OCEAN DRILLING PROGRAM

LEG 164 PRELIMINARY REPORT

GAS HYDRATE SAMPLING ON THE BLAKE RIDGE AND CAROLINA RISE

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ABSTRACT

Leg 164 was devoted to refining our understanding of the amounts and in situ characteristics of natural gas hydrate stored in marine sediments. Drilling on the Blake Ridge at Sites 994, 995, and 997 documented that finely disseminated gas hydrate occupies a minimum of 1% of the sedimentary section between 200 and 450 m below seafloor (mbsf). Some solid gas hydrate nodules also occur. Free gas is dispersed throughout a zone a few hundred meters thick below the gas hydrate-bearing zone. Coupled with geophysical data indicating that sedimentary gas hydrate occurs throughout a laterally extensive portion of the Blake Ridge, the results of Leg 164 confirm that enormous amounts of methane are contained in these sediments.

Sites 994, 995, and 997 were drilled to 700-750 mbsf on the Blake Ridge and penetrated through the predicted depth of the bottom-simulating reflector (BSR) into the sediments below. The Blake Ridge sediments consist largely of a monotonous sequence of nannofossil-rich clays that were deposited from contour currents at rates varying from 40 m/m.y. in the Pleistocene to 150-350 m/m.y. for the Miocene-Pliocene sequences. Minimal compositional or facies changes occur near the depth of the BSR (~450 m). Cores from all three sites are very gassy and underwent vigorous expansion, which resulted in low recovery. Some nodules of hydrate and one massive gas hydrate zone greater than 30 cm thick were recovered. Decomposition experiments on gas hydrate samples yielded volumetric ratios of gas to water of 130-160, and demonstrated that the gas filling the hydrates was ~99% methane. As anticipated, the ephemeral nature of gas hydrate under surface conditions made sampling difficult. Therefore, emphasis was placed on proxy sampling and downhole tool measurements that allow the in situ conditions of the gas hydrate to be reconstructed.

Closely spaced pore-water samples were taken because interstitial water chloride concentrations can be used to make quantitative estimates of the amount of gas hydrate present in the sediment before coring. During gas hydrate formation, water and methane are taken out of the pore waters, leaving the residual pore waters increasingly saline. Over time, locally elevated chloride concentrations associated with gas hydrate formation diffuse away. When gas hydrate in sediments decomposes during drilling and core recovery, water and gas are released back into the pore space, freshening the pore waters. Pore-water profiles from Sites 994, 995, and 997 are very similar and indicate three distinct chloride concentration zones: (1) a zone of progressive freshening with depth to ~200 mbsf, (2) a zone that extends to the approximate depth of the BSR (~450 mbsf) of highly variable chloride values characterized by local anomalously fresh values, and (3) a zone of nearly

constant chloride beneath the BSR. These anomalies are interpreted to indicate that a minimum of 1% of the sedimentary section within the zone from 200 to 450 mbsf is filled with gas hydrate.

An unprecedented level of success was achieved using the pressure core sampler (PCS), a device that returns a short core to the sruface at formation pressures so that gasses are not lost. Gas volumes captured by the PCS indicate that gas concentrations are grossly in excess of gas saturation, thus demonstrating that free gas exists beneath the BSR. Gases also occur throughout the sedimentary section below.

Vertical seismic profiles were used to locate the precise depth of the BSR and indicated no significant lateral changes in velocity above the BSR. However, velocities as low as 1400 m/s were measured beneath the BSR at Site 997. Well-logs disclosed distinct zones of higher electrical resistivity and velocity that coincided with chloride anomaly zones indicative of gas hydrates. Preliminary well-log analysis of the resistivity data indicate that gas hydrate occupies 3%-5% of sediment volume throughout this zone. A minimum of 13 in situ temperature measurements were made in each hole to establish temperature gradients. Extrapolation of these thermal gradients to depth makes it possible to estimate the maximum depth at which gas hydrate is stable, based on experimentally-determined phase boundaries. The results indicate that the base of gas hydrate stability is ~30 m (Site 997) to ~100 m (Site 994) below the observed BSR depth.

INTRODUCTION

Gas hydrate is a solid phase composed of water and low-molecular-weight gases (predominantly methane) that forms 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.

Large quantities of natural gas may be stored in gas hydrate-bearing sediments because as much as 164 times the saturation concentration of gas at STP conditions exists in these solid phases per unit volume (Kvenvolden, 1988a; Sloan, 1989). It is estimated that there are about 10^4 Gt (Gt = 10^{15} gm) of carbon stored in gas hydrate in sediments, which is about twice the estimate of carbon in all other fossil fuel deposits (Kvenvolden, 1988b). Moreover, there may be considerable volumes of free gas trapped beneath the overlying gas hydrate-cemented zones associated with the bottom-simulating reflector (BSR), as well as dissolved gas in the pore fluids.

Gas hydrate is believed to be common in continental margin sediments because seismic reflection data have indicated its presence in every ocean basin (Kvenvolden and Barnard, 1983; Kvenvolden, 1988a, 1988b). Gas hydrate usually is detected in seismic reflection data by the presence of 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 believed to represent the base of the gas hydrate stability zone, which occurs at depths between about 200 and 600 m below seafloor (mbsf) on continental rises. The pore spaces of sediments above the BSR are 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 and a strong reflector at the base of the gas hydrate stability zone. The Carolina Rise, particularly along the Blake Ridge, was the area where marine gas hydrate was first identified on the basis of a BSR (Fig. 1) and is an area where gas hydrate appears to be especially extensive (Markl et al., 1970; Tucholke et al., 1977; Shipley et al., 1979; Paull and Dillon, 1981; Dillon and Paull, 1983; Markl and Bryan, 1983).

ODP Leg 164 was devoted to refining our understanding of the in situ characteristics and amounts of natural gas hydrate stored in marine sediments. The program involved drilling 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 (Fig. 1). Short holes (50 m) were drilled at four 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 (Fig. 1). Because of the ephemeral nature of gas hydrate, emphasis was placed on downhole measurements and sampling strategies that allow in situ conditions of gas hydrate to be reconstructed.

The objectives of Leg 164 included:

1. Assessing the amount of gas trapped in hydrate-bearing sediments;
2. Understanding lateral variability in gas hydrate abundances;
3. Understanding the relationship between BSRs and gas hydrate development;
4. Investigating the distribution and in situ fabric of gas hydrate within sediments;
5. Establishing changes in physical properties (porosity, permeability, *P*-wave velocity, thermal conductivity, etc.) associated with gas hydrate formation and decomposition in continental margin sediments;
6. Determining whether gas contained in gas hydrate is produced locally or migrated from elsewhere;
7. Investigating the role of gas hydrate in formation of authigenic carbonates;
8. Determining the chemical and isotopic compositions, hydration number, and crystal structure of

natural gas hydrate;

9. Determining the role of gas hydrate in stimulating or modifying fluid circulation;
10. Investigating the potential connection between large-scale sediment failures and gas hydrate decomposition; and
11. Establishing the origin of the Carolina Rise Diapirs and their influence on associated sedimentary gas hydrate.

RESULTS

Sites 991/992/993

Short holes were drilled at three sites on the crest and flanks of the Cape Fear Diapir (Figs. 1 and 2). The diapir is one of about 20 large structures that originate from deep within the sediments of the Carolina Trough and penetrate through the Carolina Continental Rise. Although the core material of these diapirs is unknown, many investigators believe they are salt cored. The crest of the Cape Fear Diapir breeches the seafloor within the scar of the giant Cape Fear Slide. Although the Cape Fear Diapir occurs within a region where a BSR is present, the continuity of the BSR is lost on the flanks of the diapir. The objectives of Sites 991, 992, and 993 were to investigate the effects of diapir intrusion and large-scale sediment failure on the regional gas hydrate field and on the transport of fluid and gas through the sedimentary sequence. A second major objective was to establish the nature of the core material of the diapir.

Lithologic variations, physical property changes, and nannofossil biostratigraphy indicate that a discontinuous Neogene sediment section was recovered at Hole 991A (Fig. 3). The uppermost unit (I) (0-2.05 mbsf) consists of greenish gray nannofossil silty clay with a sharp, irregular contact at its base. Unit II (2.05-47.66 mbsf) is composed of firmer gray nannofossil silty clays. The top (2.05-12.67 mbsf) and bottom (18.37-47.66 mbsf) of this unit are characterized by zones of steeply dipping, discordant, and truncated beds and laminae of variegated colors; beds deformed by flowage, folding and faulting; and mud clasts of various sizes, shapes, and colors. However, the middle (12.67-18.37 mbsf) of this unit is apparently undeformed. Unit II is interpreted as a large slide block. A long hiatus, correlative with earliest Pleistocene to late early Pliocene times was detected within Unit II. Unit III (47.66-57.16 mbsf) is predominantly undeformed dark gray nannofossil-rich clay. Sediment at the bottom of the hole is late Miocene in age (CN9b Zone).

Two major lithologic units were recognized in Hole 992A (Fig. 3). The top unit (0-9.1 mbsf) is composed of strongly deformed gray nannofossil silty clay beds, which are similar in lithology and structural style to Unit II in Hole 991A. The unit appears to represent a mass-transport deposit that was emplaced by slumping. The bottom unit (9.1-50.75 mbsf) is a homogeneous olive gray diatom-rich nannofossil clay, which appears to be undeformed. At Hole 992A, most of the uppermost Pleistocene sequence is missing. Another long hiatus corresponding to early Pleistocene to late Miocene times was identified, and the oldest sediment recovered was middle late Miocene in age (CN9a Zone). The lithologies did not reveal the composition of the underlying diapir.

Hole 993A contains one major unit, from 0 to 47.27 mbsf, that is predominantly gray nannofossil clay (Fig. 3). The material is generally homogeneous greenish to olive gray nannofossil clay and silty clay. The only exception is a short interval from 4.43 to 4.9 mbsf that contains an indurated carbonate and overlies a carbonate silty clay (4.43-4.9 mbsf). The entire sequence is of early late Miocene age (Zone CN7).

At all three sites, the methane concentrations increased with depth, ranging from 5 to 29,000 ppm at Site 991, from 2 to 81 ppm at Site 992, and from 6 to 18,000 at Site 993. The methane-to-ethane ratios of most samples indicate a microbial origin for the methane.

Detailed pore-water profiles from Holes 991A and 993A, both of which are located on the flanks of the diapir, show that chloride concentrations increase at a rate of 2 millimolar per meter (mM/m) (Fig. 4). However, in Hole 992A, located on the crest of the diapir, the gradient is significantly less (about 0.8 mM/m). No significant trend in the Na^+/Cl^- ratio exists. There are several possible explanations for the greater pore-water chloride content at Sites 991 and 993 relative to Site 992. High dissolved chloride content may indicate that the core of the diapir is composed of evaporitic salts. The variations in chloride concentration of the interstitial waters analyzed from these sites may have been modified by fluid-circulation patterns around the diapir. The variations in the profiles also may indicate that major slumps have truncated the sedimentary sections on the flanks of the diapir more recently than those on the crest of the diapir. Thus, the present pore-water profiles on the flanks are still steeper than the pore-water gradients on the crest of the diapir. Alternatively, the variations in interstitial water chloride contents could be produced by ion exclusion associated with gas hydrate formation on the flanks of the diapir. Seismic reflection profiles indicate a strong BSR in the sediments surrounding the diapir. Sites 991 and 993, on the flanks of the diapir, are closer to the saline waters that are generated as a consequence of gas hydrate formation. Conclusions about the cause of the high pore-water chloride content await shore-based analytical work.

Dissolved sulfate content in interstitial-water samples from Site 991A decreases linearly with increasing depth, declining to negligible concentrations at ~40 mbsf. At this depth, there is a corresponding alkalinity maximum in the interstitial-water samples. Ammonium contents increase linearly with depth, passing through the base of the sulfate reduction zone without inflection. Active anaerobic methane oxidation is suggested by these profiles.

Both PCS runs at Hole 991B were only partly successful. Core 164-991B-1P was pressurized at ~2500 psi, about 70% of that expected for hydrostatic pressure at the coring depth, but contained only water. Core 164-991B-2P was pressurized at 63 psi but contained 1.04 m of homogenous nannofossil-bearing clay.

Magnetic intensities are very weak throughout the sedimentary sequence at all three sites, and no consistent magnetostratigraphy can be recognized. Rock-magnetic analysis (saturation isothermal remanent magnetization [IRM], back-field IRM, and partial anhysteretic remanent magnetization [ARM] acquisition) indicate the presence of two magnetic carriers. This paleomagnetic and rock-magnetic behavior probably is caused by dissolution of single-domain magnetite and reduction to magnetic iron sulfides. Rock magnetism, bulk magnetic susceptibility, and magnetic remanence all confirm the distinction between lithostratigraphic Units I and II at both Holes 991A and 992A. Unit I is characterized by the presence of substantial proportions of single-domain magnetite. However, single-domain magnetite is absent in Unit II and appears to have been replaced by magnetic sulfides, resulting in the loss of magnetostratigraphy. The break is sudden, collaborating the break interpreted in the depositional record. Anisotropy of susceptibility indicates a strongly foliated fabric in Unit II, consistent with overconsolidation at this depth.

In summary, the sediments recovered at Sites 991, 992, and 993 are typical Neogene continental rise deposits and do not directly indicate the composition of the underlying diapir. The sedimentary sequence has numerous stratigraphic gaps. Pre-Quaternary sediments occur between 0.5 and 30 mbsf at all three sites, indicating that the upper Quaternary section has been substantially truncated. Pervasive soft-sediment deformation was observed within the Pleistocene to Pliocene sequences from Sites 991 and 992, especially near the tops of both sections, suggesting that these unconformities resulted from vigorous mass-transport processes associated with sediment failures (e.g., slumping, sliding, and debris flows). The sediments near the surface tend to be over consolidated for their current burial depths. The relative absence of Holocene and late Quaternary age materials in a region where the Holocene and late Pleistocene sedimentation rates are known to exceed 20 cm/k.y. (Paull et al., 1996) indicates that the most recent deformation occurred within the late Quaternary and Holocene. The paucity of recent sediments around the diapir suggests that the diapir is still active.

Site 994

Site 994 is part of a transect of holes on the southern flank of the Blake Ridge that extends from an area where a BSR is not detectable to an area where an extremely well-developed and distinct BSR exists (Fig. 5). The transect is situated where variations in the development of the BSR and seismic blanking are especially distinct. However, the geology and topography along this transect are relatively simple (Fig. 6), which provides an opportunity to assess basic properties of hydrate-bearing sediments and to understand lateral hydrate variations caused by local lithologic, chemical, and hydrologic factors. Site 994 is situated at the end of the transect where the BSR is not detectable and, thus, serves as a background or reference site.

At Site 994, we recovered a 700-m-thick sequence that is dominantly composed of clay and calcareous nannofossils (Fig. 6). Three major lithologic units were identified, based on downward decreasing contents of calcareous nannoplankton. Unit I (0-14 mbsf) has the highest nannofossil contents (up to 45%) correlating with the lightest colors of any sediment found in the hole. Unit II (14-160 mbsf) consists of decimeter- to meter-thick layers of dark greenish gray nannofossil-rich clay and more carbonate-rich greenish gray nannofossil clay. Nannofossil contents average 25%, with values of 40% and higher in the lighter colored beds. Unit III (160-703.5 mbsf), which extends to the bottom of the hole and comprises the remainder of the Pliocene to uppermost Miocene, consists of a monotonous succession of dark greenish gray diatom-bearing nannofossil-rich clay, with average $CaCO_3$ contents of 20%. Within most of the section (from 180 mbsf to the bottom of the hole), grain densities are homogeneous. Within the same interval, wet-bulk density and strength increase linearly, whereas water contents gradually decrease with increasing depth. The lithologic homogeneity of sediments at Site 994 makes it an ideal reference section for comparative gas hydrate studies.

The section obtained in Hole 994C contains a continuous record spanning from the Holocene to latest Miocene (~6 Ma) in age (Fig. 7). All nannofossil zones and subzones were present, and no obvious hiatuses were identified. Measurement of discrete paleomagnetic samples allowed determination of approximate positions for the Brunhes/Matuyama (40 mbsf) and Gauss/Matuyama (150 mbsf) magnetochron boundaries and for the Olduvai subchron (90-115 mbsf). Estimated sedimentation rates increased consistently downsection, reaching a maximum of 400 m/m.y.

Sediments in many cores were very gassy. Most cores underwent extensive gas-driven self-extrusion, sometimes splitting the liners near the shoe, and one core burst its liner within the core barrel on the drill floor. Disruption of the cores due to gas expansion began occurring at ~60 mbsf. Poor recovery below 190 m is largely a result of vigorous degassing. The gas is mostly methane with secondary amounts of CO_2. Slight increases in ethane contents with depth were observed; however, the sediments did not reach the zone of thermogenic hydrocarbon production.

The chloride profiles from Holes 994A, B, and C (Fig. 8) contain anomalously low-chloride spikes superimposed on a trend of generally decreasing chloride concentration from typical seawater values at the top of the section to ~90% of seawater at 300-400 mbsf. A slight increase in chloride toward the bottom of the hole is present. The lowest measured chloride concentration is 438 mM. In the interval from 100 to 450 mbsf, chloride anomalies were found in 50% of the interstitial water samples, and they are particularly abundant and well developed at 380-440 mbsf. Detailed studies on cores from Hole 994D revealed that the anomalous low-chloride spikes extend over less than 1.5 m. The spikes are interpreted as evidence for the presence of gas hydrate, which melts and dilutes the interstitial water during coring and processing.

Gas hydrate was sampled from two cores. Section 164-994C-31X-7 (258 mbsf) contained several white nodules of hydrate that ranged in volume from ~4 to 25 cm^3. Gas volume, gas composition, and water volume of a solid piece of hydrate were determined. The gas composition of the hydrate was 98.78% methane, 1.22% CO_2, 86 ppm ethane, and 2 ppm propane. Volumetric calculations show that the cage occupancy (percentage of potential gas molecule sites in the hydrate crystal lattice that are actually filled) of the hydrate sample is at least 80%. In Section 164-994D-4X-1 (261 mbsf), a piece of hydrate that was less than 1 cm^3 was found. In the region where solid hydrate was recovered from the cores, the physical properties data do not reveal any significant changes in any sediment properties. Many cores recovered from 240 to 430 mbsf contained anomalously cold zones (measured using temperature probes on the catwalk) indicating that gas hydrate had decomposed within these cores, even though hydrate was not visually observed.

Fourteen in situ temperature measurements were attempted between 0 and 445 mbsf in Hole 994C (Fig. 9). Based on data from eight successful deployments of the Adara temperature tool and water sampler temperature probe (WSTP) tools, the average geothermal gradient in the uppermost 320 m is estimated at 38.6˚C/km. Average heat flow is 35 mW/m^2 over the entire depth range of the measurements, but 45 mW/m^2 within the upper 100 m of the hole. Anomalously low temperature (6-8˚C) measurements were made at four depths between 300 and 425 mbsf. Although there is no simple explanation for the shape of the equilibration paths associated with the anomalous records, the low in situ temperatures are consistent with those measured close to solid hydrate in the recovered cores. Such anomalously low temperatures might be produced by the endothermic decomposition of solid hydrate.

Rock-magnetic studies indicate two prominent features superimposed on a continuous sequence of magnetite to pyrite reduction. At 260 mbsf, immediately below the hydrate recovery in Core 164-994C-31X, and at 365 mbsf, coincident with an anomalously low interstitial-water chloride content, rock-magnetic signatures are similar to those found on samples from Leg 146 at the base of hydrate concentrations and "fossil hydrate zones."

A suite of wireline logs was run, including neutron density, neutron porosity, resistivity,*P*-wave sonic, shear sonic, and geochemical logs. In addition, several measurements with the geochemical tool in the inelastic mode were made in an attempt, for the first time in ODP history, to determine carbon/oxygen ratios. Initial analysis of the neutron density, resistivity, and sonic logs shows distinct changes in *P*-wave velocity and resistivity in two important regions (Figs. 10 and 11). The first corresponds to the zone below 220 mbsf from which gas hydrate was recovered. In this zone, velocity and resistivity have pronounced positive spikes. The second region at 420 mbsf, where velocity and resistivity decrease sharply, is near the predicted base of the hydrate stability field. In contrast, the density log does not show changes at corresponding depths. The formation factor (observed resistivity/seawater resistivity) increases with depth from 220 to 420 mbsf and then abruptly decreases to lower values. The relatively constant density throughout this interval suggests that the rise in resistivity is not entirely due to changes in porosity and may reflect increasing amounts of gas hydrate with depth in this zone.

Vertical seismic profiles were conducted at depths of 110-650 mbsf during five lowerings of the three-component Woods Hole Oceanographic Institution (WHOI) borehole seismometer in Hole 994D. Difficulties with the clamping arm restricted the acquisition to two walkaway VSPs at 650 and 482 mbsf and eight zero-offset clamps over the same depth range. Zero-offset air gun shots were fired with the tool suspended in the hole at 20-m intervals from 570 to 110 mbsf. A stacked record section shows clear first arrivals from 250 to 650 mbsf. A preliminary*P*-wave velocity model (Fig. 12) shows elevated velocities (with respect to background levels) in a zone from 320 to 420 mbsf and a pronounced low-velocity zone from 550 to 650 mbsf. The low-velocity zone may be due to the presence of free gas bubbles dispersed in the sediments at this depth.

Estimates of gas hydrate amounts in the sediments before recovery at Site 994 are made by assuming that diffusive equilibration prohibits significant and nonsystematic interstitial chloride concentrations from occurring between closely spaced samples (Fig. 8). Thus, chloride spikes are only a result of gas hydrate decomposition during sample recovery. To produce an estimate of the interstitial-water salinity through the zone between 200 and 450 mbsf, where erratic chloride values were measured, a polynomial was fit to the relatively smooth chloride data above 200 m and below

450 m. All but one of the measured chloride concentrations in this zone have lower values than the calculated in situ values, with some significantly lower. The differences between the calculated in situ chloride concentrations and the measured chloride concentrations were used to establish the relative chloride anomaly that is associated with each sample. The calculated chloride anomalies enable the amount of gas hydrate that was present in these samples to be estimated. Corrections for the porosity of the samples were made using the shipboard physical properties data. The estimated percent volume of the samples that was occupied by gas hydrate had a skewed distribution, ranging to as much as 7% (at 391 mbsf), with a mean value of 1.3% ± 1.8% and a median value of 1% for all the interstitial-water samples that were collected between 200 and 450 mbsf.

Calculations of the percentage of gas hydrate that is required to explain the observed change in the well-logging resistivity trend (Fig. 11) indicate that the general trend through this interval (between 212.0 and 428.8 mbsf) can be explained by the pervasive addition of up to 2.9% gas hydrate. The same calculation indicates that the horizon with the highest concentration (~239 mbsf) contains as much as 9.5% gas hydrate. It is remarkable that independent estimation of the amounts of gas hydrate from different data sets (chloride anomalies and logging data) yield similar values of a few percent gas hydrate disseminated in the sediments.

In summary, although very little gas hydrate was recovered from Site 994, the interstitial-water chloride anomalies, temperature anomalies in recovered cores, and patterns in the well-log data all indicate that gas hydrate occupies an average of 1% or more of the sedimentary section from 220 to 430 mbsf. The hydrate is inferred to occur as finely dispersed crystals within homogenous sediments. All of the inferred hydrate occurs well above the predicted base of gas hydrate stability at this site.

Site 995

Site 995 was the first site on Leg 164 at which drilling penetrated below the base of the gas hydrate stability zone and through a strong BSR (Fig. 5). The site is located on the southern flank of the Blake Ridge, 3.0 km northeast of Site 994, and within the same stratigraphic interval as Site 994. However, a strong BSR is present at Site 995 at 0.53-s sub-bottom, which is not observed at Site 994 (Fig. 5). Sites 994 and 995 are coupled sites that were intended to establish the nature of the BSR and to understand the causes of profound differences in acoustic characteristics (Fig. 5) within essentially the same sedimentary sequence.

At Site 995, we recovered a 700 m-thick sedimentary sequence that is dominantly composed of clay and nannofossils (Fig. 6). Three major lithologic units were identified, primarily based on downhole variations in carbonate contents and diatom and nannofossil abundances. Unit I (0-13.4 mbsf; Holocene to upper Pleistocene), comprises foraminifer-bearing nannofossil-rich clay and nannofossil clay, with carbonate contents as great as 50 wt% $CaCO_3$. The sediments in Unit II (13.4-131.9 mbsf; upper Pleistocene to upper Pliocene) contain abundant diatoms and have lower nannofossil contents (average 10%) than those in Unit I. The upper part of Unit II (Subunit IIA) contains foraminifer-rich winnowed layers that indicate deposition by contour currents. Unit III (131.9-704.6 mbsf) extends to the bottom of the hole and comprises an upper Pliocene to upper Miocene sequence of monotonous diatom-bearing nannofossil-rich clay, and nannofossil-bearing clay and claystone, with average $CaCO_3$ contents of 15 wt%.

Nannofossil biostratigraphy indicates that the sequence recovered at Site 995 is mostly continuous except for a short hiatus or gap detected within the uppermost Miocene (Fig. 7). The sedimentation rates for the Quaternary and lower Pliocene sequences are almost identical to those at Site 994. However, the rate for the upper Pliocene (110 m/m.y.) is about 10% higher than at Site 994. The upper Miocene sequence is estimated to have been deposited at a rate of approximately 260 m/m.y. The age of the oldest sediments cored at Site 995 (704.6 mbsf) is estimated to be 6.1 Ma. A magnetostratigraphy was determined for Hole 995A, despite remanences of <0.5 milliampere/m (mA/m), and major chron boundaries were recognized as follows: C2An/C2r (Gauss/Matuyama), 125-145 mbsf; C2Ar/C2An (Gilbert/Gauss), 295-320 mbsf; C3n/C2Ar, 320-350 mbsf; C3r/C3n, 545-580 mbsf; and C3An/C3r (Anomaly 5/Gilbert), 620-640 mbsf.

Concentrations of methane in headspace gas samples increase from 0.021 ml/kg of sediment near the sediment-water interface to a maximum of 114 ml/kg at a depth of 42.7 mbsf. Headspace methane contents then steadily decline to about 10 ml/kg near 240 mbsf and remain at 1 to 10 ml/kg throughout the rest of the hole. Methane- to-ethane ratios decrease with depth and reach a minimum of 146 at 699.4 mbsf. Higher molecular weight hydrocarbons are present in <10 ppm concentrations from 171.2-699.4 mbsf, and heptane occurs in the lower sections of Hole 995A, suggesting a small amount of thermally mature gas has migrated to the site. The total organic carbon contents of the sediments are near 1%, and the organic matter is immature, containing both terrestrial and marine components.

Interstitial-water geochemical data from Site 995 are remarkably similar to those found at Site 994 (Fig. 8). In particular, anomalously low values of interstitial-water chloride concentrations occur at the same depths at both sites. The low chloride values (as low as 466 mM) occur between 195 and 450 mbsf, coincident with the zone of anomalously low sediment temperatures measured on the catwalk after recovery, indicating that gas hydrate recently decomposed in these cores. These results imply that sites 3 km apart possess similar vertical distributions and amounts of gas hydrate.

Eleven WSTP runs from 78.7 to 200.2 mbsf were made at Site 995. The recovered samples contain 0.1%-94% interstitial water, with the proportion of interstitial water decreasing with increasing depth. After correction for the effects of dilution by borehole water, the WSTP water samples indicate that in situ chloride concentrations generally are comparable to those measured for water squeezed from whole-round core samples recovered from corresponding depths.

The PCS was successfully deployed 11 times at Site 995. Gas samples taken from the PCS are methane, with approximately 1% CO_2, that evolves from the tool at pressures below 500 psi (at 0°C). The amount of gas recovered from certain cores exceeds that expected from methane saturation of the interstitial waters at in situ pressures. Because some of these same cores were recovered from above the base of gas hydrate stability in the zone associated with the erratic interstitial-water chloride concentrations, the "excess" gas is probably derived from decomposition of methane hydrate.

Physical properties data for sediments from Hole 995A are nearly coincident with those found at Site 994. The data do not reveal major differences that could account for the remarkable lateral variability in the strength of the BSR between the sites. The data also show a 390-m-thick interval (220-610 mbsf) in which the wet-bulk density values are constant as a function of depth, an unusual observation in sediments undergoing normal compaction.

Rock magnetism defines a trend of magnetite-greigite-pyrite conversion in which greigite develops within the first 20 mbsf in response to bacterial oxidation of organic material and is progressively reduced to pyrite downhole. Below this a second generation of greigite extends downward to ~260-300 mbsf, approximately coinciding with the zone of high gas hydrate concentration inferred from interstitial-water chloride values. This sequence of reduction steps is similar to that - documented at Site 994.

Twenty in situ temperature measurements were attempted at Site 995 using the Adara and WSTP tools and a new prototype temperature probe , the Davis-Villinger temperature probe (DVTP) (Fig. 9). Based on 15 successful deployments of the temperature tools, the geothermal gradient is estimated at 33.5 ± 0.9 °C/km between 0 and 381 mbsf. Taking into account vertical variations in thermal conductivity, the average heat flow from 0 to 381 mbsf is 34.2 ± 1.7 milliwatt/m^2 (mW/m^2), which is 35% lower than previous measurements from this region. Preliminary extrapolation of the thermal gradient to 440 mbsf, the depth of the BSR at Site 995, yields a temperature of 18.3°C. This is well within the experimentally determined pressure-temperature stability field for methane hydrate.

A complete suite of wireline logs (natural gamma, resistivity, sonic, neutron porosity, lithodensity, geochemistry, Formation MicroScanner [FMS], and the experimental shear wave tool) was run in Hole 995B from 130 to 630 mbsf. Preliminary analysis of the acoustic and resistivity logs (Figs. 10 and 11) shows a pattern similar to that at Site 994, with low acoustic velocities (~1600 m/s) in the top of the hole that begin to increase at 220 mbsf to a maximum of 1900 m/s at 450 mbsf before decreasing again to 1600 m/s at 600 mbsf. The zone from 220 to 450 mbsf has higher resistivities than are found either above or below. The resistivity and acoustic velocity measurements are consistent with the presence of hydrate in the zone from 220 to 450 mbsf and with the presence of gas bubbles in the section below 450 mbsf.

VSPs were conducted at depths of 144-664 mbsf during two lowerings of the three-component WHOI borehole seismometer in Hole 995B. Walkaway VSPs were shot by the *Cape Hatteras* and recorded at eight depths from 176 to 680 mbsf. A stacked record section shows clear downgoing first arrivals and upgoing reflections, including a strong reflection from the BSR. The intersection of the downgoing first arrival and the upgoing BSR reflection indicates that the BSR is located at 440 ± 10 mbsf. A preliminary *P*-wave velocity model (Fig. 12) shows that compressional velocity reaches a maximum of 1850 m/s at 400 mbsf. Velocities decrease below this depth, reaching a minimum of about 1550 m/s at 590 mbsf, suggesting the presence of gas bubbles.

Site 996

Site 996 is located on the crest of the Blake Ridge Diapir, the southernmost in a series of ~20 diapiric structures rising from deep within sediments of the Carolina Trough (Fig. 1). The objectives at this site were to investigate (1) methane migration and gas hydrate formation in a pockmarked fault zone where methane is leaking out of the continental rise, (2) the source of fluids and gases in a seafloor seep, and (3) the influence of these fluids on the host sediments.

Five short holes were drilled at Site 996 in sediments overlying the Blake Ridge Diapir (Figs. 13 and 14). Holes 996A, 996B, and 996C are located within a seafloor pockmark that contains an active chemosynthetic community dominated by mussels. Holes 996D and 996E were drilled on the flanks of this pockmark. Overall core recovery was poor. The sedimentary sequence consists primarily of nannofossil-bearing clay and nannofossil-rich clay, both with varying amounts of foraminifers (0%-15%) and diatoms (0%-25%). Contorted and steeply dipping beds in parts of the sequence provide evidence of soft-sediment deformation that is probably related to diapir uplift. The uppermost 2 m of sediment within the pockmark consist of nannofossil-rich aragonitic clayey silt with abundant bivalve shell fragments. The shell fragments and surrounding sediments commonly show initial stages of calcite and aragonite cementation. Indurated carbonate zones occur from ~5 to 15 mbsf and from 30 to 50 mbsf. Rapid decreases in the calcium and magnesium concentrations of interstitial waters within the upper 10 mbsf and a corresponding increase in the alkalinity indicates the precipitation of carbonate within the uppermost sediments.

All of the sediments recovered at Site 996 are Quaternary in age. The lowermost cores from Holes 996A, 996D, and 996E are early Pleistocene, with a maximum age of about 1.0 Ma. Because of poor recovery, the magnetostratigraphy is very poorly defined. In Hole 996E, the Matuyama/Brunhes boundary is tentatively placed at about 33 mbsf, and the top of the Jaramillo subchron at ~40 mbsf.

Gas hydrate was recovered from all five holes (Holes 996A through E). The hydrate was white and occurred in three different forms: (1) massive pieces, cylindrical to round in shape and as much as 5 to 8 cm long, were found in sediments recovered from the uppermost 9 mbsf; (2) platy, 1-4 mm thick veins that filled wavy vertical fractures; and (3) vertically oriented rod-shaped nodules about 1 cm in diameter and 3-12 cm in length that tapered downcore. Numerous pieces of hydrate were sampled both for shipboard analyses and for storage in pressure vessels for shore-based studies.

Magnetic susceptibility and rock-magnetic studies suggest that the zone of bacterial magnetite authigenesis, present in the uppermost few meters at all other Leg 164 sites, is absent from Site 996. High-resolution gamma-ray attenuation porosity evaluator (GRAPE) data for sediments from Hole 996E indicate little variation in wet-bulk density with depth, with values averaging 1.8 g/cm^3. Porosities decrease from 75% to 50% in the uppermost 12 m of the hole, but water content decreases exponentially over the same interval, which is similar to the pattern observed in the uppermost 100 m at Site 995.

The methane (C_1) content of headspace gases in sediments from Holes 996A, 996C, and 996D increases from 1300 to 11000 ppm with increasing depth to 60 mbsf. Ethane (C_2) concentrations ranged from 1 to 10 ppm, yielding C_1/C_2 ratios near 1000. In contrast, near-surface sediments from Hole 996E, which is located outside of the pockmark, were relatively poor in C_1. However, at depths below about 10 mbsf, C_1 concentrations and C_1/C_2 ratios were comparable to those from

Holes 996A, 996B, and 996C. The free gases consist almost entirely of C_1 (greater than 90%), CO_2, and H_2S in the upper sections of each Hole. H_2S concentrations were as high as 50,000 ppm. Maximum values for C_2 and C_3 were 940 and 25 ppm, respectively.

Chloride concentrations (Fig. 4) increase to 1.8 times that of seawater with increasing depth (57.7 mbsf) at Site 996, suggesting the influence of evaporites at depth. Increasing Na/Cl ratios and a two-fold increase in K^+ concentrations are consistent with a salt source. Large (20%-30%) negative anomalies in chloride concentration also occur, probably due to gas hydrate dissociation. Large decreases in dissolved calcium and magnesium concentrations in interstitial waters from sediments within the uppermost 10 mbsf, and alkalinity maxima at approximately 15 mbsf, indicate precipitation of carbonate within the top 10-15 m of the sedimentary sequence. Sulfate approaches negligible concentrations near the seafloor (Holes 996C and 996D), and together with high levels of interstitial $\sum HS^-$ and methane, suggests active sulfate and methane consumption near the seafloor. Active pore-water advection also is suggested by the wide difference in interstitial waters sampled immediately below the seafloor chemosynthetic community (Holes 996A, 996B, and 996C) and sampled at depth in Hole 996E.

Site 997

Site 997 is located on the topographic crest of the Blake Ridge in an area where an extremely well-developed and distinct BSR exists (Fig. 5). It was the last of three sites drilled along the Blake Ridge transect.

The three lithostratigraphic units recognized at Site 997 are very similar to those documented at Sites 994 and 995 (Fig. 6). Unit I (0-6.2 mbsf) consists of interbeds of foraminifer-bearing nannofossil-rich clay with color repetition of light gray and greenish gray. Beds with disseminated and concentrated glauconite occur, especially in the lowermost portion of the unit. Total carbonate contents range from 11 to 50 wt% $CaCO_3$. Unit II (6.2-107.3 mbsf) consists of interbeds of greenish gray, intensely burrowed nannofossil-rich clay, and darker-colored bioturbated clay with lower nannofossil abundance. The top of the unit is marked by a sharp decrease in nannofossil abundance to <20% and the appearance of diatoms. Diatoms remain abundant (35%) in the interval from 37.9 to 50.4 mbsf. Total carbonate contents decrease to <30%. Unit III (107.3-750.0 mbsf) consists of homogeneous, diatom-bearing nannofossil-bearing clay and claystone, with two diatom-rich intervals at 146.9-183.2 and 452.6-587.2 mbsf. The top is marked by the last occurrence of a mottled nannofossil-bearing clay bed. Total carbonate contents decrease to <20% with nannofossil abundances <10%. Two intervals of diatom-rich sediments in Unit III from all three Blake Ridge sites (160-232 mbsf and 430-660 mbsf at Site 994, 131.9-252.3 mbsf and 464.2-656.0 mbsf at Site 995, and 146.9-183.2 mbsf and 452.6-587 mbsf at Site 997) occur at times of higher sedimentation rates, as deduced from nannofossil biostratigraphy (approximately 5.8 to 5.0 Ma and 3.0 to 2.6 Ma).

The 750-m sequence recovered at this site is Holocene to late Miocene in age (Fig. 7). Three short hiatuses were detected in the upper lower Pleistocene and upper lower Pliocene, and the fourth short hiatus is likely in the upper Miocene. Sedimentation rates increased with depth throughout the sedimentary sequence. Because of a hiatus and coring gap detected between Cores 164-997A-1H and 2H, the Quaternary sedimentation rate at Site 997 (40 m/m.y.) is only two-thirds of the value observed at Sites 994 and 995. The Pleistocene rates (129-194 m/m.y.), calculated by excluding the hiatuses, are the highest among the three sites. The minimum rate for the upper Miocene is more than 342 m/m.y., very close to the value obtained for the uppermost Miocene sequence at Hole 994C. The oldest age estimated at Hole 997B is approximately 6.4 Ma.

A well-defined magnetostratigraphy was determined for the upper part of Site 997. The lower boundary of the C1r.1n subchron (Jaramillo normal chron) is at 52 mbsf, the upper and lower boundaries of the C2n (Olduvai normal chron) are at 72 and 84 mbsf, respectively, and the C2An/C2r boundary (Gauss/Matuyama boundary) is at 122 mbsf. The C1n/C1r boundary (Brunhes/Matuyama boundary) and the upper boundary of the C1r.1n (top of Jaramillo normal chron) are tentatively defined at 36 and 41 mbsf, respectively.

Sediment physical properties at Site 997 are generally similar to those at Sites 994 and 995. Most notably, all three sites have a well-defined lowermost unit (upper boundary at 610-625 mbsf) in which wet-bulk density increases with depth more rapidly than in the overlying and largely homogeneous unit that makes up most of the sedimentary section. All three sites also are characterized by an interval in which water contents increase with depth in at least one 50-m-thick section between 50 and 200 mbsf. At Site 997, the major interval of increasing water content and porosity with depth (approximately 88-177 mbsf) corresponds to a diatom-rich layer.

Rock magnetism defines a similar downhole sequence of reduction steps to that seen at Sites 994 and 995. Magnetite authigenesis from 0 to 2 mbsf is followed by reduction of magnetite to pyrite via magnetic sulfides. Two reduction styles are apparent. The first is a trend of magnetite-greigite-pyrite conversion in which greigite apparently develops within the first 20 mbsf in response to bacterial oxidation of organic material and is progressively reduced to pyrite downhole. A second generation of greigite extends downward to ~260-300 mbsf, as observed at Sites 994 and 995.

Rock-magnetic data suggest that the second generation greigite has been largely reduced to pyrite below 300 mbsf.

Seventeen in situ temperature measurements were obtained between 0 and 414.1 mbsf in Hole 997A using the Adara, WSTP, and DVTP (Fig. 9). The data indicate that Site 997 is characterized by a linear geothermal gradient of 36.9 ± 0.4 mK/m, which is within one standard deviation of the estimated gradient at Site 994 (36.4 ± 1.3 mK/m), and 9% higher than the gradient at Site 995 (33.5 ± 0.9 mK/m). The estimated temperatures at the BSR are 18.7˚C (440 mbsf) at Site 995 and 20.0˚C (450 mbsf) at Site 997. At Site 994, where there is no BSR, the temperature at a comparable depth (440 mbsf) is estimated at 20.1˚C. On the Blake Ridge, sediments overlying a BSR (Sites 995 and 997) are not uniformly cooler than those at a comparable depth in a location with no BSR (Site 994).

The concentration of methane in headspace gas samples increases from 0.022 ml/kg of sediment near the sediment-water interface to a maximum of 180 ml/kg at a depth of 50.4 mbsf. The concentration steadily declines to about 6.6 ml/kg near 210 mbsf, and thereafter remains at concentrations ranging from 0.4 to 61 ml/kg. Notable spikes in methane concentrations occurred in the same intervals in which gas hydrate was found or inferred by temperature measurements. Methane-to-ethane ratios increase with depth and reach a minimum of 109 at 725.8 mbsf. Higher molecular-weight hydrocarbons are present throughout the hole in <100 ppm concentrations and increase with depth. Heptane occurs from 153.3 mbsf to 750.0 mbsf. The total organic carbon (TOC) contents of the sediments are near 1% above 200 mbsf and ~1.5% in the interval from 200 to 700 mbsf. The amount and composition of volatile and nonvolatile organic matter is very similar to that found at Sites 994 and 995.

The interstitial-water chemistry at Site 997 is very similar to that documented at Sites 994 and 995 (Fig. 8). Downhole profiles of all dissolved species show the same general trends with the same approximate depths for maxima and minima as those seen at the other Blake Ridge sites. Chloride profiles were used as a proxy indicator of the amount of in situ gas hydrate. The chloride excursion zone occurs at approximately the same depths (~200 to 440 mbsf) over the 10-km transect. Furthermore, the two depth intervals showing the largest chloride excursions, at ~250 and 400 mbsf, are also depth correlative. Thus, the similarity of the Cl^- profiles at the ridge sites strongly suggests that gas hydrate is correlative over the expanse of the Blake Ridge.

The PCS was successfully deployed 11 times at Site 997, including one deployment to determine the volume and composition of gas in sediment immediately below the prominent BSR at 462 mbsf. The volume of methane evolved from this particular PCS core suggests that interstitial waters at this depth are 10 times oversaturated with methane. Chemical analyses also show that pore waters at this depth do not have the low chloride concentrations associated with the presence of gas hydrate. Together these observations provide the first direct evidence for significant free gas immediately below a BSR.

Hole 997B was logged from 113.0 to 715.0 mbsf with four different tool strings (Quad combination, geochemical combination, Lamont-Doherty dipole shear tool, and the FMS). Preliminary analysis of the acoustic velocity and resistivity logs shows a pattern similar to that at Sites 994 and 995 (Figs. 10 and 11). Low acoustic velocities (about 1600 m/s) in the top of the hole begin to increase at 186 mbsf to a maximum of 2000 m/s at 450 mbsf before dramatically decreasing again to below 1200 m/s. The interval from 186 to 450 mbsf also exhibits higher resistivities. In addition, the resistivity log reveals three conspicuous high electrical resistivity intervals near 210, 365, and 440 mbsf. The anomalously high resistivities and velocities measured in the zone from 186 to 450 mbsf are likely due to the presence of gas hydrate. Numerous low-velocity zones are observed within the depth interval below 440 mbsf in Hole 997B. These apparent low-velocity zones likely contain free gas.

The VSP program at Site 997 consisted of two lowerings of the three-component WHOI borehole seismometer, each of which provided complete coverage of the hole from ~160-700 mbsf. Preliminary velocity inversions from the two lowerings yield the same background velocity structure, thus verifying the repeatability of the experiment. Stations on the second lowering were interleaved with stations from the first lowering to provide 4-m trace spacing throughout most of the hole. Results show that velocities decrease sharply from 1800 m/s to 1400 m/s at the BSR (464 mbsf) and remain low to the base of the hole. Average velocities beneath the BSR at Site 997 are substantially lower than at Sites 994 and 995 (Fig. 12), providing evidence for increased concentrations of gas beneath the crest of the Blake Ridge.

CONCLUSIONS

ODP Leg 164 was devoted to furthering our understanding of the in situ characteristics of gas hydrates and gas hydrate-bearing sediments and to ground-truthing the nature of BSRs. The Blake Ridge gas hydrate field was targeted for drilling because it is associated with an extensive and well-developed BSR that could be considered the archetypical section for BSRs.

During Leg 164, three closely spaced ~700-m-deep sections were drilled through the base of gas hydrate stability within the same stratigraphic unit on the Blake Ridge. This short transect extends 10 km from ridge flanks, where there is no BSR in the seismic profiles, to the ridge crest, where a very strong BSR exists in the seismic profiles.

Most of the materials recovered on Leg 164 were deposited during the Pliocene and Miocene at very rapid rates (as much as 350 m/m.y.) by the southerly flowing Western Boundary Undercurrent, that sweeps along the Atlantic Margin. The stratigraphic sequence is composed of lithologically monotonous hemipelagic clays; this allows the distribution of gas hydrate and the origin of the BSR to be studied with minimal lithologic complication. The sediments are moderately organic carbon rich (~1.5%) and, thus, have the raw material to produce quantities of biogenic gas.

The following conclusions were determined for the scientific objectives of this leg.

(1) *Amounts of gas trapped in hydrate-bearing sediments*
Preliminary analysis from Leg 164 drill sites on the Blake Ridge indicates that gas hydrate occupies 1% to 2% of the sediment volume in a zone that is 200-250 m thick. In fact, the site without a BSR also contained ~1% gas hydrate through a similarly thick zone. If the rest of the ~26,000-km^2 region around the Blake Ridge where BSRs are present contains as much gas hydrate, rough estimates indicate that about 10 Gt of methane carbon is stored in this region. Given the number of localities worldwide in which gas hydrate occurs, the results of ODP Leg 164 provide further evidence that methane stored as gas hydrate in marine sediments represents a signficant component of the global fossil fuel carbon reservoir.

(2) *Lateral variability in gas hydrate abundances*
Interstitial water chemistry is very similar at the three deeply drilled (~750 mbsf) sites on the transect along the Blake Ridge (Sites 994, 995, and 997). Downhole profiles of all dissolved species show the same general trends with the same approximate depths for maxima and minima. Chloride profiles were used as a proxy indicator for the amount of in situ gas hydrate. When gas hydrate forms in sediment, water and gas are removed from the pore space, causing the residual pore waters to become saltier. Over long periods of time the local salinity anomalies produced by gas hydrate formation diffuse away. However, many of the cores that were recovered contained surprisingly fresh interstitial waters, indicating that gas hydrate had decomposed within these sediments during drilling and core recovery. A zone with anomalously low chloride values occurs at approximately the same depths (~200 to 440 mbsf) over the 10-km transect. Furthermore, the

two depth intervals showing the largest chloride excursions, at approximately 250 and 400 mbsf, are also depth correlative. Thus, the similarity of the Cl^- profiles at the ridge sites strongly suggests that gas hydrate is correlative over the expanse of the Blake Ridge, including Site 994, where no BSR is present in the seismic profile.

(3) *Relationship between bottom-simulating reflectors and gas hydrate development*

Downhole sonic log and vertical seismic profile data indicate decreasing interval velocities near the depth of the BSR. The change in sediment velocity may be related to either changes in the amount of hydrate above the BSR or the presence of gas bubbles below. Both types of sonic data indicate that gas bubbles are present at greater depths, but simple shipboard analyses of the absolute velocities do not require that the gas be present immediately below the BSR at all these sites. This issue can be resolved by combining pressure core sampling data, temperatures of cores measured after recovery, and interstitial-water chloride concentrations. Whereas the pressure core sampler data indicates that there must either be hydrate or gas bubbles present, the temperature and interstitial-water chloride data demonstrate that gas hydrate is not present below the BSR. Thus, there are gas bubbles beneath the BSR at these sites.

(4) *Distribution and in situ fabric of gas hydrate within sediments*

As anticipated, the recovery of gas hydrate proved to be difficult. The cores were very gassy, causing sediment to extrude from the liners as the cores arrived on deck. Some large pieces of gas hydrate were recovered. Gas hydrate recovered at Site 996 occurred as massive pieces, as veins filling vertical fractures, and as rod-shaped nodules. Fine-grained hydrate was not directly observed in sediments from any of the sites, but proxy measurements, such as the chloride concentration of interstitial pore waters, indicated that fine-grained hydrates had been present prior to core recovery. Calculations indicate that sediments in the zone from 200 to 450 mbsf had a minimum average gas hydrate content of 1% and that some individual samples contained more than 8% gas hydrate.

(5) *Changes in physical properties (porosity, permeability, P-wave velocity, thermal conductivity, etc.) associated with gas hydrate formation and decomposition in continental margin sediments*

Well-log measurements show the gas hydrate-bearing and free gas-bearing zones are associated with distinct characteristics, whereas shipboard lithologic and physical properties measurements did not indicate any differences in these sediments. The distinctions between shipboard and downhole measurements are believed to result from the presence of gas hydrate in situ and will be the subject of shore-based research.

(6) *Source of gas contained in gas hydrate (local production or migration)*

As discussed below, the interstitial-water chemical data at Site 996 suggest that methane is transported upward along faults from underlying gas hydrate-bearing sediments. This is consistent with the occurrence of hydrate as vein fillings. At Sites 994, 995, and 997, constraints on the sources of gas contained in gas hydrate must await shore-based isotopic and organic geochemical studies, as well as detailed analysis of the PCS data that will delineate the distribution of hydrate, free gas, and methane dissolved in interstitial waters.

(7) *Role of gas hydrate in formation of authigenic carbonate*

Fine-grained, disseminated authigenic carbonate was present in sediments at all sites. Indurated diagenetic carbonate was recovered primarily at Site 996 but also from one horizon at Site 993. At Site 996, intersititial-water chemical data suggests that carbonate precipitation is caused by intense microbial oxidation of methane, which results in high alkalinity and high bicarbonate concentrations. The methane arriving at the seafloor at this site is largely biogenic and has a composition similar to that of the gases from Sites 994, 995, and 997. Fluids and gases venting at Site 996 have probably been transported upward from the underlying gas hydrate-bearing sediment section that slopes up around the diapir.

(8) *Chemical and isotopic composition, hydration number, and crystal structure of natural gas hydrate*

Gas hydrate decomposition experiments indicate volumetric ratios of gas:water range from 130 to 160 and show that gas in the hydrate is ~99% methane. Numerous hydrates were sampled for storage in pressure vessels and will be used for shore-based isotopic and crystallographic studies.

(9) *Role of gas hydrates in stimulating or modifying fluid circulation*

An intriguing association of pore waters was documented. Pore waters are systematically fresher than seawater within the gas hydrate-bearing sections. One of the potential explanations of such patterns is that salinity changes associated with gas hydrate decomposition may be stimulating fluid circulation in these sedimentary sections. Other anomalies await shore-based isotopic and modeling studies, including variations in the amounts of free gas and gas hydrate and the sedimentary section, the occurrence of both thermogenic and biogenic hydrocarbon gases, and unexplained patterns of both the major and minor elements in dissolved pore waters.

(10) *Connection between large-scale sediment failures and gas hydrate decomposition*

Drilling along the top of the Cape Fear Diapir, which breeches the seafloor within the scar of the giant Cape Fear Slide, revealed soft-sediment deformation features and several biostratigraphic gaps. Both are the result of mass-transport processes associated with sediment failure and were caused by the Cape Fear Slide or emplacement of the diapir. The results of drilling did not provide any direct evidence as to whether large-scale sediment failures are related to gas hydrate decomposition.

(11) *Origin of the Carolina Rise Diapirs and their influence on associated sedimentary gas hydrate*

The chloride concentration of interstitial waters from sediments overlying the Cape Fear Diapir (Sites 991, 992, 993) and the Blake Ridge Diapir (Site 996) are high; the ratio of Cl^- to other ions suggests nearby sources of evaporitic salts. Thus, it seems likely that both diapirs are salt cored. Presumably the salt has risen from deep within sediments of the Carolina Trough, the base of which is approximately 8 km below the seafloor at these sites.

REFERENCES

Claypool, G.E., and Kaplan, I.R., 1974. Methane in marine sediments. *In* Kaplan, I.R. (Ed.), *Natural Gases in Marine Sediments,* New York (Plenum Press), 99-139.

Dillon, W.P., and Paull, C.K., 1983. Marine gas hydrates: II Geophysical Evidence. *In* Cox, J.L. (Ed.)*, Natural Gas Hydrates, Properties, Occurrence and Recovery.* Woburn, Mass. (Butterworth), 73-90.

Kvenvolden, K., 1988a. Methane hydrates and Global Climate. *Global Biochem. Cycles,* 2:221-229.

Kvenvolden, K., 1988b. Methane hydrate—A major reservoir of carbon in the shallow geosphere? *Chem. Geol.*, 71:41-51.

Kvenvolden, K., and Barnard, L.A., 1983. Hydrates of natural gas in continental margins. *In* Watkins, J.S., and Drake, C.L. (Eds.), Studies in Continental Margin Geology. *AAPG Mem.*, 34:631-640.

Markl, R.G., and Bryan, G.M., 1983. Stratigraphic evolution of the Blake Outer Ridge. *AAPG Bull.*, 67:663-683.

Markl, R.G., Bryan, G.M., and Ewing, J.I., 1970. Structure of the Blake-Bahama Outer Ridge. *J. Geophys. Res.*, 75:4539-4555.

Paull, C.K., and Dillon, W.P., 1981. Appearance and distribution of the gas hydrate reflector in the Blake Ridge Region, Offshore southeastern United States. *USGS Miscellaneous Field Studies Map*, 1252.

Paull, C.K., Buelow, W.J., Ussler, W., III, and Borowski, W.S., 1996. Increased continental margin slumping frequency during sea level lowstands above gas hydrate-bearing sediments. *Geology,* 24:143-146.

Shipley, T.H., Houston, M.H., Buffler, R.T., Shaub, F.J., McMillen, K.J., Ladd, J.W., and Worzel, J.L., 1979. Seismic reflection evidence for widespread occurrence of possible gas-hydrate horizons on continental slopes and rises. *AAPG Bull.*, 63:2204-2213.

Sloan, E.D., 1989. *Clathrate Hydrates of Natural Gases*: New York (Marcel Decker, Inc.), 641 p.

Tucholke, B.E., Bryan, G.M., and Ewing, J. I., 1977. Gas hydrate horizon detected in seismic reflection-profiler data from the western North Atlantic. *AAPG Bull.*, 61:698-707.

FIGURES

Figure 1. Location map of Leg 164 sites on the southeastern North American continental margin (modified after Dillon and Paull, 1983). Contours are in meters. Shaded region along the Blake Ridge and Carolina Rise indicates the areas where gas hydrate occurrence has been inferred on the basis of BSRs.

Figure 2. Bathymetry (3.5 kHz precision depth recorder) over the Cape Fear Diapir showing the location of Sites 991, 992, and 993.

Figure 3. Composite stratigraphic sections for Sites 991, 992, and 993 showing core recovery in all holes, a simplified summary of lithology, depth of lithologic-unit boundaries, and age.

Figure 4. Interstitial-water chloride profiles at the (A) Cape Fear Diapir (Sites 991, 992, and 993) and (B) Blake Ridge Diapir (Site 996).

Figure 5. Seismic reflection profile (CH-06-92 Line 31) for the transect of Blake Ridge Sites 994, 995, and 997. The profile crosses perpendicular to the topography of the Blake Ridge. Vertical scale is in seconds of two-way traveltime.

Figure 6. Composite stratigraphic section for Sites 994, 995, and 997 showing simplified lithostratigraphy, depth of lithologic-unit boundaries, biostratigraphic ages, and total carbonate contents (wt% $CaCO_3$) of the sediments.

Figure 7. Age-depth relationships of biostratigraphic markers of calcareous nannofossils at Site 994 (dashed line), Site 995 (thin solid line), and Site 997 (thick solid line). Vertical error bars show sample interval uncertainties, and the box indicates combinations of sample interval uncertainty and age uncertainty. The horizontal bar at the bottom of the figure indicates the range of *Amaurolithus amplificus*.

Figure 8. Interstitial-water chloride concentration profiles for Sites 994, 995, and 997.

Figure 9. Preliminary results of in situ temperature measurements at Sites 994, 995, and 997. Triangles indicate measurements made with the Adara tool, squares are WSTP measurements, and circles denote data collected with a prototype probe designed by E. Davis and H. Villinger.

The open squares correspond to anomalous temperature measurements obtained within the gas hydrate stability field at Site 994. Errors in temperature are estimated subjectively, based on the quality of the equilibration record and the magnitude of the correction applied to the raw data. Errors in the depths of the measurements have not yet been taken into account. The reported gradients were calculated from linear regressions weighted proportional to the inverse of the squared error. None of the thermal gradients are in equilibrium with the temperatures recorded at the mudline, and heat flow estimated using these gradients and laboratory thermal-conductivity measurements is more than 20% lower than determined during conventional surveys at the same Blake Ridge locations in 1992.

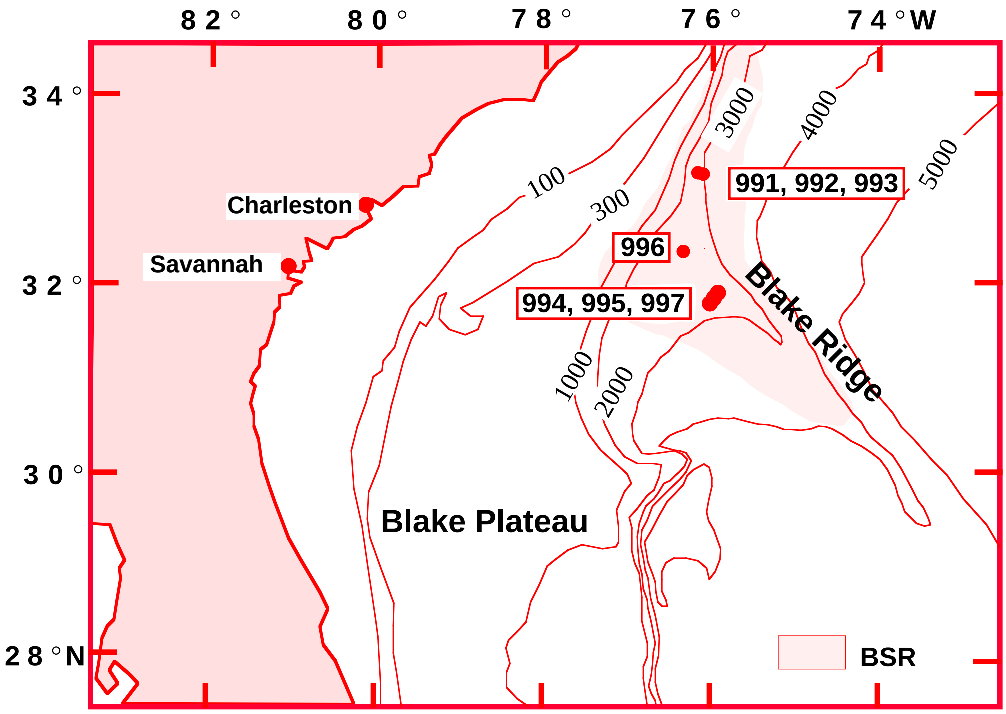
Figure 10. Acoustic velocity log for Sites 994, 995, and 997. Data are shown for both near (DTLN) and far (DTLF) measurements from the long spacing sonic tool (LSS).

Figure 11. Resistivity log for Sites 994, 995, and 997 showing deep-reading electrical-resistivity data from the phasor dual induction tool (DIT).

Figure 12. Velocity profiles based on the results of the zero-offset VSP at Sites 994, 995, and 997. From the flank of the Blake Ridge to the crest, the profiles show similar, possibly slightly increasing, velocities above the hydrate stability zone (~450 mbsf) and a significant decrease in velocity toward the crest below this zone. These preliminary velocity-depth functions were produced by inverting the air gun first-arrival times using a weighted, damped, least-squares inversion that weights mean traveltimes by the inverse of their standard error. The velocity-depth curves were produced by assigning equal weight to fitting the traveltime data and to producing a smooth velocity-depth function.

Figure 13. Single-channel seismic line acquired over the Blake Ridge Diapir showing the location of Site 996. Data have undergone constant velocity migration (1500 m/s) and a mild three-trace mix. Note the highly reflective sediments in the center of the figure bounded above by a reversed polarity reflector interpreted as the base of hydrate stability. Vertical scale is in seconds of two-way traveltime.

Figure 14. Bathymetry (3.5 kHz precision depth recorder) over the Blake Ridge Diapir showing the location of Site 996. Detailed summary lithologic columns for Site 996 reflect the position of holes drilled into a small depression on the crest of the diapir. H = gas hydrate occurrences and C = carbonate nodules. Subunits are indicated with arrows.



82 °
80 °
78 °
76 °
74 °W
34 °
32 °
30 °
28 °N
Charleston
Savannah
100
300
1000
2000
3000
4000
5000
991, 992, 993
996
994, 995, 997
Blake Ridge
Blake Plateau
BSR

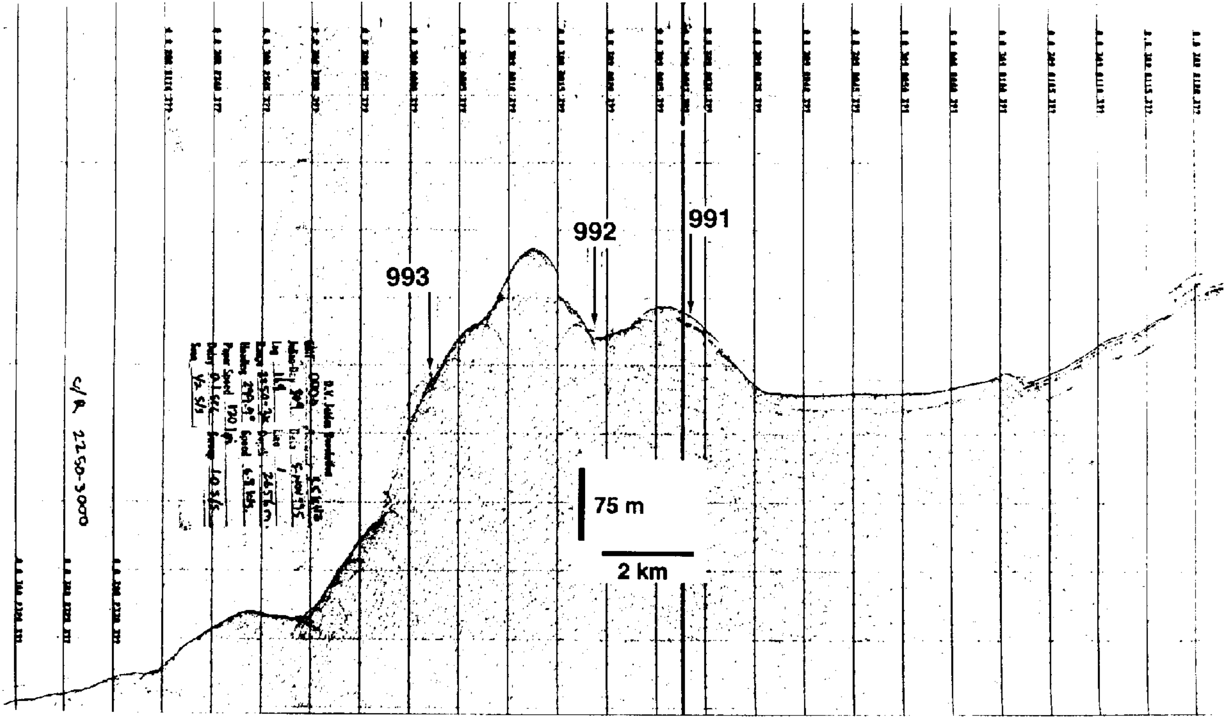
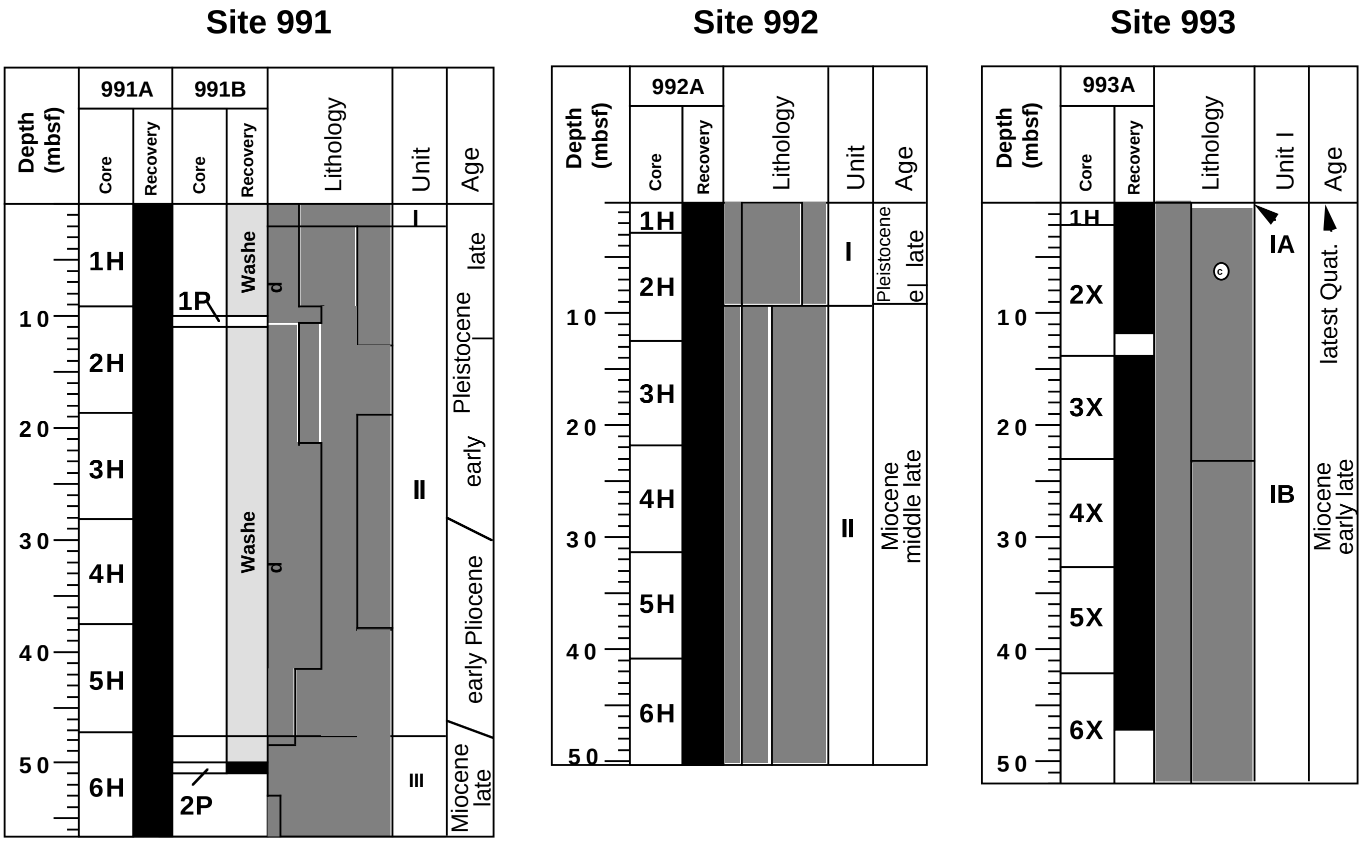
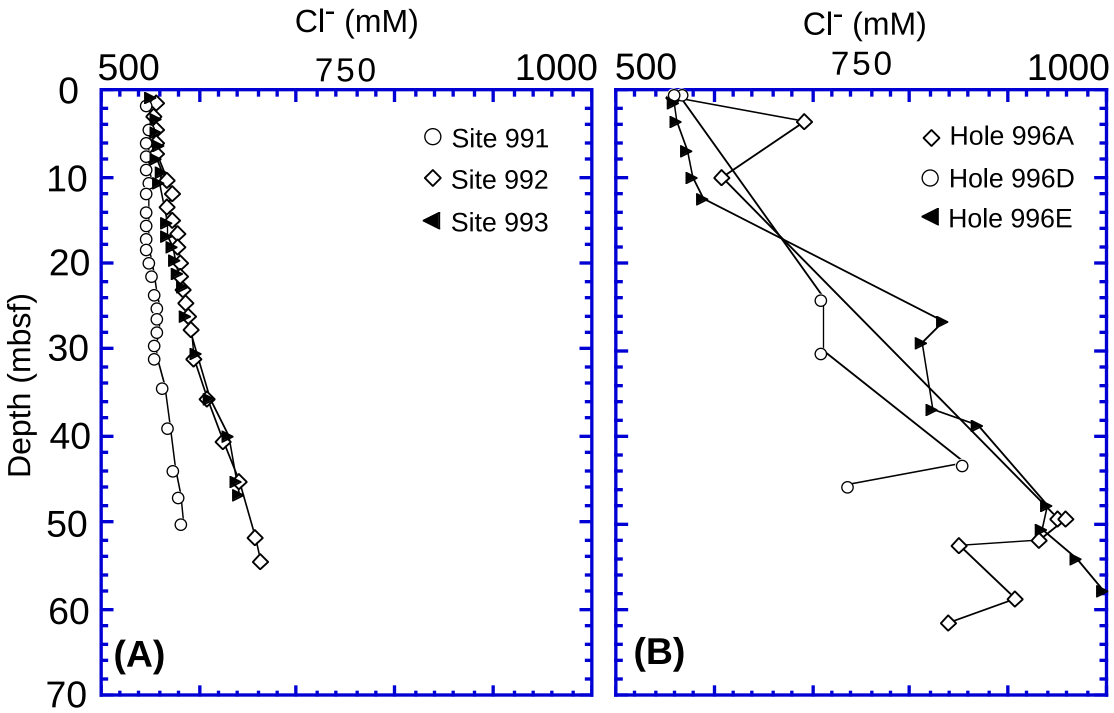
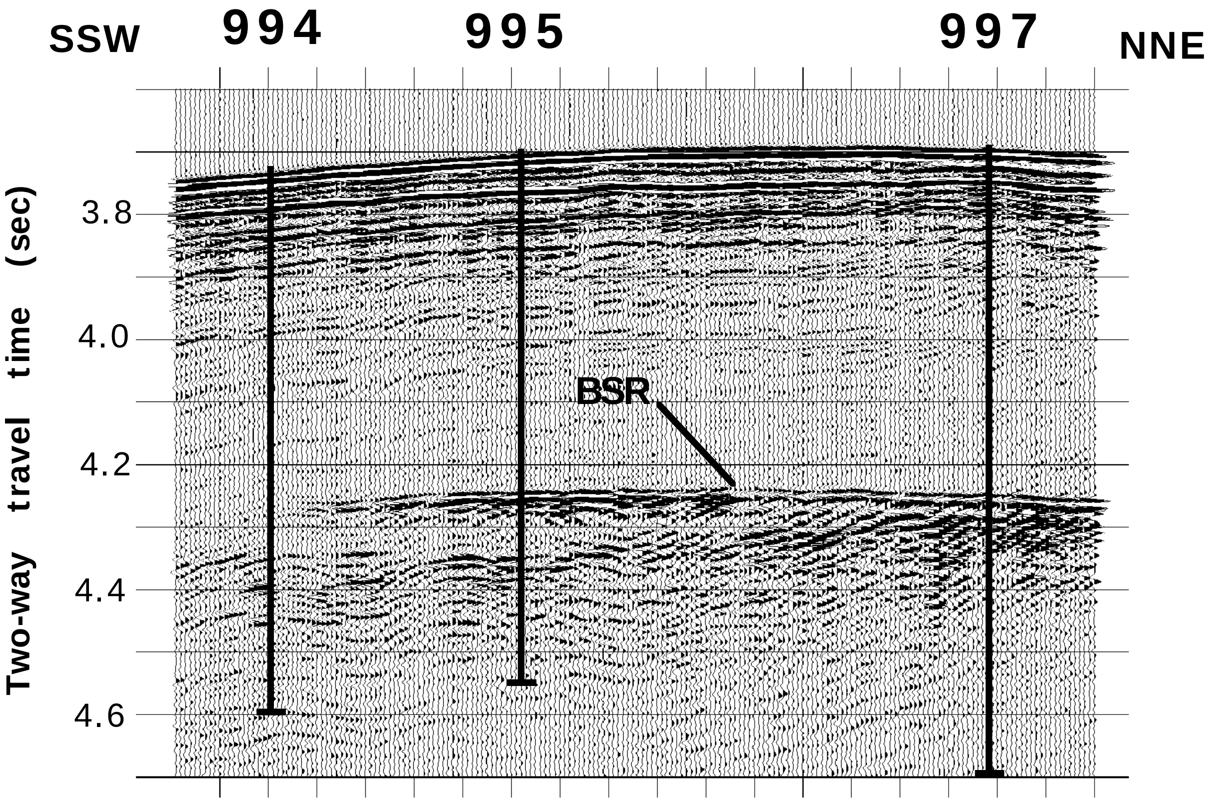


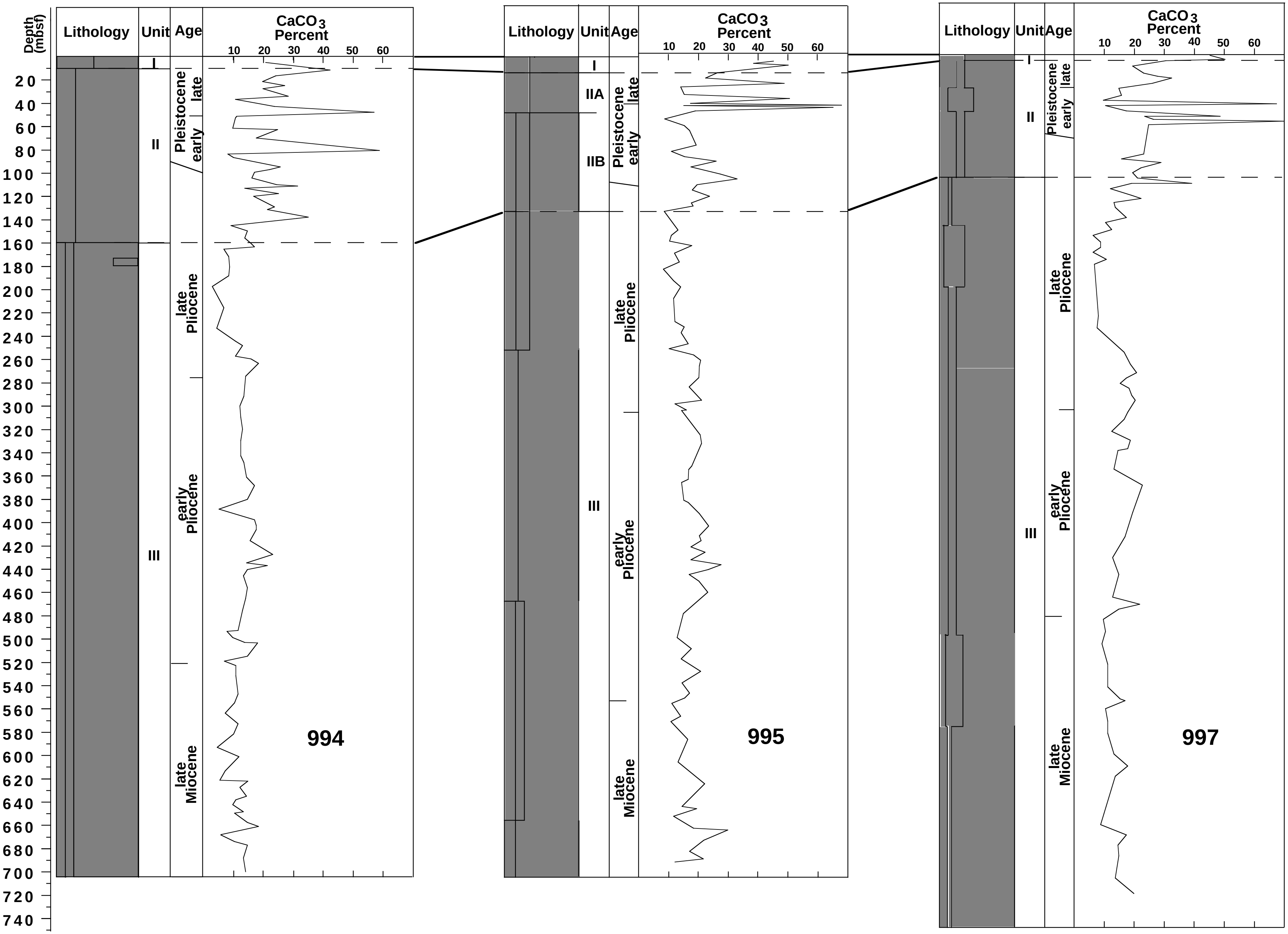
Figure 2

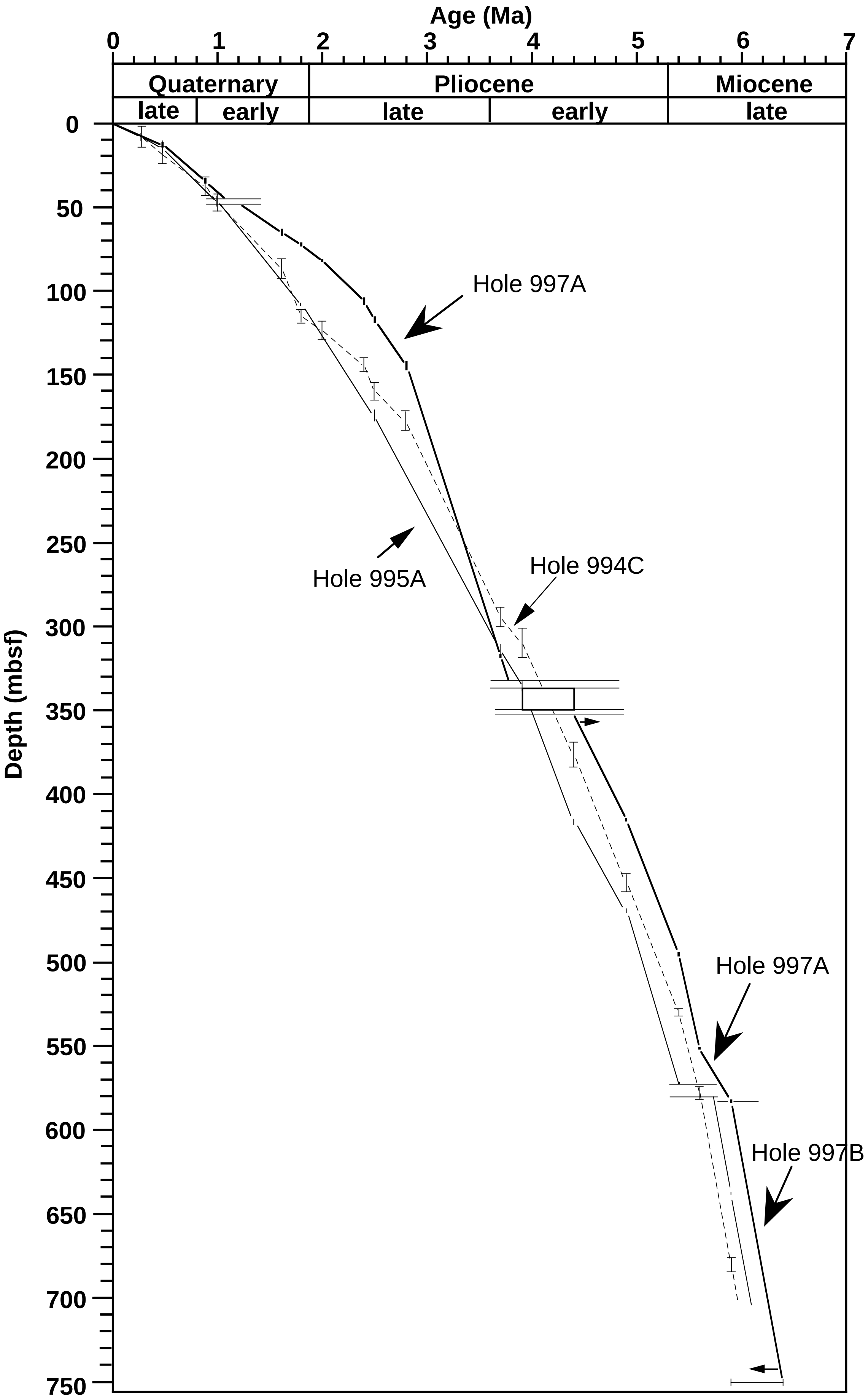

Site 991
Site 992
Site 993
Depth (mbsf)
991A
991B
992A
993A
Core
Recovery
Lithology
Unit
Unit I
Age
1H
2H
3H
4H
5H
6H
1P
2P
1H
2H
3H
4H
5H
6H
1H
2X
3X
4X
5X
6X
Washed
Washed
I
II
III
I
II
IA
IB
late Pleistocene
early Pleistocene
early Pliocene
late Miocene
late Pleistocene
el
middle late Miocene
latest Quat.
early late Miocene
c
10
20
30
40
50

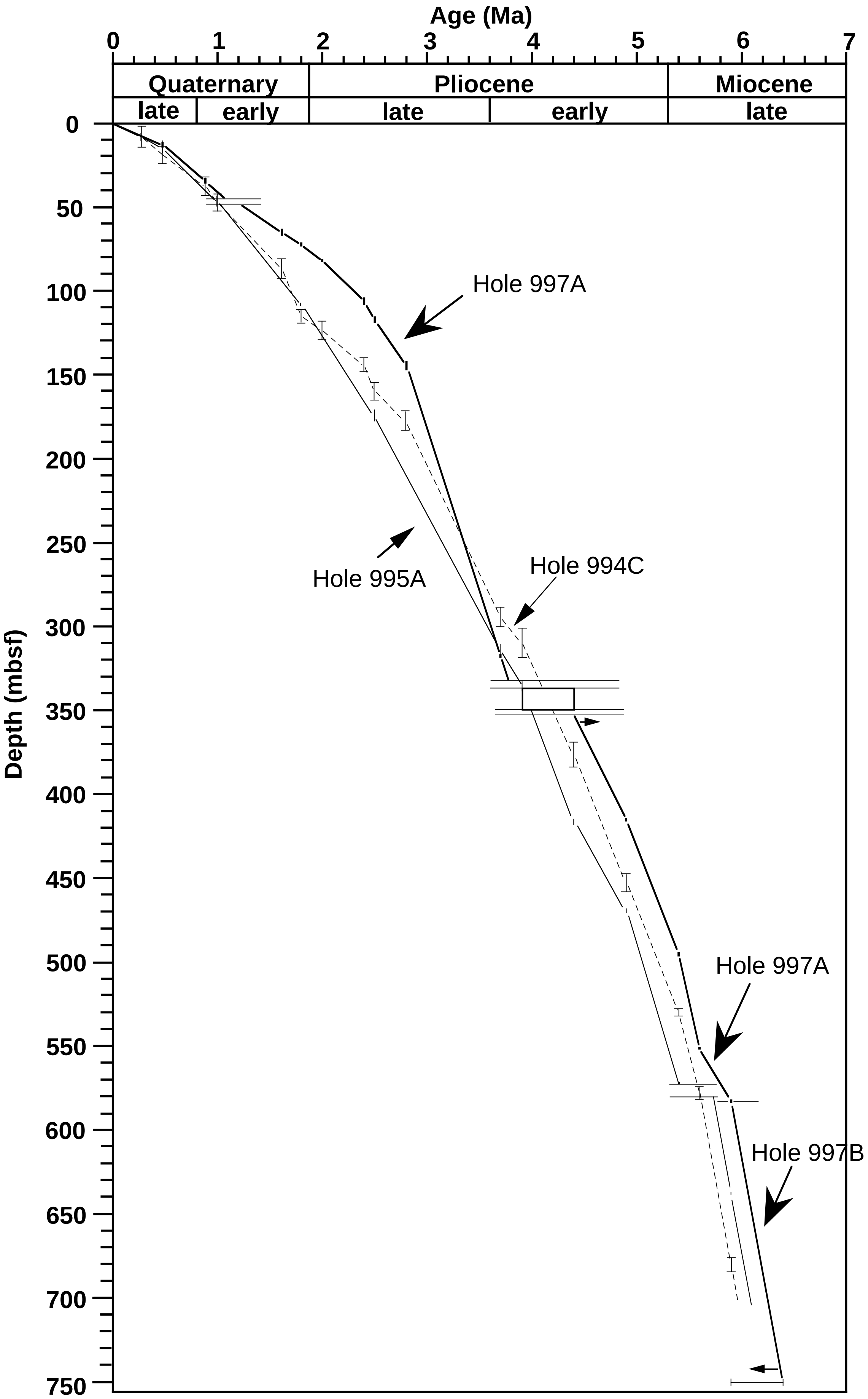


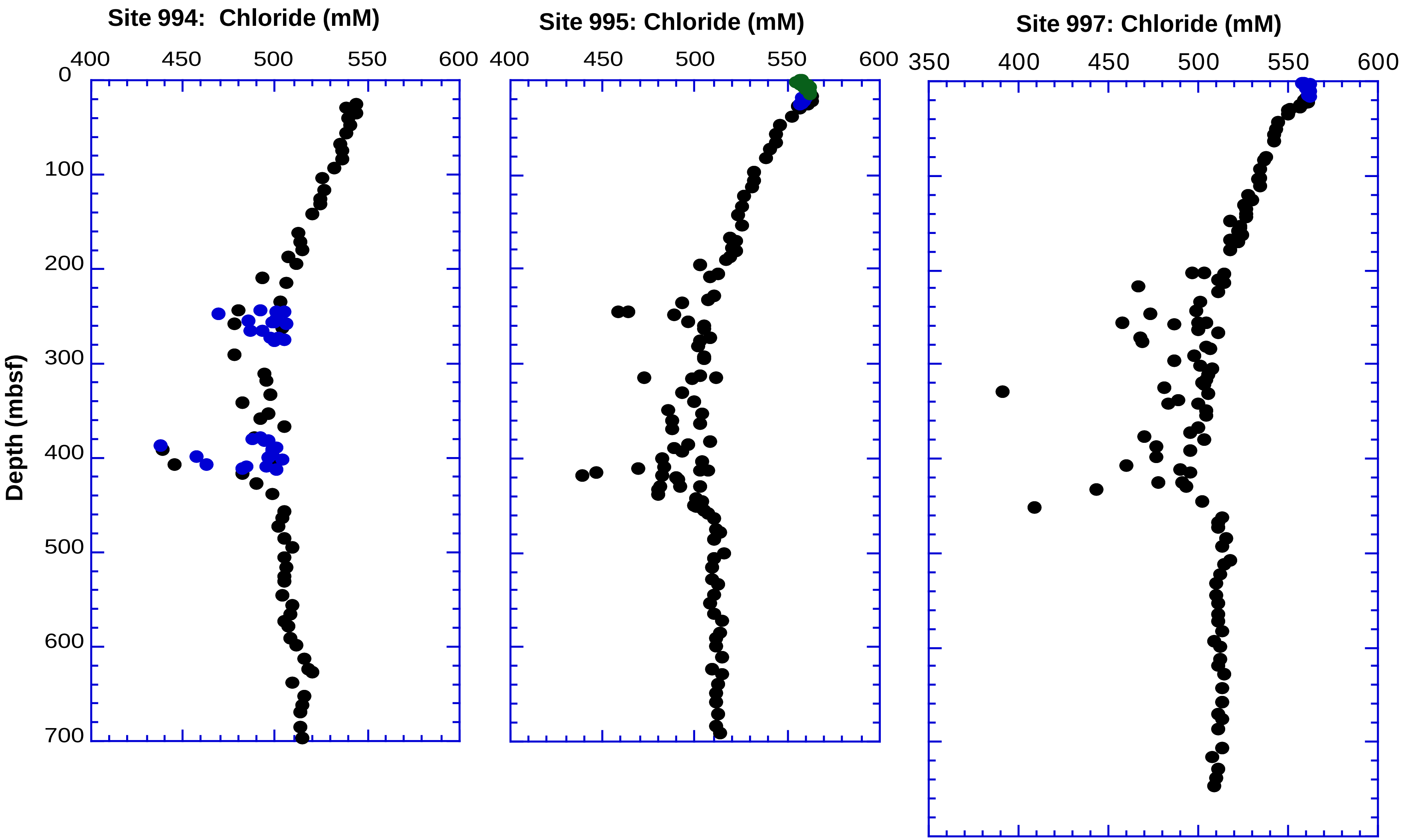
Cape Fear Diapir **Blake Ridge Diapir**


SSW
994
995
997
NNE
Two-way travel time (sec)
3.8
4.0
4.2
4.4
4.6
BSR

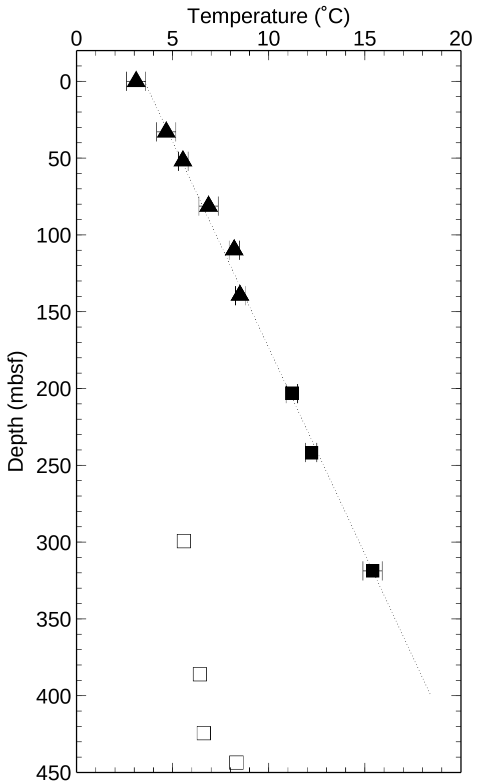

Depth (mbsf)
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
540
560
580
600
620
640
660
680
700
720
740
Lithology
Unit
Age
CaCO3 Percent
10 20 30 40 50 60
I
II
III
late
early
Pleistocene
late Pliocene
early Pliocene
late Miocene
994
Lithology
Unit
Age
CaCO3 Percent
10 20 30 40 50 60
I
IIA
IIB
III
late
early
Pleistocene
late Pliocene
early Pliocene
late Miocene
995
Lithology
Unit
Age
CaCO3 Percent
10 20 30 40 50 60
I
II
III
late
early
Pleistocene
late Pliocene
early Pliocene
late Miocene
997


Age (Ma)
0
1
2
3
4
5
6
7
Quaternary
Pliocene
Miocene
late
early
late
early
late
Depth (mbsf)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
Hole 997A
Hole 995A
Hole 994C
Hole 997A
Hole 997B


Age (Ma)
0
1
2
3
4
5
6
7
Quaternary
Pliocene
Miocene
late
early
late
early
late
Depth (mbsf)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
Hole 997A
Hole 995A
Hole 994C
Hole 997A
Hole 997B

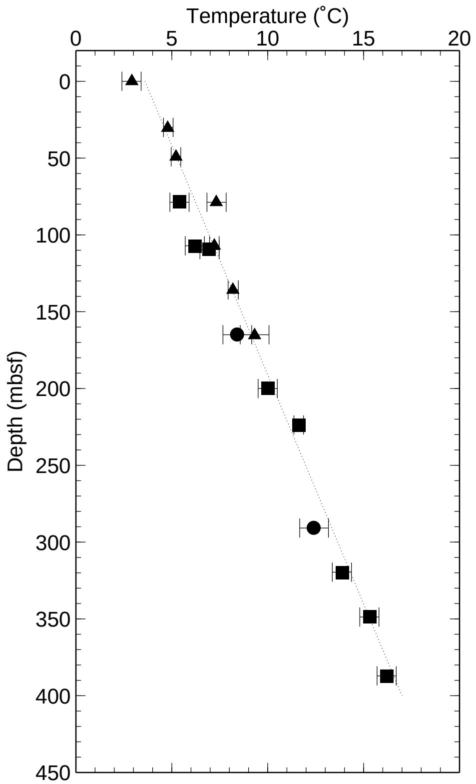

Site 994: Chloride (mM)
Site 995: Chloride (mM)
Site 997: Chloride (mM)
Depth (mbsf)
0
100
200
300
400
500
600
700
400
450
500
550
600
400
450
500
550
600
350
400
450
500
550
600

Site 994



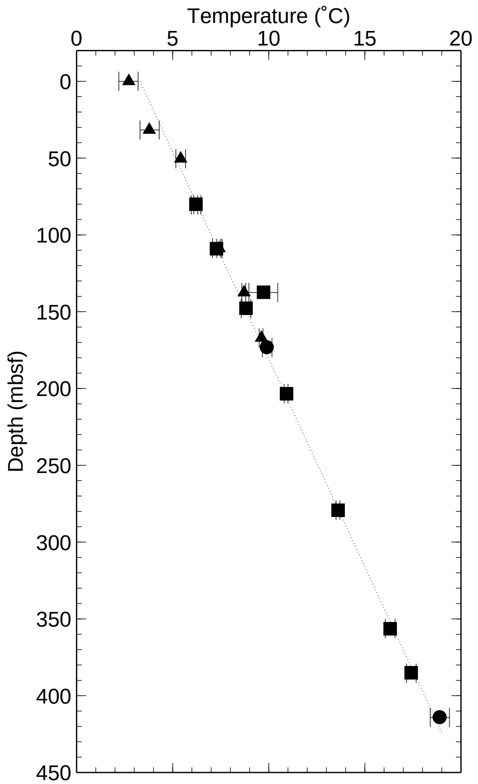
Gradient = 36.4+/-1.3 mK/m

Site 995

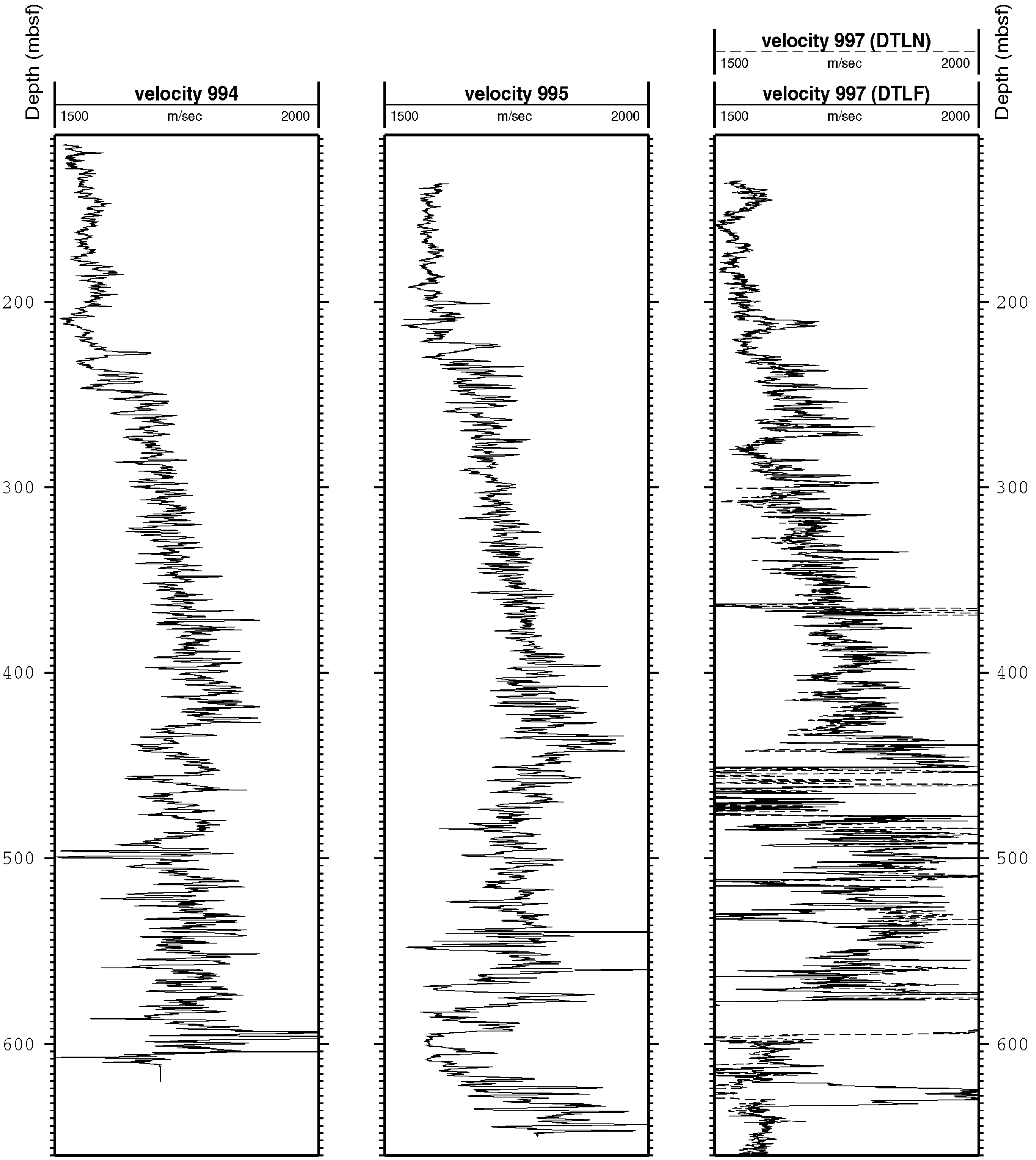


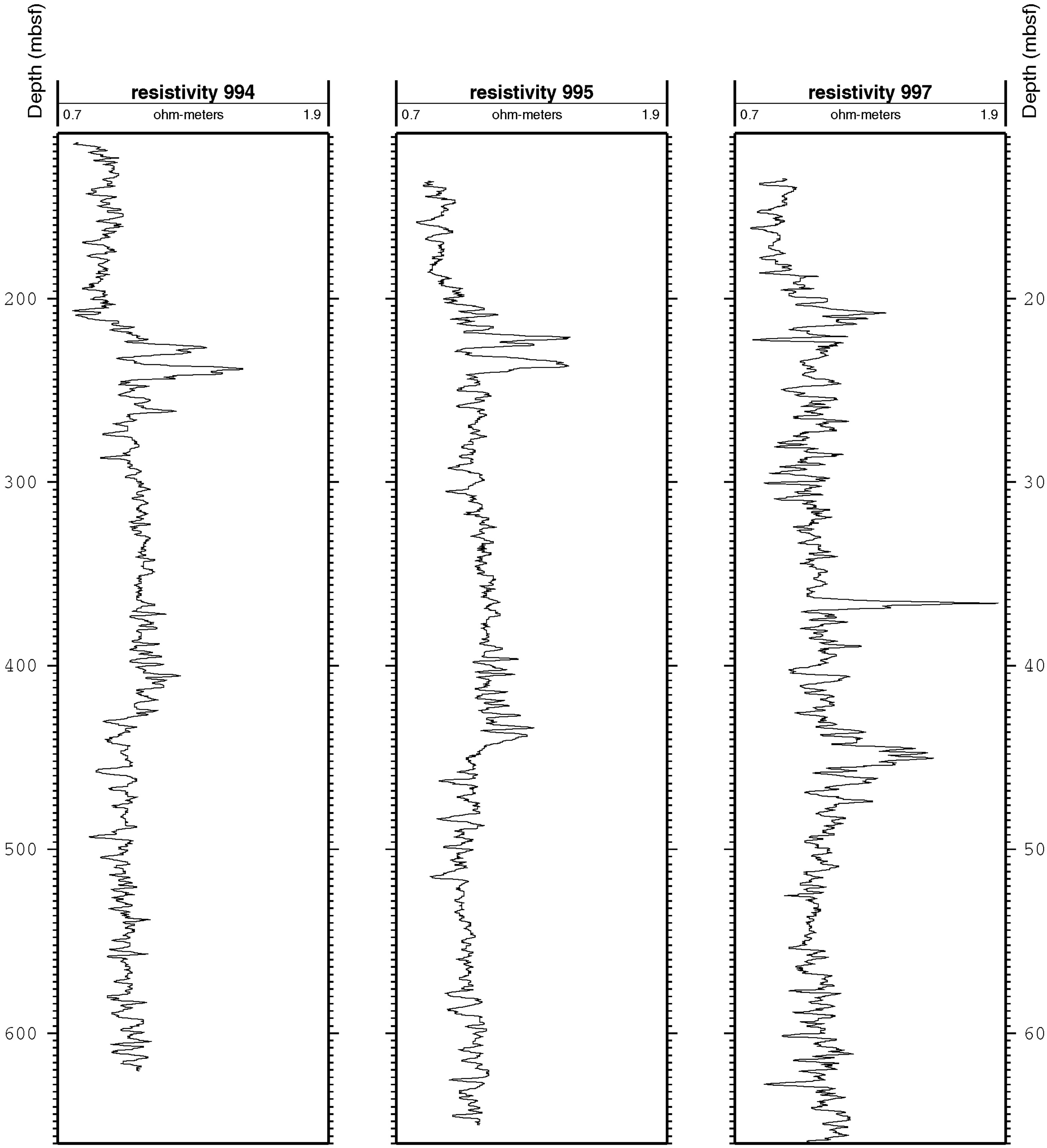
Gradient = 33.5+/-0.9 mK/m

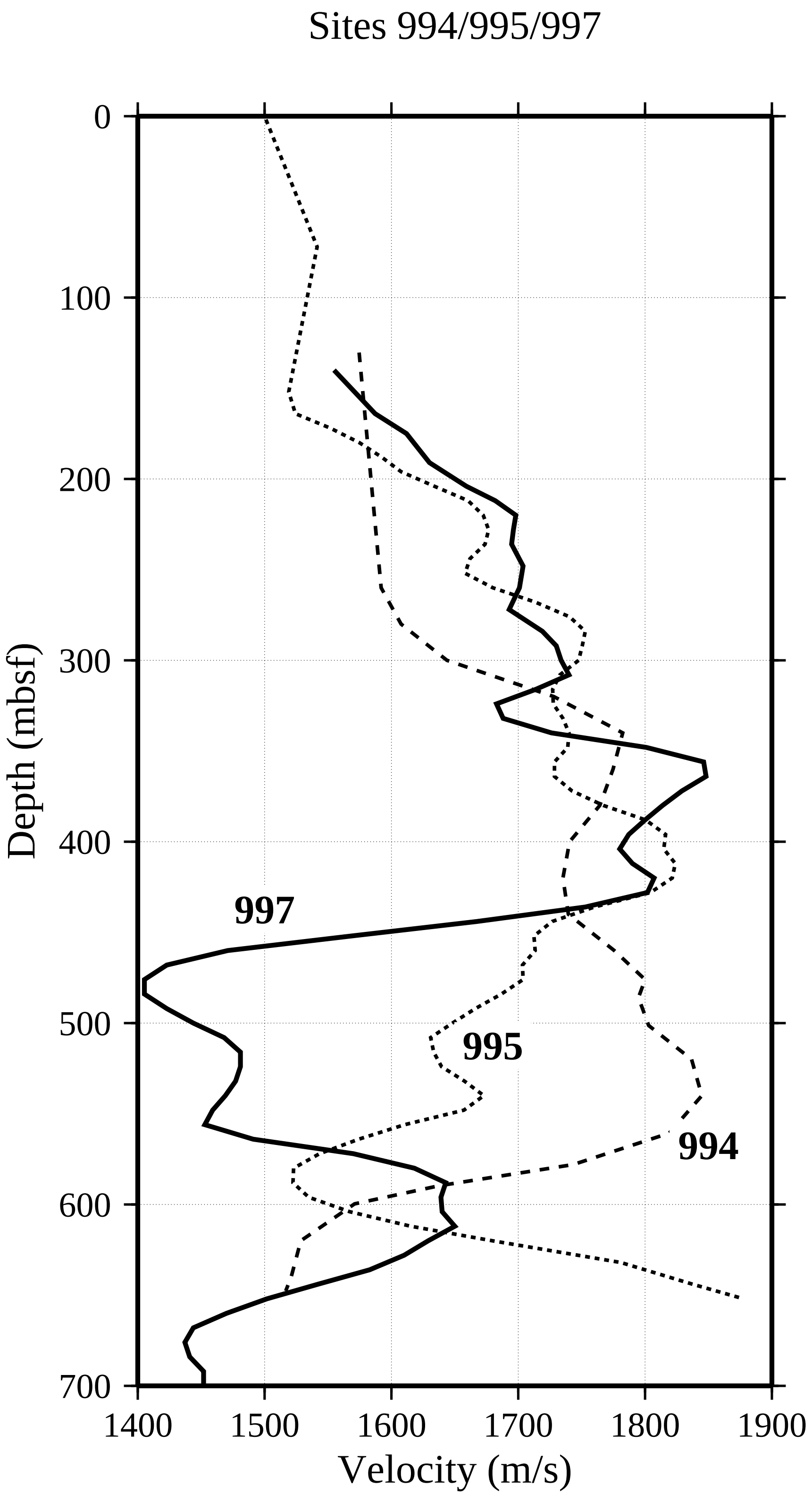
Site 997



Gradient = 36.8+/-0.4 mK/m


Depth (mbsf)
velocity 994
1500
m/sec
2000
velocity 995
1500
m/sec
2000
velocity 997 (DTLN)
1500
m/sec
2000
velocity 997 (DTLF)
1500
m/sec
2000
Depth (mbsf)
200
300
400
500
600


Depth (mbsf)
resistivity 994
0.7
ohm-meters
1.9
resistivity 995
0.7
ohm-meters
1.9
resistivity 997
0.7
ohm-meters
1.9
Depth (mbsf)
200
300
400
500
600
200
300
400
500
600


Sites 994/995/997
0
100
200
300
400
500
600
700
Depth (mbsf)
1400
1500
1600
1700
1800
1900
Velocity (m/s)
997
995
994

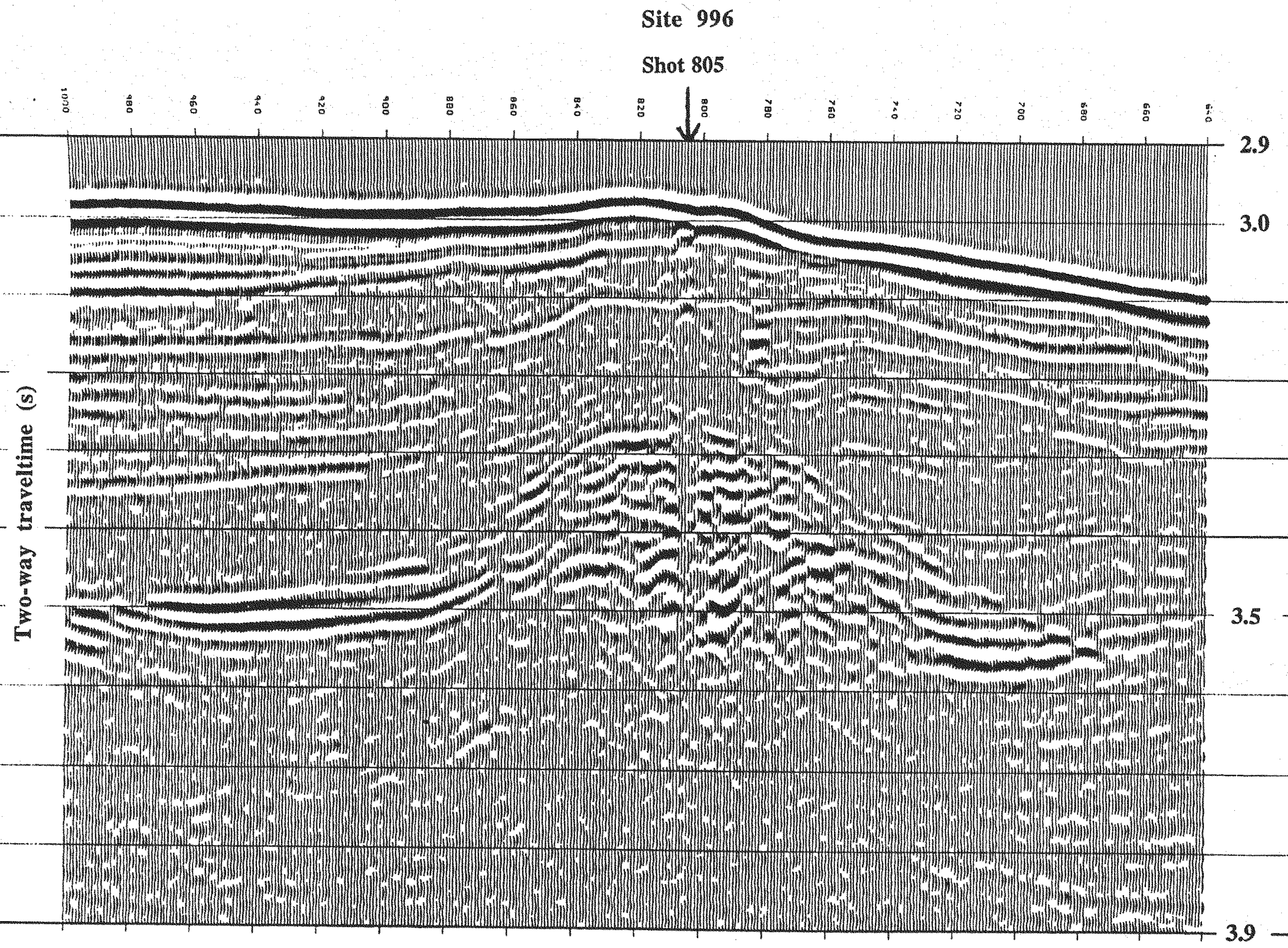
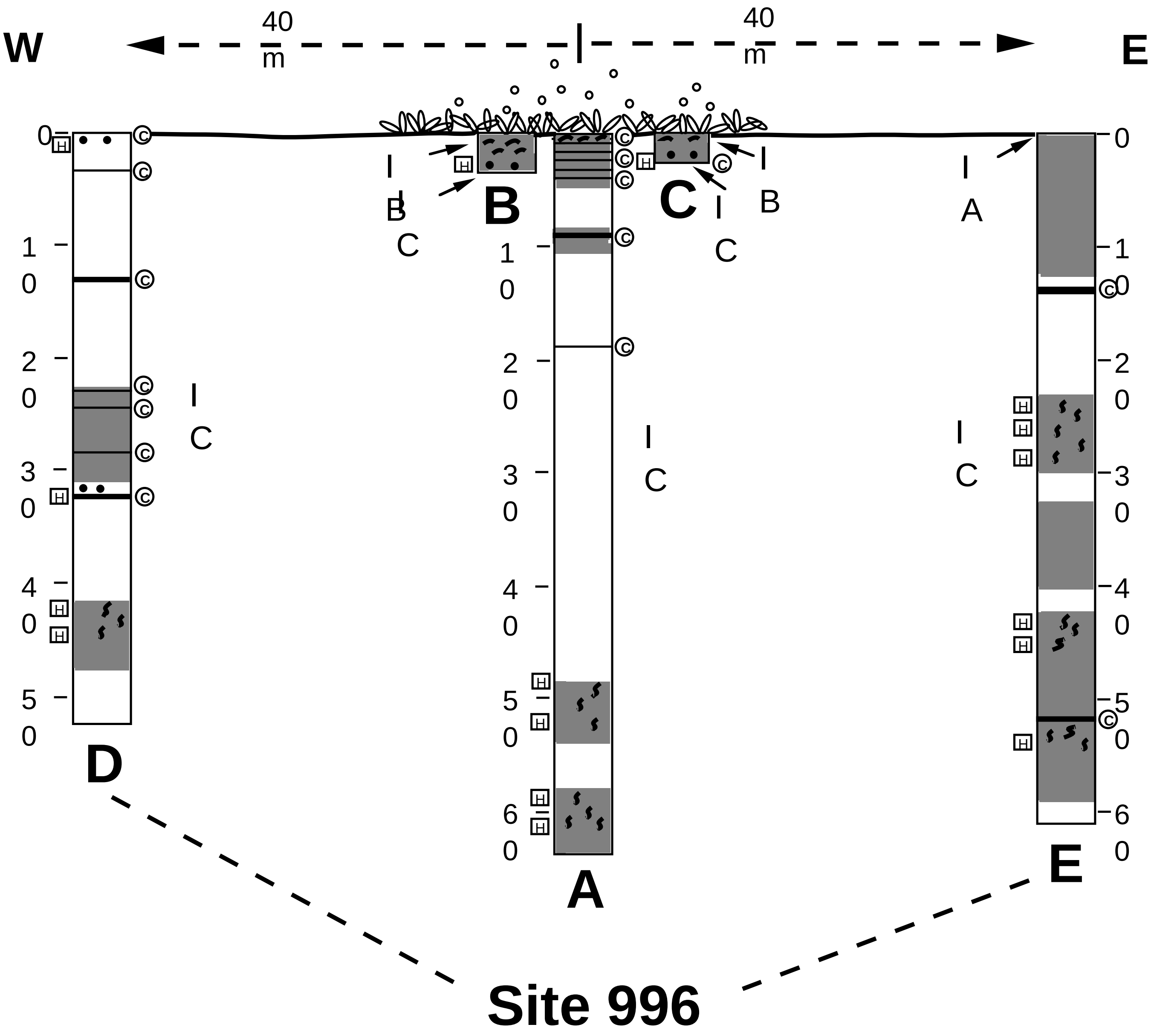

Site 996
Shot 805
1000
980
960
940
920
900
880
860
840
820
800
780
760
740
720
700
680
660
640
2.9
3.0
3.5
3.9
Two-way traveltime (s)

Figure 13


W
40 m
40 m
E
0
10
20
30
40
50
IC
IB
IC
B
C
IB
IC
IA
A
D
E
60
Site 996

OPERATIONS REPORT

The ODP Operations and Engineering personnel aboard *JOIDES Resolution* for Leg 164 were:

Operations Superintendent:	Gene Pollard
Schlumberger Engineer:	Steve Kittredge
ODP Development Engineer:	Matthew Stahl
Drilling Engineer:	Jürgen Hohnberg
Drilling Engineer:	Masayuki Kawasaki

HALIFAX PORT CALL

Leg 164 began with the first line ashore at 1030 hr on 7 October at the Atlantic Wharf (old sugar dock) on the Dartmouth side of Halifax harbor, Nova Scotia, Canada. The Leg 164 port call was originally scheduled to begin on 28 October; however, Leg 163 was terminated three weeks early when the ship sustained damage from a severe storm, including the loss of both radar units. The *Gaddus Atlantica* accompanied the *JOIDES Resolution* to Halifax as a radar picket and was released from contract on arrival.

Ship repairs in port started with a general ship inspection, including an inspection of the hull by divers. The pacing item at the port call was the repair of Thruster Pod No. 1, which had a crack in the pod and had been flooded. The trunk and pod were removed on 13 October, repaired, and reinstalled on 29 October. A number of other items were repaired or replaced. The missing "F" hydrophone, and the broken port window and starboard clear-view window on the bridge were all replaced. The radar units were repaired. Thyrig bays were inspected, and Lifeboats No. 1 and 3 were repaired. A bent I-beam was replaced in the mezzanine deck, and plates were replaced on the poop deck.

The regular Ocean Drilling Program/Overseas Drilling Limited (ODP/ODL) crew change was made on schedule on 28 October, and routine port-call operations were completed while the repairs continued. The Physical Properties Lab was remodeled. Numerous tours and public-relations events were conducted in concert with the Canadian ODP. Sepiolite mud (74 metric tons) was loaded onboard for the extensive logging and VSP program planned for Leg 164. An outfitted engineering van was sent out and installed on the roof of the Core Tech Shop. The pressure core sampler (PCS) gas manifold was set up in the van and tested in preparation for its later use.

TRANSIT FROM NOVA SCOTIA TO SITE 991

The ship departed from Halifax, Nova Scotia, at 1620 hr on 31 October, 1995. The transit to Site 991 covered 1908 km in 95.6 hr at an average speed of 10.8 kt. The ship's course was initially set at 191° to cross roughly perpendicular to the east edge of the Gulf Stream rather than combat the current, and to avoid the shipping lanes on the east coast of the United States. The ship's speed over ground was reduced to about 10.4 kt for 4 hr when crossing the Gulf Stream, and then a more direct course was taken. The main-shaft rpm was reduced again on 3 November in a Force 6-7 gale to reduce spray over the bow in heavy seas with 15-ft waves and 40-kt winds.

SITE 991
(Proposed Site CFD-5)

Hole 991A

A 83-km seismic survey was run in 6.8 hr at 6.0 kt over Sites 991, 992, and 993 and the Cape Fear Slide. The ship returned to the Global Positioning System (GPS) coordinates for Site 991, and a Datasonics 354M commandable recall beacon was dropped at 0022 hr on 5 November (for all of Leg 164 the ship was in the U.S. Eastern Time Zone; ship time is therefore equivalent to Greenwich Mean Time [GMT] - 5 hr). Hole 991A was spudded at 0835 hr on 5 November. The water depth was measured as 2567.5 m below sea level (mbsl) based on recovery of the mudline in Core 164-991A-1H. Advanced Piston Cores (APC) 164-991A-1H to 6H were taken from 0 to 56.6 m below seafloor (mbsf), with 58.66 m recovered (103.6% recovery). The cores were relatively dry and well compacted and were not gassy. They contained a minor amount of H_2S as follows: 2 ppm in 1H, 10 ppm in 3H, 22 ppm in 5H, and 20 ppm in 6H. There were no gas voids and little extrusion from the liner ends. Coring was halted for 0.5 hr for repairs when the forward core winch had an intermittent electrical control problem that caused it to jump at times. Hole 991A was terminated and the bit was pulled above the seafloor at 1418 hr on 5 November.

Hole 991B

The ship was moved 10 m south, and Hole 991B was spudded at 1507 hr on 5 November. The seafloor was assumed to be at 2567.5 mbsl, based on offset Hole 991A. Hole 991B was spudded at 1507 hr on 5 November, and the hole was washed to 10.0 mbsf for the first Pressure Core Sampler (PCS) run. Core 164-991B-1P was taken with the PCS from 10.0 to 11.0 mbsf. A push-in type shoe and basket catcher were used. When retrieved, the PCS ball valve had closed and the pressure chamber held 2550 psi when first checked. The pressure fell slowly to 2270 psi in 2 min. The hydrostatic pressure was calculated at 3804 psi; therefore, some formation pressure was trapped. No core was recovered and it appeared that none entered the PCS catcher. The hole was drilled ahead from 11.0 to 50.0 mbsf, and PCS Core 164-991B-2P was taken from 50.0 to 51.0 mbsf. A push-in type shoe and basket catcher were again used. A 104 cm core of moderately compacted green-gray clay was recovered, but only 64 psi pressure was trapped. The core barrel was jammed full and the basket core catcher was partially broken off. The Fisseler Water Sampler was run for the first time at 51.0 mbsf and recovered 46 ml of water. Hole 991B was terminated and the bit was pulled above the seafloor at 1953 hr on 5 November.

SITE 992
(Proposed Site CFD-6)

Hole 992A

The 4.3-km move in dynamic positioning (DP) mode required 4 hr. The location of Site 992 was changed to a point located at latitude 32° 58.5317'N, longitude 75° 54.9968'W on the seismic line acquired onsite by the ship. After a water core, Hole 992A was spudded at 0210 hr on 6 November. The seafloor was estimated at 2586.9 mbsl. APC Cores 164-992A-1H to 6H were taken from 0 to 50.3 mbsf, with 50.3 m cored and 52.62 m recovered (104.6% average recovery). Hole 992A was terminated, and the bit was pulled above the seafloor at 0640 hr on 6 November.

SITE 993
(Proposed Site CFD-7)

Hole 993A

The ship was moved 2.8 km in DP mode in 2.75 hr. A Datasonics 354M beacon (S/N 778, 16.0 kHz) was dropped at 0849 hr on 6 November. After several water cores, the bit was run in to feel for bottom on the sloping diapir and slide area. Hole 993A was spudded at 1345 hr on 6 November. The 12-kHz precision depth recorder (PDR) indicated a water depth of 2616.5 mbsl; however, the seafloor was at 2641.8 mbsl based on recovery of the mudline. APC Core 164-993A-1H was rejected in hard, dry clay and a 1.9-m stroke was assumed based on the 1.88 m recovery. The Adara tool was used to measure water temperature near the seafloor (3.1°C). Extended Core Barrel (XCB) Cores 164-993A-2X to 6X were taken from 1.9 to 51.9 mbsf, with 50.0 m cored and 43.81 m recovered (87.6% average recovery). Hole 993A was terminated, and the bit was pulled above the rotary table at 0020 hr on 7 November.

TRANSIT TO HOLE 994A

The 135-km sea voyage to Site 994 required 6.5 hr at an average speed of 11.2 kt. The Datasonics 354M beacon (S/N 779, 14.0 Khz) was dropped on GPS coordinates at 1408 hr on 7 November.

SITE 994
(Proposed Site BRH-4)

Hole 994A

The operational plan at Site 994 called for two short holes from which sediments would be sampled for microbiological studies, followed by an APC/XCB hole to 750 mbsf. The APC/XCB bit and bottom-hole assembly (BHA) used at Sites 991, 992, and 993 were used in this hole as well. The first APC core attempt had full recovery and no mudline. The pipe was moved up 5 m, and Hole 994A was spudded at 2108 hr on 7 November. The seafloor was 2797.6 mbsl, based on recovery. APC Cores 164-994A-1H to 4H were taken from 0 to 36.4 mbsf. During this time a Force 9 storm hit with rain and continuous lightning, 55-kt winds, and 15-ft seas. The ship was forced 55 m off location, resulting in a yellow 2% (of water depth) warning light; coring operations, however, continued unabated. After the coring objective was reached, the hole was terminated, and the pipe cleared the seafloor at 2350 hr on 7 November.

Hole 994B

Hole 994B was drilled to obtain a single mudline core. Hole 994B was spudded at 0030 hr on 8 November, without moving the ship from the position of Hole 994A. The seafloor was 2797.6 mbsl based on recovery. APC Core 164-994B-1H was taken from 0 to 6.9 mbsf, and the hole was then terminated.

Hole 994C

The ship was moved 10 m south, and Hole 994C was spudded at 0115 hr on 8 November. The seafloor was 2799.1 mbsl based on recovery. Seventeen APC Cores 164-994C-1H to 19H were taken from 0 to 158.4 mbsf, with PCS cores taken at 9P and 18P. Cores were oriented using the tensor tool starting with Core 3H and including all other APC cores. The Adara temperature tool was run with 10 min burial at Cores 4H, 6H, 10H, 13H, 16H, and 20H. When liners were removed from the core barrel, some gas pockets were noted in the cores and occasional splits in the liners occurred, but no special precautions were taken because of low total gas volumes and pressures.

The FWS was run at 51.0 mbsf and again at 100.4 mbsf. For both runs, the sampler was buried with 10k lb set-down weight for a 10-min sample period. When retrieved after each run, the 2-micron screen filter on the sampler was clogged with clay. Water recovered from both runs was determined by analysis to be a mixture of borehole water and water that is loaded into the tool for operational reasons before the run.

Fifty-seven XCB Cores 164-944C-20X to 84X were taken from 158.4 to 703.5 mbsf, with 537.1 m cored and 332.63 m recovered (61.9% recovery). Cores 164-944C-28X and 29X had very low recovery, and mud was found on the check valve, indicating that it had been blown out of the top of the liner. Core 164-944C-30X had enough gas pressure in the inner core barrel to blow out the core and liner, which then fell down the V-door slide.

Ten PCS cores were taken at Hole 994C, with a total of 10.0 m cored and 1.28 m recovered (12.8% recovery). The PCS retained greater than 75% of hydrostatic pressure upon retrieval in nine of these runs and greater than 98% of hydrostatic pressure in six runs. It also recovered more than 15 cm of sediment in seven of these runs. The new PCS push-in-type shoes were run twice (Cores 36P and 45P), and the new PCS rotary auger-type bit was run eight times. Coring parameters were varied in an effort to maximize recovery. The pressure in the PCS chamber was checked as soon as possible, and the chamber was placed in an ice barrel. Pressured gas and water samples were recovered first through a choke manifold in the engineering van, and the core was recovered last (usually several hours later). At this time, the core was examined for lithologic details and a section was squeezed for interstitial water. The sampling manifold was simplified several times to facilitate depressurization of the core and to reduce sampling losses.

Hole 994D

The ship was moved 20 m north-northeast, and Hole 994D was spudded at 0300 hr on 15 November in order to provide a more in-gage hole for VSP clamping and logging. The seafloor was 2799.1 mbsl, based on Hole 994C. An 11-7/16 in. hole was drilled from 0 to 100.0 mbsf. One APC core (Core 164-994D-1H) was taken from 100.0 to 109.6 mbsf. The hole was drilled with a center bit from 109.6 to 241.8 mbsf. Four XCB cores (Cores 164-994D-2X to 5X) were taken from 241.8 to 280.3 mbsf. The hole was then drilled with a center bit from 280.3 to 376.7 mbsf. Four XCB cores (Cores 164-994D-6X to 9X) were taken from 376.7 to 415.0 mbsf, after which the hole was drilled with a center bit to 670.0 mbsf. A 35-bbl sepiolite mud sweep was circulated and a wiper trip was made to 70 mbsf to condition the hole for logging. The hole was reamed from 508 to 670 mbsf with 22 m of fill on bottom (clay pushed to bottom without circulation or rotation). The sediments from 240 to 300 mbsf and below 450 mbsf were elastic, and reaming was ineffective because the hole closed in quickly after the bit was withdrawn. The hole was displaced with sepiolite/seawater mud. At 0515 hr on 16 November, the *Cape Hatteras* arrived on location from Beaufort, N.C., in order to conduct a two-ship walkaway vertical seismic profile experiment.

The initial attempt to run the VSP log with the pipe at 494.5 mbsf was unsuccessful because of tight hole conditions. The drill pipe was pulled to 75 mbsf, and the conical side-entry sub (CSES) was inserted so that the drill pipe could be used to punch through constrictions that logging tools could not go through. The CSES was picked up in 4.75 hr ,and drill pipe was run to 661 mbsf with as much as 35k lbs drag. The VSP tool was deployed and pushed through the XCB bit by pumping; however, the logging cable was damaged, and the tool had to be pulled together with the CSES and drill pipe. The cable was reheaded, and the VSP tool was deployed again using the CSES and drill pipe. This time, the Gearhart fitting on the pendant rotated, damaging the conductors in the Gearhart head. After retrieval, the Gearhart head was repaired. Just before the fourth deployment, the VSP tool was found to have an electrical leakage. The backup WHOI tool was deployed in its place and rerun through the CSES and drill pipe to 650 mbsf, after which the first walkaway VSP began with the *Cape Hatteras*. The VSP tool stuck at 635 mbsf on its second clamping and was worked free; however, the clamping arm drive train was damaged. The VSP tool was retrieved through the CSES.

While the two VSP tools were repaired, the Quad-combination logging tool (without the compensated neutron log [CNL]) was run to 628 mbsf using the CSES. The first VSP tool was rerun with the CSES to 650 mbsf, after which the *Cape Hatteras* conducted a walkaway VSP. The VSP clamping arm failed after three clampings, and the *Cape Hatteras* was released at 1110 hr on 19 November. The zero-offset VSP was continued to 113 mbsf by suspending the tool in the hole at 20-m intervals and confirming arrivals on the geophone using the scope in the Underway Geophysics Lab. After the zero-offset VSP was completed, the bit was washed in the last 30 m. The shear wave tool was then run to 615 mbsf, and logs were taken successfully. The CSES was pulled back to the moonpool, and the logging tool was retrieved. Hole 994D was then terminated, and the bit cleared the seafloor at 0340 hr on 20 November. The bit was pulled 100 m above the seafloor for the move in DP mode to Site 995.

SITE 995

(Proposed Site BRH-6)

Hole 995A

The ship was moved 3.0 km to the GPS coordinates for Site 995, and a Datasonics 354M beacon was dropped at 0749 hr on 20 November. A near-seafloor water sample was taken with the PCS tool at 2693.7 mbsl (approximately 84.8 m above the seafloor). After several water cores using an incorrect PDR setting, Hole 995A was spudded at 1400 hr on 20 November. The water depth was 2778.5 mbsf, based on recovery. Eighteen APC cores (164-995A-1H to 20H) were taken from 0 to 165.2 mbsf, with 163.5 m cored and 170.3 m recovered (104% recovery). Two PCS cores (164-995A-9P and 18P) were taken in the APC hole, with a total of 2.0 m cored and 1.69 m recovered (84% recovery). Cores were oriented using the tensor tool, starting from Core 3H and including all APC cores. Adara temperature measurements were taken with 10-min burial time at Cores 2H, 4H, 6H, 10H, 13H, 16H, and 20H.

When liners were removed from the core barrel, gas voids were noted in the cores. The release of the gas in the voids caused some cores to self-extrude from both the tops and bottoms of the liner. The core liner split full length on Core 17H (145.2 mbsf), after which gassy core safety precautions were followed. APC coring was terminated when Core 20H was a partial stroke, required 50k lbs overpull, and the liner was crunched in the inner core barrel and had to be pumped out.

XCB Cores 164-995A-21X to 83X were taken from 165.2 to 704.6 mbsf. Very large gas voids were noted often, and core recovery was reduced by extensive extrusion of sediments from the tops of core liners. Mud smeared the length of nearly empty core liners and was present on the tools at the top of the liner. A temperature probe developed by Davis and Villinger (DVTP) was run for the first time after Cores 164-995A-20H and 995A-33X, and it successfully recorded data during both runs that WSTP temperature and water samples were taken after Cores 3H, 10H, 13H, 18P, 27P, 30X, 34X, 38X, 41X, and 46X. Nine PCS cores were taken at Cores 164-995A-9P, 18P, 27P, 36P, 45P, 48P, 52P, 60P, and 70P, with a total of 9.0 m cored and 4.58 m recovered (50.9% recovery). In addition, a borehole water sample was taken with the PCS after Core 51X.

The new PCS push-in-type shoes were run as deep as possible on Hole 995A to establish their practical range of use, which appears to be down to about 380 mbsf (in moderately indurated claystones requiring XCB drilling at 18k lb weight on bit [wob]). The shoes were pushed in with 5 to 18k lb weight to a depth of ±0.7 m (depending on the extension sub and formation induration) and then rotated at 10-40 rpm for 2 min to penetrate an additional±0.3 m. The new PCS rotary auger-type bit was run three times in Hole 995A. The optimum parameters appear to be 15k lb wob at 40 rpm with 150 amps torque, circulating 200 gpm at 475 to 550 psi (to clean the larger bit).

After drilling to 704.6 mbsf, Hole 995A was terminated. The hole was displaced with gel mud, and the pipe was pulled. The bit cleared the seafloor at 1308 hr on 26 November.

Hole 995B

The ship was moved 20 m north-northeast in DP mode, and Hole 995B was spudded at 1520 on 26 November. The water depth was 2776.9 mbsf based on recovery. A single mudline APC Core (164-995A-1H) was taken from 0 to 8.3 mbsf. The hole was drilled from 8.3 to 16.0 mbsf, and Core 2H was taken from 16.0 to 25.5 mbsf. The hole was drilled from 25.5 to 100.0 mbsf, and Core 3H was taken from 100.0 to 109.5 mbsf. A WSTP temperature measurement and water sample were taken, and the hole was then drilled ahead from 109.5 to 155.0 mbsf. The WSTP was run a second time, after which the hole was drilled from 155.0 to 200.0 mbsf. A third WSTP run was made, and the hole was then drilled ahead with a wash barrel to 235.0 mbsf.

XCB Cores 5X to 6X were taken from 235.0 to 254.2 mbsf (16% recovery) in an unsuccessful attempt to recover hydrate (gas hydrate was recovered from approximately this depth at Site 994). The hole was drilled ahead with a center bit to 308.5 mbsf. PCS Core 7P was taken from 308.5 to 309.5 mbsf. Two XCB half-length cores (8X to 9X) were taken from 309.5 to 319.5 mbsf in an effort to obtain better recovery in the suspected hydrate-bearing zone (Hole 995A had 3% recovery at this depth). The two half-length cores had 94% recovery. PCS Core 10P was taken from 319.5 to 320.5 mbsf by pushing in the shoe (no rotation or circulation) and recovered 0.65 m of core. A center bit was used to drill from 320.5 to 410.0 mbsf. Five XCB Cores (11X to 15X) were taken from 410.0 to 456.3 mbsf. The hole was then drilled with a center bit from 456.3 to 700.0 mbsf.

A 35-bbl sepiolite mud sweep was circulated and a wiper trip was made to 100 mbsf to condition the hole for logging. A maximum overpull of 20k lb was encountered pulling out of the hole, with a maximum drag of 40k lb at 530 mbsf while running in. The hole was reamed from 530 to 700 mbsf, with 25 m of fill on bottom. The hole was displaced with sepiolite/seawater mud. The pipe was pulled back to 106 mbsf, and the CSES was rigged.

At 1130 hr on 28 November, the *Cape Hatteras* arrived on location in order to conduct a two-ship walkaway VSP experiment. The WHOI triaxial vertical seismic profile tool was run and had to be pumped out of the pipe with 250 gpm at 500 psi. The walkaway VSP was conducted for 27.75 hr with the *Cape Hatteras.* The VSP tool was clamped at 72-m intervals from 680 to 176 mbsf. The *Hatteras* then conducted a seismic survey in the area before returning to Beaufort, N.C. The pipe was run in to 683 mbsf and a zero-offset VSP was run at 8-m station spacing from 662 to 144 m in 22 hr using the ship's guns. The VSP clamping arm stopped working, and the tool was pulled. A kink was found in the logging cable. About 50 m of logging cable was cut off, the cable was reheaded, and the VSP logs were finished at 0900 hr on 1 December.

A digital dual induction/long-spaced sonic/natural gamma spectrometry (DITE/LSS/NGTC) logging tool was run from 337 to 660 mbsf without the CSES. The pipe was then pulled to 135 mbsf and logging was continued to 135 mbsf. High-temperature lithodensity/dual porosity compensated neutron/natural gamma spectrometry (HLDT/CNTG/NGTC), Geochemical (GLT), and Formation MicroScanner (FMS) logs were run to 660 mbsf without problems. The Lamont-Doherty shear sonic tool (SST) was also deployed. Logging required 41.5 hr. Hole 995B was then terminated, the pipe was pulled, and the bit cleared the rotary table on the rig floor at 1150 hr on 3 December.

TRANSIT TO SITE 996

A 72-km transit was completed in 3.2 hr at 12.2 kt, and a 63-km seismic survey was conducted over Site 996 in 4.8 hr at 7.0 kt. A Datasonics 354M beacon was dropped on GPS coordinates 32°29.629'N, 76°11.480'S. The same APC/XCB drill string was run with a flapper valve and without a monel drill collar. The vibration-isolated television (VIT) frame was run with a television (TV) camera, sonar, a VIT frame beacon, and a deployable beacon. A TV and sonar survey was run from 150 m west to 70 m east of the GPS coordinates. Carbonate crusts were evident over most of the transect, and a chemosynthetic mussel bed was located about 30-50 m east by 10 m north to 10 m south of the GPS coordinates. The seafloor was tagged with the bit at 2169.6 mbsl water depth, and the bit was positioned in the center of the mussel bed.

SITE 996
(Proposed Site BRD-1)

Hole 996A

Hole 996A was spudded at 0545 hr on 4 December. The first APC core shot was observed with the TV, and the seafloor was at 2169.6 m water depth. APC Cores 164-996A-1H to 2H were taken from 0 to 9.5 mbsf. Core 2H was a partial stroke that hit a hard carbonate. The VIT frame was pulled to permit rotation with the XCB coring system. Cores 3X to 6X were taken from 9.5 to 47.5 mbsf. Coring parameters indicated a soft matrix with a hard crust from 10 to 15 mbsf and 28 to 30 mbsf. The last three XCB cores had no recovery. PCS Core 7P was taken from 47.5 to 48.5 mbsf and recovered 3326 psi. APC Cores 8H to 9H were taken from 48.5 to 63.0 mbsf. Verbal approval was obtained from ODP to core from 50 to 63 mbsf to collect more hydrate. H_2S was noted in APC Cores 1H to 2H with concentrations of 60 to more than 100 ppm (maximum detector range). Gas masks were used, and entry to the catwalk area was restricted. A fan was used to blow gas out of the area. Cores were sectioned and laid on the grating to degas, and holes were drilled in the liners. Most cores degassed within 30 min, but some cores required more than 2 hr to reach less than 10 ppm H_2S. Some core liners were cut in the lab and carried outside to be split and opened for degassing. As a result of the H_2S gas, hydrate could not be readily sampled in the upper cores.

Hole 996B

The ship did not move, and Hole 996B was spudded at 1735 hr on 4 December in an effort to obtain near-surface sediments for shore-based microbiological studies. The bit was positioned at 2166.6 mbsl (3 m higher than on Hole 996A) for Core 164-996B-1H, but the core blew apart in the liner, and the sediment blew out on the deck. Recovery was 3.4 m.

Hole 996C

The ship did not move, and Hole 996C was spudded at 1855 hr on 4 December in an effort to obtain more near-surface sediments. The bit was positioned at 2163.6 m (6 m higher than on Hole 996A), but Core 164-996B-1H was an incomplete stroke. The core barrel could not be retrieved after 2.5 hr, so the drill string was pulled. The core barrel was bent by the impact with a hard layer (probably carbonates) within 2.6 m of the surface.

Hole 996D

While running in the hole with the same BHA, the ship was moved 40 m west. Hole 996D was spudded at 0725 hr on 5 December. The seafloor was estimated at 2173.1 mbsl, based on an apparent seafloor penetration of 3.5 m into a hard crust. Core had apparently fallen out of the core barrel (i.e., actual recovery on Core 164-996D-1H from 0 to 3.5 mbsf was only 0.40 m). The core barrel was bent and had a broken shoe section. The XCB coring system was picked up, and XCB Cores 2X to 3X were taken from 3.5 to 22.6 mbsf, with 1% recovery. Coring parameters indicated a soft matrix with a moderately hard crust from 13 to 14 mbsf and 17 to 19 mbsf. Core 4H from 22.6 to 32.1 mbsf had 92% recovery, but the overpull was 60k lb, with a hard carbonate layer at 29 to 32 mbsf. Core 5X was taken from 32.1 to 41.7 mbsf, with 3% recovery. APC Core 6H was taken from 41.7 to 51.2 mbsf, and PCS Core 7P was taken from 51.2 to 52.2 mbsf. It was recovered at 2974 psi (91% of hydrostatic pressure at the recovery depth) but contained no sediment.

Hole 996E

The ship was moved 80 m east of Hole 996D, and Hole 996E was spudded at 0725 hr on 5 December. The seafloor was estimated at 2170.0 mbsl, based on recovery. APC Cores 164-

996E-1H to 2H were taken from 0 to 13.6 mbsf in a soft matrix and bottomed out in a hard crust. XCB Core 3X was taken from 13.6 to 23.2 mbsf in the hard crust. APC Cores 4H and 5H were taken from 23.2 to 42.2 mbsf in a soft matrix. XCB Core 6X was taken from 42.2 to 51.8 mbsf in a hard crust. A final APC Core (7H) was taken from 51.8 to 61.3 mbsf in a soft matrix, and PCS Core 8P was taken from 61.3 to 62.3 mbsf. It was recovered at 944 psi (29% hydrostatic) but contained no core. The PCS actuator was found to be sanded up. The drill string was pulled and inspected on the way out. The beacon-recall sender unit in the hull was found to be defective, and both beacons were recalled with the portable unit and recovered. This could explain the two beacon-recall failures earlier in the leg.

TRANSIT TO SITE 997

The sea voyage to Site 997 covered 98 km in 4.2 hr at 12.6 kt average. A Datasonics 354M beacon was dropped at the GPS coordinates. Drillers were advised of the increased potential for hydrocarbons at Site 997A, based on geological and seismic evidence, dynamic well-control procedures were reviewed, and 10.5-ppg kill-weight mud was prepared.

SITE 997

(Proposed Site BRH-1a)

Hole 997A

The same BHA was run with a PDC bit and nonmagnetic drill collar. Hole 997A was spudded at 1825 hr on 6 December. The seafloor was estimated at 2770.1 mbsl, based on recovery. Nineteen APC Cores 164-997A-1H to 17H and 19H to 20H were taken from 0 to 146.9 mbsf and 147.9 to 166.9 mbsf, with a total of 165.9 m cored (104.7% recovery). A single PCS core (Core 18P) was taken from 146.9 to 147.9 mbsf, with 1.0 m cored and 0.45 m recovered. Cores were oriented using the tensor tool, starting with Core 3H and including all APC cores. Adara temperature measurements were taken at Cores 2H, 4H, 10H, 13H, 16H, and 20H. WSTP temperature and water samples were taken after Cores 6H, 10H, 13H, 16H, and 18P. The FWS was deployed before Core 15H.

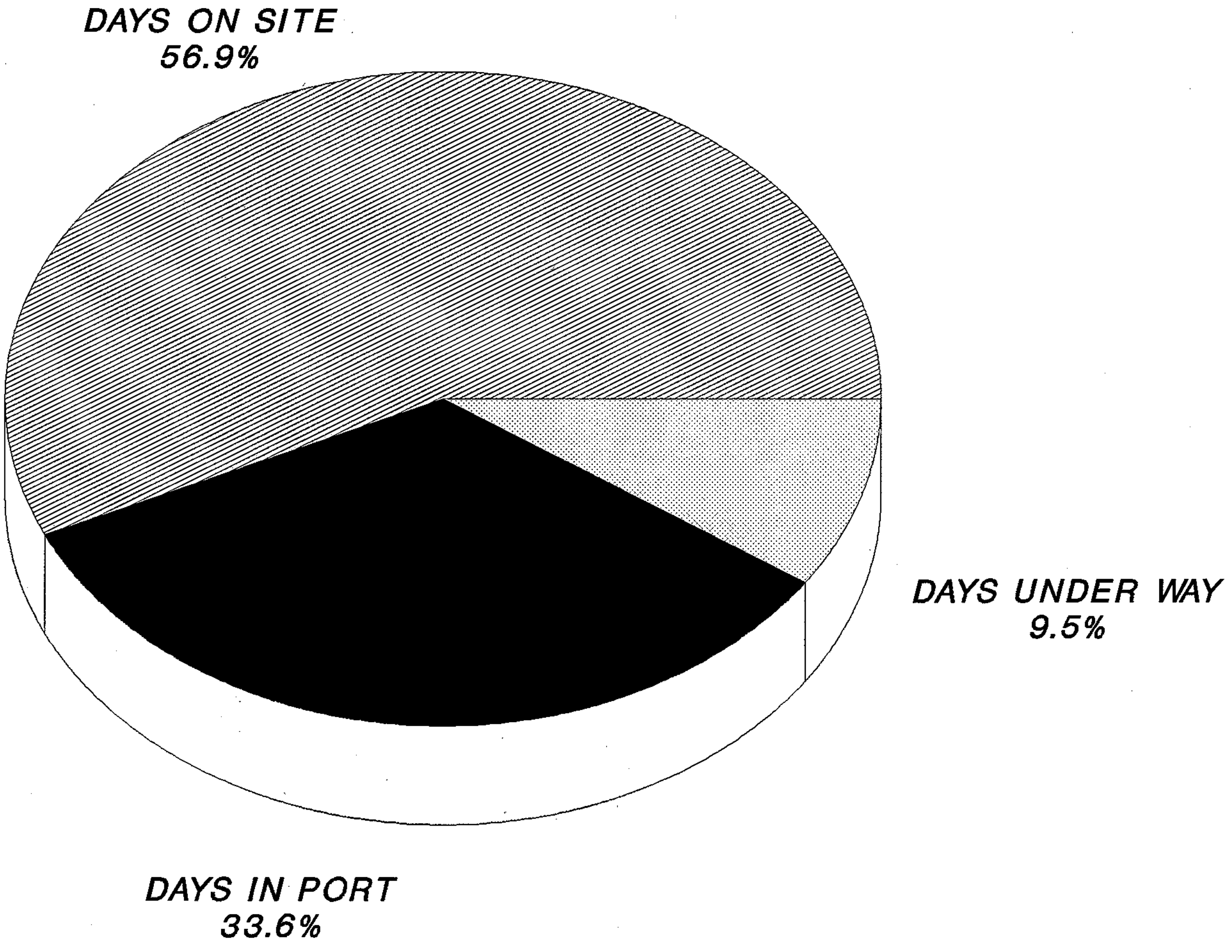
Twenty-eight XCB cores and seven PCS cores were taken from 166.9 to 434.3 mbsf. Twenty-eight XCB cores (Cores 21X through 54X) were obtained by coring 260.4 m (64.1% recovery). Seven PCS cores (18P, 25P, 29P, 33P, 40P, 49P, 51P, and 55P) were obtained by coring 7.0 m, with 1.47 m recovered (21.0% recovery). Massive hydrate was recovered in Core 42X (327.4 to 318.7 mbsf).

OCEAN DRILLING PROGRAM
OPERATIONS RESUME
LEG 164

Total Days (07 October 1995 to 19 December 1995)		72.14
Total Days in Port (Repairs)		24.27
Total Days Underway (Includes Survey Time)		6.85
Total Days on Site		41.01
	days	
Tripping Time	4.23	
Coring	19.46	
Reentry Time	0.00	
W.O.W.	0.00	
Stuck pipe/Hole Trouble	0.14	
Drilling	3.08	
Mechanical Repair Time (Contractor)	0.02	
Logging/Downhole Science	14.24	
Other	0.58	
Total Distance Traveled (nautical miles)		1645.0
Average Speed Transit (knots):		10.8
Number of Sites		7
Number of Holes		17
Number of Cores Attempted		344
Total Interval Cored (m)		2785.9
Total Core Recovery (m)		1974.3
% Core Recovery		70.9%
Total Interval Drilled (m)		1613.8
Total Penetration		4399.7
Maximum Penetration (m)		704.6
Minimum Penetration (m)		2.6
Maximum Water Depth (m from drilling datum)		2810.1
Minimum Water Depth (m from drilling datum)		2181.0

LEG 164

TOTAL TIME DISTRIBUTION



TOTAL DAYS=72.14

HOLE	LATITUDE	LONGITUDE	WATER DEPTH (mbrl)	NUMBER OF CORES	INTERVAL CORED (meters)	CORE RECOVERED (meters)	PERCENT RECOVERED (percent)	DRILLED (meters)	TOTAL PENETRATION (meters)	TIME ON HOLE (hours)	TIME ON SITE (days)
991A	32°59.018'N	75°55.801'W	2578.4	6	56.6	58.66	103.6%	0.0	56.6	13.75	0.57
991B	32°59.018'N	75°55.796'W	2578.4	2	2.0	1.04	52.0%	49.0	51.0	5.75	0.24
		CFD-5 SITE TOTALS:		**8**	**58.6**	**59.70**	**101.9%**	**49.0**	**107.6**	**19.50**	**0.81**
992A	32°58.542'N	75°54.961'W	2597.7	6	50.3	52.62	104.6%	0.0	50.3	7.25	0.30
		CFD-6 SITE TOTALS:		**6**	**50.3**	**52.62**	**104.6%**	**0.0**	**50.3**	**7.25**	**0.30**
993A	32°57.779'N	75°53.685'W	2652.6	6	51.9	45.69	88.0%	0.0	51.9	21.50	0.90
		CFD-7 SITE TOTALS:		**6**	**51.9**	**45.69**	**88.0%**	**0.0**	**51.9**	**21.50**	**0.90**
994A	31°47.141'N	75°32.751'W	2808.6	4	36.4	36.70	100.8%	0.0	36.4	9.50	0.40
994B	31°47.139'N	75°32.740'W	2808.6	1	6.9	6.94	100.6%	0.0	6.9	1.00	0.04
994C	31°47.139'N	75°32.753'W	2810.1	84	703.5	494.39	70.3%	0.0	703.5	168.50	7.02
994D	31°47.142'N	75°32.750'W	2810.1	9	86.2	69.43	80.5%	583.8	670.0	122.50	5.10
		BRH-4 SITE TOTALS:		**98**	**833.0**	**607.46**	**72.9%**	**583.8**	**1416.8**	**301.50**	**12.56**
995A	31°48.210'N	75°31.343'W	2789.8	83	704.6	480.41	68.2%	0.0	704.6	149.50	6.23
995B	31°48.217'N	75°31.336'W	2788.2	14	104.4	61.27	58.7%	595.6	700.0	166.50	6.94
		BRH-6 SITE TOTALS:		**97**	**809.0**	**541.68**	**67.0%**	**595.6**	**1404.6**	**316.00**	**13.17**
996A	32°29.633'N	76°11.454'W	2181.0	9	63.0	16.45	26.1%	0.0	63.0	20.75	0.86
996B	32°29.634'N	76°11.455'W	2184.1	1	3.4	3.40	100.0%	0.0	3.4	0.75	0.03
996C	32°29.638'N	76°11.455'W	2182.1	2	2.6	2.61	100.4%	0.0	2.6	8.00	0.33
996D	32°29.634'N	76°11.478'W	2181.0	7	52.2	15.88	30.4%	0.0	52.2	13.75	0.57
996E	32°29.632'N	76°11.428'W	2181.4	8	62.3	44.49	71.4%	0.0	62.3	16.25	0.68
		BRD-1 SITE TOTALS:		**27**	**183.5**	**82.83**	**45.1%**	**0.0**	**183.5**	**59.50**	**2.48**
997A	31°50.588'N	75°28.118'W	2781.6	55	434.3	343.08	79.0%	0.0	434.3	83.75	3.49
997B	31°50.598'N	75°28.110'W	2781.6	47	365.3	241.25	66.0%	385.4	750.7	175.25	7.30
		BRH-1A SITE TOTALS:		**102**	**799.6**	**584.33**	**73.1%**	**385.4**	**1185.0**	**259.00**	**10.79**
		LEG 164 TOTALS:		**344**	**2785.9**	**1974.31**	**70.9%**	**1613.8**	**4399.7**	**984.25**	**41.01**

Previous PCS runs on Leg 164 were evaluated to determine the optimum conditions for recovery. The most successful PCS coring technique was to force the push-in shoe as deep as possible using a push-in force of 15-20k lb wob for 5 min, followed by 0.5 m (or 5 min) advance by rotation at 20-30 rpm. Circulation at 200 gpm was used, if required, to force the shoe to advance. The 36-3/8 in. long extension was used until the formation became hard, followed by the 18-1/8 in. extension. The basket core catcher was used while the supply lasted. The auger shoe would be used when recovery decreased below 0.20 m. The PCS cores were all obtained using the push-in shoe.

Cores 29P, 33P, and 40P were pushed in without rotation and had no recovery; however, they were followed by successful coring runs in which rotation was used. This result suggests that rotation is useful in moderately compacted clays after pushing-in. The PCS push-in shoe unscrewed from the core barrel after taking Core 55P. An attempt to recover the shoe with a modified GS overshot tool was unsuccessful. Two set screws were added to the PCS push-in and auger-type shoes to lock them on the core barrel. The PDC bit would be destroyed by rotation on the shoe; therefore, coring was terminated. The hole was filled with sepiolite mud, the pipe was pulled, and it cleared the seafloor at 0010 hr on 10 December.

Hole 997B

The ship was moved 20 m northeast, and Hole 997B was spudded at 0045 hr on 10 December. The same seafloor depth of 2770.1 mbsl was used. The hole was drilled with a center bit to 318.5 mbsf at 41.1 m/hr. Three XCB cores were taken over the interval in Hole 997A where a large hydrate section was recovered. Cores 164-997B-1X to 3X were taken from 318.5 to 347.3 mbsf, with 28.8 m cored and 12.57 m recovered (43.6% recovery). The hole was drilled with a center bit from 347.3 to 414.2 mbsf at 26.7 m/hr.

Eight PCS and 35 XCB cores were taken from 414.2 to 750.7 mbsf. One PCS water sample was taken after Core 28X at 606.5 mbsf. Eight PCS cores (6P, 10P, 15P, 21P, 25P, 32P, 36P, 40P, and 44P) were taken, with 8.0 m cored and 1.62 m recovered (20.3% recovery). The practical depth limit for the PCS push-in shoe appears to be about 450 mbsf in these clays. Thirty-five XCB cores (4X to 47X) were taken from 414.2 to 750.7 mbsf, with 357.3 m cored and 239.63 m recovered (67.1% recovery).

The formation was predominately a gassy, dry clay except for a 2-m hard section at 447-449 mbsf (near the BSR at about 450 mbsf). Core was lost by extrusion from the liner top and most cores showed clear indications of gas expansion. The C_1/C_2 ratio in headspace gas samples declined from 16,000-20,000 near the top of the hole (36-66 mbsf) to 109 at 726 mbsf, indicating that the mostly methane gas was biogenic in origin with some migration of heavy hydrocarbons especially below 450 mbsf. A geothermal gradient of 36.9°C/km was assumed based on Hole 997A. The C_1/C_2 ratios declined in vacutainer samples from 108 mbsf and remained steady below 466 mbsf. Iso/normal $C_{4\text{-}6}$ ratios decreased below 466 mbsf, a mild to strong petroleum odor was common, and a light yellow fluorescence was noted in sediments from 452.6 to 568.0 mbsf.

A 35-bbl sepiolite mud sweep was circulated and a wiper trip was made to 80 mbsf to condition the hole for logging. A maximum overpull of 40k lb was encountered pulling out of the hole, with a maximum drag of 40k lb at 578 mbsf running in. The hole was reamed from 565 to 660 mbsf with no fill on bottom. No sticking tendency was noted. The hole was displaced with sepiolite/seawater mud. The pipe was pulled back to 103 mbsf, and the comical side-entry sub was rigged up. Following a downhole tool failure, a DITE/SST/NGTC log was run in 13 hr to 747.4 mbsf with the CSES.

The WHOI triaxial VSP tool was run, and the pipe was run with the CSES to 690 mbsf. The tool stopped at 314 mbsf and had to be pumped out of the pipe with 800 psi. A zero-offset VSP survey was conducted in 13.25 hr, with the tool clamped at 8-m intervals from 714 mbsf. The 300 in^3. water gun failed, so the survey was run with an air gun only. The dipole shear tool was run, but the tool failed and the Gearhart Owens head was replaced. The tool was run with the CSES to 660.8 mbsf and was pumped out of the drill string. A log was run in from 660.8 mbsf. The geochemical combination was run next, followed by the FMS. Following the logging runs, another zero-offset VSP was run using the WHOI triaxial VSP tool and both air and water guns. Hole 997B was then terminated, with the bit clearing the rotary table at 0730 hr on December 17. The ship was underway for Miami at 0815 hr on December 17.

TECHNICAL REPORT

The ODP Technical and Logistics personnel aboard *JOIDES Resolution* for Leg 164 were:

Tim Bronk	Marine Lab Specialist (Chemistry)
Brad Cook	Marine Lab Specialist (Photographer)
Randy Current	Marine Electronics Specialist
Sandy Dillard	Marine Lab Specialist (Storekeeper)
John Eastlund	Marine Computer Specialist
Margaret Hastedt	Assistant Lab Officer (Paleomagnetism)
Rick Johnson	Marine Computer Specialist
Brad Julson	Lab Officer
Kuro Kuroki	Assistant Lab Officer
Mont Lawyer	Marine Lab Specialist (Underway Geophysics)
Jaque Ledbetter	Marine Lab Specialist (X-ray)
Greg Lovelace	Marine Lab Specialist (Physical Properties)
Erinn McCarty	Marine Lab Specialist (Curator)
Chris Nugent	Marine Lab Specialist (Downhole Tools, Thin Section Lab)
Anne Pimmel	Marine Lab Specialist (Chemistry)
Jo Ribbens	Marine Lab Specialist (Yeoman)
Nancy Smith	Marine Lab Specialist (Curatorial Assistant)
Bill Stevens	Marine Electronics Specialist

PORT CALL ACTIVITIES - HALIFAX

The Leg 164 crew arrived on the ship the morning of 28 October 1995. Many of the Leg 163 crew were released early, and the crew crossed over with the remaining technicians from the off-going crew. Most of the oncoming shipments arrived before our crew arrived and were loaded onto the ship. During the port call, the corroded deck plates on the fantail were replaced. The magnetometer winch and level winds were cut away and reinstalled later.

We received two new copiers to replace our aging copiers. The service representative did not appear until the final day to install them. A new cellular phone was brought to the ship, and an antenna was mounted on the lab roof.

OPERATIONS

There were a couple of rendezvous with the *Hatteras*. There was a personal and a medical evacuation of two of our technicians onto the *Hatteras* which later took the people to shore. These rendezvous also brought out camera crews, reporters, and supplies. Samples for bacteria studies were transferred to the *Hatteras* and later inoculated with biological tracers. At one point, we were informed that naval exercises would be taking place near us. We only saw a helicopter and planes that occasionally flew around the ship.

CORE LAB ACTIVITIES

One of the co-chiefs set up a system to measure the quantity of gas in a section of core. The "gas chambers" are degassing tubes made of polyvinyl chloride pipe into which sections of core can be placed. Evolving gas was piped to a graduated cylinder filled with water. The quantity of gas could then be measured and sampled for analysis on the gas chromatographs. Gas amounts were also measured with digital flowmeters. Temperature changes were recorded in a Labview program on a Macintosh computer. Volumes of gas that were unusually large were piped back through tubing into large gas bags in trash cans outside the lab for sampling.

H_2S gas was expected before the cruise, and necessary safety precautions were put into effect. All scientists and technicians were given a class on the dangers of H_2S and how to use breathing apparatus in case of an emergency. Both permanent and portable H_2S monitors were installed in the labstack, and on the catwalk and drill floor. The sensors were calibrated, and there were shipboard H_2S drills.

Because of the volume of gas expected, "gassy core" safety procedures were put into effect. Kevlar material was made into aprons, gloves, and blankets to protect individuals from the possibility of core liners shattering as they were handled. This equipment, as well as hard hats with face masks, was designed to protect the people working around the cores. Fortunately, we did not encounter any cores that were so gassy the liners exploded. The tendency of the liners to explode may depend on the condition, age, and material composition of the liner.

Since the objective of the leg was to look for clathrates, which are unstable under surface conditions, the cores were carefully examined as they were retrieved. Holes were drilled in the liners, and the cores were probed with digital thermometers to search for cold spots that might show clathrates. The core sections were searched on the catwalk or brought into the splitting room. Clathrates were put in pressure vessels or in liquid nitrogen. One scientist brought a series of freezers to store his pressure containers. The catwalk was always packed with people, and it was difficult to curate the cores as people searched for hydrates.

New plastic sampling trays were installed in the sampling area. New core boxes designed to reduce the use of staples and tape were tried for the first time. New bookshelves were also installed in the lab.

Color scans were made on all of the cores while they were described. The FAXITRON was set up on the lower tween deck. The FAXITRON was used to X-ray structure in sediment slabs. The photographs were developed in the photo lab.

UNDERWAY LAB/FANTAIL ACTIVITIES

Routine underway activities commenced soon after we left Halifax. Bathymetric data was collected during the transits between sites. Seismic data was collected as we approached two of the sites. The seismic data was collected at 6 kt using a single 80-in.^{3} water gun. We installed a new version of WinFrog at the beginning of the leg, but it did not work. A new version was brought out during a rendezvous, and it allowed us to fix most of the bugs and to plot the magnetometer signal. Two new Differential Global Positioning Systems (DGPS) were installed and the antennas temporarily installed. The system worked well and allowed us to more accurately plot our positions. All three GPSs are plotted in the WinFrog program.

The lab was heavily used for vertical seismic profiles (VSPs). There were two dual-ship "walkaway" VSPs, using the *Hatteras*, and the standard single-ship VSP. A Reftek data-acquisition system was set up in the lab to collect the data and additional personal computers (PCs), Suns, and Hewlett Packard (HP) computers were connected to the network. The Woods Hole three-axis geophone tool was used downhole; a 400-in.^{3} water gun and a 300 in.^{3} air gun were used as sources for our ship. The *Hatteras* used generator-injector (GI) guns. An air-powered tugger was used to deploy a hydrophone on a faired kevlar cable to be used on the initial shot. The results of the initial tool placements were e-mailed from the *Hatteras* to shore and then received on the *Resolution* to confirm the system was working well.

Corroded deck plates on the fantail were replaced during the port call. The magnetometer winches and level winds were later welded back in place. One level wind control box was found flooded, presumably during the heavy seas encountered during Leg 163. The control box was cleaned and put back into service. The large water gun and the air gun were rebuilt a number of times to support the VSP experiments.

PHYSICAL PROPERTIES LAB

The new multisensor track (MST) LabView software, installed during the port call, was used for the first time. The new program had a few bugs, thus the program will need to be modified. The MST is now run by two Macintosh computers instead of four PCs. The program was well received by the scientists. The physical properties' technician was forced to leave the ship with a medical emergency but the scientists were able to keep the lab running.

CHEMISTRY LAB

This lab was heavily used by organic and inorganic scientists. High-resolution interstitial-water sampling resulted in a new record for the most pore-water samples squeezed on a leg. The scientists searched for indications of clathrates in the core by observing salinity and chlorinity changes in the pore water. Sulfate reduction was also monitored in the upper sections of the cores. The Dionex ion chromatograph ran almost continuously the entire leg. The alkalinity program was modified to store all the titration data on the hard disc. Samples of pore water from the water sampler temperature probe (WSTP) tool and the pressure core sampler (PCS) were also analyzed.

The compositions and concentrations of hydrocarbons and other gases in the sediments were monitored around the clock. Gas was sampled by vacutainers and headspace vials from cores on the catwalk. Gas samples were also taken and analyzed from the co-chief's degassing tubes and the PCS. Gas hydrate samples were dissociated and the resulting gas was analyzed on the gas chromatographs. The Rock-Eval was used for the characterization of organic matter. The extraction and analysis of high-molecular-weight hydrocarbons and long-chain alkenones were performed on a capillary gas chromatograph.

PALEOMAGNETIC LAB

This was a very quiet leg in the lab. Recovery was low, and magnetite reduction made intensities even lower, making conditions very difficult for taking measurements. Even split core intensities were essentially in the noise range of the cryomagnetometer. Fortunately, the scientists knew about this, so there was no disappointment about the near-total lack of magnetostratigraphy. Rock-magnetic studies were the order of the day and were very successful. The cryomagnetometer performed more than 1220 runs at various demagnetization levels.

X-RAY LAB

No samples were run on the X-ray fluorescence (XRF) machine this leg. The X-ray diffraction (XRD) machine was heavily used for the analysis of clay samples. A new Macintosh (“free ware”) application to analyze XRD data was acquired from a member of the Leg 164 shipboard scientific party. It was installed in the core lab and in the X-ray lab and used exclusively throughout the leg to plot and interpret the XRD diffractograms. The new Phillips APD software upgrade (Version 3.6) arrived on the rendezvous and was installed. JCPDSWIN and JCPDS-DOS software and a new (1994) CD-ROM drive were also received and installed. The new laser printer was installed and connected to the network. The XRD powdered standards were consolidated, rebottled, relabeled, and alphabetized. Inventory and reorganization of the XRD rock standards are in progress. About 30 analysis programs were written for the new MacDiff software.

COMPUTERS

The computer inventory was updated to reflect changes in hardware for the DEC service contract. A number of scientists brought their own computers. We attached them to the network so they could analyze geophysical data. ccMail had a few glitches but it was brought back on line each time and the database was recovered with very little loss of files.

The computer machine room preparations were started for the Alpha servers. These two computers will be the servers for the JANUS database. These computers will be installed during port call, and TRACOR personnel will sail next leg to install the software for the first phase of the JANUS program.

CURATION

Sampling objectives for this leg were to determine the changes in ephemeral chemical and physical properties associated with gas hydrate and to investigate the distribution and fabric of gas hydrate within the sediments. This involved rapid sampling of gas hydrate-bearing sediments, closely-spaced interstitial-water sampling, sampling for methane flux analyses, sampling for shore-based physical properties experiments, and frequent sampling for gas analyses.

The curators were especially busy this leg trying to keep up with the scientists sampling clathrates. Compounding this was the H_2S gas found at a couple of sites. There was a large frozen shipment at the end of the leg. All the clathrate samples not analyzed on the ship were sent back in pressure vessels or dewars. The pressure vessels were shipped in large coolers covered in dry ice.

DOWNHOLE MEASUREMENTS LAB

This lab was heavily used to try to understand the in situ characteristics of natural gas hydrate. Temperature measurements in advanced hydraulic piston corer (APC) cores were taken using the Adara temperature tool. The WSTP tool was used for temperature measurements and pore-water sampling in extended core barrel (XCB) type cores.

A new third-party temperature tool, Davis-Villanger Temperature Probe (DVTP) prototype, was used for the first time. It was deployed four times in consolidated material, was very easy to use, and is an example of the new trend in heat-flow measurement tools. The tool collects two channels of temperature data, two channels of accelerometer data (to measure the movement of the tool, especially after it is inserted into the sediment) and two channels of data to measure the drift in the electronics as the tool cools. Pressure measurements will be added later.

A new pore-water sampling tool, the Fisseler Water Sampler (FWS) prototype, also debuted this leg. This tool is designed to slowly extract the pore water from the sediment using a syringe type suction.

The PCS was used heavily this leg. The PCS was run to recover both hydrate/sediment and in situ gasses. The PCS manifold was set up to measure the quantity of gas evolved and collected the gas for later analysis. The PCS was quite successful this leg and brought up core samples at the same pressure they were taken.

PALEONTOLOGY/MICROSCOPE LAB

There was only one paleontologist this leg, so this lab was primarily used for experiments by other scientists. In one area, the geophysicists set up a computer station to analyze their seismic data. In the prep lab, one chemist precipitated sulfide in the hood. Another chemist set up a clathrate collection and measurement station.

PHOTO LAB

Before the leg there were requests to take videos of the cores containing clathrates to monitor the change in physical properties as the clathrates dissociated. Because of the excitement of finding the clathrates, the only video taken was from an individual scientist's personal video recorder. Photos were taken of the clathrates before they were put into pressure containers.

During the beginning of the leg, the densitometer failed. Fortunately, a new model was brought to the ship during a rendezvous. Consequently, the color exposures were different over the course of the leg.

MISCELLANEOUS

The Marine Emergency Technical Squad (METS) trained with the ship's emergency crew. Drills were held once a week and covered everything from fires to stopping an oil leak. A cellular phone was purchased to reduce communication costs. Unfortunately, for most of the leg, we were outside the reach of the cellular service area. The ship will be closer to the continental United States in the future, and the cellular phone will be used then. There is continuing research into less-expensive types of communication. We are currently looking into a stationary satellite over the United States that has much less expensive rates than currently available commercial satellites. A representative from this company will visit the ship during the port call and will look at installing a gymballed antenna.

LEG 164 LAB STATISTICS

General:

Sites	7
Holes	18
Cored Interval (m)	2,785.90
Core Recovered (m)	1,974.31
Percent Recovered	70.9
Total Penetration (m)	4399.7
Time on Site (Days)	42.18
Number of Cores	344
Number of Samples	21.892
Whole Rounds	923
Boxes of Core	305

Samples Analyzed:

Inorganic Carbon ($CaCO_3$)	368
Total Carbon (NCHS)	290
Water Chemistry (the suite includes pH, alkalinity, sulfate, calcium, magnesium, chlorinity, potassium, silica, salinity)	541
Pyrolysis Evaluation (Rock Eval and GHM)	100
Gas Samples	1,000
Extractions	3
Thin Sections	8
XRF	0
XRD	514
MST Runs	5,020
Cryomagnetometer Runs:	1,220
Cubes	214
Oriented Cores	55
Physical Properties Velocity	113
Thermal Conductivity	425
Index Properties	1,520
Resistivity	0
Shear Strength	309
MST	1555

Underway Geophysics:

Bathymetry (NM)	1,645
Seismic Survey (NM)	79
XBT's launched	4

Downhole Tools:

WSTP	32
Adara	23
DVTP	4
PCS	46

Additional:

Close-up Photos	194
Whole-Core Photographs	344
Rolls of Microphotographs	5
Color Transparencies	380
Black-and-White Prints	3157