TOP OF JURASSIC STRATA
MULTICHANNEL SEISMIC PROFILE
FAULT NEAR SEA FLOOR – HACHURES INDICATE LOCATIONS OF THE MAPPED FAULTS ON SEISMIC PROFILES

Figure 3

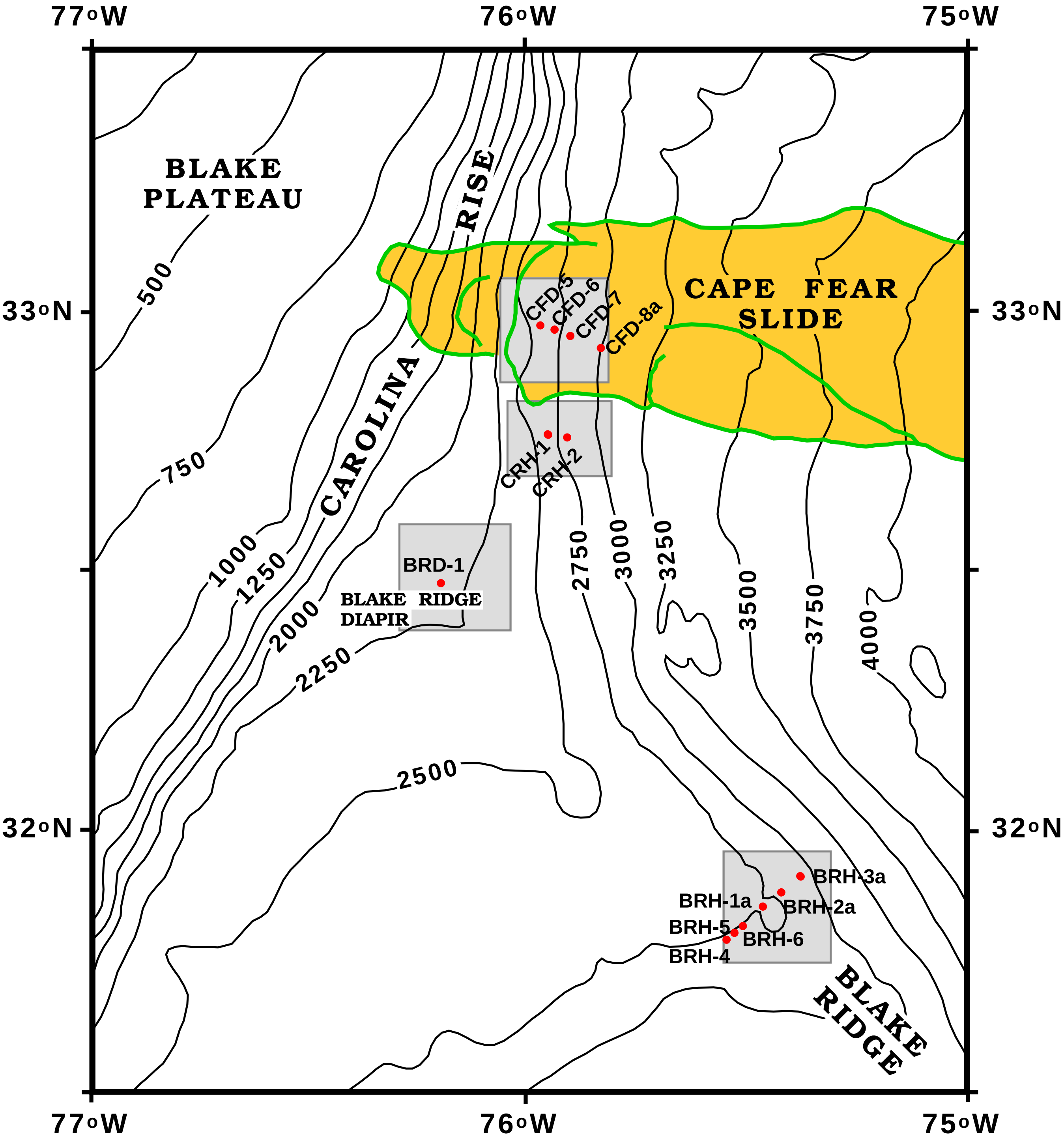


Figure 4. Map showing bathymetry of region proposed for drilling during ODP Leg 164 and the location of Cape Fear Slide scar (from GLORIA Atlas, 1991). Lines within the Cape Fear Slide scar indicate internal boundaries. The areas covered in the detailed maps shown in Figures 5, 7, 9, and 11 are outlined.

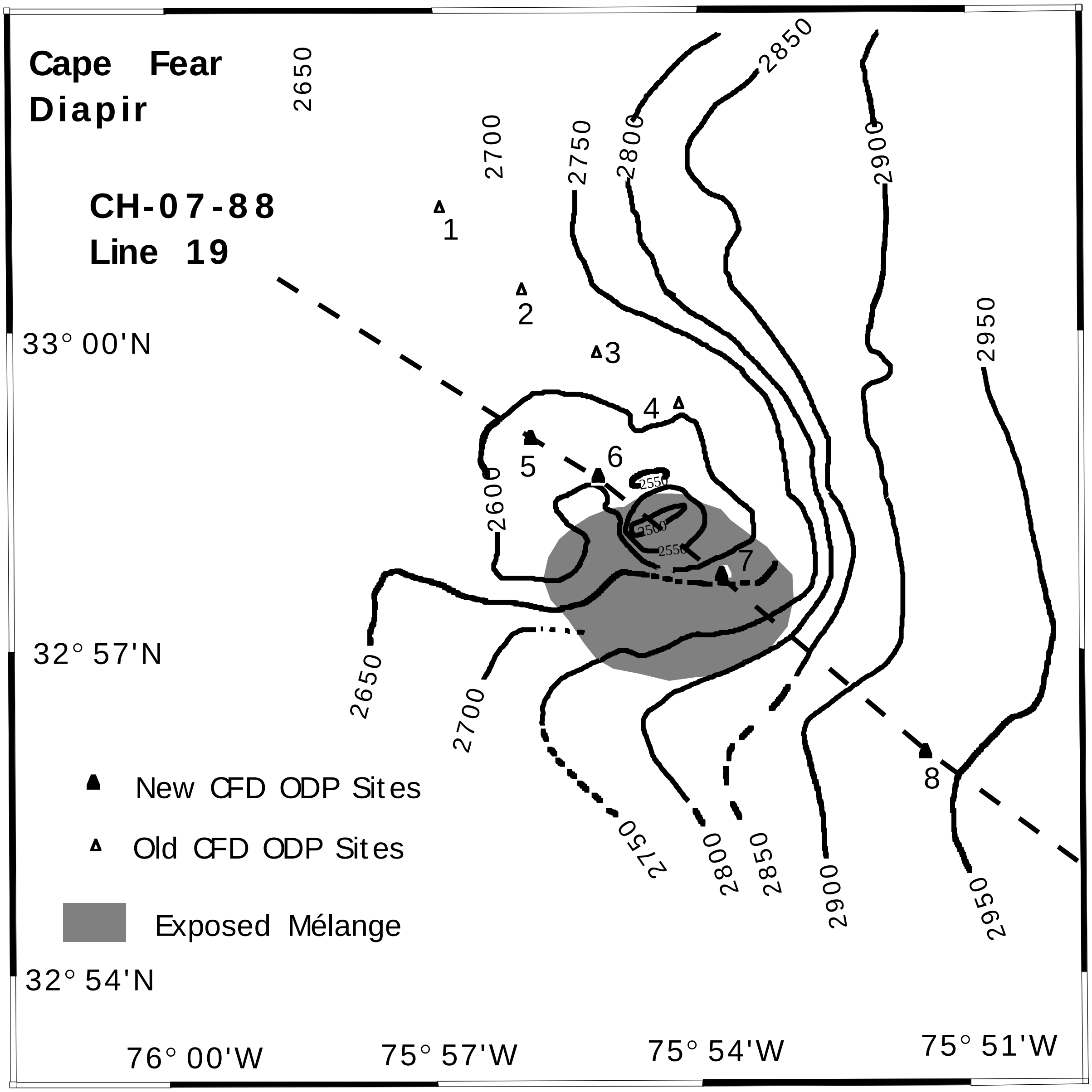
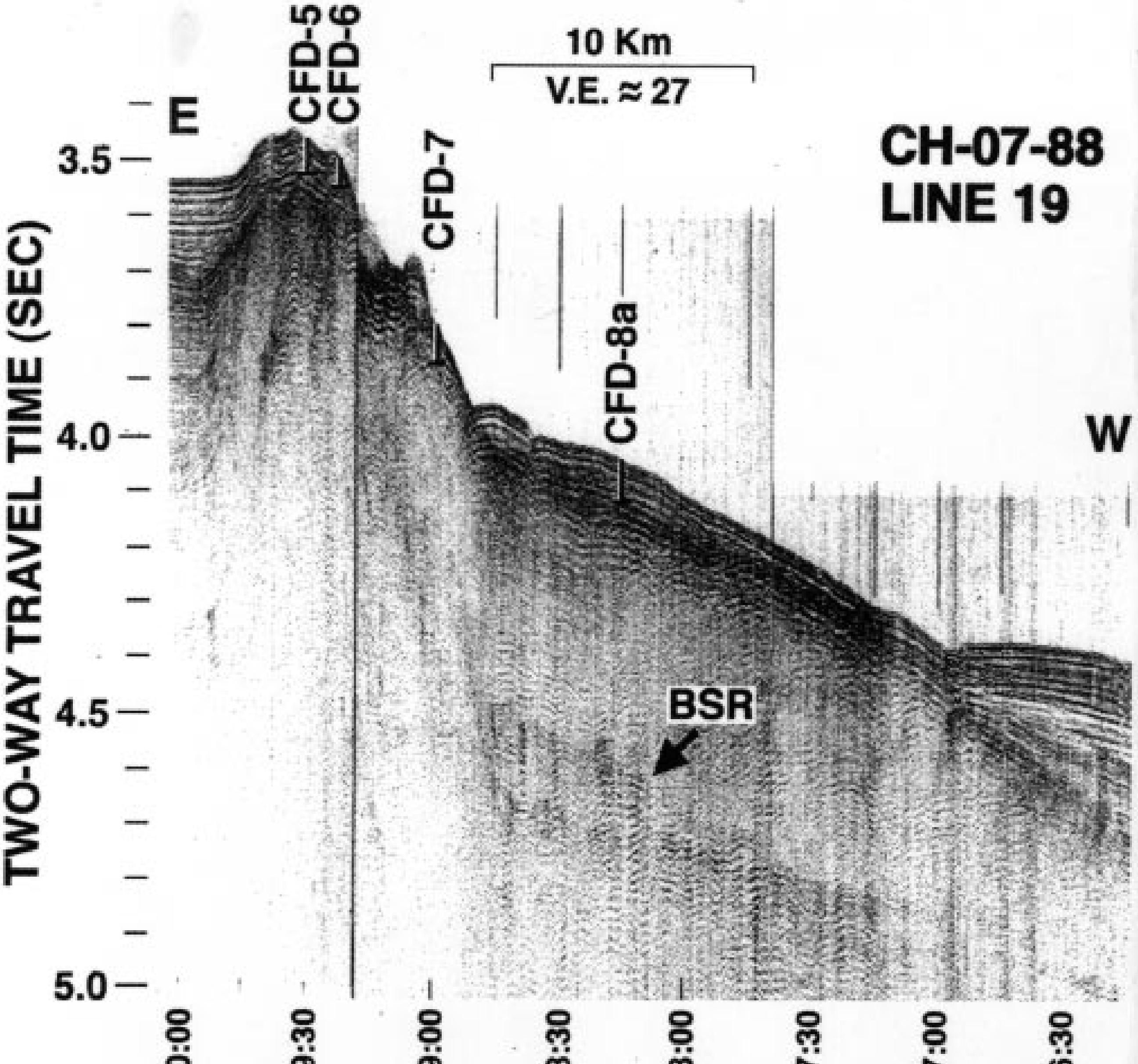


Figure 5. Map showing the bathymetry (in meters) of the Cape Fear Diapir with respect to the Cape Fear Diapir drilling transect. Both the location of the original CFD sites and the new CFD sites (CFD-5, CFD-6, CFD-7, and CFD-8a) are shown. Location of CH-07-88 line 19, which passes over this transect of sites, is also indicated. Contours are in meters.



TWO-WAY TRAVEL TIME (SEC)
3.5
4.0
4.5
5.0
E
W
CFD-5
CFD-6
CFD-7
CFD-8a
10 Km
V.E. ≈ 27
CH-07-88
LINE 19
BSR
20:00
19:30
19:00
18:30
18:00
17:30
17:00
16:30

Figure 6

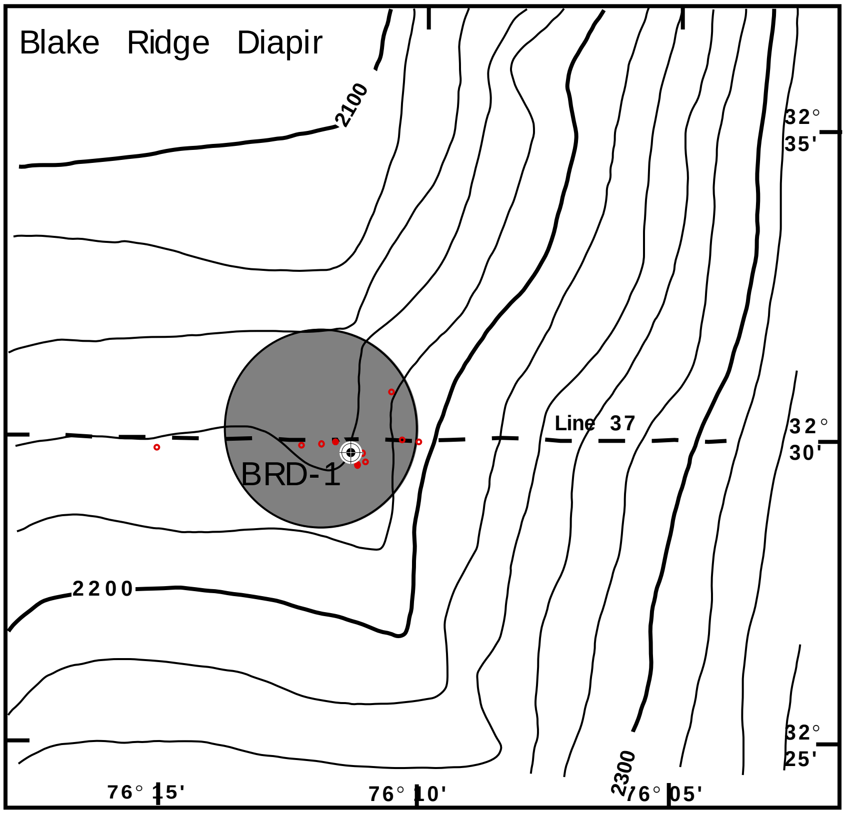


Figure 7. Map showing the bathymetry over the Blake Ridge Diapir with respect to the BRD-1 site (indicated with "bull's-eye"). The area where the diapir occurs in the subsurface is indicated with the large, dot-filled circle. Location of CH-06-92 line 37 (Fig. 8), which passes near this site, is indicated by the dashed line. The small fault along which seepage occurs is indicated by the short line through the drill site. Small circles are piston core locations. Contours are in meters.

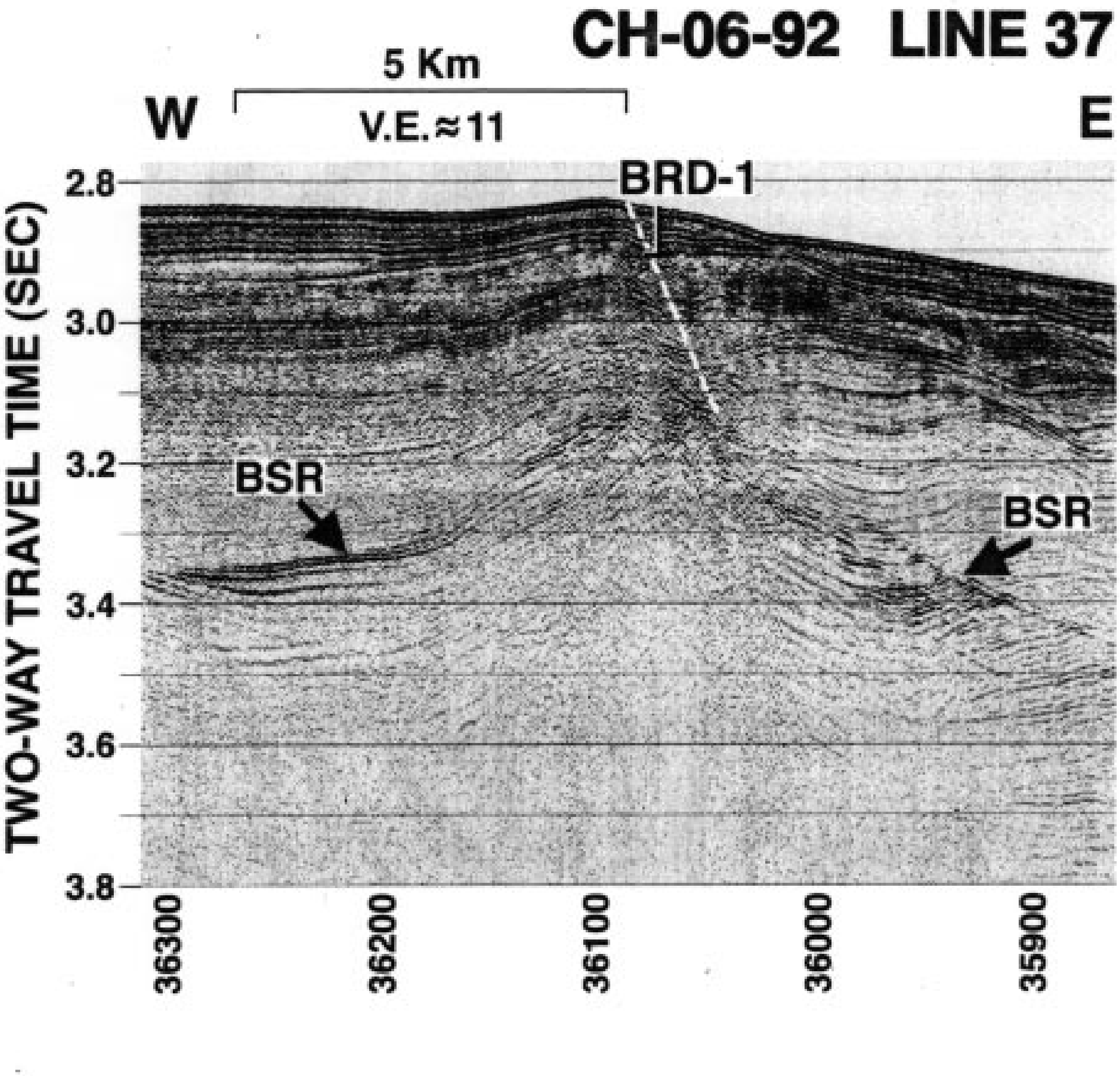

CH-06-92 LINE 37
5 Km
V.E.≈11
W
E
BRD-1
BSR
BSR
TWO-WAY TRAVEL TIME (SEC)
2.8
3.0
3.2
3.4
3.6
3.8
36300
36200
36100
36000
35900

Figure 8

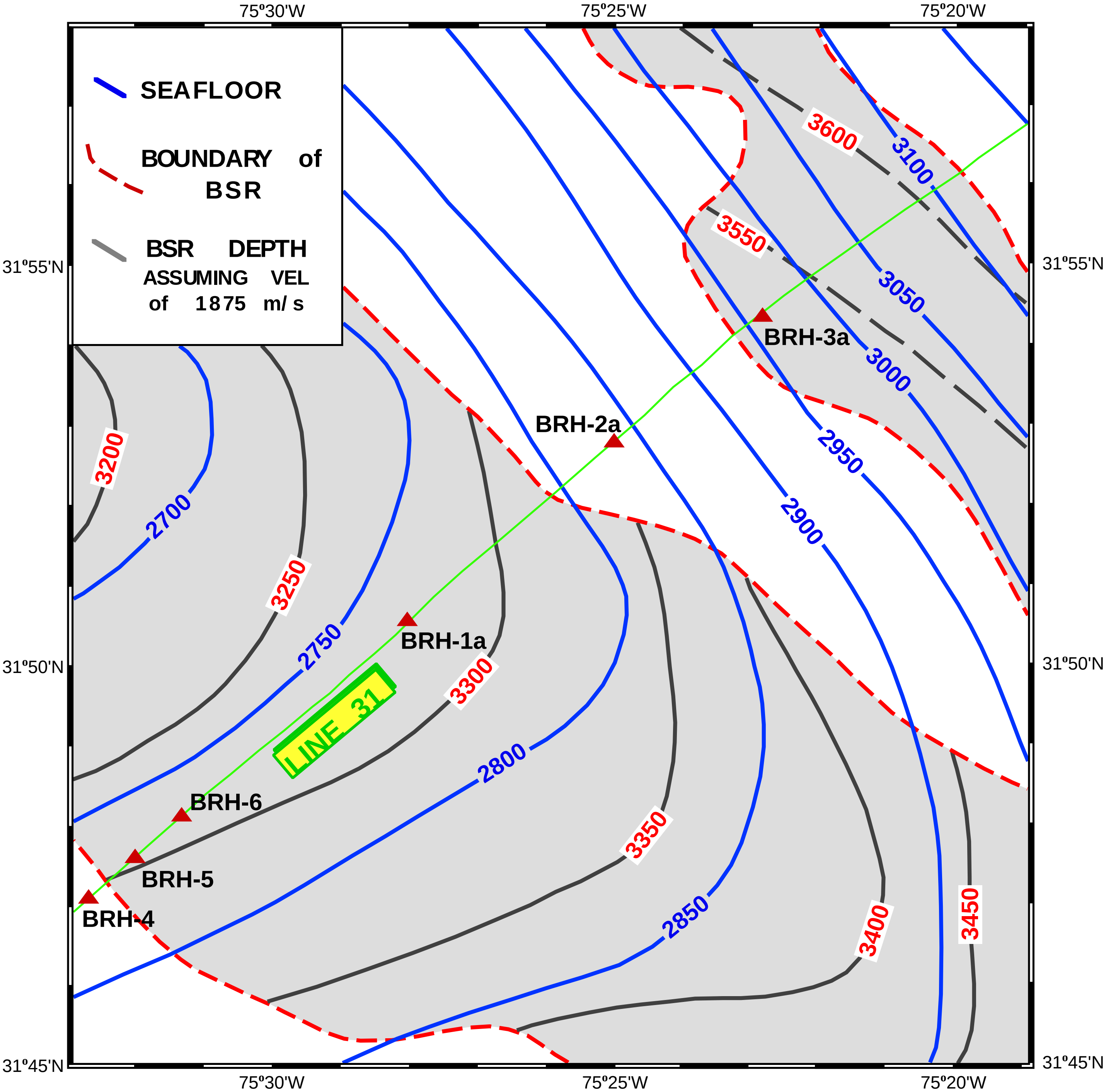


Figure 9. Map showing detailed bathymetry, distribution of BSR, depth to the BSR surface (assuming a velocity of 1875 m/s), and position of seismic profile CH-06-92 line 31 (shown in Fig. 10) in the area where the Blake Ridge hydrate transect (BRH-1a, BRH-2a, and BRH-3a or BRH-4, BRH-5, and BRH-6) is proposed. The patchy distribution of the BSR suggests stratal control. Contours are in meters.

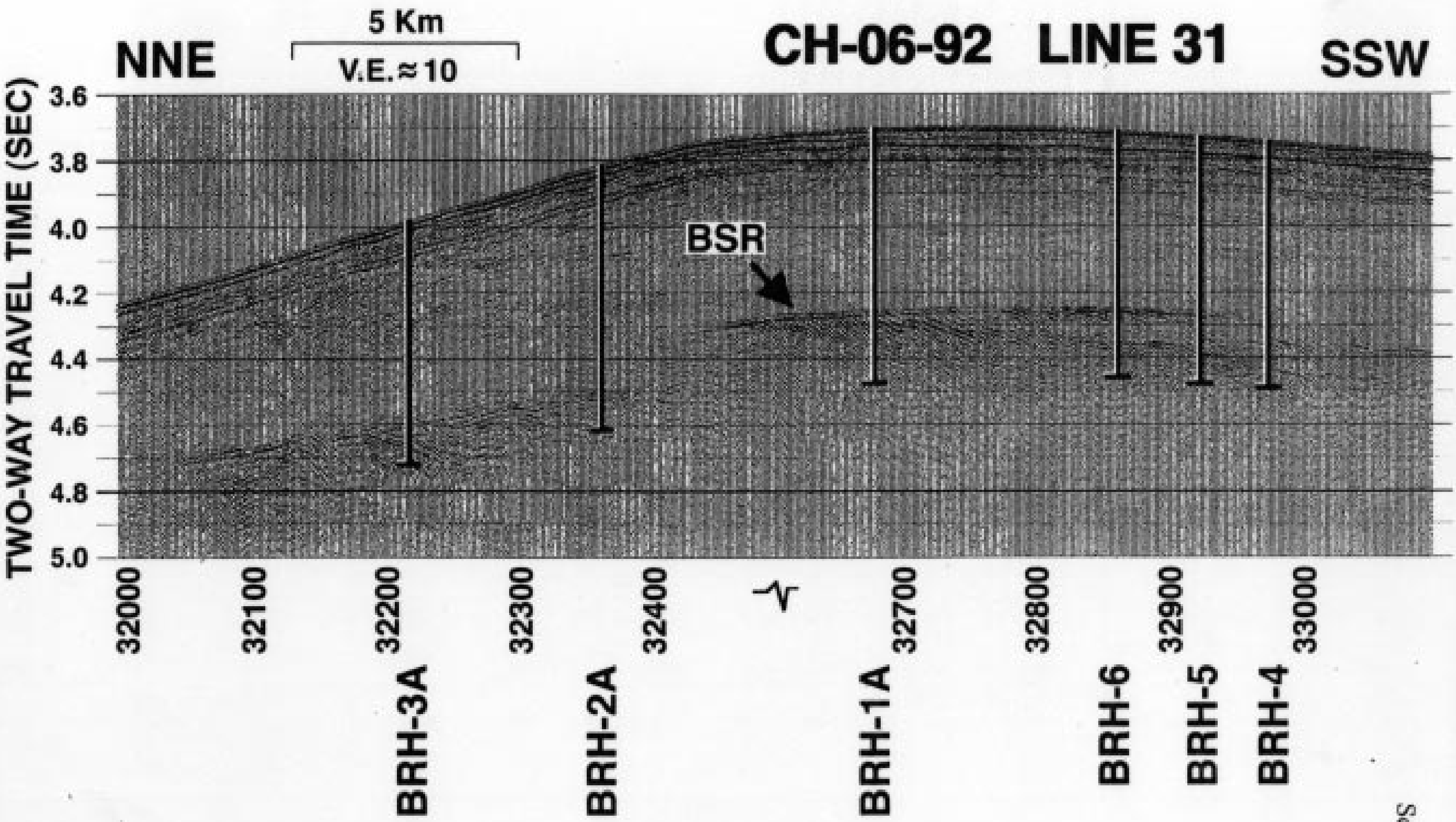


Figure 10

Scientific P

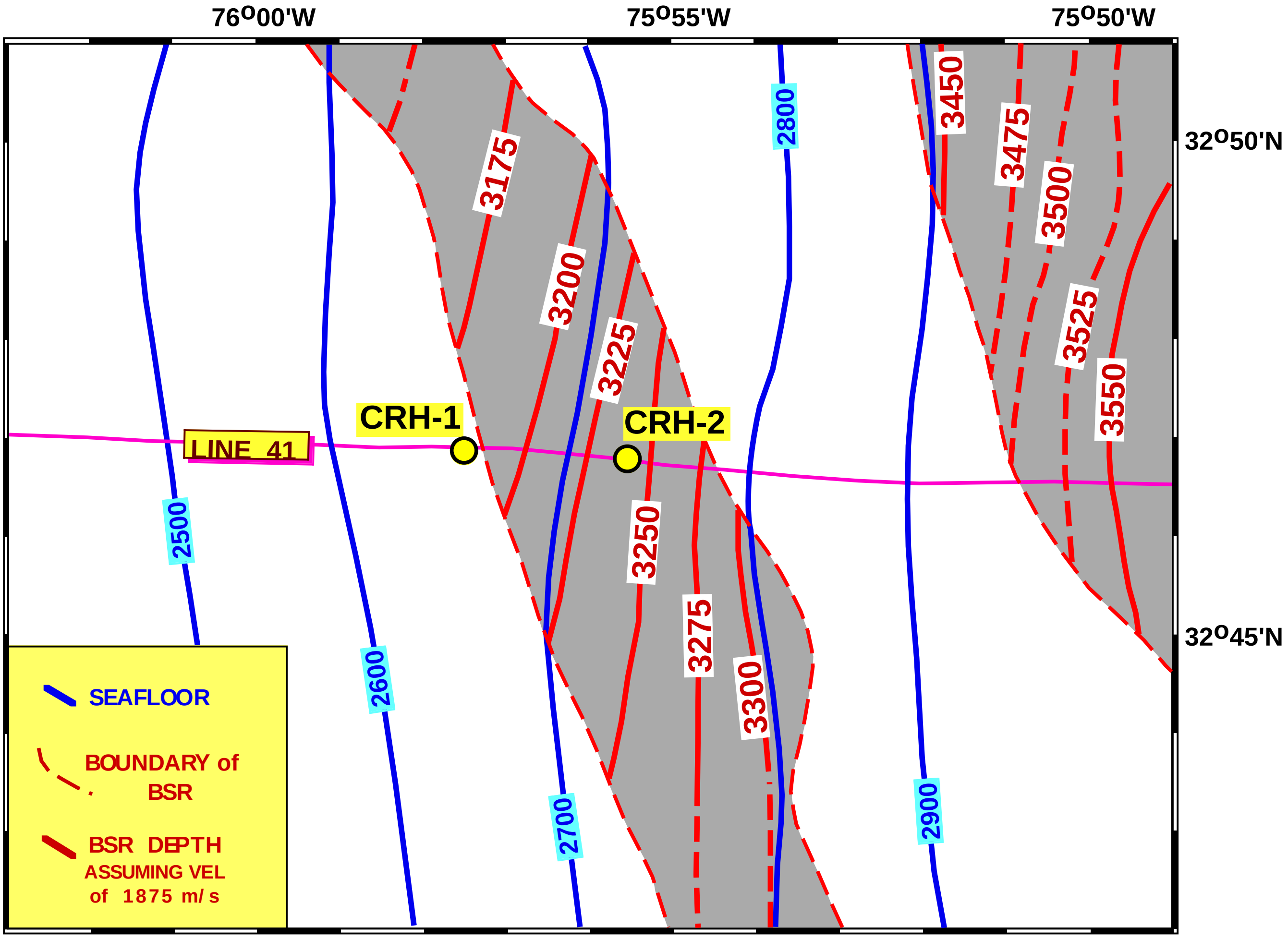


Figure 11. Map showing detailed bathymetry, distribution of the BSR, depth to the BSR surface (assuming a velocity of 1875 m/s), and position of seismic profile CH-06-92 line 41 (shown in Fig. 12) in the area where the Carolina Rise hydrate transect (CRH-1 and CRH-2) is proposed. Note the banded distribution pattern of the BSR, suggesting stratal control. Contours are in meters.

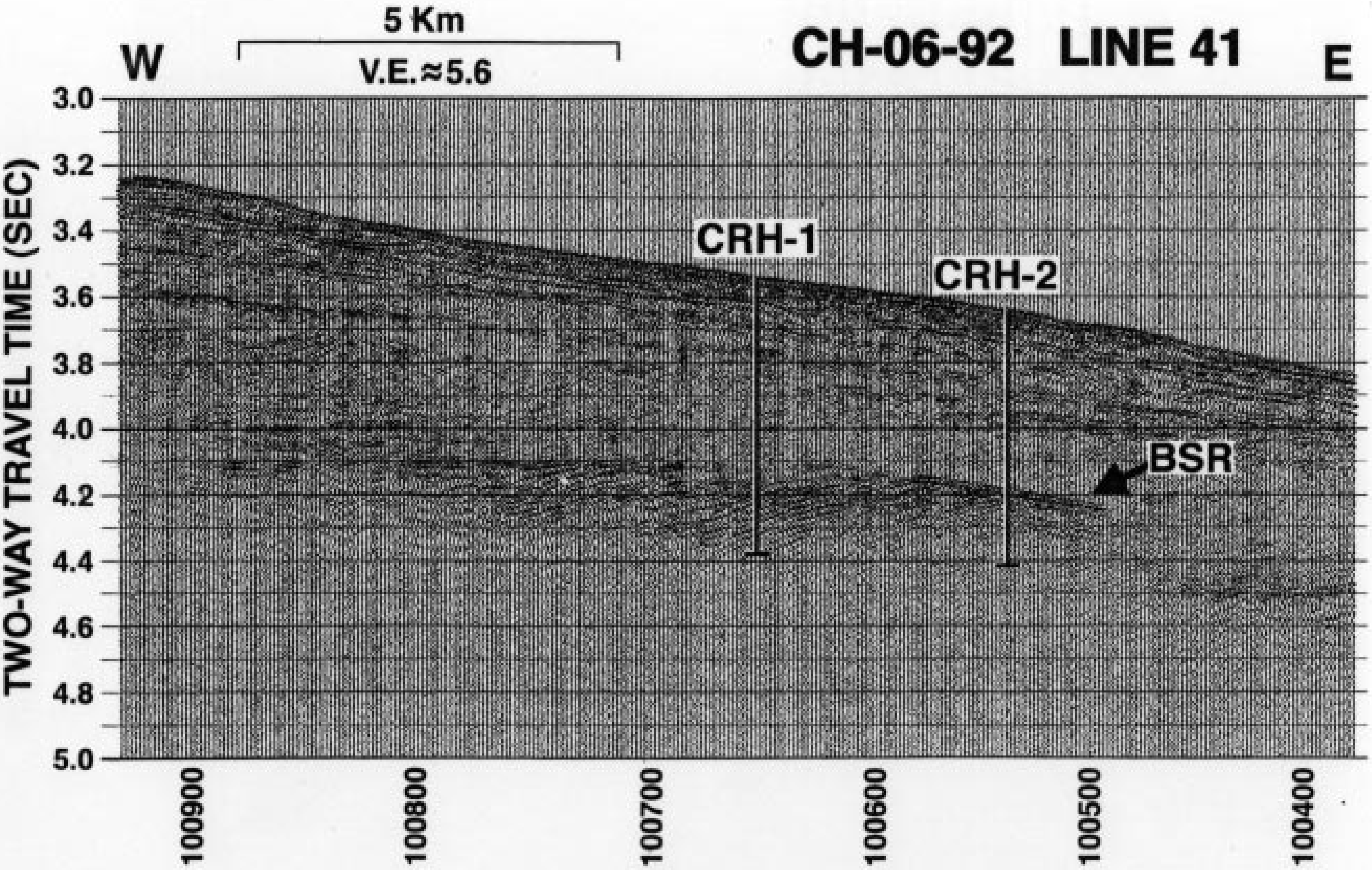

5 Km
V.E.≈5.6
W
E
CH-06-92 LINE 41
TWO-WAY TRAVEL TIME (SEC)
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
CRH-1
CRH-2
BSR
100900
100800
100700
100600
100500
100400

Figure 12

Site: BRH-1a
Priority: High
Position: 31˚50.59´N; 75˚28.12´W
Water Depth: 2722 m
Sediment Thickness: ~2000 m
Total Penetration: 750 mbsf
Seismic Coverage: CH-06-92 lines 31 (SP 32675) and 33 (SP 34032); near USGS lines TD-2 and BT-1 (MCS)

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments in an area where seismic data indicate an especially strong BSR.

Drilling Program:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. Four ADARA heat-flow measurements, 7 WSTP runs, and 6 PCS cores are planned.
Hole B: Wash to hole A refusal depth and RCB to 750 m. Seven runs of the WSTP are scheduled.

Logging: Three well-log runs (Quad, Geo-chem, and FMS) plus VSP.

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: BRH-2a
Priority: Secondary
Position: 31˚52.84´N; 75˚25.11´W
Water Depth: 2828 m
Sediment Thickness: ~2000 m
Total Penetration: 800 mbsf
Seismic Coverage: CH-06-92 lines 31 (SP 32354) and 36 (SP 35156); near USGS lines TD-2 and BT-1 (MCS)

Objectives: Drill through the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data do not indicate a BSR. However, BSRs exist both up- and downslope of this site.

Drilling Program: Site BRH-2a is not part of the existing Leg schedule. However, if time is available the general plan at this site is as follows:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. ADARA heat-flow measurements, WSTP runs, and PCS cores desirable.
Hole B: Wash to hole A refusal depth and RCB to 800 m. WSTP desirable.

Logging: Three well-log runs (Quad, Geo-chem, and FMS).

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: BRH-3a
Priority: Secondary
Position: 31˚54.40´N; 75˚23.02´W
Water Depth: 2965 m
Sediment Thickness: ~2000 m
Total Penetration: 750 mbsf
Seismic Coverage: CH-06-92 lines 31 (SP 32206) and 4; near USGS lines TD-2 and BT-1 (MCS)

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data indicate reflective sediments beneath the base of gas hydrate stability.

Drilling Program: Site BRH-3a is not part of the existing Leg schedule. However, if time is available the general plan at this site is as follows:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. ADARA heat-flow measurements, WSTP runs, and PCS cores desirable.
Hole B: Wash to hole A refusal depth and RCB to 750 m. WSTP desirable.

Logging: Three well-log runs (Quad, Geo-chem, and FMS). VSP desirable.

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: BRH-4
Priority: High
Position: 31˚47.14´N; 75˚32.75´W
Water Depth: 2775 m
Sediment Thickness: 2000 m
Total Penetration: 750 mbsf
Seismic Coverage: CH-06-92 line 31 (SP 32970); USGS line TD-2 (MCS)

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data do not indicate a BSR. With BRH-5 and BRH-6, this site forms a ~3.5-km transect from no BSR to a strong BSR.

Drilling Program:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. 12 ADARA heat-flow measurements, 7 WSTP runs, and 6 PCS cores are planned.
Hole B: Wash to hole A refusal depth and RCB to 750 m. Seven runs of the WSTP are scheduled.

Logging: Four well-log runs (Quad, Geo-chem, FMS, and Dipole Shear). VSP with second ship walkaway shooting.

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: BRH-5
Priority: High
Position: 31˚47.71´N; 75˚32.00´W
Water Depth: 2750 m
Sediment Thickness: 2000 m
Total Penetration: 750 mbsf
Seismic Coverage: CH-06-92 line 31 (SP 32930); USGS line TD-2 (MCS)

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data indicate a transition in the strength of BSR development. With BRH-4 and BRH-6, this site forms a ~3.5-km transect from no BSR to a strong BSR.

Drilling Program:
Hole A: RCB to 750 m.

Logging: Three well-log runs (Quad, Geo-chem, and FMS).

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: BRH-6
Priority: High
Position: 31˚48.21´N; 75˚31.34´W
Water Depth: 2760 m
Sediment Thickness: 2000 m
Total Penetration: 750 mbsf
Seismic Coverage: CH-06-92 line 31 (SP 32867); USGS line TD-2 (MCS)

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data do not indicate a BSR. With BRH-5 and BRH-6, this site forms a ~3.5-km transect from no BSR to a strong BSR.

Drilling Program:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. 12 ADARA heat-flow measurements, 7 WSTP runs, and 6 PCS cores are planned.
Hole B: Wash to hole A refusal depth and RCB to 750 m. Seven runs of the WSTP are scheduled.

Logging: Four well-log runs (Quad, Geo-chem, FMS, and Dipole Shear). VSP with second ship walkaway shooting.

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: CFD-5
Priority: High
Position: 32˚58.98´N; 75˚55.83´W
Water Depth: 2583 m
Sediment Thickness: >8000 m
Total Penetration: 50 mbsf
Seismic Coverage: CH-07-88 line 19 @ 19:30 Z and CH-06-92 line 44 (SP 106272); between USGS lines 32 and TD-6 (MCS)

Objectives: Investigate the diagenetic effects associated with the sole of a major slump scar and the influence of diapirs on gas hydrates.

Drilling Program:
Hole A: Oriented APC/XCB to 50 m.
Hole B: Wash into ~40 m. Two PCS cores.

Logging: None.

Nature of Rock Anticipated: Neogene hemipelagic silts and clays. Cap-rock alteration possible.

Site: CFD-6
Priority: High
Position: 32˚58.61´N; 75˚55.11´W
Water Depth: 2650 m
Sediment Thickness: >8000 m
Total Penetration: 50 mbsf
Seismic Coverage: CH-07-88 line 19 @ 19:19 Z and CH-06-92 line 60 (SP 120699); between USGS lines 32 and TD-6 (MCS)

Objectives: Investigate the diagenetic effects associated with the sole of a major slump scar and the influence of diapirs on gas hydrates.

Drilling Program:
Hole A: Oriented APC/XCB to 50 m.
Hole B: Wash into ~40 m. Two PCS cores.

Logging: None.

Nature of Rock Anticipated: Neogene hemipelagic silts and clays. Cap-rock alteration possible.

Site: CFD-7
Priority: High
Position: 32˚57.76´N; 75˚53.70´W
Water Depth: 2700 m
Sediment Thickness: >8000 m
Total Penetration: 50 mbsf
Seismic Coverage: CH-07-88 line 19:00 Z and at the intersection of two deep-tow photographic runs; between USGS lines 32 and TD-6 (MCS)

Objectives: Investigate the core of the breached diapir.

Drilling Program:
Hole A: Oriented APC/XCB to 50 m.
Hole B: Wash into ~40 m. Two PCS cores.

Logging: None.

Nature of Rock Anticipated: Allochtonous materials from the core of the diapir. Age may range from Quaternary to Jurassic. Salt and cap-rock alteration possible.

Site: CFD-8a
Priority: Secondary
Position: 32˚55.46´N; 75˚50.27´W
Water Depth: 2988 m
Sediment Thickness: 8000 m
Total Penetration: 75 mbsf
Seismic Coverage: CH-07-88 line 19 @ 18:15 Z

Objectives: Investigate the diagenetic effects and establish the nature of geochemical re-equilibration associated with the sole of a major slump scar.

Drilling Program: Site CRH-2 is not part of the existing Leg schedule. However, if time is available, the general plan at this site is:
Hole A: APC/XCB to 75 m. 2 PCS runs. 4 ADARA HF measurements.

Logging: None.

Nature of Rock Anticipated: Neogene hemipelagic silts and clays.

Site: BRD-1
Priority: High
Position: 32˚29.629´N; 76˚11.480´W
Water Depth: 2167 m
Sediment Thickness: ~8000 m
Total Penetration: 50 mbsf
Seismic Coverage: Near CH-06-92 lines 37 (SP 36070) and 45 (SP 109359);
Gillis-79-5, line 10-2, 79 @ July 18, 20:20 Z; USGS lines TD-2 and BT-1 (MCS)

Objectives: Three shallow holes will be drilled across an area where a fault intersects the seafloor. Fluids and/or gases are escaping along this fault that are believed to be venting from the base of the gas hydrate stability zone. BRD-1 offers the potential to sample these migrating fluids and/or gases, to establish the influences of these fluids on the host sediments, and to investigate the nature of the plumbing.

Drilling Program: Three 50-m holes will be placed in an east-west transect that crosses the area affected by fluid and gas venting. The exact positioning of these holes will be based on a video camera survey that is run upon arriving at the site.
Holes A, B, and C are all planned with the oriented APC/XCB tools. Four PCS runs are planned at this site.

Logging: None.

Nature of Rock Anticipated: Quaternary hemipelagic silts and clays.

Site: CRH-1
Priority: Secondary
Position: 32˚46.88´N; 75˚57.40´W
Water Depth: 2647 m
Sediment Thickness: ~8000 m
Total Penetration: 800 mbsf
Seismic Coverage: CH-06-92 lines 41 (SP 100653), CH-06-92 line 46 (SP 111210), and CH-12-92 line 1 (SP 2784); near USGS line 32 (MCS)

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data do not indicate a BSR. Sites CRH-1 and CRH-2 form a transect from no BSR to a strong BSR.

Drilling Program: Site CRH-1 is not part of the existing Leg schedule. However, if time is available, the general plan at this site is:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. ADARA heat-flow measurements, WSTP runs, and PCS cores desirable.
Hole B: Wash to hole A refusal depth, and RCB to 750 m. WSTP desirable.

Logging: Three well-log runs (Quad, Geo-chem, and FMS). VSP desirable.

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

Site: CRH-2
Priority: Secondary
Position: 32˚46.74´N; 75˚55.20´W
Water Depth: 2732 m
Sediment Thickness: ~8000 m
Total Penetration: 750 mbsf
Seismic Coverage: CH-06-92 line 41 (SP 100539), CH-06-92 line 46 (SP 110508), and CH-06-92 line 50; near USGS line 32

Objectives: Drill the entire gas hydrate stability zone, through the base of gas hydrate stability and well into the underlying sediments where seismic data indicate a strong BSR. Sites CRH-1 and CRH-2 form a transect from no BSR to a strong BSR.

Drilling Program: Site CRH-2 is not part of the existing Leg schedule. However, if time is available, the general plan at this site is:
Hole A: APC/XCB until refusal. For calculation, refusal is predicted at 450 m depth. ADARA heat-flow measurements, WSTP runs, and PCS cores desirable.
Hole B: Wash to hole A refusal depth, and RCB to 750 m. WSTP desirable.

Logging: Three well log runs (Quad, Geo-chem, and FMS). VSP desirable.

Nature of Rock Anticipated: Neogene hemipelagic silt and clay.

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TECHNICAL STAFF SUBJECT TO CHANGE.

TABLE 1 - PRIMARY SITE TIME ESTIMATES

Proposed Site	Position	Water Depth (m)	Penetration (mbsf)	Drilling Operations (days)	Logging (type)	Logging (days)	Transit Time (days)
Transit - Halifax to CFD-5							3.51
CFD-5	32°58.98'N 75°55.83'W	2583	50	0.75	None	0	
Dynamic Positioning Move							
CFD-6	32°58.61'N 75°55.11'W	2650	50	0.46	None	0	
Dynamic Positioning Move							
CFD-7	32°57.76'N 75°53.70'W	2700	50	0.75	None	0	
Transit - CFD-7 to BRD-1							0.25
BRD-1	32°29.629'N 76°11.480'W	2167	50	0.42	None	0	
Transit - BRD-1 to BRH-4							0.23
BRH-4	31°47.14'N 75°32.75'W	2775	750	6.37	Q, Gc, F, T, D, V	4.63	
Dynamic Positioning Move							
BRH-5	31°47.71'N 75°32.00'W	2750	750	3.23	Q, Gc, F	3.67	
Dynamic Positioning Move							
BRH-6	31°48.21'N 75°31.34'W	2760	750	5.84	Q, Gc, F, T, D, V	5.32	
Dynamic Positioning Move							

BRH-1a	31°50.59'N 75°28.12'W	2722	750	6.53	Q, Gc, F, V	3.85	
Transit to Miami							1.67
Total				24.35		17.47	5.66

Total days at sea = 47.5

Q = quad combo log, Gc = geochemical log, F = FMS log, D = Dipole Shear, T = ADARA/WSTP temperature measurements, V = VSP

TABLE 2 - ALTERNATE SITE TIME ESTIMATES

Alternate Site	**Position**	**Water Depth** (m)	**Penetration** (mbsf)	**Drilling Operations** (days)	**Logging** (type)	**Logging** (days)
CFD-8a	32°55.46'N 75°50.27'W	2988	75	0.85	None	0
BRH-2a	31°52.84'N 75°25.11'W	2828	800	5.1	Q, Gc, F, T	2.4
BRH-3a	31°54.40'N 75°23.02'W	2965	750	4.5	Q, Gc, F, T, V	2.1
CRH-1	32°46.88'N 75°57.40'W	2647	800	4.7	Q, Gc, F, T, V	2.4
CRH-2	32°46.74'N 75°55.20'W	2732	750	3.8	Q, Gc, F, T, V	2.4

Q = quad combo log, Gc = geochemical log, F = FMS log, D = Dipole Shear, T = ADARA/WSTP temperature measurements, V = VSP