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27. Data Report: Nuclear Magnetic Resonance Logging while Drilling, ODP Leg 204[1]

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ABSTRACT

Most published gas hydrate volumetric estimates have of necessity been made by broad extrapolation based on only general knowledge of local geologic conditions. The amount of gas that might be stored in a gas hydrate accumulation is dependent on a number of reservoir parameters, including the areal extent and thickness of the gas hydrate occurrence, sediment porosities, and the degree of gas hydrate saturation. Downhole logs often serve as a source of critical gas hydrate reservoir data. Before Ocean Drilling Program (ODP) Leg 204, however, only about seven gas hydrate occurrences had been sampled and surveyed with open hole well logging devices. From 16 July through 25 July 2002, a complex logging-while-drilling (LWD) and measurement-while-drilling program was conducted on Hydrate Ridge during ODP Leg 204. During the cruise, and for the first time during ODP, the LWD tool string included Schlumberger's Nuclear Magnetic Resonance While Drilling tool (proVision).

Postcruise research with the proVision data has consisted of estimating bound fluid volumes and total fluid porosities, along with comparing nuclear magnetic resonance (NMR)-derived porosities with those derived from downhole measured neutron and density logs and core measurements. These efforts have focused on calculating gas hydrate concentrations by indirect methods using NMR data. It has been shown that it is possible to obtain gas hydrate saturations (percent of pore space occupied by gas hydrate) from downhole logging–measured NMR porosities. In this study, porosities derived from the NMR proVision

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tool were used along with porosity data from the Azimuthal Vision Density Neutron tool to calculate gas hydrate saturations at all nine LWD logging sites on Hydrate Ridge. The NMR-density-porosity relation yielded gas hydrate saturations ranging from high values near the crest of the ridge of ~50% and higher in Hole 1249A to much lower values along the flanks of the ridge.

INTRODUCTION

Leg 204 Operations

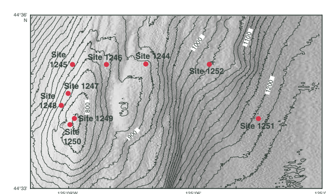
One of the primary goals of Ocean Drilling Program (ODP) Leg 204 was to determine the distribution and concentration of gas hydrates beneath Hydrate Ridge, which is located ~90 km off the coast of Oregon (USA). After coring the first site (Site 1244), logging-while-drilling (LWD) data were acquired from an additional 10 holes at 8 respective sites (Table T1). The LWD data confirmed the general position of key seismic stratigraphic horizons and yielded estimates of gas hydrate concentrations through various downhole logging proxies. These records proved to be of great value in planning subsequent coring. After completing the 10-day LWD program, the LWD tools were removed from the ship by an open-ocean small boat transfer. The remaining portion of the cruise dealt with coring more than 45 holes at 9 sites on Hydrate Ridge. Eight of these sites were the same sites that were already drilled and logged during the LWD program. The Hydrate Ridge coring program also included acquisition of conventional wireline logs from an additional six holes.

T1. Leg 204 holes surveyed with LWD and MWD tools, p. 22.

LWD Program

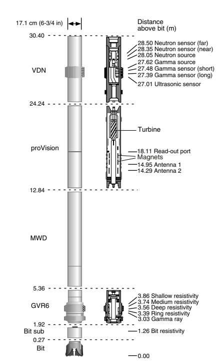
The downhole logging program during Leg 204 was specifically designed to obtain the data needed to assess the occurrence and concentration of gas hydrates on Hydrate Ridge. During Leg 204, four LWD and measurement-while-drilling (MWD) tools were deployed at eight sites on southern Hydrate Ridge (Table T1; Fig. F1). These tools were provided by Schlumberger Drilling Services of Youngsville, Louisiana (USA), under contract with the Lamont-Doherty Earth Observatory (LDEO) Borehole Research Group in Palisades, New York (USA).

F1. Map of Hydrate Ridge, p. 11.



Leg 204 LWD operations began on 16 July 2002 with initial bottom-hole assembly (BHA) makeup and spudding of Hole 1244D. Figure F2 shows the configuration of the LWD/MWD BHA used during Leg 204. The tools (6¾-in collars) deployed in nine of the ten LWD logged holes during Leg 204 included the GeoVision resistivity-at-the-bit or "RAB" tool with a 9⅛-in button sleeve, a Power-Pulse MWD tool, the Nuclear Magnetic Resonance While Drilling tool (proVision), and the Azimuthal Vision Density Neutron (VDN) tool. Table T1 contains a detailed listing of the LWD data acquired during Leg 204. This was the first time that any downhole magnetic resonance device (proVision) was used during ODP. As shown in Table T1, the proVision was deployed a total of nine times during Leg 204, and in all cases the quality of acquired data was very good.

F2. LWD drill configuration on Leg 204, p. 12.



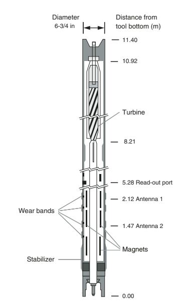
LWD measurements are made shortly after the hole is drilled and before extended pumping and coring operations adversely affect in situ hole condition and all subsequent downhole measurements. Fluid invasion into the borehole wall is also reduced relative to wireline logging because of the shorter elapsed time between drilling and taking the measurements. The LWD equipment is partially battery powered and uses erasable/programmable read-only memory chips to store logging data until they are downloaded. The LWD tools take measurements at evenly spaced time intervals and are synchronized with a system on the rig floor that monitors time and drilling depth. After drilling, the LWD tools are retrieved and the data downloaded from each tool through an RS-232 serial link to a computer. Synchronization of the uphole and downhole clocks allows merging of the time-depth data (from the surface system) and the downhole time-measurement data (from the tools) into depth-measurement data files. The resulting depth-measurement data, like the traditional wireline well logs, are transferred to the processing systems in the Downhole Measurements Laboratory on board the *JOIDES Resolution* for reduction, analysis, and transfer. Differing from wireline logging, however, the merged LWD depth-measurement data are not spaced at even depth intervals, although they vary only slightly in many instances where the drilling rate is well controlled.

METHODS

Nuclear Magnetic Resonance Logging

The U.S. Department of Energy provided funding support to deploy the proVision tool during Leg 204. The basic technology behind this tool is similar to modern wireline nuclear magnetic resonance (NMR) technology (Kleinberg et al., 2003; Horkowitz et al., 2002), based on measurement of the relaxation time of the magnetically induced precession of polarized protons. A combination of magnets and directional antennas are used to focus a pulsed, polarizing field into the formation. Figure F3 shows a schematic of the proVision tool. The antennas on the proVision tool measure the relaxation times of polarized molecules in the formation, which can be used to assess sediment porosities.

F3. Schlumberger proVision tool, p. 13.



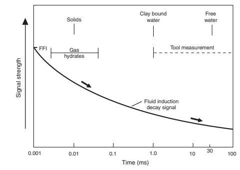
During Leg 204, the proVision tool acquired formation and engineering information in memory and transmitted some data to the surface via MWD. The relaxation time spectra were recorded downhole and porosity estimates were transmitted to the surface in real time. These spectra were stacked in postprocessing to improve the measurement precision. Data were also acquired while pulling the tool upward (sliding, not rotating) over short open-hole intervals to compare measurements with and without the effect of lateral vibrations induced while drilling and rotating.

NMR Logging Fundamentals

In recent years there have been significant developments in the field of NMR well logging (reviewed by Horkowitz et al., 2002). Similar to neutron porosity devices, NMR tools primarily respond to the presence of hydrogen molecules in the pore fluids in rock formation. Unlike neutron porosity tools, however, NMR tools use the electromagnetic properties of hydrogen molecules to analyze the nature of atomic interactions within pore fluids. Relative to other pore-filling constituents, gas hydrates exhibit unique chemical structures and hydrogen concentrations. In theory, therefore, it should be possible to develop NMR well logging evaluation techniques that would yield accurate reservoir porosities and water saturations in gas hydrate–bearing sediments.

Under the effect of a strong magnetic field, hydrogen nuclei tend to align with the induced magnetic field. A certain amount of time, called the longitudinal magnetization decay time (T_1), is required for this alignment. When the magnetic field is pulsed, the hydrogen nuclei returns to a disordered state with a characteristic relaxation time, called the transverse magnetization relaxation time (T_2). T_2 depends on the relaxation characteristics of the hydrogen-bearing substances in the rock formation. For example (Fig. **F4**), T_2 for hydrogen nuclei in solids is very short, however, T_2 for hydrogen nuclei in fluids can vary from tens to hundreds of milliseconds depending on fluid viscosities and interactions with nearby surfaces (reviewed by Kleinberg et al., 2003).

F4. NMR T_2 for a typical sediment, p. 14.



When deployed in the LWD tool configuration, the NMR measurement represents the in situ NMR properties of hydrogen in the formation. Initially, the hydrogen atoms are aligned in the direction of a static magnetic field (B_0). The hydrogen atoms are then tipped by a short burst from an oscillating magnetic field that is designed so that they precess in resonance in a plane perpendicular to B_0. The precession of the hydrogen atoms induces a signal in the tool's antenna, and the decay of this signal is measured from the echo amplitudes in the pulse sequence from which T_2 is calculated. Because the formation contains hydrogen in different forms (in water in large pores and small pores, bound in clay minerals, and in gas hydrate), there is a distribution of T_2 times; for Leg 204 sites, T_2 times were recorded in a range set between 3 ms and 3 s.

NMR Log Quality

The proVision signal investigates an ~15-cm cylindrical volume of the borehole, and for a 9⅞-in bit size, the depth of investigation of the measurement is ~5 cm into the formation. In most cases, drilling with the LWD tools proceeded at ~25 m/hr. Using this relatively slow average penetration rate, enhanced NMR spectral resolution and a data sampling rate of approximately one sample per 15-cm depth interval was achieved. This high data density improved NMR spectral resolution after postprocess stacking and enhanced the overall logging data quality.

Lateral tool motion may reduce proVision data quality in some circumstances. Thus, accelerometers and magnetometers are contained in the tool to measure downhole motion and to evaluate data quality. The maximum resolvable relaxation time can be computed from this information. In addition, after reaching the total depth in three of the LWD holes on Hydrate Ridge (Holes 1244D, 1246A, and 1250B), the LWD tools were pulled upward while sliding (without rotating) for ~30 m to compare the measurements while drilling downward over the same interval. Comparing the proVision spectra with and without the effect of the lateral vibration due to drilling allowed further refinement of the measurement resolution. Table **T1** shows the holes in which sliding tests were conducted. The sliding data were not processed; they were used by the logging engineer to verify the quality of the proVision spectra being collected during drilling.

The proVision data quality is high throughout most of the logged interval in all nine holes drilled during Leg 204. ProVision data quality is degraded, however, when the distance between the tool sensor and the wall of the borehole is greater than 1 in. To evaluate this, the differential caliper log (DCAL) is recorded by the LWD density tool and provides a measure of this distance. DCALs from the LWD drill holes measure values <1 in over 90%–95% of the total interval drilled in all nine LWD holes. In each hole, however, the uppermost 10–30 meters below seafloor (mbsf) was typically washed out to >1 in because of drilling disturbance of the softer subseafloor sediments. Deeper intervals in only one hole (Hole 1244D) show deflections of the DCAL measurement of up to 1 in where borehole breakouts occurred below 250-m depth. NMR measurements may be degraded in these particular intervals.

LWD Data Processing

During ODP, some shipboard data processing is conducted in order to verify data content and quality. In addition, both real-time and memory data from LWD and conventional wireline logging data are transmitted via Inmarsat B satellite from the *JOIDES Resolution* to LDEO and, in some cases, then transferred to Schlumberger for reprocessing and data quality assessment. The general data processing for the LWD logging data from Leg 204 followed the steps as described below (for more detailed description of the Leg 204 logging data processing effort, see the processing documentation notes under each site entry on the ODP Logging Services Web site: **www.ldeo.columbia.edu/BRG/ODP/DATABASE /DATA/search.html**):

1. **Depth shift:** Original logs are first depth-shifted to the seafloor. The seafloor depth was determined by the step in gamma ray and resistivity values at the sediment/water interface.
2. **Neutron porosity data processing:** The neutron porosity measurements are corrected for bit size, temperature, mud salinity, and mud hydrogen index (mud pressure, temperature, and weight).
3. **Density data processing:** Density data are processed to correct for the irregular borehole using a technique called "rotational processing," which is particularly useful in deviated or enlarged boreholes with irregular or elliptical shapes. This statistical method measures the density variation while the tool rotates in the borehole, estimates the standoff (distance between the tool and the borehole wall), and corrects the density reading.
4. **Resistivity data:** The resistivity curves are sampled at a 0.0304-m (1.2 in) sampling rate.
5. **NMR:** The T_2 distribution is the basic output of NMR measurement. It is further processed to give the total pore volume (the total porosity) and pore volumes within different ranges of T_2, such as the bound- and free-fluid volumes. However, it is important to note that in a gas hydrate–bearing section, the NMR tool only measures the liquid-filled portion of the porosity. The NMR tool used during Leg 204 was an experimental tool; the processing was performed on shore by Schlumberger.

DATA AND RESULTS

Leg 204 Well Logging Data Access

The ODP Logging Database contains the majority of the logging data collected during ODP and all of the downhole logging data collected during Leg 204; it can be accessed and searched through the ODP Logging Services Web site: **www.ldeo.columbia.edu/BRG/ODP/DATABASE/DATA/search.html**. The Web site provides convenient methods for downloading large amounts of data, as well as information about the applications of logging data to scientific problems. In addition, logging data are also distributed on a CD-ROM included in the Leg 204 *Initial Reports* volume (Tréhu, Bohrmann, Rack, Torres, et al., 2003).

The NMR LWD data from Leg 204 as presented on the ODP Logging Service Web site is stored in two ASCII files.

1. Files named like 1249A-nmr.dat contain the following one-dimensional NMR log data:
   DEPTH (mbsf) = Subbottom depth,
   MRP (%) = Magnetic resonance porosity,
   BFV (%) = Bound-fluid volume,
   FFV (%) = Free-fluid volume, and
   T2LM (ms) = Log mean T_2 relaxation time.
2. Files named like 1249A-t2dist.dat contain the T_2 distribution (spectra):
   DEPTH (mbsf) = Subbottom depth and
   T_2 (%) = At each depth, values of percent volume are given for 30 T_2s ranging from 3 to 3000 ms. The scale is logarithmic, and T_2 is given both in milliseconds and as the $\log_{10}$ of the time in milliseconds

NMR Properties of Gas Hydrate

Because gas hydrates are solids consisting of weakly interacting host and guest molecules, NMR methods of analysis, which are sensitive to the mobility of the guest and host molecules, are useful in establishing the presence of gas hydrates in high-resolution laboratory studies (Davidson and Ripmeester, 1984). Moreover, the high-resolution capabilities of modern NMR laboratory devices can provide valuable information about clathrate structures. No laboratory experiments, however, have been conducted to analyze the response of wellbore NMR devices to the presence of gas hydrate.

There are numerous studies in which laboratory apparatuses have been used to characterize the nuclear magnetic properties of gas hydrates. Results of these laboratory NMR studies were summarized by Ripmeester and Ratcliffe (1989), from which most of the following discussion has been obtained. In Davidson et al. (1986), NMR line shapes were obtained from a Gulf of Mexico gas hydrate sample. These laboratory experiments clearly showed that the sample contained substantial amounts of gas hydrate. Davidson et al. (1986) did not report any gas hydrate relaxation times or free-fluid indexes (FFIs); however, they did publish several gas hydrate NMR spectrums from which it is possible to obtain relaxation times.

If published NMR line shapes for Structure I methane hydrates are assumed to be Gaussian in nature, it can also be assumed that the free induction decay is also Gaussian and the second moment (or mean square line width) is then inversely related to T_2 (J.A. Ripmeester, pers. comm., National Research Council Canada, 1999). Thus, if a NMR second moment of ~33 Gauss is assumed, T_2 of the water molecules in the Structure I gas hydrate is ~0.01 ms.

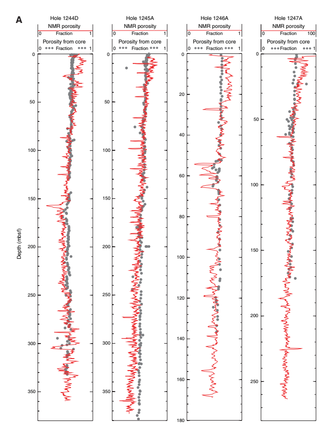
The example free-fluid induction decay signal plot in Figure F4 shows that the gas hydrate clathrate T_2 of 0.01 ms is very similar to the relaxation times of other solids such as the rock matrix. T_2s on the order of 0.01 ms are sufficiently short to be lost in the "dead time" (below the detectable limit of the tool) of standard NMR borehole instruments. Gas hydrates, therefore, cannot be directly detected with today's downhole NMR technology. It is possible, however, that existing NMR well logs could still yield very accurate gas hydrate saturation data. In theory, due to the short T_2s of the water molecules in the clathrate, gas hydrates would not be "seen" by the NMR tool and the in situ gas hydrate would be assumed to be part of the solid matrix. Thus, the NMR-calculated FFI and associated porosity estimate in a gas hydrate–bearing sediment would be apparently lower than the actual porosity. With an independent source of accurate in situ total porosities, such as density or neutron porosity logging measurements, it would be possible to accurately estimate gas hydrate saturations by comparing the apparent NMR-derived porosities with the actual total porosities. The above-described calculations were originally presented by Collett (2000); more recently Kleinberg et al. (2003) have been able to demonstrate the use of this approach with acquired field data.

NMR Log-Derived Porosities

Data from the LWD NMR logs have been used to calculate sediment porosities in all nine Leg 204 holes surveyed with the proVision tool (Fig. F5A, F5B). Core-derived physical property data have also been used to both calibrate and evaluate the proVision-derived sediment porosities. The sediment porosities derived by the proVision in all nine holes ranged from ~80% near the seafloor to ~35% near the bottom of one the deepest holes on Hydrate Ridge (Hole 1245A).

In studies of downhole logging data it is common to compare porosity data from different sources to evaluate the results of particular measurements. The comparison of core-derived and proVision log-derived porosities in Figure F5A and F5B reveals that the proVision porosities are generally similar to the core-derived porosities. Dissimilarities occur in the upper portion of several holes where the proVision porosity log is degraded by washouts. In numerous cases, the proVision porosity logs also exhibit anomalous low-porosity zones within the interval of expected gas hydrate stability. The differences between the proVision porosity log and core values and other porosity logs (not shown) may also be due to the effects of elastic rebound (e.g., Hamilton, 1976; Goldberg, 1997), excessive lateral motion of the tool (Horkowitz et al., 2002), and the distinctive physical properties of gas hydrates (e.g., Collett, 2000; Kleinberg et al., 2003). The response of the proVision porosity log in the gas hydrate–bearing sediments on Hydrate Ridge was one of the primary focuses of the postcruise research activities as discussed below.

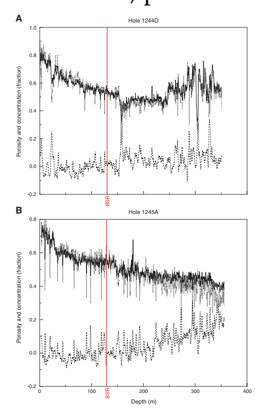
F5. ProVision- and core-derived porosity, p. 15.



NMR Logging-Derived Gas Hydrate Saturations

The presence of gas hydrate at most of the sites drilled during Leg 204 was documented by direct sampling, with pieces of gas hydrate being recovered from cores (Shipboard Scientific Party, 2002). Gas hydrates were also inferred to occur in every hole drilled on Hydrate Ridge during Leg 204 based on geochemical core analyses, infrared image analysis of cores, and downhole logging data. Gas hydrate occurrences are generally characterized by increases in logging electrical resistivities and acoustic velocities and apparent reductions in NMR porosities (Collett, 2000; Kleinberg et al., 2003). Most of the Leg 204 downhole logging data from Hydrate Ridge show that the sedimentary section above the expected depth of the bottom-simulating reflector (BSR) is characterized by distinct zones of elevated values of electrical resistivity and acoustic velocity. In addition, the proVision NMR tool often reveals low-porosity zones within the same high-resistivity intervals, suggesting the possible occurrence of gas hydrate. By quantifying this difference, the NMR logging data have been used to estimate the amount of gas hydrate at each LWD site drilled on Hydrate Ridge during Leg 204 (Fig. F6). For the purpose of this discussion, it is assumed that the relatively low NMR porosities in comparison to the density-derived porosities above the depth of the BSR at each site (Fig. F6) are due to the presence of gas hydrate. The simple relationship below between density porosity (DPHI) and NMR porosity (TNMR) was used to calculate gas hydrate saturations in each LWD hole on Hydrate Ridge:

F6. Porosities and derived gas hydrate saturations, p. 17.



$$Sh = (DPHI - TNMR)/DPHI.$$

A more rigorous result can be obtained by further assessing the effect of gas hydrate on the density log measurement (Kleinberg et al., 2003).

As shown in Figure F6, the assumed gas hydrate saturations in the section above the BSR ranges from –10% (erroneous negative values) to values approaching 50% at Site 1249. However, the scatter of the NMR-derived values in intervals where free gas and gas hydrate are not present (Sh = 0) ranges from –10% to +10%, which probably represents a measure of the relative of uncertainty of the NMR porosity measurement. Although large spikes in the NMR-derived gas hydrate concentration reaching 20%–30% are observed above the BSR at most of the Leg 204 sites, it appears that the NMR-derived gas hydrate saturations on Hydrate Ridge are lower on average than those calculated by the Archie method (Collett et al., 2003).

The response of the NMR logging tool to free gas is similar to the response in gas hydrate (Kleinberg et al., 2003). Both show an apparent reduction in the measured NMR porosity. In Figure F6, we also see "apparent" gas hydrate–bearing zones below the depth of the BSR at several sites, a result that is theoretically impossible. Combining Archie resistivity, density, and neutron porosity logging analyses has confirmed the occurrence of free gas below the BSR on Hydrate Ridge. These zones are also characterized by low wireline logging acoustic velocities (Shipboard Scientific Party, 2002), another strong indication of the presence of free gas. Free gas saturations in some of these localized zones have been estimated to exceed 50%, such as in the Horizon A turbidite sequence (Collett et al., 2003; Tréhu et al., 2004). In Figure F6, the estimation of gas hydrate concentration from the NMR logs is therefore only valid above the BSR.

SUMMARY

The downhole logging program during Leg 204 was designed to obtain the data needed to assess the occurrence and concentration of gas hydrate beneath Hydrate Ridge. It has been shown that it is possible to obtain gas hydrate saturations (percent of pore space occupied by gas hydrate) from NMR downhole logging data. In this study, NMR and density porosity data from the proVision and VDN density tools were used to calculate gas hydrate saturations at all eight LWD logging sites on Hydrate Ridge. The downhole logging–inferred distribution of gas hydrate beneath Hydrate Ridge and the adjacent slope basin is heterogeneous, with NMR-density-porosity–derived gas hydrate saturations at Site 1249, located near the crest of the ridge, ranging from 0% to nearly 50% in several intervals. In the slope basin sites, however, the NMR-density-porosity–derived gas hydrate saturations are much lower, ranging from 0% to a few percent along the flanks of the ridge. NMR-density-porosity logs from Leg 204 LWD logging sites also reveal the presence of significant free gas occurrence below the depth of the BSR on Hydrate Ridge.

ACKNOWLEDGMENTS

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REFERENCES

Collett, T.S., 2000. Quantitative well-log analysis of in-situ natural gas hydrates [Ph.D. dissert.]. Colorado School of Mines, Golden.

Collett, T.S., Goldberg, D.S., Janik, A., and Guerin, G., 2003. Downhole log assessment of gas hydrate and free-gas concentrations on Hydrate Ridge. *Eos, Trans. Am. Geophys. Union,* 84(46):OS51C-0876. (Abstract)

Davidson, D.W., Garg, S.K., Gough, S.R., Handa, Y.P., Ratcliffe, C.I., Ripmeester, J.A., Tse, J.S., and Lawson, W.F., 1986. Laboratory analysis of a naturally occurring gas hydrate from sediment of the Gulf of Mexico. *Geochim. Cosmochim. Acta,* 50(4):619–623. **doi:10.1016/0016-7037(86)90110-9**

Davidson, D.W., and Ripmeester, J.A., 1984. NMR, NQR and dielectric properties of clathrates. *In* Atwood, J.L., Davies, J.E.D., and MacNichol, D.D. (Eds.), *Inclusion Compounds* (Vol. 3): London (Academic Press), 69–127.

Goldberg, D., 1997. The role of downhole measurements in marine geology and geophysics. *Rev. Geophys.,* 35(3):315–342. **doi:10.1029/97RG00221**

Hamilton, E.L., 1976. Variations of density and porosity with depth in deep sea sediments. *J. Sediment. Petrol.,* 46:280–300.

Horkowitz, J., Crary, S., Ganesan, K., Heidler, R., Luong, B., Morley, J., Petricola, M., Prusiecki, C., Poitzsch, M., Scheibal, J.R., and Hashem, M., 2002. Applications of a new magnetic resonance logging-while-drilling tool in a Gulf of Mexico deepwater development project. *Trans. SPWLA Annu. Logging Symp.,* 14.

Kleinberg, R.L., Flaum, C., Straley, C., Brewer, P.G., Malby, G.E., Peltzer, E.T., III, Freiderich, G., and Yesinowski, J.P., 2003. Seafloor nuclear magnetic resonance assay of methane hydrate in sediment and rock. *J. Geophys. Res.,* 108(B3):2137. **doi:10.1029/2001JB000919**

Ripmeester, J.A., and Ratcliffe, C.I., 1989. Solid-state NMR studies if inclusion compounds. *Natl. Res. Counc. Can., [Rep.] NRCC,* C1181-89S.

Shipboard Scientific Party, 2002. Leg 204 Preliminary Report. *ODP Prelim. Rpt.,* 204 [Online]. Available from World Wide Web: <**http://www-odp.tamu.edu/publications/prelim/204_prel/204PREL.PDF**>. [Cited 2006-09-21]

Tréhu, A.M, Bohrmann, G., Rack, F.R., Torres, M.E., et al., 2003. *Proc. ODP, Init. Repts.,* 204: College Station, TX (Ocean Drilling Program). **doi:10.2973/odp.proc.ir.204.2003**

Tréhu, A.M., Flemings, P.B., Bangs, N.L., Chevallier, J., Gràcia, E., Johnson, J.E., Liu, C.-S., Liu, X., Riedel, M., and Torres, M.E., 2004. Feeding methane vents and gas hydrate deposits at south Hydrate Ridge. *Geophys. Res. Lett.,* 31:L23310. **doi:10.1029/2004GL021286**

Figure F1. Map of sites cored and logged during Leg 204 on Hydrate Ridge.

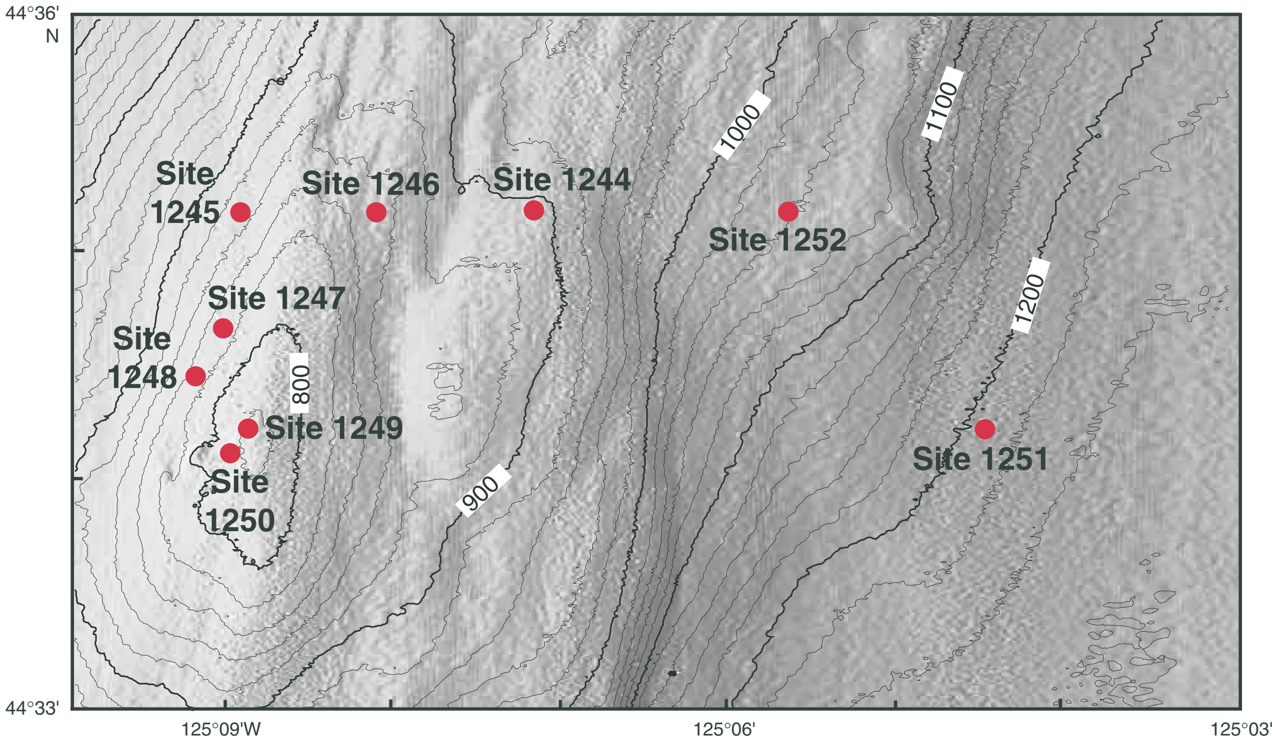


Figure F2. Configuration of the drill string used for LWD operations on ODP Leg 204. VDN = Vision Density Neutron tool. MWD = measurement-while-drilling tool. GVR = GeoVision resistivity-at-the-bit tool.

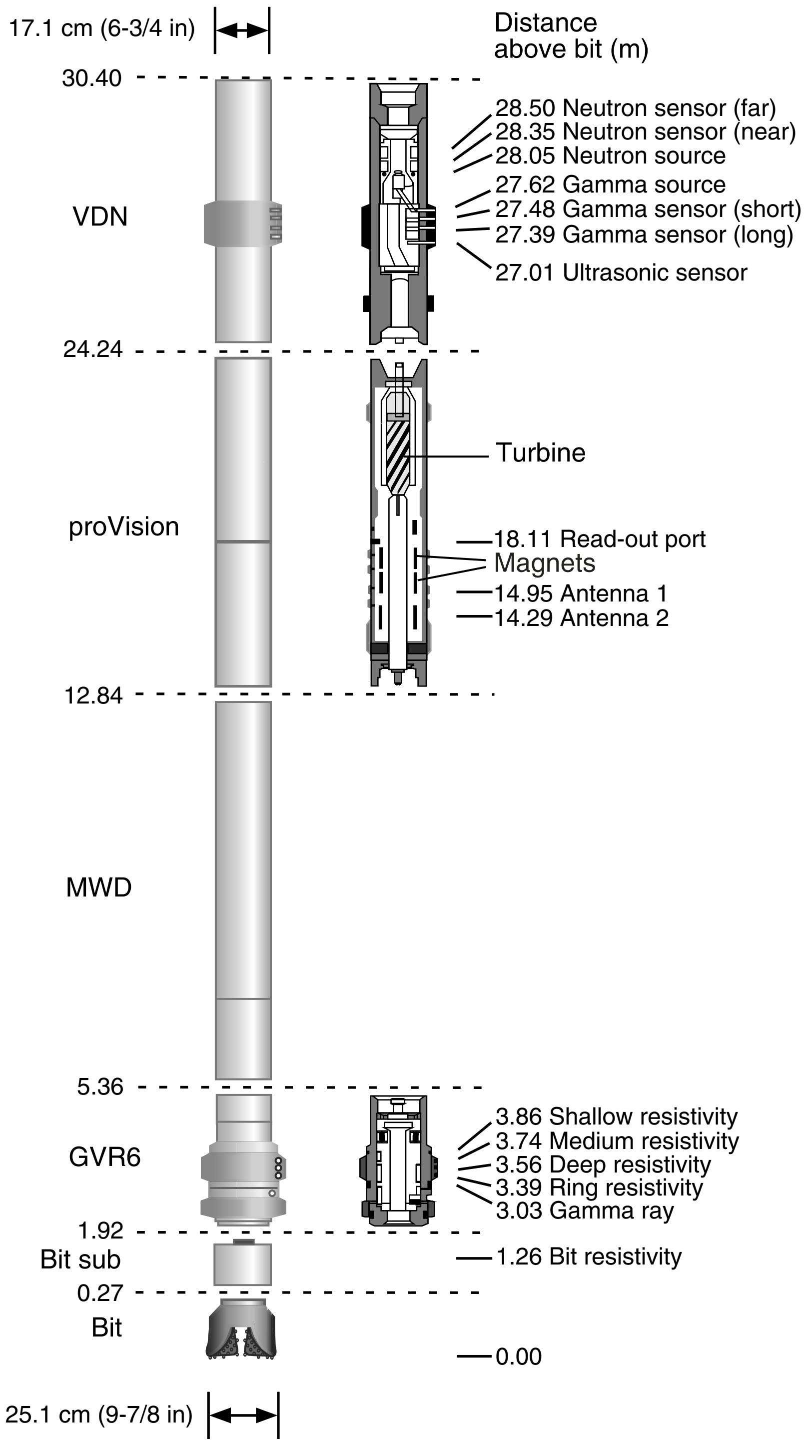


Figure F3. Schematic illustration of the Schlumberger proVision NMR-While-Drilling tool.

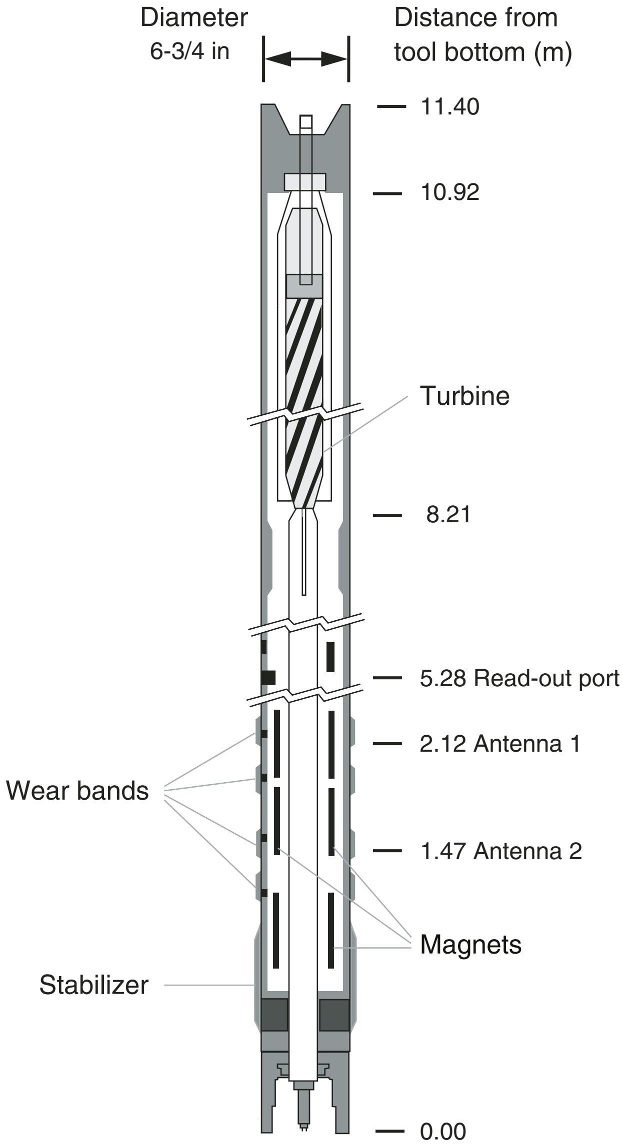


Figure F4. NMR transverse magnetization relaxation times (T_2) for a typical sediment containing gas hydrate and/or water (depicted as a fluid induction decay signal). FFI = free-fluid index.

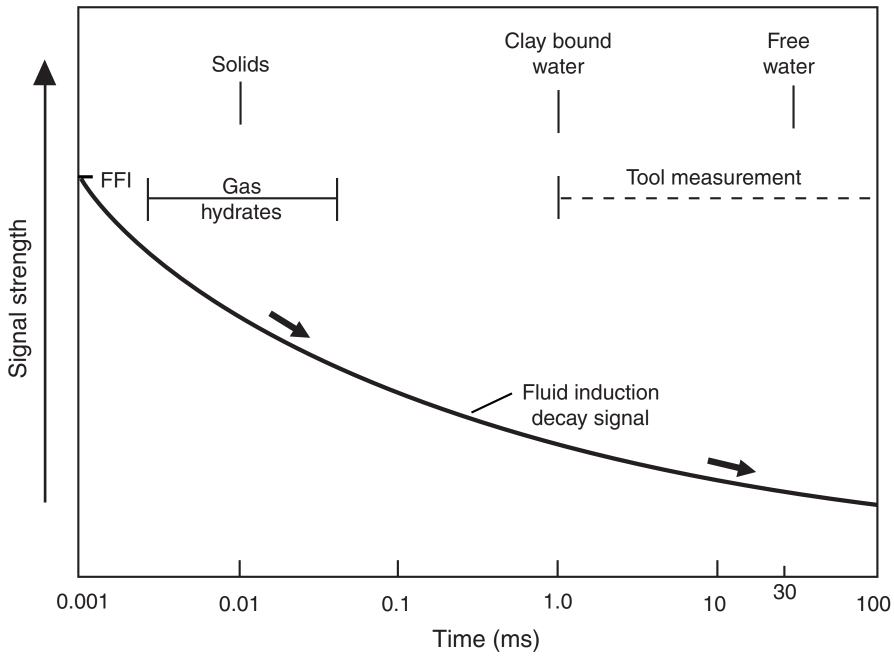


Figure F5. A. ProVision- and core-derived porosity from four of nine holes drilled on Hydrate Ridge during Leg 204 (Holes 1244D, 1245A, 1246A, and 1247A). NMR = nuclear magnetic resonance. (Continued on next page.)

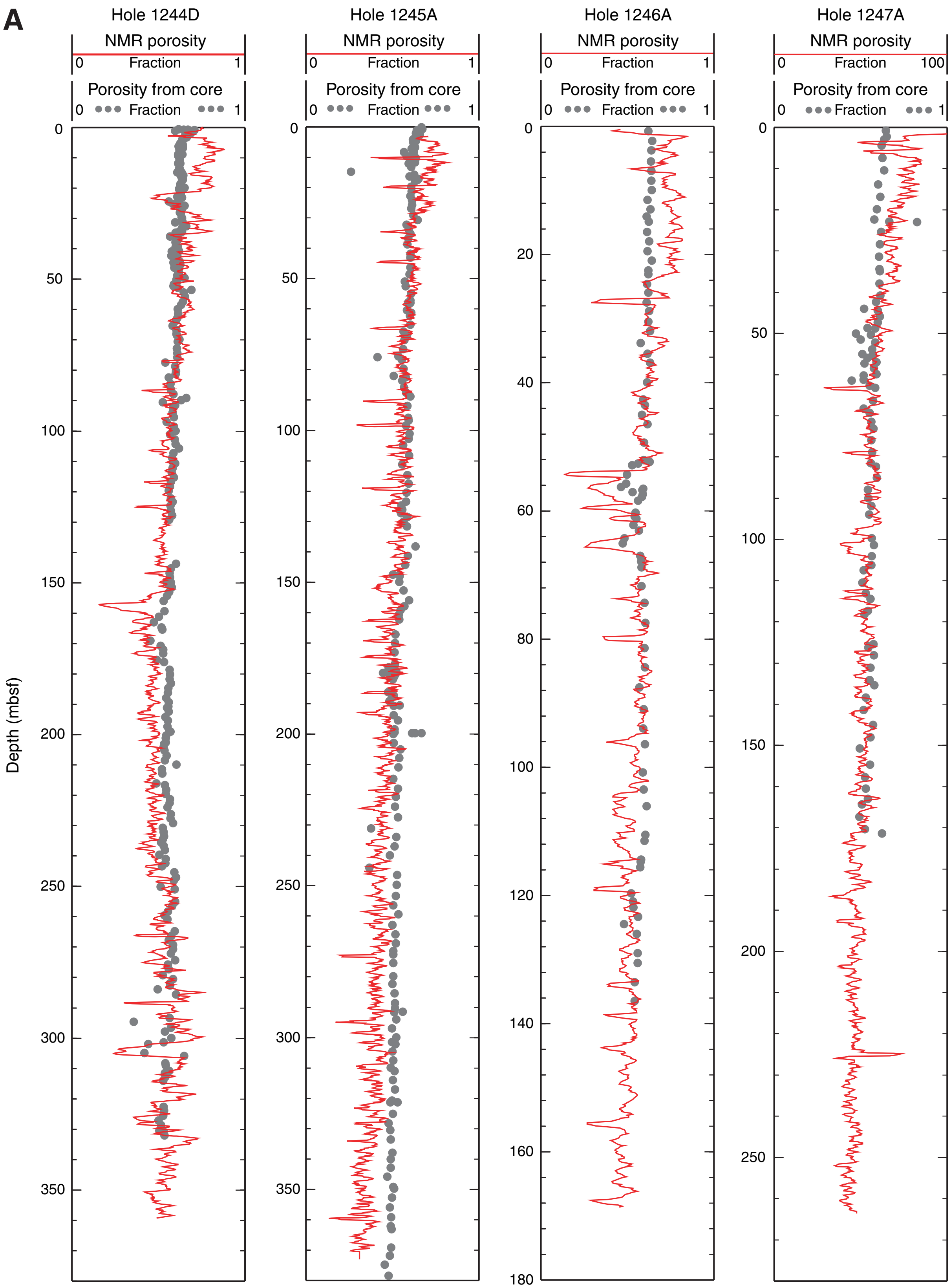
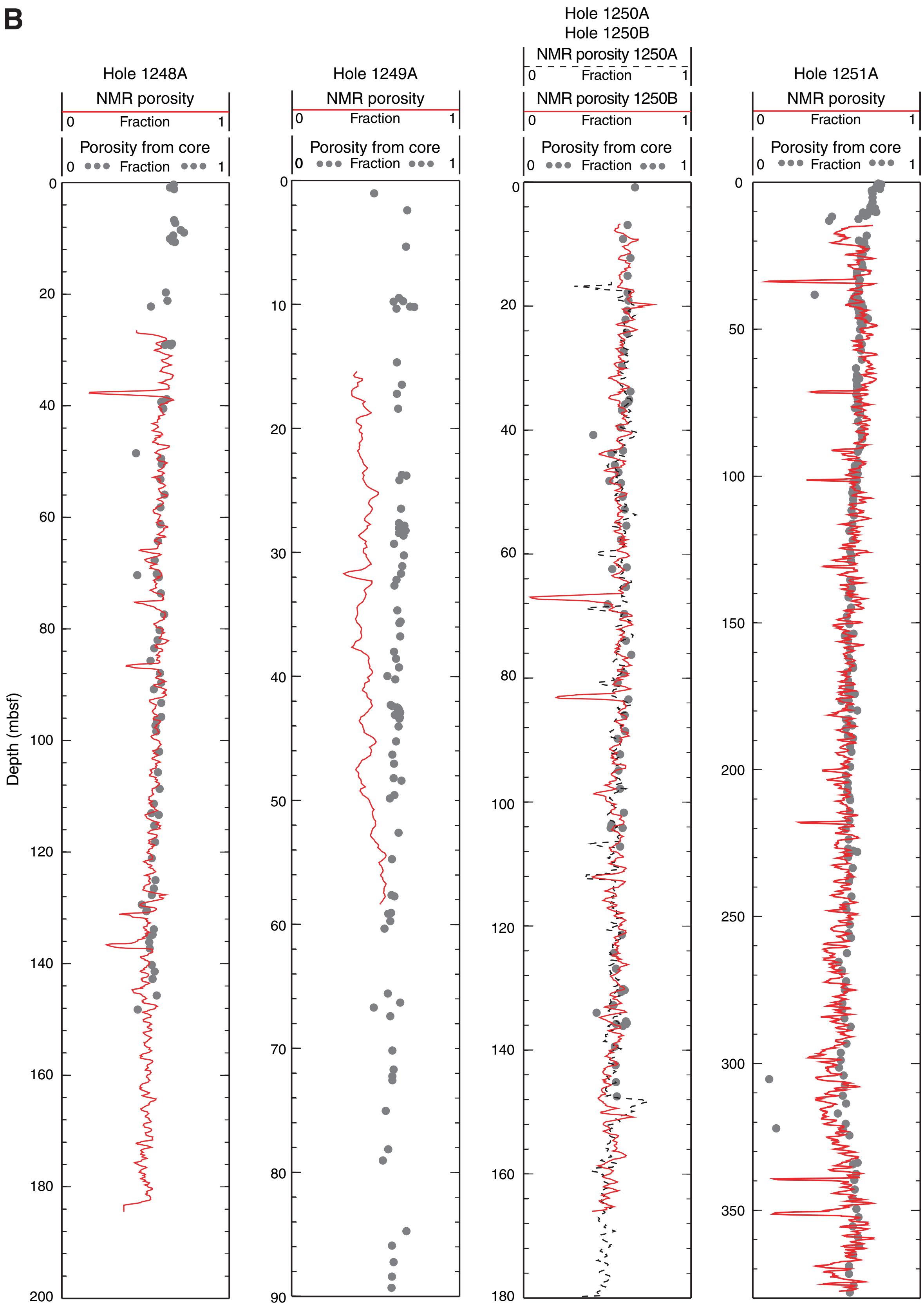


Figure F5 (continued). B. ProVision- and core-derived porosity from five of nine holes drilled on Hydrate Ridge during Leg 204 (Holes 1248A, 1249A, 1250A, 1250B, and 1251A). NMR = nuclear magnetic resonance.



Figures F6. A–I. ProVision- and density log-derived porosities and derived gas hydrate (GH) saturations (shown as concentrations) for nine holes drilled on Hydrate Ridge during Leg 204 (Holes 1244D, 1245A, 1246A, 1247A, 1248A, 1249A, 1250A, 1250B, and 1251A). BSR = bottom-simulating reflector. NMR = nuclear magnetic resonance. (Continued on next four pages.)

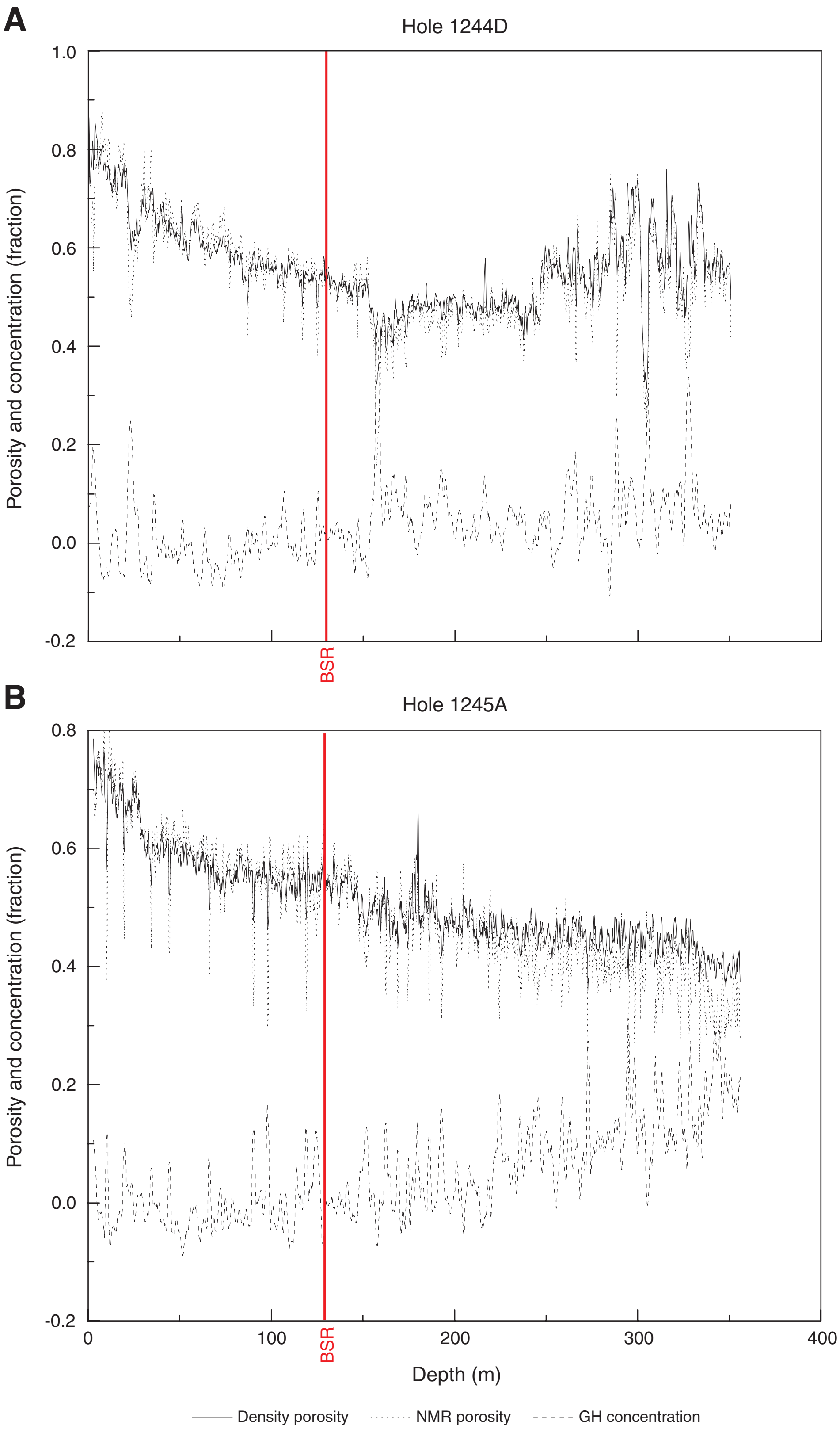


Figure F6 (continued).

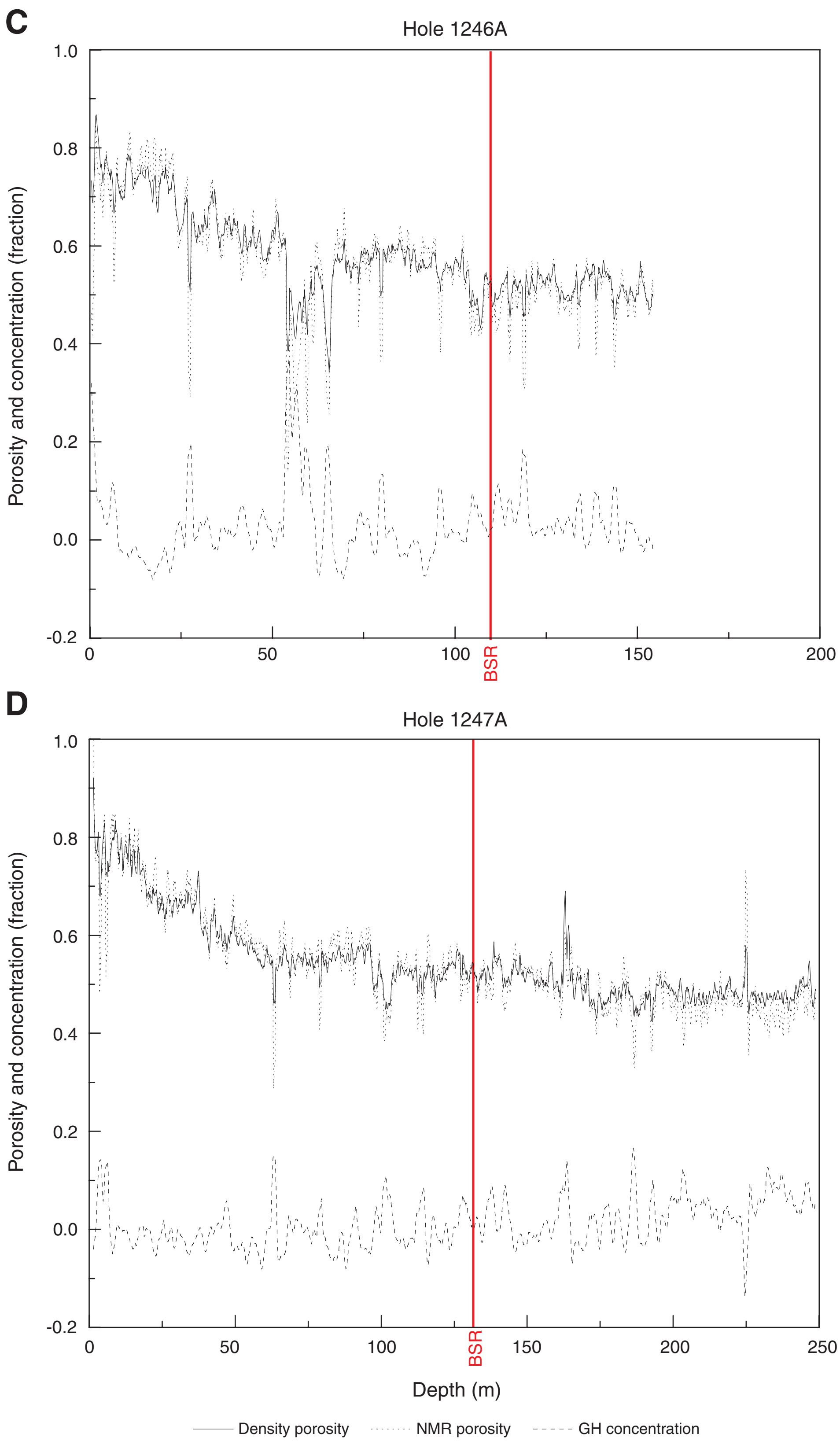


Figure F6 (continued).

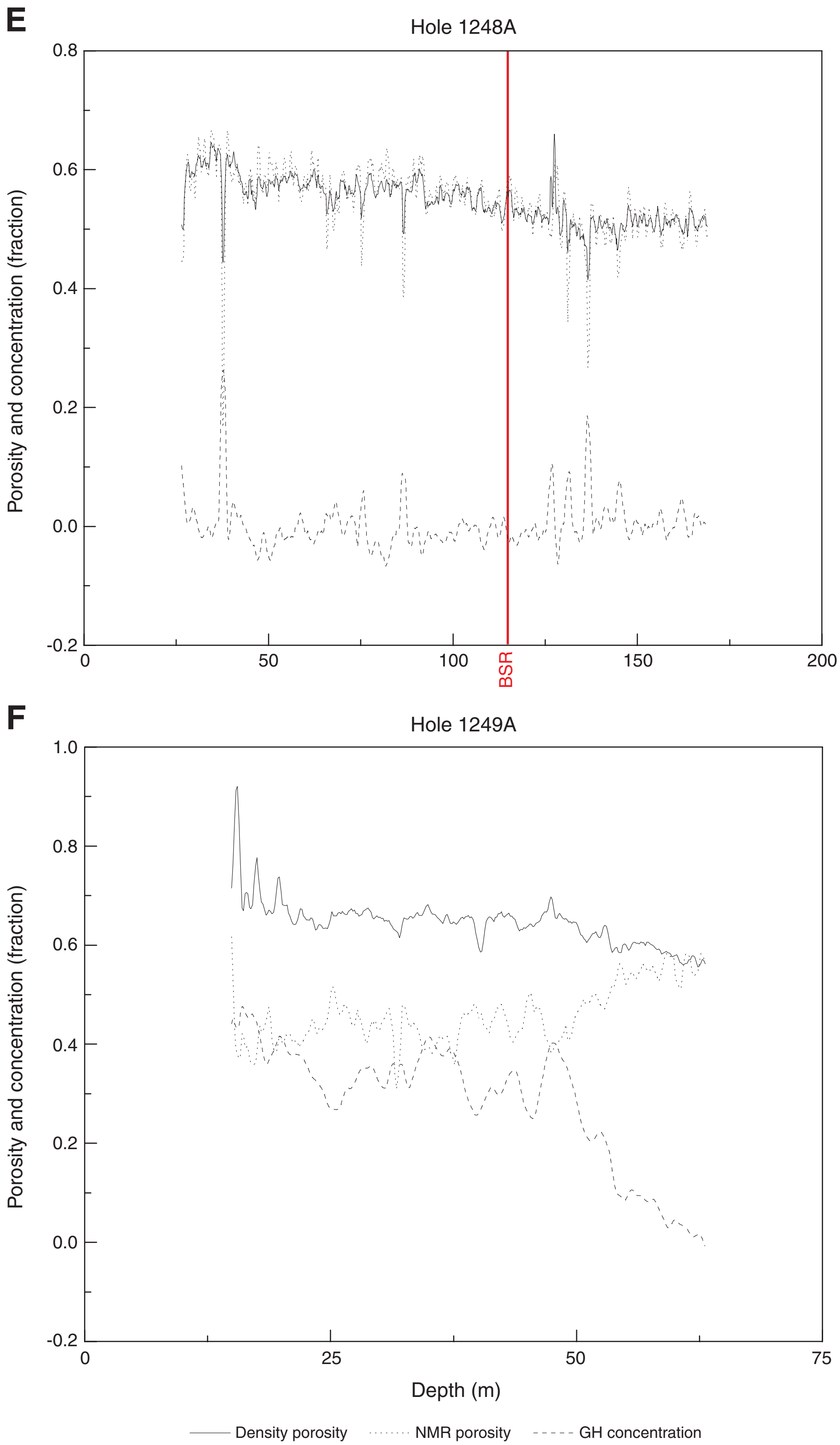


Figure F6 (continued).

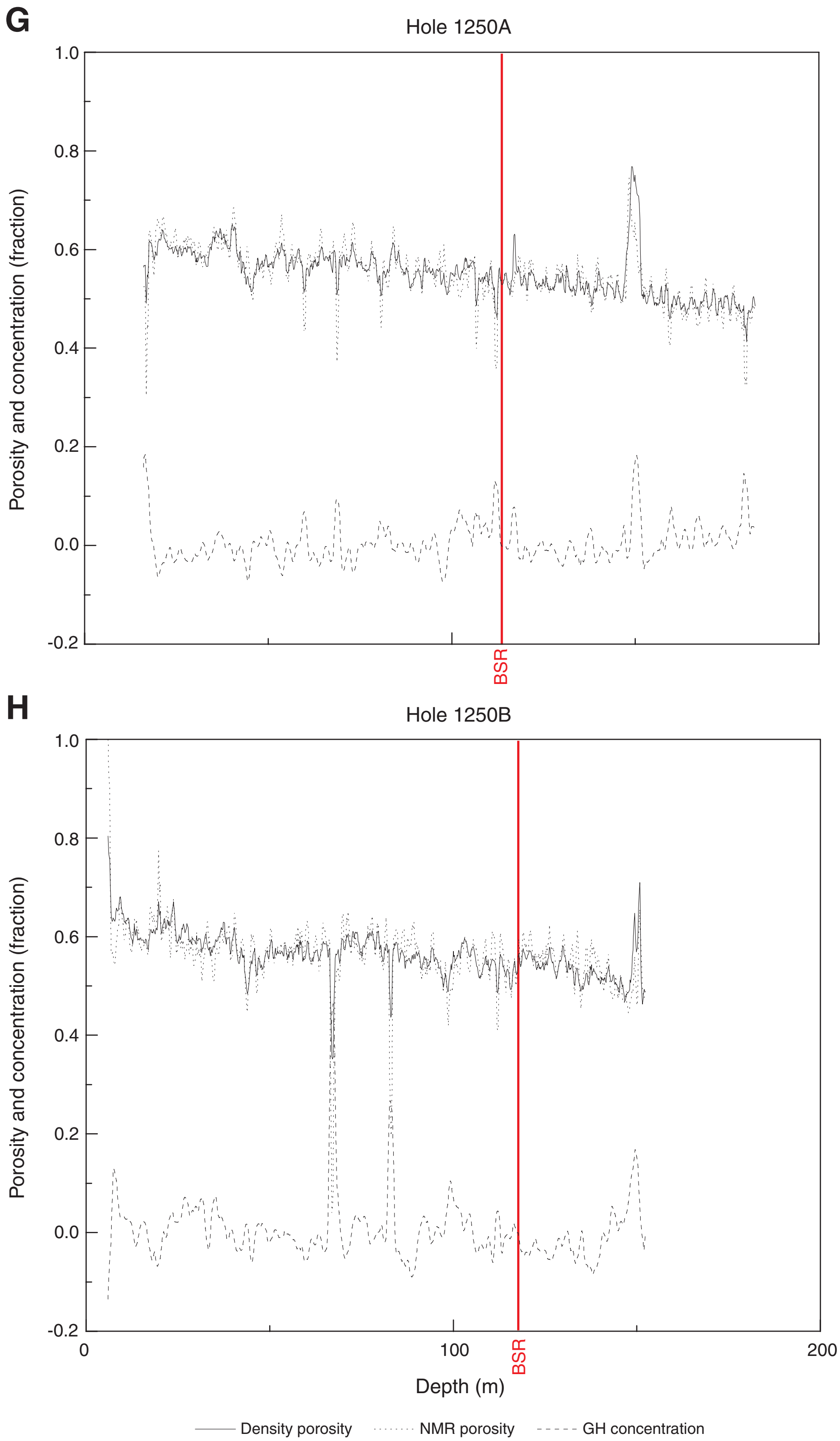


Figure F6 (continued).

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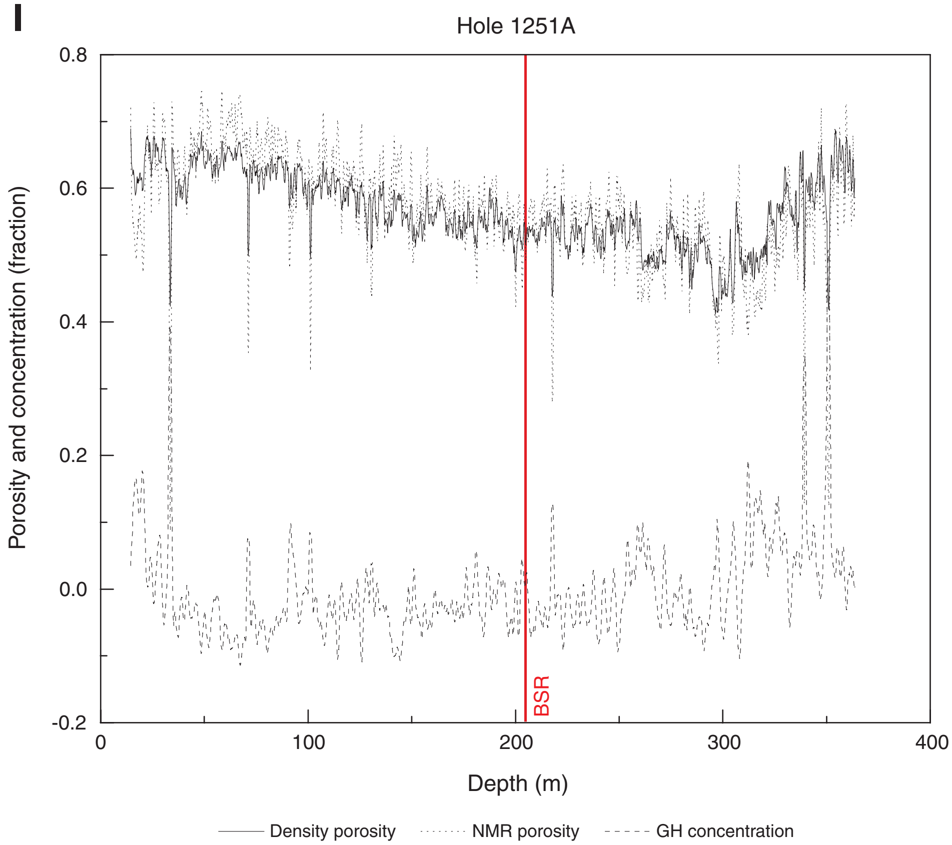

Table T1. List of ODP Leg 204 sites and holes surveyed with logging-while-drilling and measurement-while-drilling tools.

Hole	Water depth (mbrf)	LWD interval (mbsf)	proVision deployed	proVision sliding test
1244D	906.0	0–380	Yes	Yes
1245A	882.0	0–380	Yes	No
1246A	859.0	0–180	Yes	Yes
1247A	837.0	0–270	Yes	No
1248A	839.0	0–194	Yes	No
1249A	787.0	0–90	Yes	No
1249B	787.0	0–90	No	No
1250A	806.0	0–210	Yes	No
1250B	806.0	0–180	Yes	Yes
1251A	1216.5	0–380	Yes	No
1252A	1051.0	—	—	—

Notes: LWD = logging while drilling. — = not LWD logged.