Paull, C.K., Matsumoto, R., Wallace, P.J., and Dillon, W.P. (Eds.), 2000
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 164

19. DETECTION OF GAS HYDRATE WITH DOWNHOLE LOGS AND ASSESSMENT OF GAS HYDRATE CONCENTRATIONS (SATURATIONS) AND GAS VOLUMES ON THE BLAKE RIDGE WITH ELECTRICAL RESISTIVITY LOG DATA[1]

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ABSTRACT

Leg 164 of the Ocean Drilling Program was designed to investigate the occurrence of gas hydrate in the sedimentary section beneath the Blake Ridge on the southeastern continental margin of North America. Sites 994, 995, and 997 were drilled on the Blake Ridge to refine our understanding of the in situ characteristics of natural gas hydrate. Because gas hydrate is unstable at surface pressure and temperature conditions, a major emphasis was placed on the downhole logging program to determine the in situ physical properties of the gas hydrate–bearing sediments. Downhole logging tool strings deployed on Leg 164 included the Schlumberger quad-combination tool (NGT, LSS/SDT, DIT, CNT-G, HLDT), the Formation MicroScanner (FMS), and the Geochemical Combination Tool (GST).

Electrical resistivity (DIT) and acoustic transit-time (LSS/SDT) downhole logs from Sites 994, 995, and 997 indicate the presence of gas hydrate in the depth interval between 185 and 450 mbsf on the Blake Ridge. Electrical resistivity log calculations suggest that the gas hydrate–bearing sedimentary section on the Blake Ridge may contain between 2 and 11 percent bulk volume (vol%) gas hydrate. We have determined that the log-inferred gas hydrates and underlying free-gas accumulations on the Blake Ridge may contain as much as 57 trillion m^3 of gas.

INTRODUCTION

Gas hydrates are crystalline substances composed of water and gas, in which a solid water lattice accommodates gas molecules in a cage-like structure, or clathrate. Gas hydrates are widespread in permafrost regions and beneath the sea in sediment of outer continental margins. While methane, propane, and other gases can be included in the clathrate structure, methane hydrate appears to be the most common in nature (Kvenvolden, 1988). The amount of methane sequestered in gas hydrate is probably enormous, but estimates of the amounts are speculative and range over three orders of magnitude from about 3,114 to 7,634,000 trillion m^3 (reviewed by Kvenvolden, 1993). The amount of gas in the hydrate accumulations of the world greatly exceeds the volume of known conventional gas reserves. Gas hydrates also represent a significant drilling and production hazard. Russian, Canadian, and American researchers have described numerous problems associated with gas hydrate, including blowouts and casing failures (reviewed by Yakushev and Collett, 1992). Recent studies indicate that atmospheric methane, a greenhouse gas, is increasing at a rate such that the current concentration will probably double in the next 50 years (Kvenvolden, 1988). Because methane is 21 times more radiatively active than carbon dioxide, it is predicted that methane will surpass carbon dioxide as the predominant atmospheric greenhouse gas in the second half of the next century. The source of this atmospheric methane is uncertain; however, numerous researchers have suggested that destabilized natural-gas hydrate may be contributing to the build-up of atmospheric methane (reviewed by Kvenvolden, 1988).

One of the fundamental problems that links the gas hydrate resource, hazard, and climate issues is the need for accurate assessments of the gas volumes within gas hydrate accumulations. Most of the published gas hydrate resource estimates have of necessity been made by broad extrapolation of only general knowledge of local geologic conditions. Gas volumes that may be attributed to gas hydrate are dependent on a number of reservoir parameters, including the areal extent of the gas-hydrate occurrence, reservoir thickness, reservoir porosity, and the degree of gas-hydrate saturation (Collett, 1993). Two of the most difficult reservoir parameters to determine are porosity and the degree of gas-hydrate saturation. Well logs often serve as a source of porosity and hydrocarbon saturation data; however, downhole-log calculations within gas hydrate–bearing intervals are subject to error. The primary reason for this difficulty is the lack of previous quantitative laboratory and field calibration studies.

Leg 164 of the Ocean Drilling Program (ODP) was designed to investigate the occurrence of gas hydrate on the Blake Ridge (Paull, Matsumoto, Wallace, et al., 1996). The presence of gas hydrate in this area has long been suspected because of seismic reflection data showing a strong bottom-simulating reflector (BSR), which often represents the interface between gas hydrate–bearing sediments and underlying gas-charged sediments. Sites 994, 995, and 997 were drilled on the Blake Ridge to refine our understanding of the in situ characteristics of natural gas hydrate. During Leg 164, a major emphasis was placed on the downhole logging program to obtain critical information about the in situ nature of gas hydrate on the Blake Ridge.

The primary objectives of this report are to document the various downhole log responses to the occurrence of gas hydrate on the Blake Ridge and to use the downhole electrical resistivity log data from Sites 994, 995, and 997 to assess the concentration (saturation) and volume of gas hydrate and associated free gas on the Blake Ridge. This report begins with a technical overview of previous gas hydrate downhole log studies and a review of the known responses of downhole logs to the presence of gas hydrate. The main body of the report deals with the development and utilization of quantitative downhole log evaluation techniques used to calculate the degree of gas-hydrate saturation within the known and logged gas hydrate occurrences on the Blake Ridge. This report concludes with an estimate of the potential volume of gas associated with the downhole log–inferred gas hydrate occurrences on the Blake Ridge.

[1]Paull, C.K., Matsumoto, R., Wallace, P.J., and Dillon, W.P. (Eds.), 2000. *Proc. ODP, Sci. Results,* 164: College Station, TX (Ocean Drilling Program).
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PREVIOUS GAS HYDRATE DOWNHOLE LOG STUDIES

Gas hydrate has been inferred to occur at about 50 locations throughout the world (reviewed by Kvenvolden, 1988). Previous to Leg 164, however, gas hydrate had been sampled and surveyed with downhole logging devices at only three locations: (1) North Slope of Alaska (Collett, 1993), (2) Middle-America Trench off the Pacific coast of Guatemala (Shipboard Scientific Party, 1985), and (3) Cascadia continental margin off the Pacific coast of Canada (Shipboard Scientific Party, 1994). The downhole log data from the North Slope of Alaska and Middle-America trench have been the focus of several published studies (Collett et al., 1984; Mathews, 1986; Collett, 1993); however, the available downhole log data from the Cascadia continental margin have not been examined in detail. In the next section of this report, we have reviewed the results of the completed gas hydrate downhole log studies in northern Alaska and offshore Guatemala.

North Slope of Alaska Gas Hydrate Occurrence

The only confirmed gas hydrate occurrence on the North Slope of Alaska was obtained in 1972, when a core containing this substance was recovered from a depth of about 657 m in the Northwest Eileen State-2 well (Collett, 1993). The confirmed gas hydrate occurrence in the Northwest Eileen State-2 well is characterized by relatively high electrical resistivities and acoustic velocities. In Collett et al., (1984) it was assumed that a Pickett crossplot could be used to determine the degree of gas-hydrate saturation in a gas hydrate– and water-bearing rock unit. The accuracy of this procedure to determine gas-hydrate saturation is not known. In Collett (1993), a series of Pickett crossplots were used to calculate gas-hydrate saturations in four gas-hydrate occurrences overlying the Prudhoe Bay and Kuparuk River oil fields on the North Slope of Alaska. Mathews (1986) also used the Pickett crossplot technique to estimate gas-hydrate saturations in the Northwest Eileen State-2 well.

The confirmed gas-hydrate occurrence in the Northwest Eileen State-2 well presents itself as an ideal starting point for the development of gas-hydrate downhole-log evaluation techniques. The responses of the commonly available downhole logs within the confirmed gas-hydrate interval of the Northwest Eileen State-2 well are summarized below (modified from Collett, 1983).

1. Electrical Resistivity (Dual Induction) Log: there is a relatively high electrical-resistivity deflection on this log in a gas-hydrate zone, compared to that in a water-saturated horizon.
2. Spontaneous Potential (SP): there is a relatively lower (less negative) spontaneous-potential deflection in a gas hydrate–bearing zone when compared to that associated with a free-gas zone.
3. Caliper Log: the caliper log in a hydrate usually indicates an oversized borehole resulting from spalling associated with gas-hydrate decomposition.
4. Acoustic Transit-Time Log: within a gas hydrate there is a decrease in acoustic transit time in comparison to a unit saturated with either water or free gas.
5. Neutron Porosity: in a gas hydrate there is a slight increase in the neutron porosity; this response contrasts with the apparent reduction in neutron porosity in a free-gas zone.
6. Density Log: within a gas hydrate there is a slight decrease in density compared to a unit saturated with water.

In most gas hydrate studies, only two downhole logging devices are consistently used to identify potential gas hydrate: they are the electrical resistivity and acoustic transit-time logs.

DSDP Site 570 Gas Hydrate Occurrence

In 1982, while conducting research coring operations on Leg 84 of the Deep Sea Drilling Project (DSDP), a 1.05-m-long core of massive gas hydrate was recovered at Site 570 in the Middle-America Trench off the Pacific coast of Guatemala. The cored gas hydrate sample was determined to be from the interval between 247.4 and 251.4 m sub-bottom depth. Downhole log surveys indicated that the actual thickness of the massive gas hydrate occurrence was about 3 to 4 m (Mathews, 1986). The massive gas hydrate was characterized by high electrical resistivities (~155 Ωm), high acoustic transit-time velocities (~3.6 km/s), high neutron porosities (~67%), and low apparent densities (~1.05 g/cm^3).

Mathews (1986) estimated the amount of methane gas within the gas hydrate occurrences at Site 570 by using a log normalization technique. At Site 570, the resistivity log "plateaus" in the massive gas hydrate zone, indicating a 100% gas-hydrate saturated interval. Mathews (1986) normalized the resistivity data and assumed that a value of 1.0 indicates a 100% pure gas hydrate. Therefore, any deviation from 1.0 indicates that gas hydrate has been replaced by rock matrix material and/or formation water.

REGIONAL GEOLOGY

The Atlantic continental margin of the United States is a classic "passive" margin and is generally used as an example of a geologic feature developed during continental rifting (Bally, 1981). During rifting of North America from North Africa and subsequent subsidence, a thick wedge of Mesozoic and Cenozoic sediments built out onto the subsiding continental margin. Major deltaic systems prograded across the continental shelf, which occasionally were interrupted by more open-marine conditions. Carbonate reefs and micritic limestone buildups marked the shelf-slope break. The major sedimentary basins along the Atlantic Margin are generally elongated parallel to the present-day coast and most contain more than 10,000 m of sediment. The major basins include the Scotian, Georges Bank, Baltimore Canyon Trough, Carolina Trough, and Blake Plateau. North of the Carolinas, the continental margin above 2000-m bathymetric depth is less than 150 km wide, whereas to the south, into the Florida-Bahama region, the continental margin broadens to about 500 km. Beneath this broad continental shelf region are located the Carolina Trough and Blake Plateau Basin, which is bounded to the northeast by the Blake Ridge (Fig. 1). For a more complete description of the geology of the Blake Ridge see the review by Dillon and Popenoe (1988).

Seismic profiles along the Atlantic Margin are often marked by large-amplitude bottom simulating reflectors (BSRs) (Dillon et al., 1993; Lee et al., 1993), which in this region are believed to be caused by a large acoustic impedance contrast at the base of the gas-hydrate stability zone that juxtaposes sediments containing gas hydrate with sediments containing free gas. BSRs have been extensively mapped at two locations off the east coast of the United States—along the crest of the Blake Ridge and beneath the upper continental rise of New Jersey and Delaware (Tucholke et al., 1977; Dillon et al., 1993). The Blake Ridge is a positive topographic sedimentary feature on the continental slope and rise of the United States (Fig. 1). The crest of the ridge extends approximately perpendicular to the general trend of the continental rise for more than 500 km to the southwest from water depths of 2000 to 4800 m. The Blake Ridge is thought to be a large sediment drift that was built upon transitional continental to oceanic crust by the complex accretion of marine sediments deposited by longitudinal drift currents (Tucholke et al., 1977). The Blake Ridge consists of Tertiary to Quaternary sediments of hemipelagic muds and silty clay (Paull, Matsumoto, Wallace, et al., 1996). The thickness of the methane-hydrate stability zone in this region ranges from zero along the northwestern edge of the continental shelf to a maximum thickness of about 700 m along the eastern edge of the Blake Ridge (Collett, 1995). The first direct evidence that gas hydrate might be present along the Atlantic Margin was found during deep-sea drilling on the Blake Ridge in 1970 (Shipboard Scientific Party, 1972). Cores recovered from DSDP Sites 102, 103, and 104 contained large quantities of methane, which suggested the presence of gas hydrate. In addition, measured acoustic velocities (>2 km/s) within the suspected gas hydrate–bearing section exceeded normal marine sediment velocities, indicating the presence of gas hydrate. The occurrence of gas hydrate on the Blake Ridge was confirmed during Leg 76 of the DSDP when a sample of gas hydrate was recovered from a sub-bottom depth of 238 m at Site 533 (Shipboard Scientific Party, 1983).

Leg 164 of the ODP (Paull, Matsumoto, Wallace, et al., 1996) was the first drilling leg dedicated to the research of natural gas hydrate (Fig. 1). Sites 994, 995, and 997 compose a transect of holes that penetrate below the base of gas hydrate stability within the same stratigraphic interval over a relatively short distance (9.6 km). This transect of holes on the Blake Ridge extends from an area where a BSR is not detectable to an area where an extremely well-developed and distinct BSR exists (Fig. 2). A BSR is not observed at Site 994, a modest BSR occurs at 995, and a strong BSR is seen at Site 997. However, the geology and topography along this transect are relatively simple (Paull, Matsumoto, Wallace, et al., 1996), which provides an opportunity to assess the basic properties of gas hydrate–bearing sediments and to understand lateral variations caused by local lithologic, chemical, and hydrologic factors. Because drilling at all three sites on the Blake Ridge penetrated below the base of gas hydrate stability, they provide critical information on the amounts of gas and gas hydrate in the sediments as well as the nature of the BSR itself.

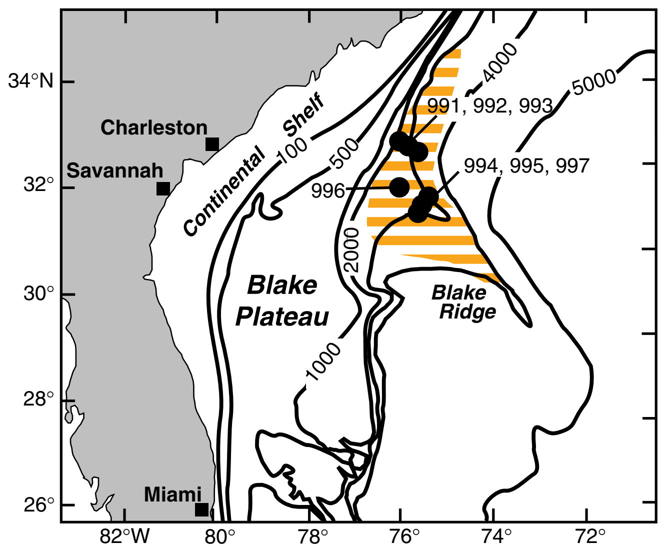

Figure 1. Physiographic map of the southeastern continental margin of North America. Location of Leg 164 drill sites are indicated. Also shown is the area (horizontally shaded area) where gas hydrate occurrence has been mapped on the basis of bottom-simulating reflectors (BSRs). Bathymetric contours are in meters.

DOWNHOLE LOGGING PROGRAM

Logging tool strings deployed on Leg 164 (Table 1) included the Schlumberger quad- and split-combination (NGT, LSS-SDT, DITE, CNT-G, HLDT), Formation MicroScanner (FMS), and the Geochem-

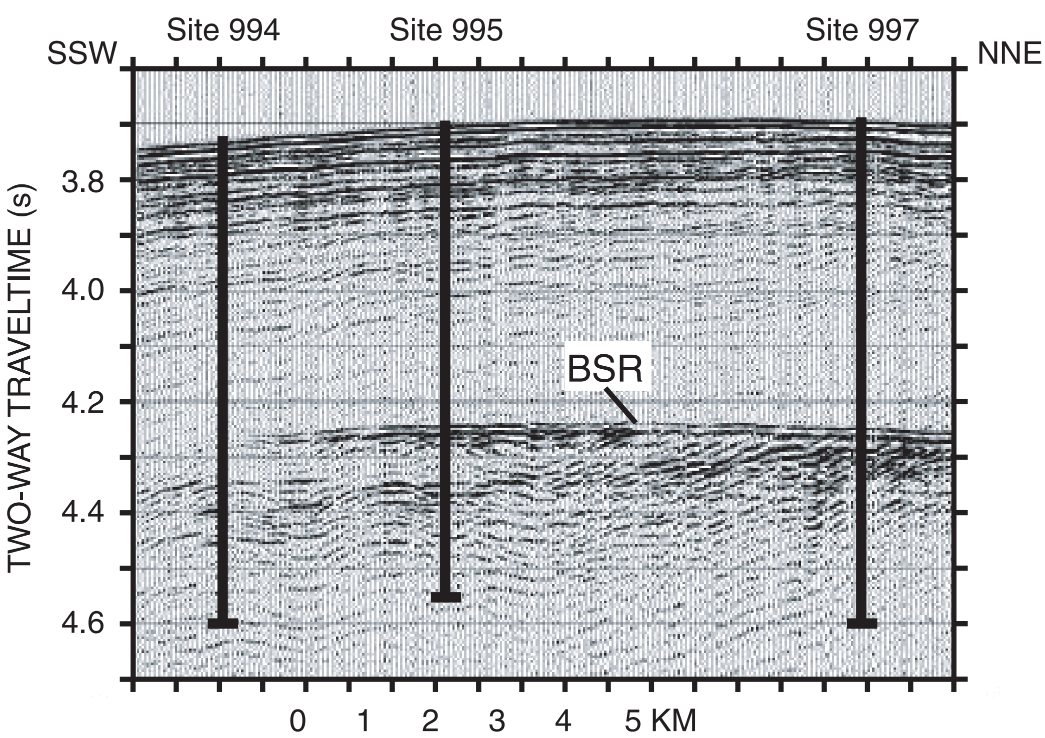

Figure 2. Seismic profile along which Sites 994, 995, and 997 are located. Note that Site 994 is not associated with a distinct BSR, although a very strong BSR occurs at Sites 995 and 997.

Table 1. Leg 164 downhole logging program.

Hole	Total hole penetration (mbsf)	Log run	Logging string	Interval logged (mbsf)
994C	703.5	1	DITE/SDT/HLDT/CNT-G/ NGT/LDEO-TLT	76.0-450.0
		2	GST(AACT/GST/NGT) (13 inelastic stations)	52.0-320.0
994D	670.0	1	DITE/LSS-SDT/HLDT/ NGT	114.0-618.0
		2	LDEO-SST	191.0-613.0
995B	700.0	1	DITE/LSS-SDT/NGT/ LDEO-TLT	134.0-639.0
		2	HLDT/CNT-G/NGT	134.0-639.0
		3	GST(AACT/GST/NGT) (18 inelastic stations)	135.0-634.5
		4	LDEO-SST	136.0-658.7
		5	FMS/GPIT/NGT (2)	145.0-658.7
997B	750.7	1	DITE/LSS-SDT/HLDT NGT/LDEO-TLT	113.0-715.0
		2	GST(AACT/GST/NGT) (13 inelastic stations)	115.0-683.0
		3	LDEO-SST	115.0-683.0
		4	FMS/GPIT/NGT (2)	115.0-681.0

ical Combination Tool (GLT). The split-combination tool string consisted of separate runs of the seismic stratigraphic and lithoporosity combinations (Paull, Matsumoto, Wallace, et al., 1996).

The quality of the log measurements on Leg 164 were moderately to severely degraded by the size and irregular nature (rugosity) of the borehole. The caliper logs in Holes 994C, 994D, 995B, and 997B (Fig. 3) show borehole diameters greater than the 46.9-cm maximum range of the caliper for a significant portion of the hole. The comparison of log data from Holes 994C and 994D (Shipboard Scientific Party, 1996a), reveals that the log data from Hole 994D are of superior quality; therefore, we have focused our interpretive efforts at Site 994 on the log data from Hole 994D. The natural gamma-ray spectrometry (NGT), lithodensity (HLDT), and compensated neutron porosity (CNT-G) tools are particularly susceptible to adverse affects from large and irregular hole diameters. The NGT logs from Hole 995B were not significantly affected by the size of the borehole. However, the NGT logs from Holes 994D and 997B are highly degraded because of enlarged borehole sizes and the rugosity of the borehole. The HLDT, which is an excentered device, has a caliper arm that forces the tool against the wall of the borehole. If the hole is larger than the maximum reach (46.9 cm) of the caliper arm the density tool may lose contact with the formation. In general, the density logs in all of the holes drilled on the Blake Ridge were degraded because of poor tool contact with the borehole wall. Data from the density logs have been used to calculate sediment porosities; however, the results of these calculations are unsatisfactory (additional information on density log porosity calculations is provided later in this report). The compensated neutron porosity logs (CNT-G) are severely affected by enlarged boreholes in all of the holes drilled on the Blake Ridge, and all of the neutron porosity data from Leg 164 have been disregarded in this study (additional information on neutron porosity data is provided later in this report). The acoustic velocity (LSS-SDT) and electrical resistivity (DITE) logs provided invaluable information on sediment porosities and gas-hydrate saturations in all of the Leg 164 Blake Ridge drill sites. The GLT also provided useful information; however, the GLT measurements have also been degraded by the enlarged borehole conditions, which required extensive shore-based processing to rectify (Paull, Matsumoto, Wallace, et al., 1996).

The absolute depths, relative to seafloor, for all of the logs were fixed by identifying the gamma-ray signal associated with the seafloor and depth shifting the log data appropriately. The natural gamma-ray log pick for the seafloor in Holes 994D, 995B, and 997B were 2,809.0, 2,786.0 and 2,775.0 m below the dual elevator stool (DES)

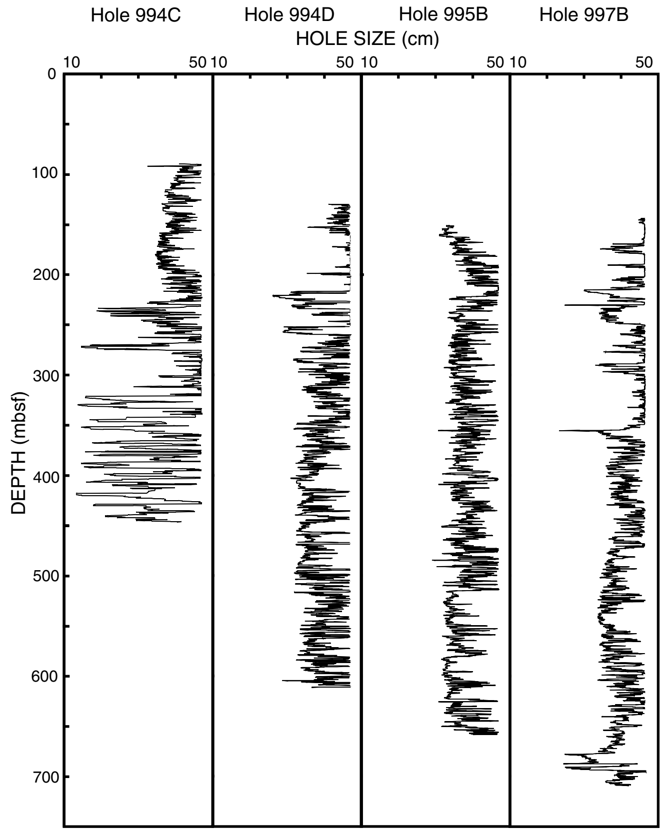

Figure 3. Caliper logs recorded from the lithodensity (HLDT) tool in Holes 994C, 994D, 995B, and 997B.

on the drilling mask, which is located on the ship 11.4 m above sea level.

LOGGING UNITS

The description of the logged intervals in Holes 994D, 995B, and 997B are divided into three "logging units" on the bases of obvious changes in the natural gamma-ray (NGT), bulk-density (HLDT), acoustic velocity (LSS-SDT), and electrical resistivity measurements (DITE) (Table 2; Fig. 4A-C). The elemental yield data from the geochemical combination tool (GLT) has also been used to assess the mineralogy of the sediments in the delineated logging units. A more detailed assessment of the GLT interpreted mineralogy at Sites 995 and 997 have been included in Collett and Wendlandt (Chap. 21, this volume).

Logging Unit 1

Logging Unit 1 is characterized by relatively low gamma-ray, density, velocity, and resistivity log values (Fig. 4A–C). All of the recorded logs are affected by the enlarged borehole, which exceeds the maximum recording size (46.9 cm) of the caliper throughout most of Unit 1. In most cases, the gamma-ray log shows an abrupt upward step in value at the boundary between Unit 1 and Unit 2. The caliper log (Fig. 3) shows that the hole diameters are reduced across the boundary from Unit 1 to Unit 2. The bulk-density and acoustic velocity increase more gradually across the boundary between Units 1 and 2. Within Unit 1, the weight percent of K and Al are relatively low and remain constant. Analyses of K and Th elemental yields reveal that the clays in Unit 1 are predominately montmorillonites and some illites (Collett and Wendlandt, Chap. 21, this volume).

Logging Unit 2

Logging Unit 2 is characterized by increasing velocities (1.65 km/s at the top to over 2.0 km/s at the bottom) with depth. The natural gamma-ray and bulk-density logs are nearly constant throughout Unit 2. Both the acoustic velocity and resistivity logs are characterized by a distinct baseline shift to relatively higher values throughout Unit 2. The resistivity logs reveal several conspicuous high electrical resistivity intervals near the top of Unit 2 in all three boreholes. At the base of Unit 2, across the boundary into Unit 3, the acoustic velocity and resistivity logs step down to lower values. In Hole 997B (Fig. 4C), the acoustic log (DTLF) has been used to precisely select a depth for the boundary between Units 2 and 3. This acoustic velocity (DTLF) boundary does not exactly match the drop in resistivity observed near the base of Unit 2. This discrepancy of about 8 m is likely a result of the presence of a significant amount of free gas below the deepest gas hydrate occurrence. Analyses of K and Th elemental yields suggest that the clays in logging Unit 2 are mostly montmorillonites (Collett and Wendlandt, Chap. 21, this volume).

Table 2. Depth to the top and bottom of the downhole log identified logging units in Holes 994D, 995B, and 997B (See Fig. 4A–C).

Hole	Logging unit	Depth to top of logging unit (mbsf)	Depth to bottom of logging unit (mbsf)
994D	1	Base of pipe (114.0)	212.0
	2	212.0	428.8
	3	428.8	End of log (618.0)
995B	1	Base of pipe (134.0)	193.0
	2	193.0	450.0
	3	450.0	End of log (658.7)
997B	1	Base of pipe (113.0)	186.4
	2	186.4	450.9
	3	450.9	End of log (715.0)

Logging Unit 3

Logging Unit 3 is characterized by consistently lower velocities and resistivities with respect to Unit 2. Anomalous low-velocity intervals are seen in Unit 3; velocities within these anomalous intervals decrease to below 1.5 km/s, which suggests the presence of free gas. The higher resistivities, near the boundary between Units 2 and 3 in Hole 997B, may be a result of the presence of free gas, which supports the acoustic log observations. In logging Unit 3, the natural gamma-ray, density, and electrical resistivity logs show slight increases with depth, which is characteristic of a normally compacting sedimentary section.

GAS HYDRATE OCCURRENCES

The presence of gas hydrate at Sites 994 and 997 was documented by direct sampling; however no gas hydrate was conclusively identified at Site 995 (Shipboard Scientific Party, 1996b). Although a BSR

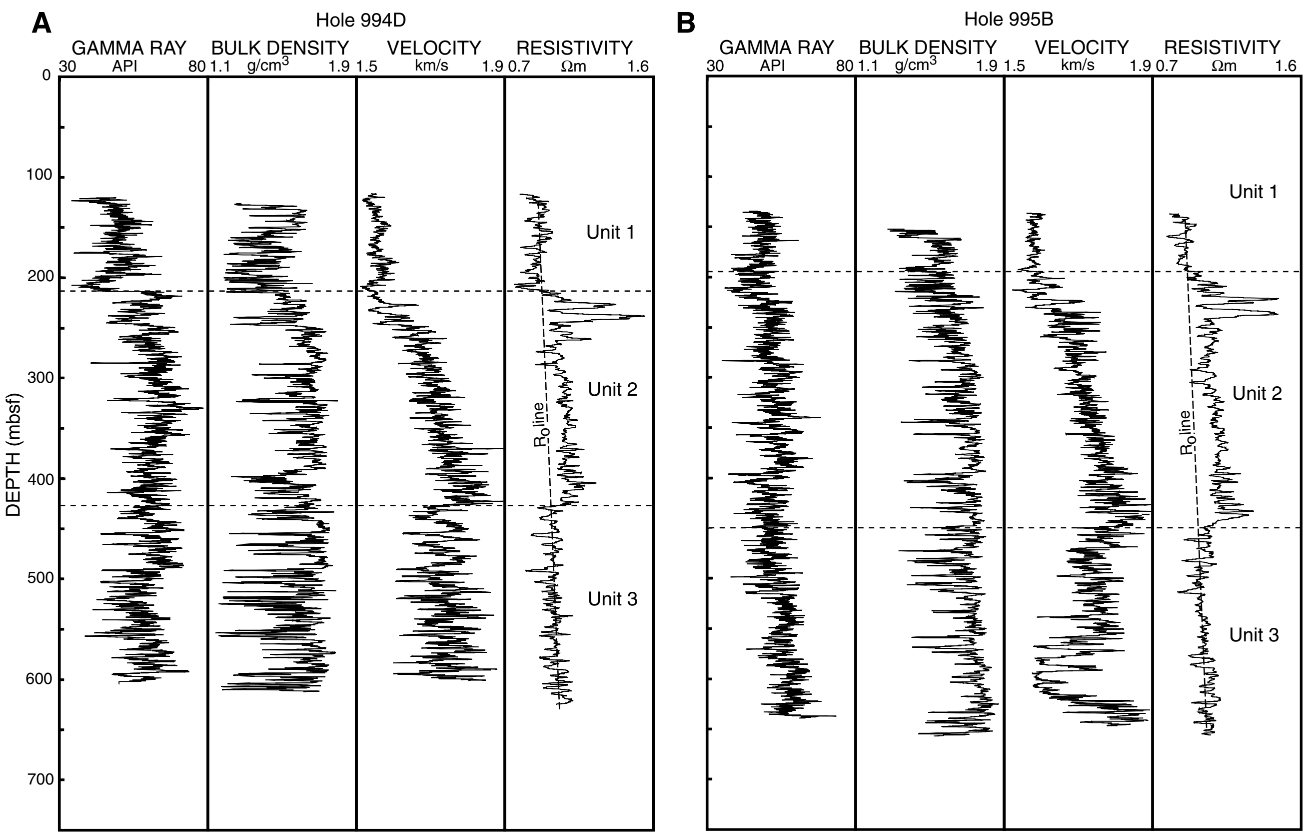

Figure 4. **A.** Downhole log data from Hole 994D. Data shown include the natural gamma-ray log from the NGT, bulk-density data from the HLDT, acoustic velocity data from the LSS-SDT, and deep-reading electrical resistivity data from the DITE. Also shown are the depths of logging Units 1, 2, and 3 (Table 2) and the projected R_o baseline. **B.** Downhole log data from Hole 995B. Data shown include the natural gamma-ray log from the NGT, bulk-density data from the HLDT, acoustic velocity data from the LSS-SDT, and deep-reading electrical resistivity data from the DITE. Also shown are the depths of logging Units 1, 2, and 3 (Table 2) and the projected R_o baseline. (Continued on next page.)

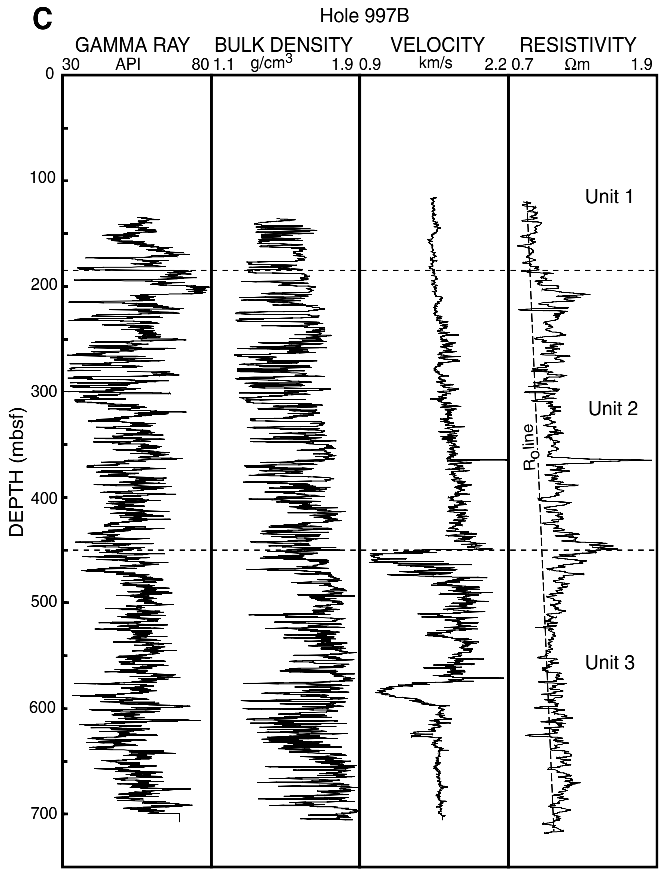

Figure 4 (continued). **C.** Downhole log data from Hole 997B. Data shown include the natural gamma-ray log from the NGT, bulk-density data from the HLDT, acoustic velocity data from the LSS-SDT, and deep-reading electrical resistivity data from the DITE. Also shown are the depths of logging Units 1, 2, and 3 (Table 2) and the projected R_o baseline.

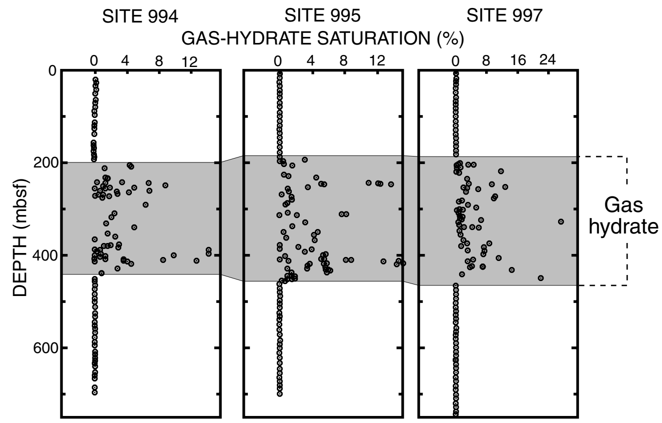

Figure 5. Plot of gas-hydrate saturations (percent of pore space occupied by gas hydrate) calculated from interstitial water chlorinities, assuming that the chloride anomalies at each site (Sites 994, 995, and 997) are solely produced by gas-hydrate decomposition during core recovery (modified from Paull, Matsumoto, Wallace, et al., 1996).

does not occur in the seismic reflection profiles that cross Site 994, several pieces of gas hydrate were recovered from 259.90 mbsf in Hole 994C and disseminated gas hydrate was observed at almost the same depth in Hole 994D. One large, solid piece (about 15 cm long) of gas hydrate was also recovered from about 331 mbsf at Site 997 (Hole 997A). Despite these limited occurrences of gas hydrate, it was inferred, based on geochemical core analyses and downhole logging data, that disseminated gas hydrate occur in logging Unit 2 (which extends from a depth of about 190 to 450 mbsf) of all the holes drilled on the Blake Ridge (Table 2). The presence of gas hydrate in logging Unit 2 at Sites 994, 995, and 997 was inferred on the basis of the following observations (Shipboard Scientific Party, 1996a, 1996b, 1996c). (1) Cores from all three sites were observed to evolve large amounts of gas, which is indicative of gas hydrate–bearing cores. It is also speculated that gas evolution from decomposing gas hydrate may have been a factor that contributed to the low core recovery at all the Blake Ridge drill sites. (2) Pressure-coring (PCS) data indicate that the sediments on the Blake Ridge between about 200 and 450 mbsf contain methane concentrations that exceed expected methane pore-water saturations. The only known source for this methane is the decomposition of gas hydrate; thus, it was concluded that gas hydrate must occur within this interval of over-saturated gas. (3) Both the general trend of the interstitial-water chloride concentrations and the inter-sample variation in chloride concentrations (chloride anomalies) between 190 and 450 mbsf suggest the presence of gas hydrate throughout logging Unit 2. Gas-hydrate decomposition during core recovery releases water and methane into the interstitial pores, resulting in a freshening of the pore waters. (4) Temperatures of cores recovered on the Blake Ridge transect were quite variable within logging Unit 2. Low-temperature anomalies are interpreted as indicating areas where gas hydrate decomposition has occurred during core recovery. (5) Data from downhole logs also were interpreted as indicating the presence of gas hydrate in logging Unit 2. The downhole log evidence for gas hydrate is discussed in more detail later in this report.

The depths to the top and the base of the zone of gas-hydrate occurrence at Sites 994, 995, and 997 were determined using interstitial-water chloride anomalies (Shipboard Scientific Party, 1996a, 1996b, 1996c) and downhole log data (Table 2). Interstitial-water chloride anomalies established whether gas hydrate occurred within a given core sample. The observed chloride anomalies also allow the amount of gas hydrate to be established by calculating the amount of interstitial-water freshening that can be attributed to gas hydrate disassociation. The estimated volume percentage of gas hydrate in the recovered cores had a skewed distribution, ranging from a maximum of about 7.0 and 8.4 vol% at Sites 994 and 995 to a maximum of about 13.6 vol% at Site 997 (Fig. 5). However, these are minimum estimates because the baseline (undisturbed interstitial-water chlorinities) used to calculate these values may be lower than the actual in situ interstitial-water salinities. For a more complete discussion on the chlorinity-calculated gas hydrate contents, see Paull, Matsumoto, Wallace, et al. (1996).

As previously discussed, natural gas hydrate occurrences are generally characterized by an increase in log-measured acoustic velocities and electrical resistivities. The comparison of logging Units 1, 2, and 3 in all three holes on the Blake Ridge (Holes 994D, 995B, and 997B), reveal that logging Unit 2 is characterized by a distinct stepwise increase in both electrical resistivity (increase of about 0.1–0.3 Ωm) and acoustic velocity (increase of about 0.1-0.2 km/s) (Fig. 4A–C). In addition, the deep reading resistivity device (RILD) reveals several anomalous high resistivity zones within the upper 100 m of Unit 2 at all three sites on the Blake Ridge (anomalous resistivities ranging from 1.4 to 1.5 Ωm). At Site 994, gas hydrate was recovered (depth 259.90 mbsf) from the same interval that exhibits anomalous high resistivities in the upper part of Unit 2. Further comparisons indicate that the anomalous high resistivity zones do not correlate to any apparent acoustic velocity anomalies at Sites 994 or 995. However, at Site 997 the anomalous high resistivity zones in the upper part of Unit 2 are characterized by an acoustic velocity increase of about 0.3 km/s. The zone from which gas hydrate was recovered at Site 997 (depth of about 331 mbsf in Hole 997A) is also characterized by anomalous high resistivities and acoustic velocities. At Site 994, below the anomalous high resistivity zones at 216 and 264 mbsf, the resistivity log values are almost constant throughout logging Unit 2, whereas the acoustic velocities increase with depth over the same interval. However, both electrical resistivities and acoustic velocities in Unit 2 increase with depth at Sites 995 and 997. Examination of the natural gamma-ray and bulk-density logs from all three sites (Fig. 4A–C) reveals no apparent lithologic causes for the observed velocity and resistivity increases in Unit 2. The above observations are consistent with a material of increased resistivity and acoustic velocity but similar density, partially replacing some of the pore water in Unit 2. The depth of the boundary between logging Units 2 and 3 on the Blake Ridge is in rough accord with the predicted base of the methane hydrate stability zone and it is near the lowest depth of the observed interstitial-water chlorinity anomaly (Fig. 5). It has been concluded that logging Unit 2 at Sites 994, 995, and 997 contains some amount of gas hydrate.

POROSITY CALCULATIONS

Sediment porosities can be determined from analyses of recovered cores and from numerous borehole log measurements (reviewed by Serra, 1984). At Sites 994, 995, and 997 we have attempted to use data from the lithodensity (HLDT), neutron porosity (CNT-G), and electrical resistivity (DITE) logs to calculate sediment porosities. Core-derived physical property data, including porosities (Shipboard Scientific Party, 1996a, 1996b, 1996c), have been used to both calibrate and evaluate the log-derived sediment porosities.

Core Porosities

On Leg 164, water content, wet bulk density, dry bulk density, and grain density were routinely determined from recovered sediment cores. Other related physical property data, including sediment porosities, were calculated from these "index properties" (Paull, Matsumoto, Wallace, et al., 1996). The core-derived porosities actually represent the measured total water content of the sediments, which include interlayer, bound, and free water. Most downhole logs also measure the total water content of the sediments; thus the core- and log-derived sediment porosities should be the same. Sediment core porosities determined from Sites 994, 995, and 997 are shown in Figure 6. In general, the core-derived sediment porosities decrease from about 80% near the top of each hole to about 50% at the bottom.

Density Log Porosities

The HLDT log measurements of bulk density in Holes 994D, 995B, and 997B (Fig. 4A-C) are highly variable and range from a maximum of about 1.9 g/cm^3 to a minimum value of about 1.2 g/cm^3. Other physical property data from the Blake Ridge, including core-derived sediment wet bulk densities and porosities (Fig. 6) (Shipboard Scientific Party, 1996a, 1996b, 1996c), are not consistent with the density log measurements. The core-derived bulk densities are relatively constant with depth and are characterized by a relatively limited range of values. It is likely that the density logs from all three sites have been severely degraded by both the rugosity and the enlarged size of the boreholes. Before using the log-derived bulk-density data to calculate sediment porosities, we have attempted to systematically remove the erroneous data from the recorded density logs at Sites 994, 995, and 997. The detailed analysis of the recorded logs indicates that the density log yields erroneous low values when the borehole exceeded a diameter of about 36 cm. In addition, it appears that when the borehole size is reduced, below a diameter of about 28 cm, the density log yields erroneous high values. Therefore, we have systematically deleted all of the density log data from the portion of Holes 994D, 995B, and 997B where the caliper log from the density tool indicates that the hole diameter is more than 36 cm or less than 28 cm. The edited density log curve still contained numerous unreasonably low density "spikes" that usually consist of only one or two data points. Therefore, any log measured bulk density values of less than 1.6 g/cm^3 were also deleted from the recorded log traces. The edited bulk-density (ρ_b) log measurements were then used to calculate sediment porosities ($\varnothing$) in Holes 994D, 995B, and 997B using the standard density-porosity relation: $\varnothing = (\rho_m - \rho_b)/(\rho_m - \rho_f)$ (Serra, 1984). Water densities (ρ_f) were assumed to be constant and equal to 1.05 g/cm^3 for each hole; however, variable core-derived grain/matrix densities (ρ_m) were assumed for each calculation. The core-derived grain densities (ρ_m) in Holes 994C, 995A, and 997A range from an average value at the seafloor of about 2.72 g/cm^3 to about 2.69 g/cm^3 at the bottom of each hole (Shipboard Scientific Party, 1996a, 1996b, 1996c). The density log porosity calculations from all three sites yielded values ranging from about 50% to near 70% (Fig. 6). The density log-derived porosities are more variable and generally higher than the core-derived porosities also shown in Figure 6. It appears that the density log porosities overestimate both the range and absolute porosities for the sediments on the Blake Ridge. It is likely the high clay content and unlithified nature of the sediments on the Blake Ridge have contributed to the inability of the density tool to make good contact with the borehole wall, which leads to erroneous density log measurements that cannot be further corrected. Data from the density logs in Holes 994D, 995B, and 997B can be used to assess general porosity trends but not for quantitative calculations.

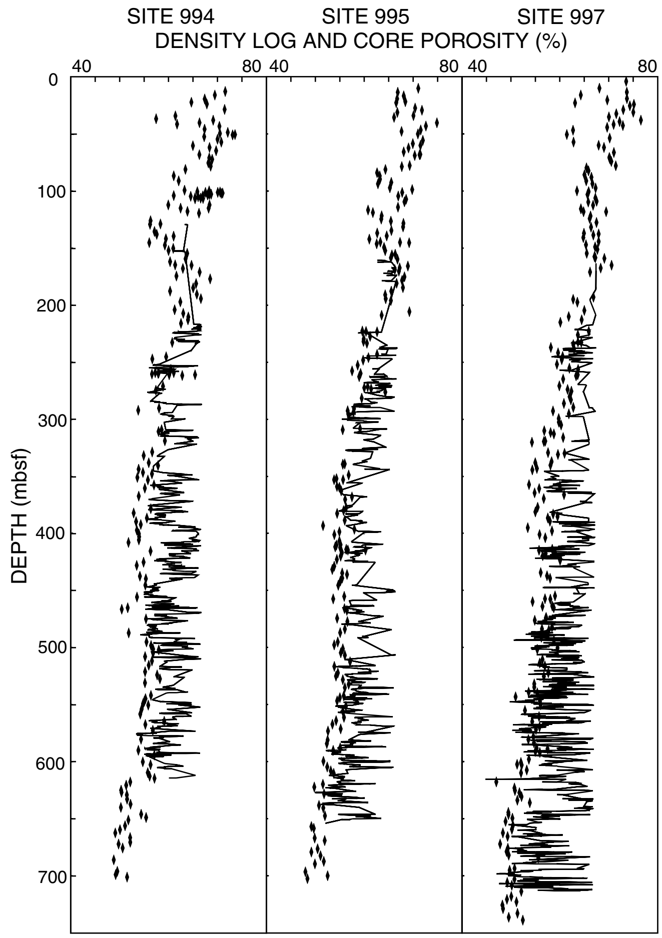

Figure 6. Sediment porosities (shown as continuous line plots) derived from downhole density log (HLDT) data at Sites 994, 995, and 997. For comparison purposes, diamonds show the core-derived porosities (as discrete point measurements).

Neutron Porosity Log

Because of poor hole conditions, the CNT-G was run in only two holes (Holes 994C and 995B) on the Blake Ridge. The CNT-G measures the amount of hydrogen within the pore space of a sedimentary sequence, which is mostly controlled by the amount of water that is present. The CNT-G has two pairs of detectors that indirectly measure both epithermal (intermediate energy level) and thermal (low energy) neutrons, which provide two porosity measurements. The recorded neutron porosity log data from Holes 994C and 995B reveal an average thermal porosity of about 50%, and the epithermal porosity averages about 100%. The thermal and epithermal porosity logs are calibrated to read 50% and 100%, respectively, in water (no sediment). Therefore, the neutron porosity log in Holes 994C and 995B only detected the hydrogen in the borehole waters and the porosity data from the neutron log is of no value. In "standard" industry applications the CNT-G is run with a bowspring that keeps the tool near the wall of the hole, thus reducing the effects of an enlarged borehole. Because of the size limitation of running the logs through the drillpipe, it is impossible to use a bowspring on the CNT-G in ODP holes.

Resistivity Log Calculated Porosities

One approach to obtaining sediment porosities from downhole logs is to use the electrical resistivity logs (Fig. 4A–C) and Archie's relationship between the resistivity of the formation (R_t) and porosity ($\varnothing$): $R_t/R_w = a\,\varnothing^{-m}$, where a and m are constants to be determined and R_w is the resistivity of the pore-waters (Archie, 1942).

The resistivity of pore-waters (R_w) is mainly a function of the temperature and the dissolved salt content (salinity) of the pore waters. Pore-water salinity data from Sites 994, 995, and 997 are available from the analyses of interstitial water samples collected from recovered cores at each site (Shipboard Scientific Party, 1996a, 1996b, 1996c). The interstitial water salinity trends at all three core sites mimic the interstitial water chloride trends discussed earlier in this report (Fig. 5). In general, the core-derived interstitial water salinities decrease with depth from a maximum value of about 35 ppt near the sediment-water interface to about 31 ppt within the upper part of logging Unit 2. Similar to the chloride profiles in logging Unit 2, the interstitial water salinities are also more variable within this inferred gas hydrate–bearing sedimentary section. Formation and seabed temperatures have been directly measured at all three core sites on the Blake Ridge, as described in Shipboard Scientific Party (1996a, 1996b, 1996c). Listed in Table 3 are the measured seabed temperatures and geothermal gradients for Sites 994, 995, and 997 (modified from Shipboard Scientific Party, 1996a, 1996b, 1996c). Arps' formula (Serra, 1984) was used to calculate the pore-water resistivity (R_w) at each site from the available core-derived interstitial water salinities and measured formation temperatures (Table 3; Fig. 7). In general, the calculated pore-water resistivities (R_w) reach a maximum of about 0.34 Ωm within 100 m of the seafloor and decrease with depth to a value below 0.20 Ωm at the bottom of each borehole. The small increase in water resistivities in logging Unit 2, depicted in Figure 7, are a result of the presence of freshwater in the analyzed cores, which was expelled from gas hydrate that had disassociated in the cores. To avoid introducing errors into the subsequent resistivity porosity calculations, the gas hydrate–affected pore-water resistivities from logging Unit 2 have been excluded and the pore-water resistivities from logging Units 1 and 3 have been used to statistically project undisturbed pore-water resistivities (R_w) for logging Unit 2 (Fig. 7).

To determine the Archie constants a and m, we used the method described by Serra (1984) and the log-measured resistivities and core-derived porosities (Paull, Matsumoto, Wallace, et al., 1996) from each site drilled on the Blake Ridge. The log-measured resistivity data from logging Unit 2 in each hole have been omitted from this calculation of the Archie constants to avoid introducing an error caused by using resistivity log-measurements that have been affected by the occurrence of in situ gas hydrate. In addition, log-measured resistivities from expected free-gas zones in Unit 3 of each hole have also been omitted from the determination of the Archie constants. Linear trends in resistivity log and core porosity data from logging Units 1 and 3 (exclusive of logging Unit 2) in each hole have been used to calculate representative (100% water saturated) formation resistivities (R_o) and porosities ($\varnothing$). From these representative values the slope, m, and the intercept, ln a, of the function $\ln (R_o/R_w) = -m \ln \varnothing + \ln a$ were calculated for each of the logged boreholes. The calculated a and m Archie con-

Table 3. Leg 164 formation temperature data and Archie constants (a and m) needed to calculate pore-water resistivities (R_w; See Fig. 7) and water saturations (S_w; See Fig. 9A–C).

Site	Seafloor temperature (°C)	Geothermal gradient (°C/100 m)	Archie constants a	Archie constants m
994	3.0	3.64	0.53 ?	3.68 ?
995	3.0	3.35	1.03	2.53
997	3.0	3.68	1.07	2.59
		Assumed constants:	1.05	2.56

Notes: Temperature data from Paull, Matsumoto, Wallace, et al. (1996). ? = uncertain value.

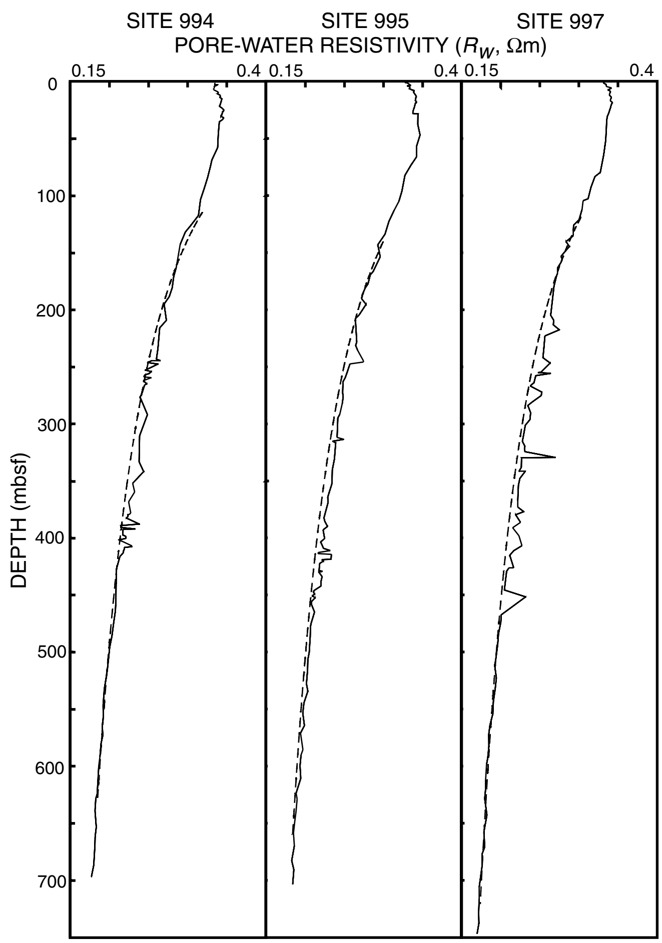

Figure 7. Pore-water resistivities (R_w) derived from interstitial water (core samples) salinities and downhole measured formation temperatures (Table 3) at Sites 994, 995, and 997. The dashed continuous line plots are the assumed undisturbed pore-water resistivities (R_w).

stants for Holes 994D, 995B, and 997B have been listed in Table 3. The Archie constants (*a* and *m*) calculated for Holes 995B and 997B are similar and fall within the "normal" range of expected values (Serra, 1984). However, the values of the *a* and *m* constants for Hole 994D fall outside of the "normal" range of values. The cause of these anomalous Archie constants in Hole 994D is likely because of poor hole conditions in logging Unit 1, which has contributed to degraded resistivity log measurements. Because all three boreholes penetrated similar lithologic sections and because they are located in relatively close proximity to each other, we decided to use an average value (calculated from Holes 995B and 997B) for the *a* and *m* Archie constants throughout this study of the Blake Ridge (Table 3: $a = 1.05$, $m = 2.56$).

Given the Archie constants (*a* and *m*) and pore-water resistivities (R_w), we can now calculate sediment porosities (∅) from the resistivity log using Archie's relation. The results of these calculations are the porosity logs shown in Figure 8. The calculated resistivity porosities should be considered "apparent" porosity values because the Archie relation assumes that all of the void space within the sediments are filled with water (no gas hydrate), which is not true. In all three holes, the resistivity-derived porosities decrease with depth (Fig. 8) though this is not the normal exponential consolidation trend that would be expected if the pore space were decreasing with depth primarily from the weight of increasing overburden (Lee and others, 1993); instead we see an almost linear porosity decrease. Relative to Units 1 and 3, Unit 2 exhibits a baseline shift to higher resistivities and lower calculated resistivity porosities. The assumption that all of the pore space within the sediments of Unit 2 is filled with only water is not valid. Some of the pore space in Unit 2 is occupied by gas hydrate that exhibits higher electrical resistivities and would contribute to an "apparent" reduction in resistivity-derived porosities.

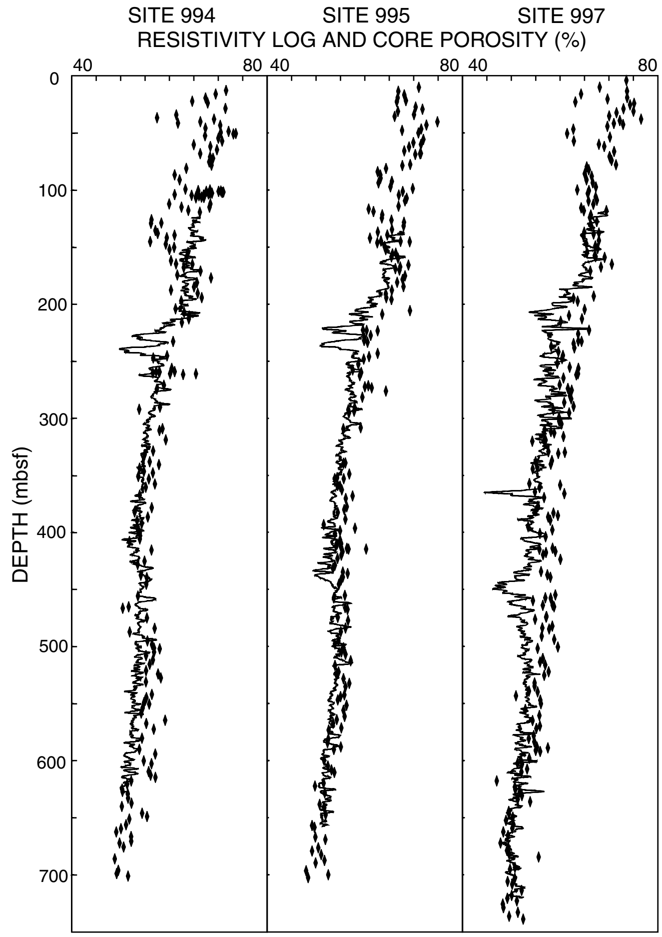

Figure 8. Sediment porosities (shown as continuous line plots) derived from downhole electrical resistivity log (DITE) data at Sites 994, 995, and 997. For comparison purposes, diamonds show the core-derived porosities (as discrete point measurements).

Porosity Calculations—Summary

The comparison of core- and log-derived porosities in Figures 6 and 8, reveals that the resistivity log-derived porosities are generally similar to the core porosities. The density log-derived porosities, however, are generally higher than the core porosities. It is likely that the density log measurements have been degraded by poor borehole conditions. The resistivity log-derived porosities in Figure 8 are the best downhole-derived porosity logs for all three holes on the Blake Ridge. However, because of gas hydrate–induced resistivity effects in logging Unit 2, the resistivity-derived porosity data from Leg 164 should be used with caution and the core-derived sediment porosities are the best available porosity data from the Blake Ridge.

GAS HYDRATE SATURATIONS

Electrical resistivity and acoustic transit-time downhole logs from Sites 994, 995, and 997 indicate the presence of gas hydrate in the depth interval between 185 and 450 mbsf on the Blake Ridge (logging Unit 2). Electrical resistivity downhole log data can be used to quantify the amount of gas hydrate in a sedimentary section as discussed in Leg 164 *ODP Proceedings, Initial Reports* volume (Paull, Matsumoto, Wallace, et al., 1996) and in Collett (1998). In the following section, we have used data from the electrical resistivity (DITE) logs in Holes 994D, 995B, and 997B to quantify the amount of gas hydrate in logging Unit 2 (approximate depth interval of 185–450 mbsf) on the Blake Ridge.

For the purpose of discussion we have assumed that the anomalous high resistivities and velocities measured in logging Unit 2 on the Blake Ridge are a result of the presence of in situ natural gas hydrate. However, an alternative hypothesis suggests that interstitial water salinity changes could account for the electrical resistivity log responses observed at Sites 994, 995, and 997. Geochemical analyses of cores from logging Unit 2 at all three sites on the Blake Ridge have revealed the presence of pore water with relatively low chloride concentrations (Shipboard Scientific Party, 1996a, 1996b, 1996c). This may indicate that logging Unit 2 contains waters with relatively low salt concentrations that will contribute to an increase in the measured electrical resistivities. However, because the acoustic log is not affected by changes in pore-water salinities, it appears to refute the hypothesis that salinity changes are contributing to the anomalous acoustic velocity and resistivity properties of logging Unit 2. To further evaluate the effect of pore-water salinity on the measured log values at Sites 994, 995, and 997, we have attempted to quantify the observed changes in electrical resistivity in logging Unit 2 in respect to potential pore-water salinity changes. We have determined that to account for the high resistivities (as high as 1.50 Ωm) observed in the upper part of logging Unit 2 (Fig. 4A–C), would require the pore waters to be diluted, relative to a seawater baseline of 32 ppt, by almost 72% (to ~9 ppt NaCl). A required pore-water salinity change of 72% is much greater than the maximum observed chlorinity changes measured in the recovered cores, which was determined to be about 15% (Shipboard Scientific Party, 1996a, 1996b, 1996c). Therefore, it is unlikely that interstitial salinity differences could account for the observed resistivity log trends. To further evaluate the effect of variations in pore-water salinities on the log-measured formation resistivities, it is possible to compare the formation water resistivities (R_w) (Fig. 7) calculated from the recovered core water samples at Sites 994, 995, and 997 with the log measured formation resistivities (R_t). The log measured formation resistivities (R_t) in logging Unit 2 on the Blake Ridge is characterized by a maximum resistivity range of 1.5 Ωm (Fig. 4A-C). However, the observed pore-water salinity variations in cores recovered from logging Unit 2 correspond to a formation water resistivity (R_w) range of only 0.05 Ωm, which is less than 4% of the total formation resistivity (R_t) range measured in logging Unit 2. Therefore, the observed formation resistivities (R_t) variations in logging Unit 2 cannot be attributed only to changes in pore-water salinities, and the resistivity log in logging Unit 2 is likely responding to the presence of in situ gas hydrate.

Two forms of the Archie relation (Archie, 1942), discussed in the Leg 164 *ODP Proceedings, Initial Reports* volume (Paull, Matsumoto, Wallace, et al., 1996) and in Collett (1998), have been used to calculate water saturations (S_w) [gas-hydrate saturation (S_h) is equal to (1.0–S_w)] from the available electrical resistivity log data (DITE) at Sites 994, 995, and 997. In the first computation, the "standard" Archie equation [$S_w = (a\,R_w / \varnothing^m R_t)^{1/n}$] has been used with two different sets of sediment porosity data to calculate two comparable water saturations. Both sets of porosity data used in the standard Archie equation were from the core-derived physical property data (Paull, Matsumoto, Wallace, et al., 1996). In the first calculation, the absolute value (not statistically manipulated) of the core-derived porosities were used and the sediment porosities between the core measurements were linearly interpolated. However, in the second standard Archie calculation of water saturation (S_w), the required sediment porosities were obtained from a regression trendline (power function) projected through the core porosity data in each hole. The formation water resistivities (R_w) (Fig. 7), calculated from the recovered core water samples in logging Units 1 and 3, were used in both standard Archie calculations along with the *a* and *m* Archie constants discussed in the sediment porosity section of this report (a = 1.05, m = 2.56). The value of the empirical constant *n* was assumed to be 1.9386 as determined by Pearson et al. (1983). In Figure 9A-C, the results of the two standard Archie calculations are shown as water saturation (S_w) log traces for Holes 994D, 995B, and 997B [gas-hydrate saturation (S_h) is equal to (1.0–S_w)].

In all three holes (Holes 994D, 995B, and 997B), the standard Archie relation yielded water saturations (S_w) ranging from about 100% to a minimum of about 80% (Fig. 9A–C). In comparison, the standard Archie calculation, which used the nonstatistically manipulated core porosities, resulted in the calculation of more highly variable water saturations; whereas, the standard Archie calculation, which employed the average core porosities, yielded more consistent water saturations within each hole. The zones in each hole characterized by water saturations exceeding 100%, which is impossible, are likely caused by poor hole conditions that have degraded the resistivity log measurements. In an enlarged borehole, such as in logging Unit 1 of all three holes, the resistivity log will underestimate the true formation resistivity, which will correspond to an apparent increase in water saturations. The low water saturations in logging Unit 3 of all three holes, which is most pronounced in Hole 997B, is likely because of the presence of free gas as discussed earlier in this report.

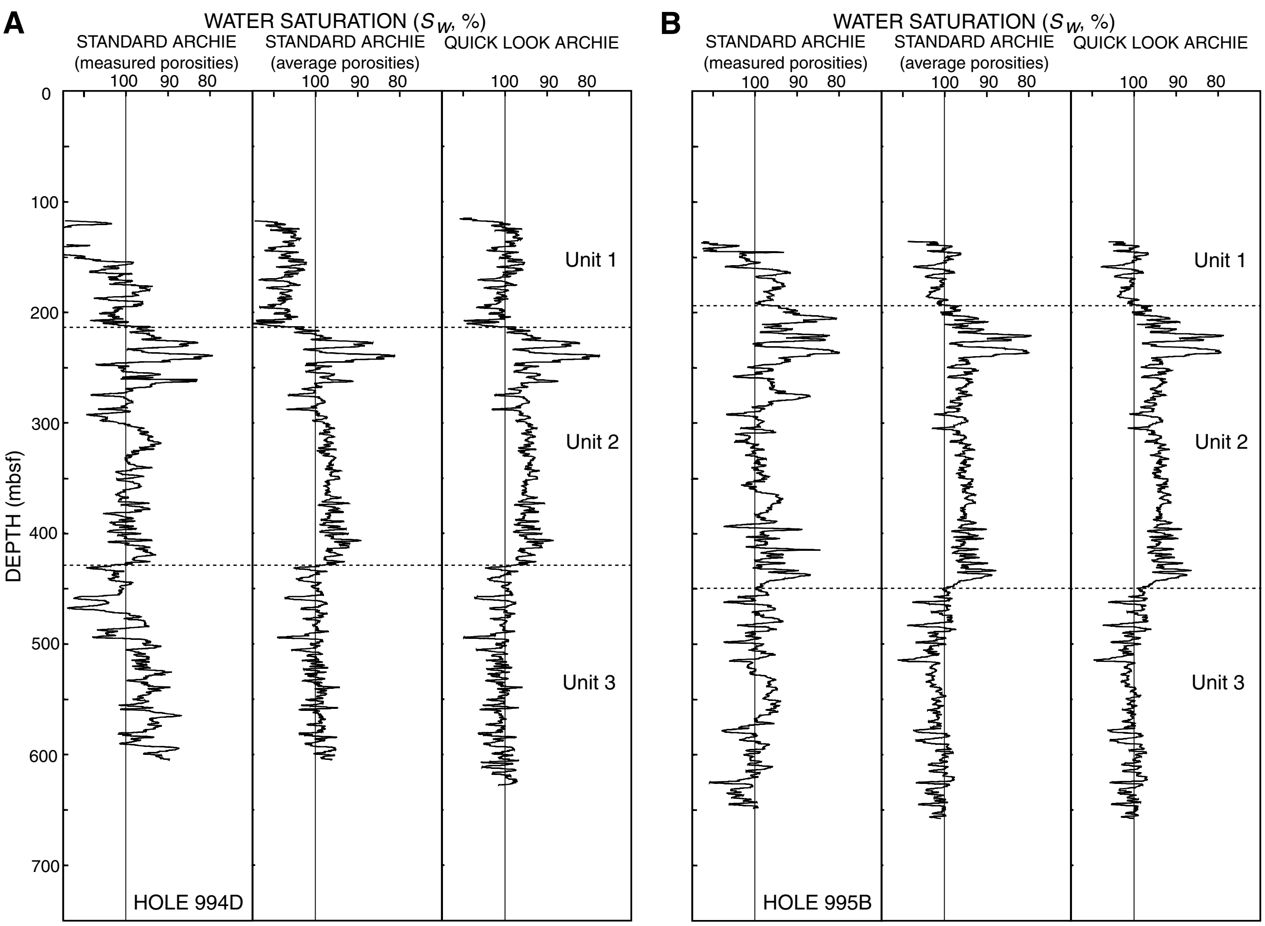

Figure 9. **A.** Standard and quick-look Archie derived water saturations (S_w) [gas-hydrate saturation (S_h) is equal to (1.0–S_w)] calculated from the downhole electrical resistivity log (DITE) at Hole 994D. The two standard Archie calculations assume different sediment porosities: (1) directly measured and (2) average core porosity trends. **B.** Standard and quick-look Archie derived water saturations (S_w) [gas-hydrate saturation (S_h) is equal to (1.0–S_w)] calculated from the downhole electrical resistivity log (DITE) at Hole 995B. The two standard Archie calculations assume different sediment porosities: (1) directly measured and (2) average core porosity trends. (Continued on next page.)

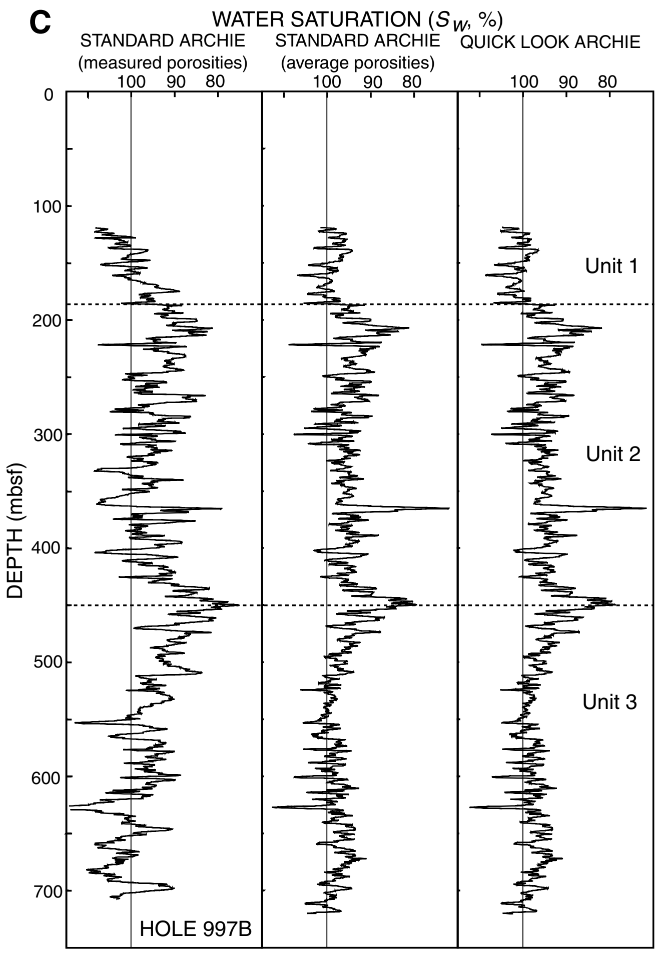

Figure 9 (continued). **C.** Standard and quick-look Archie-derived water saturations (S_w) [gas-hydrate saturation (S_h) is equal to (1.0–S_w)] calculated from the downhole electrical resistivity log (DITE) at Hole 997B. The two standard Archie calculations assume different sediment porosities: (1) directly measured and (2) average core porosity trends.

The next resistivity log approach used to assess gas-hydrate saturations is based on the modified "quick-look" Archie log analysis technique (discussed in Collett, 1998) that compares the resistivity of water-saturated and hydrocarbon-bearing sediments. Electrical resistivity (R_t) log measurements from Holes 994D, 995B, and 997B (Fig. 4A–C) were used to calculate water saturations (S_w) [gas-hydrate saturation (S_h) is equal to ($1.0 - S_w$)] using the following modified Archie relationship: $S_w = (R_o/R_t)^{1/n}$, where R_o is the resistivity of the sedimentary section if it contained only water ($S_w = 1.0$), R_t is the resistivity of the gas hydrate–bearing intervals (log values), and n is an empirically derived constant. This modified Archie relationship is based on the following logic: if the pore space of a sediment is 100% saturated with water, the deep-reading resistivity device will measure the resistivity of the 100% water-saturated sedimentary section (R_o). This measured R_o value is considered to be a relative baseline from which hydrocarbon saturations can be determined within nearby hydrocarbon-bearing intervals. To determine R_o for logging Unit 2 in all three holes, we have used the measured deep resistivity log data from the non gas–bearing portions of logging Units 1 and 3 ($S_w = 1.0$), to project a R_o trend-line for Unit 2 (Fig. 4A–C). Laboratory experiments on different sediment types have yielded a pooled estimate for n of 1.9386 (reviewed by Pearson et al., 1983). Now knowing R_t, R_o, and n, it is possible to use the modified quick-look Archie relationship to estimate water saturations. Displayed in Figure 9A–C, along with the standard Archie derived water saturations, are the water saturations calculated by the quick-look Archie method. The quick-look calculated water-saturations are very similar to the water saturations calculated by the standard Archie relation that employed average core porosities. However, the quick look–derived water saturations are 2% to 3% higher, which is mostly controlled by the method used to select the R_o baseline.

Gas-Hydrate Saturation Calculations—Summary

In logging Unit 2 (approximate depth of 185 to 450 mbsf) of all three holes (Holes 994D, 995B, and 997B) on the Blake Ridge the standard Archie relation yielded for the most part gas-hydrate saturations (S_h) ranging from 0% to a maximum near 20% (Fig. 9A–C); which are similar to the range of gas-hydrate saturations calculated from interstitial water chloride freshening trends (Fig. 5). In comparison, the standard Archie relation that employed the nonstatistically manipulated core porosities resulted in the calculation of more highly variable gas-hydrate saturations than the saturation calculations that used average core porosities. The use of data from different sources (downhole logs and core data) and noncompatible downhole depths have likely contributed to the more variable nature of the gas-hydrate saturations calculated with the nonstatistically manipulated core porosities. In comparison, however, the use of average porosity trends will mask localized porosity variations in complex geologic systems, which could lead to erroneous gas-hydrate saturation calculations. Because of the uniform nature of the sedimentary section cored on Leg 164, the log analysis methods that use both the nonstatistically manipulated and average core porosities yield similar results. The quick-look Archie method also yielded reasonable gas-hydrate saturations (Fig. 9A–C); however, the quick-look method is very dependent on the selection of an accurate R_o baseline.

In general, the Archie relation appears to yield accurate hydrocarbon (gas-hydrate and free gas) saturations on the Blake Ridge in spite of the fact that the sedimentary section at all three core sites on the Blake Ridge consists of mostly clay (shale), which exhibits unique electrical properties that must be corrected for in "conventional" log analysis studies. In conventional log studies, a clay can be modeled as consisting of two components: electrically inert dry clay and bound water. The electrical conductivity of a clay-rich rock is modeled as being derived solely from the clay-bound and free water. Because the porosity data used in the Archie resistivity log studies of the Blake Ridge gas hydrate accumulation actually represent the total water content of the sediments, which include both the clay-bound and free water, the Archie relation accounts for the electrical properties of both the clay-bound and free water. This assumes the electrical conductivity of the clay-bound and free water are similar, which is likely true in these low salinity pore-water systems. It should be noted that there are several electrical conductivity models that offer improvements over the Archie relationship when considering clay-rich sediments (Serra, 1984). Application of these extended electrical conductivity models would be a step forward to fully understand the electrical logs from the Blake Ridge boreholes. However, the use of these complex extended Archie relations are beyond the scope of this paper.

VOLUME OF GAS HYDRATE AND FREE GAS

Recent estimates of the volume of gas that may be contained in the gas hydrate and free gas beneath the gas hydrate on the Blake Ridge range from about 70 trillion m^3 of gas over an area of 26,000 km^2 (Dickens et al., 1997) to about 80 trillion m^3 of gas for an area of 100,000 km^2 (Holbrook et al., 1996). The difference between these two estimates has been attributed to the observation that the amount of free gas directly measured within pressure-core samples (Dickens et al., 1997) from beneath the gas hydrate is significantly larger than that estimated from borehole vertical seismic profile data (Holbrook et al., 1996). Other published studies indicate that the gas hydrate at the crest of the Blake Ridge alone (area of about 3,000 km) may contain more than 18 trillion m^3 of gas (Dillon et al., 1993). The broad range of these estimates demonstrates the need for high-resolution measurements of the gas-hydrate and associated free-gas volumes on the Blake Ridge. The log-interpreted gas-hydrate and free-gas saturations from Sites 994, 995, and 997 in this report provide several of the critical parameters needed to accurately calculate the volume of gas on the Blake Ridge. The volume of gas that may be contained in a gas hydrate accumulation depends on five "reservoir" parameters (modified from Collett, 1993): (1) areal extent of the gas hydrate occurrence, (2) "reservoir" thickness, (3) sediment porosity, (4) degree of gas-hydrate saturation, and (5) the hydrate gas yield volumetric parameter that defines how much free gas (at standard temperature and pressure [STP]) is stored within a gas hydrate (also known as the hydrate number). In the following section, the five "reservoir" parameters (Table 4) needed to calculate the volume of gas associated with the gas hydrate on the Blake Ridge area are assessed. In addition, the volume of free gas trapped beneath the gas hydrate on the Blake Ridge is also assessed (Table 5).

The region in which seismic reflection profiling indicates the occurrence of gas hydrate on the Blake Ridge (shaded area on the map in Fig. 1) extends over an area of ~26,000 km^2 (Dillon and Paull, 1983; Dickens et al., 1997). Despite the fact that the reflection seismic characteristics of the bottom-simulating reflector (BSR) and inferred gas hydrate occurrences are similar throughout the Blake Ridge, it may be inappropriate to extrapolate gas hydrate and other geologic data from Sites 994, 995, and 997 to the entire 26,000 km^2 gas hydrate accumulation. Most certainly there are local variations in the distribution of gas hydrate on the Blake Ridge that need to be further evaluated; however, this work is beyond the scope of this study. The following volumetric assessment of the amount of gas hydrate, therefore, has been conducted on a site-by-site basis; that is, for each site drilled on the Blake Ridge (Sites 994, 995, and 997) we have individually calculated the volume of gas hydrate and associated free gas within a 1 km^2 area surrounding each drill site (Tables 4, 5). For this "resource" assessment, we have defined the thickness of the gas hydrate–bearing sedimentary section at all three drill sites to be the total thickness of logging Unit 2, which ranges from about 217 to 265 m thick (Table 4). The core-derived sediment porosities in logging Unit 2 range from about 50% to 80%, and average ~58% (Table 4). Gas-hydrate saturations in logging Unit 2 at all three drill sites, calculated from the standard Archie relation (Fig. 9A–C), range from an average value of about 3% to 6% (Table 4). The hydrate gas yield parameter or hydrate number is a factor that describes how much of the clathrate-cage structure is filled with gas. In this assessment, we have assumed a hydrate number of 6.325 (90% gas filled clathrate), which corresponds to a gas yield of 164 m^3 of methane (at STP) for every cubic meter of gas hydrate (Collett, 1993). Our calculations indicate that the potential volume of gas within the log-inferred gas hydrate at each drill site (Sites 994, 995, and 997) on the Blake Ridge ranges from about 670,000,000 to 1,450,000,000 m^3 gas per km^2 (Table 4).

For comparison purposes only, if we assume the geologic conditions and gas hydrate distribution at Site 997 (Table 4) is representative of the entire seismic delineated gas hydrate accumulation (26,000 km^2) on the Blake Ridge, it can be assumed that there is about 37.7 trillion m^3 of gas within the Blake Ridge gas hydrate accumulation. One of the reasons that this estimate differs from that of Dickens et al. (1997) and Holbrook et al. (1996) is because both of these previous studies have included the volume of free gas trapped beneath the gas hydrate in their total gas "resource" estimate. Therefore, we have also used the available log data from Sites 994, 995, and 997 to calculate the volume of free gas (Table 5) below the gas hydrate on the Blake Ridge. The available acoustic and resistivity downhole log data have been used to identify free gas–bearing zones within logging Unit 3 of Holes 994D, 995B, and 997B (Table 5). At Site 994, one 64-m-thick free-gas zone has been identified, while at Sites 995 and 997, two laterally continuous free gas–bearing zones have been delineated with combined total thicknesses of 72 and 194 m, respectively (Table 5). The average porosity of the sediments within the free gas–bearing zones at all three drill sites on the Blake Ridge range from about 53% to 55% (Table 5). The free gas–bearing zones at Sites 994 and 995 are characterized by free-gas saturations, calculated from the standard Archie relation of about 1% (Fig. 9A–C; Table 5). However, the free-gas saturations within the zone immediately below the base of the gas hydrate at Site 997 average about 5% (Table 5). Our calculations indicate that the potential volume of gas within the log inferred free gas–bearing zones at each drill-site (Sites 994, 995, and 997) on the Blake Ridge ranges from about 743,000,000 m^3 of gas (at STP) per km^2 at Site 997 to about 55,000,000 m^3 of gas (at STP) per km^2 at Site 995 (Table 5). If we follow Dickens et al.'s (1997) suggestion and assume that the volume of free gas below the gas hydrate at Site 997 is representative of the free gas volumes trapped below the gas hydrate throughout the Blake Ridge area (26,000 km^2), then the total volume of gas occurring as free gas on the Blake Ridge is about 19.3 trillion m^3 (at STP). Thus, the combined volume of gas within the gas hydrate and underlying free-gas

Table 4. Volume of natural gas within the downhole log–inferred gas-hydrate occurrences at Sites 994, 995, and 997 on the Blake Ridge.

Site	Depth of logging Unit 2 (mbsf)	Thickness of hydrate-bearing zone (m)	Sediment porosity (%)	Gas-hydrate saturation (%)	Volume of hydrate/km^2 (m^3)	Volume of gas within hydrate/km^2 (m^3)
994	212.0-428.8	216.8	57.0	3.3	4,083,577	669,970,673
995	193.0-450.0	257.0	58.0	5.2	7,731,352	1,267,941,673
997	186.4-450.9	264.5	58.1	5.8	8,839,915	1,449,746,073

Note: Gas volume calculation assumes a hydrate number of 6.325 (90% gas-filled clathrate), 1 m^3 of gas hydrate = 164 m^3 free gas at STP.

Table 5. Volume of natural gas within the downhole log–inferred free-gas occurrences at Sites 994, 995, and 997 on the Blake Ridge.

Site	Depth of identified free-gas zones (mbsf)	Thickness of free gas–bearing zone (m)	Sediment porosity (%)	Free-gas saturation (%)	Volume of in-place gas/km^2 (m^3)	Volume of gas within free-gas/km^2 at STP (m^3)
994	541-605	64	53.2	1.38	468,761	96,096,005
995	450-480	30	55.4	0.60	99,010	24,752,500
995	582-624	42	52.5	0.64	141,640	30,594,240
997	451-520	69	54.5	4.83	1,818,083	410,886,758
977	567-692	125	52.9	2.63	1,740,780	332,488,980

Notes: Volume of in-place gas at in situ pressure and temperature conditions. STP: pressure = 101 kPa, temperature = 15°C.

accumulations on the Blake Ridge would be about 57 trillion m^3 of gas, which is near the volume (70 trillion m^3 of gas) estimated by Dickens et al. (1997). However, it is unlikely that the Site 997 downhole log or pressure core–calculated gas-hydrate concentrations are representative for the entire Blake Ridge. We know, for example, that the volume of free gas below the gas hydrate at Site 995 is much less than the volume of free gas at Site 997 (Table 5). More work is needed to assess the regional distribution and variability of both the gas hydrate and associated free-gas accumulations on the Blake Ridge before accurate resource estimates can be made.

CONCLUSIONS

Gas hydrate is known and inferred to occur on the Blake Ridge within the depth interval from about 185 to 450 mbsf. Based primarily on core-derived physical property data, the average sediment porosities within the gas hydrate–bearing interval on the Blake Ridge have been determined to range from about 57% to 58%. The standard and quick-look Archie relations yielded for the most part accurate gas-hydrate saturations, ranging from 0% to a maximum near 20%, within the ODP Leg 164 boreholes on the Blake Ridge. Downhole electrical resistivity log data have also been used to assess the volume of free gas beneath the gas hydrate accumulation on the Blake Ridge. The downhole log-derived gas-hydrate saturations, in combination with other reservoir data, indicate that the potential volume of gas within the log inferred gas hydrate at each drill site (Sites 994, 995, and 997) on the Blake Ridge ranges from about 670,000,000 to 1,450,000,000 m^3 of gas per km^2. Well log calculations from the Blake Ridge also indicate that the potential volume of gas within the log-inferred free-gas zones at each core site (Sites 994, 995, and 997) range from about 743,000,000 m^3 of gas (at STP) per km^2 at Site 997 to about 55,000,000 m^3 of gas (at STP) per km^2 at Site 995. Collectively, the volume of gas within the gas-hydrate and free-gas accumulations on the Blake Ridge may be about 57 trillion m^3 of gas.

ACKNOWLEDGMENTS

We wish to thank the international supporters of the Ocean Drilling Program for the opportunity to participate in Leg 164. Special thanks is extended to Drs. C.K. Paull and R. Matsumoto, Co-Chief Scientists of Leg 164, for their support of an ambitious gas hydrate research cruise. We also wish to thank Dr. D. Goldberg and the entire staff of the Borehole Research Group of the Lamont-Doherty Earth Observatory for the special support they afforded the Leg 164 well logging program. Without the laboratory and computer facilities of the U.S. Geological Survey this project would not have been possible. This study was partially funded by the U.S. Geological Survey Energy Resources Program, which was greatly appreciated.

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Date of initial receipt: 21 April 1998
Date of acceptance: 10 December 1998
Ms 164SR-219