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47. INVESTIGATION OF NEUTRON-POROSITY LOG UNCERTAINTIES: OCEAN DRILLING PROGRAM HOLE 642E[1]

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ABSTRACT

The dual-detector, neutron-porosity tool used on Leg 104 (Norwegian Sea) of the Ocean Drilling Program indicated erroneously high porosities in the basalt flows encountered in Hole 642E. A qualitative theoretical analysis of the response of this tool suggests that the discrepancy could be caused by the relatively large thermal neutron-absorption cross section of basalt. This analysis also indicates that, given the proper cross-section data, a calibration or redesign of this type of tool for use in igneous rocks should be straightforward.

INTRODUCTION

Often, porosity measurements performed on core specimens do not reflect the true porosity of a formation. This problem is of special concern in fractured igneous formations where core recovery is poor and, perhaps, selective in the sense that only competent material is recovered. Furthermore, even if core recovery were excellent, the relatively small core samples are not necessarily representative of the bulk properties of the formation. In these cases, downhole logging techniques are better suited for the determination of porosity. Such techniques have been under development for some time by the hydrocarbon-production industry, primarily for use in sedimentary formations. These techniques, or combination of techniques, are applicable in most portions of a hole, be it cased, open or washed out, and they interrogate between one and three orders of magnitude more formation material than is attainable by coring. However, logging techniques are far from infallible.

From the viewpoint of a logging specialist, physical properties in general fall into two categories: those properties that can be readily determined downhole and those properties that are of importance, but are difficult to measure directly using wireline tools. The first category includes such properties as resistivity, sonic velocity, temperature, and the transport characteristics of the formation for neutrons and gamma rays. These properties are often used in hole-to-hole correlations and they are also important in their own right. The second category includes porosity, permeability, lithology, oxidation state, thermal diffusivity, and oil saturation. Herein lies one of the main difficulties of log interpretation in that the correlations between the first and second categories of physical properties are often uncertain, ambiguous, and empirical. Thus, depending on the measured and desired properties in question, log interpretation can be more magical than scientific.

Porosity determinations often are made from downhole measurements of resistivity, sonic velocity, and neutron and gamma-ray transport properties of a formation (Hearst and Nelson, 1985). The electrical and mechanical (velocity) techniques rely on quasi-empirical mixture rules that relate, e.g., the bulk resistivity to the resistivity of the pore fluid and rock matrix material with porosity as a weighting factor. Such rules can be made to work, but they tend to be formation-dependent and thus are not well suited to scientific programs that do not dwell on any particular formation.

Nuclear logging concepts are less formation-dependent than electrical and mechanical techniques because their mixture rules are more exact. Thus nuclear tools are good candidates for porosity determinations in scientific drilling efforts. Electron densities are measured by noting the Compton (gamma ray) scattering properties of a formation. Since there is a good correlation between the electron density and the bulk density, Compton scattering measurements yield quite reasonable formation densities. However, to obtain the porosity from the bulk density, one must know the average grain density. The uncertainty in the grain density introduces the major error of this logging technique.

Steady-state neutron logs are based on the premise that the hydrogen contained in the pore water is the major moderator of high-energy neutrons. While this assumption is generally good, these logs can be influenced by the presence of hydroxyl water in shales and clays. Furthermore, neutron logs can be influenced by the presence of elements that are strong absorbers of neutrons. This influence can be minimized if two neutron detectors with long source-to-detector spacings are utilized in the logging tool (Allen et al., 1967). A good logging strategy for use in scientific drilling programs that penetrate unknown formations is to run both gamma density and neutron-porosity logging devices. Then, one technique can check the other and the differences between porosity determinations should be small, certainly less than 5 porosity units (1 porosity unit is a porosity of 1%). This strategy is commonly used in the Ocean Drilling Program and was used on Leg 104.

Neutron tools, like other logging devices, are influenced by environmental factors such as borehole size, temperatures, tool stand-off from the wall of the hole, etc. Thus the raw neutron data taken in Leg 104 were corrected using the technique of Gilchrist et al. (1986) as is discussed in the Appendix. In spite of this correction, a difference of about 13 porosity units was noted between the results of the two nuclear porosity logging techniques used in basalt flows, see Figure 1, and a comparison between log and laboratory porosities indicated that the neutron log was at fault and was reading an abnormally high porosity. Since the Schlumberger CNT-G tool in question had performed within manufacturer's specifications both before and after each of the logging runs, it is unlikely that the problem was a malfunction. Furthermore, similar difficulties have been observed in other legs of the Ocean Drilling Program (Anderson, 1987) and Schlumberger has noted previously a difficulty when their tools are used in igneous rocks (Khatchikian, 1983). Thus the neutron problem transcends the specific difficulties noted on

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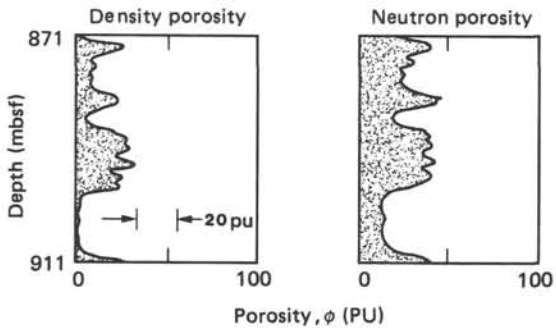

Figure 1. Comparison of porosities obtained from the gamma density log and the neutron-porosity logs that were run in Hole 642E. Shale and clay-free material of near solid density occurs between 900 and 908 mbsf. Core recovery in this region was good. Density porosities were obtained from gamma density log data assuming a constant grain density of 2.9 g/cm^3 for basalt. The neutron porosities are corrected for environmental effects or as discussed in the Appendix.

Leg 104, and the current work was undertaken to investigate its origin. This was accomplished by a theoretical analysis coupled with log data obtained in the basalt flow intersected by Hole 643E at 900 to 908 meters below sea floor (mbsf).

In the next section of this paper, a simple model of a neutron-porosity logging tool is presented. This model is sufficient to develop the concept of dual-detector neutron logging and to show the influence of trace elements that are strong thermal neutron absorbers on the porosity measurement. The final section of this paper puts forth the conclusions of this study and indicates directions for future efforts.

QUALITATIVE THEORY OF NEUTRON-POROSITY LOGGING

Tool Model

Neutron-porosity logging tools utilize a radioactive source such as the Am-Be system to inject a cloud of nominally 2- to 4-Mev neutrons into the formation. (Other neutron tools use pulsed sources; they were not used on Leg 104 and they are not considered herein). The injected neutrons move through the formation, suffer collisions with formation atoms that slow them to thermal energy (the kinetic energy at which the neutrons are in temperature equilibrium with their environment) and are eventually captured by a formation atom. Because the mass of a neutron and of a proton are essentially equal and because both masses are substantially less than that of other common crustal elements, the prime moderator of the fast neutrons is hydrogen. For example, the average number of collisions required to slow a neutron with an initial energy of 2 MeV to thermal energy (0.025 ev) is 18, 114, and 260 for hydrogen, carbon, and silicon, respectively (Glasstone and Sesonske, 1967). Neutron-porosity logs take advantage of this contrast between hydrogen and other common formation elements by interrogating the moderating process.

A detailed analysis of a neutron tool requires a solution of the Boltzmann transport equation (e.g., Henry, 1975). High-order approximations to this exact integral-differential equation have been applied to porosity logs (Ullo, 1986). The use of this detailed analysis requires design information that is unavailable for Schlumberger tools. This deficiency limits the scope of any theoretical investigation, and the spirit of the present effort is to seek only qualitative answers to the neutron-log problems. Thus the relatively simple, homogeneous, one-dimensional, diffusion approximation to the transport equation developed by Allen et al. (1967) for neutron logs will be followed. A discussion of the approximations pertaining to the diffusion model and to the constitutive coefficients in the diffusion equation may be found in Henry (1975) and in Glasstone and Sesonske (1967).

In the homogeneous, one-dimensional model, the effects of the borehole, logging cable, tool housing, detector shielding, etc. are all neglected. Effectively, the neutron-porosity tool is approximated by a point source of neutrons located at the origin of a spherical coordinate system. This geometry is not as contrived as it appears at a first glance. Neutrons propagate nearly a meter into the formation and thus the volume of formation material that is interrogated is larger than that of extraneous material.

The probability of various interactions of neutrons with atoms are described by appropriate cross sections for scattering, absorption, inelastic collisions, fusion, and other interaction phenomena. These cross sections are dependent upon the energy of the neutron. Consequently, the cross-section-dependent coefficients in the diffusion equation are also dependent on the energy of the neutron, and a single solution of the diffusion equation with assumed constant coefficients is not very accurate. Thus it is customary to solve a set of coupled diffusion equations such that "high" energy equations provide the source terms to "lower" energy equations and that the assumption of constant coefficients within a group is more reasonable. Two energy groups are sufficient for the present effort. The low-energy group, designated by the subscript 2, accounts for the thermal neutrons; the high-energy group, designated by 1, accounts for the remaining energies. Under the above conditions, the two neutron fluxes, $\psi_{1,2}$, are defined by the equations

$$D_1\nabla^2\psi_1 - \Sigma_{r1}\psi_1 + Q = 0, \tag{1}$$

and

$$D_2\nabla^2\psi_2 - \Sigma_{r2}\psi_2 + \Sigma_{r1}\psi_1 = 0. \tag{2}$$

In Equations (1) and (2), Q is the source strength (neutrons/second), $D_{1,2}$ are the diffusion coefficients (cm) and $\Sigma_{r1,r2}$ are the removal cross sections (cm^{-1}). The solutions to the above equations are

$$\psi_1(r) = Q(4\pi D_1 r)^{-1}e^{-r/L_2} \tag{3}$$

and

$$\psi_2(r) = QL_2[4\pi D_2(L_1^2 - L_2^2)r]^{-1}[e^{-r/L_1} - e^{-r/L_2}], \tag{4}$$

where the diffusion lengths, $L_{1,2}$, are

$$L_{1,2} \sim (3\Sigma_{s1,s2}\,\Sigma_{r1,r2})^{-0.5}. \tag{5}$$

In Equation (5), $\Sigma_{s1,s2}$ are scattering cross sections of the formation material (cm^{-1}). Like the removal cross sections, the scattering cross sections are dependent on the type and relative amount of rock matrix material and pore fluid. These and other constitutive parameters will be discussed in more detail following the present theoretical development. For now, note that the information concerning the moderation process is contained in the quantity Σ_{r1}, and the flux ψ_1 is most pristine since it contains fewer constitutive parameters. However, from an experimental point of view, the measurement of the thermal flux is easier to accomplish because detectors are more efficient at low energies. Note, the Schlumberger tool used on Leg 104 measured both thermal and epithermal neutron fluxes. The epithermal mea-

surements were developmental and were not available to the Leg 104 logging team.

Let μ, A, and V be the efficiency (the probability of a neutron inside of the detector exciting it per unit time), the cross sectional area of a thermal neutron detector aligned along a radius vector in the spherical coordinate system, and the velocity of a thermal neutron, respectively. Then the thermal neutron density (neutrons/cm^3) is $V^{-1}\psi_2(r)$ and the number of counts/s produced by this detector, I, is

$$I = \mu V^{-1} \int \psi_2 d(\text{vol}) \sim \mu V^{-1} A \int \psi_2 dr. \qquad (6)$$

(volume of detector; length of detector)

The approximation made in the right-hand integral of equation (6) is that the solid angle subtended by the area A is small. (Note that some tools measure capture gamma rays instead of thermal neutrons. Such a measurement does not change the principle of the logging technique.)

An important concept was recognized by Allen et al. (1967). Specifically, "...essentially all dependence of a thermal neutron measurement upon thermal neutron parameters can be eliminated simply by making measurements at two sufficiently distant points...and taking their ratio." We will follow this advice by forming the ratio, R,

$$R = I(\text{far detector})/I(\text{near detector}), \qquad (7)$$

but we pose the question, "What difficulty will occur if the detectors are not distant from the source?" Note that the ratio is dependent only upon the tool geometry and the diffusion lengths $L_{1,2}$.

Constitutive Parameters

Constitutive parameters are the scattering and removal cross sections that are required to evaluate equation (7). They carry the information of interest concerning the formation material and they influence L_1 and L_2 through equation (5).

The scattering cross sections are energy dependent and will be somewhat different for the high- and low-energy groups. Furthermore, these cross sections vary approximately as the cross sectional area of the formation atoms or about as the atomic mass to the two-thirds power (Glasstone and Sesonske, 1967). Since crustal rock material consists largely of elements of about the same atomic mass, the scattering cross sections are not a strong function of lithology. Herein they are assumed to be independent of lithology (but not porosity) for both high- and low-energy neutrons.

For saturated rocks, the high-energy removal cross section is dependent primarily on the hydrogen content; neutrons are readily moderated by hydrogen and thereby removed from the high-energy group. The influence of various crustal elements other than hydrogen on Σ_{r1} is small and it will be neglected. Thus, herein L_1 is assumed to be a function of porosity alone. Neutron data concerning igneous rocks are very sparce so SiO_2 was chosen to represent basalt in this study (other choices were limestone and dolomite). The effect of various rock constituents on L_1 has been investigated by Kreft (1974).

Allen et al. (1967) generated data on the parameters L_1 and L_2 for fresh and salt water (100,000 ppm NaCl) saturated sands. A fit to these data for L_1 is

$$L_1 = -3.03 \ln(\phi/10), \qquad (8)$$

where ϕ is measured in porosity units/100. A similar fit, but using an extrapolation between the fresh and salt water data to accommodate the salinity of sea water, yields

$$L_2 = -3.52 \ln(\phi/1.67). \qquad (9)$$

Unlike L_1, L_2 will be influenced by the formation constituents through its dependence on the thermal neutron absorption cross section of the rock matrix material, Σ_m.

Recently there has been a considerable interest in measuring the thermal neutron absorption of formation materials. This activity stems from the interest of the hydrocarbon production industry in obtaining better neutron log measurements. Thus, most of the work has been done on sedimentary materials, and the results of some of these measurements are given in Table 1 (Allen and Mills, 1974; Lysne, 1988a, b). Also included in this table are the results of all measurements known to this author that have been done on igneous materials (Allen and Mills, 1974; Kreft et al., 1984). Note that the cross sections of the igneous materials tend to be much larger than those of sedimentary materials, and basalt has a value of about 22 CU. This phenomenon is due to the presence of trace elements with very large cross sections, e.g., a few ppm gadolinium.

Let $\hat{L}_2$ be the porosity- and formation-dependent diffusion length. Then, from equation (5) and the assumed constancy of the scattering cross section,

$$\hat{L}_2 = L_2 (\Sigma_{r1}/\hat{\Sigma}_{r1})^{0.5}, \qquad (10)$$

where Σ_{r1} and $\hat{\Sigma}_{r1}$ are the removal cross sections of the seawater-saturated sandstone used to generate the data represented by equation (9) and a similarly saturated formation with a different matrix material, respectively.

In general, any cross section of a saturated material is

$$\Sigma_{\text{saturated}} = \phi\Sigma_{\text{fluid}} + (1 - \phi)\Sigma_{\text{matrix}}. \qquad (11)$$

Thus

$$\hat{L}_2 = L_2 \left\{\frac{35\phi + 5.2(1 - \phi)}{35\phi + S_m(1 - \phi)}\right\}^{0.5} \qquad (12)$$

where 35 CU is the cross section of sea water and 5.2 CU is the cross section of the reference sandstone (calculated from the data of Allen et al., 1967). Note one capture unit (CU) equals 10^{-3} cm^{-1}.

With the above constitutive information, the ratio R becomes a function of both the porosity and the cross section of the formation matrix material. Figure 2 illustrates contour plots of this surface for several source-to-detector-array spacings. In these calculations, the efficiency and cross-sectional area of the two detectors were taken to be equal, the separation between the near and far detectors was 10 cm and the length of the near and far detectors was 20 and 30 cm, respectively. The correlation between these source and detector geometries and that of any commercial tool is coincidental.

CONCLUSIONS

The contour curves of Figure 2 represent the locus of points for which the response of a dual-detector neutron tool are equivalent. Stated otherwise, if a tool were calibrated for use in a formation possessing a low thermal neutron absorption cross section, it would yield an anomalously large porosity when used in another formation with a larger absorption effect. The curves of Figure 2 also indicate that this situation is exacerbated by short source-to-detector spacings. (Note the dilemma faced by the tool designer in that long spacings decrease both the lithology dependence and the neutron counting rate.)

Although data on the absorption properties of igneous rocks are not comprehensive, they indicate that igneous rocks are stronger absorbers than sedimentary rocks, and thus the noted anomalously large porosity measured by the Schlumberger tool

Table 1. Selected thermal neutron absorption cross sections.

Sedimentary Rocks	
[1]Ottawa Sand (Frac-Sand)	[5,6] 4.8 CU
[2]Mesaverde Sands	11.0
[1]Royer Dolomite	[6] 5.6
[1]Skiatook Dolomite	10.7
[3]Carthage Marble	9.7
Igneous Rocks	
[1]Burnet Red Granite	22.0
[1]Knippa Basalt	33.2
[1]North Carolina Olivine	12.0
[4]Basalt S4	21.5
[4]Basalt S7	23.8
[4]Basalt S10	21.5

[1] Allen and Mills, 1974
[2] Lysne, 1988b (Average of 80 specimens. A grain density of 2.6 g/cm^3 was used to convert CU/density to CU.)
[3] Lysne, 1988a (A grain density of 2.7 gm/cm^3 was used to convert CU/density to CU.)
[4] Kreft et al., 1984 (A grain density of 2.9 g/cm^3 was used to convert CU/density to CU.)
[5] One capture unit (CU) equals 10^{-3} cm^{-1} equals 10^{21} barns/cm^3.
[6] Anomalously low cross section indicative of a relatively low concentration of trace elements with large absorption cross sections, e.g., Gd, Sm, B.

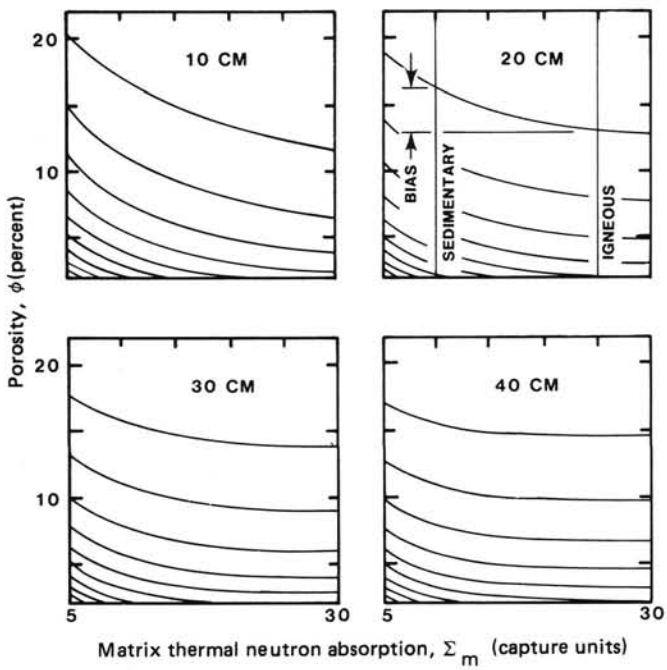

Figure 2. Contour plots of the response of a hypothetical neutron-porosity tool. The distances shown represent the spacing between the source and the closest detector in the two-detector array. Array dimensions are given in the text. Neutron-porosity logs are typically calibrated for sedimentary formations with cross sections of about 10 CU. Igneous rocks are considerably stronger absorbers of thermal neutrons; cf. Table 1. One figure illustrates the concept of a bias porosity.

on Leg 104 is plausibly due to absorption effects. Schlumberger has recognized that the CNL porosity tool, which for our purposes is identical to the CNT-G tool, exhibits such a lithology effect. To account for this effect, correction curves have been published (Ellis et al., 1987) for limestone, sandstone, and dolomite. These curves are based on a nonlinear fit to experimental and computer-generated data. An extrapolation of this fit to low porosities indicates that the CNT-G tool would be about 2 PU high in a zero-porosity sandstone with a matrix cross section of 25 CU. This correction is not sufficient to explain the results of Leg 104 (about 13 PU high) or the results of Khatchikian (1983) in another basalt flow (about 10 PU high). However, experimental results for the lowest porosity sand (15 PU) used to generate the correction curves indicate that excess porosity accumulated at about 0.8 PU/CU for matrix material with a cross section greater than 6 CU. Thus a material with a cross section of 23 CU would possess 13 excess porosity noted in field data. Note that basalt exhibits cross-section values in excess of 20 CU; c.f. Table 1.

The model of a dual-spaced porosity tool developed in this paper was not intended to be quantitative. Furthermore, while the detector geometries used in the calculations are thought to be reasonable (they are, after all, constrained by neutron diffusion distances and shapes that can fit into a borehole), they may bear little resemblance to the CNT-G tool. Thus, one should not extrapolate the results of this study to, say, a set of correction curves for the Schlumberger tool. Nevertheless, a few general conclusions may be made in regard to the porosity log problem:

1. In an ideal tool, the slope of the contour curves of Figure 2 would be zero. This would mean that the tool response was independent of the thermal neutron absorption properties of the formation. Note that this slope decreases both with increasing source-to-detector spacings and increasing absorption. The latter effect indicates that a calibration of existing neutron-porosity tools for use in general igneous formations may be easier than a similar calibration for sedimentary formations since minor perturbations in the absorbing properties of an absorbing formation are less consequential.

2. For a given array geometry, the porosity difference between any two contour curves is not a strong function of the absorption cross section. This fact suggests that a constant "bias" porosity could be subtracted from the log porosity to obtain a reasonable estimate of the true porosity, c.f. Figure 2. The accuracy of this technique is dependent upon the tool geometry as well as the variation of the cross section values within the igneous formation. This technique is being used by D. Moos and C. Broglia (pers. comm., 1986) in the reduction of Leg 102 data. An approximate correction to the Leg 104 data (Eldholm, Thiede, Taylor et al., 1987) may be made by subtracting 14 porosity units from the Schlumberger traces. This correcting is comprised of 13 PU for lithology effects and 1 PU for environmental effects; c.f. Appendix.

3. Very little is known about the neutron-absorbing properties of igneous formations other than that they are larger than that of sedimentary formations. (The six entries of Table 1 constitute all of the measurements known to this author.) The data base concerning these properties must be expanded to make any calibration of present neutron tools meaningful. Such work could augment the data base being generated for sedimentary formations by the International Atomic Energy Agency.

4. The approximate model used in this study utilized a two-group diffusion approximation to the Boltzmann transport equation. This model coupled with the ratio technique of Allen et. al. (1967) leads to dual-detector tool responses which are depen-

dent on both the porosity and the absorption cross section, and this dual-dependence is the crux of the neutron logging problem. However, the fact that there is a measurable problem means that a three-detector tool, with one detector near the source so as to maximize the lithology response, can measure simultaneously the porosity and the absorption properties of the formation. In fact, such an idea has been patented (Flaum, 1980) and the development of such a tool is justified if the cross-section variations for igneous rocks prove to be so large as to negate a simple calibration of existing tools. Note that the cross-section data provide a measure of the presence of elements with large individual cross sections and rudimentary lithology information might be gleaned from cross-section measurements.

In conclusion, note that most commercial logging tools and their interpretation techniques are optimized for usage in the hydrocarbon production industry. There, emphasis is on sedimentary formations and running logs quickly. The neutron-log difficulty encountered on Leg 104 is only one of numerous problems that will crop up when this production technology is applied to the different needs of scientific drilling programs.

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APPENDIX

The data obtained from the CNT-G Tool do not yield immediately the true porosity, and environment corrections must be made (Gilchrist et al., 1986; Ellis et al., 1987). Other logs run in Hole 642E supplied data pertinent to the environmental correction and they provide a measure of the quality of the data obtained from the CNT-G Tool. Plots of all logs and data obtained from core specimens may be found in Eldholm, Thiede, Taylor, et al. (1987). All logs were run by Schlumberger.

The CNT-G Tool is influenced by the size of the hole; its diameter was measured with a caliper tool. In the portion of the hole between 871 and 911 mbsf, cf. Figure 1, the caliper indicated a nominal hole diameter of 27.4 cm with a jitter of ± 1.0 cm. In the basalt flow between 900 and 908 mbsf, the caliper record was essentially a constant 27.4 cm.

The gamma tool run on the same tool string as the neutron tool provides a measure of the formation density. In the basalt flow, the log density was 2.85 to 2.92 gm/cm^3 and these values are in good agreement with the core results of 2.83 to 2.91 gm/cm^3. The gamma tool also provides a measure of log quality by comparison of two density measurements made at different source-to-detector spacings. This *delta rho* measurement was ± 0.02 gm/cm^3 in the basalt flow. This value is considered to be very good, and it indicates that the tool was property eccentered in the hole.

Several different data analysis algorithms are available for generating log plots from CNT-G data. On Leg 104, the matrix material was chosen to be limestone and the hole diameter was taken to be the bit size of 25.1 cm. (Note that the CNT-G Tool is calibrated in limestone, so all other formation materials are referenced to it.) The uncorrected apparent limestone porosity measured in the basalt flow is 14 ± 1 PU following Gilchrist et al.(1986).

Environmental corrections were made for the difference between the bit size and the caliper hole diameter, the salinity of sea water in the hole and limestone pores (30,000 ppm), and the water pressure. None of these corrections were large and the true limestone porosity is 13 ± 1 PU. A similar true limestone porosity of 10 PU for a long run in another near-zero porosity basalt flow has been reported (Khatchikian, 1983).

Unfortunately, Schlumberger does not provide equivalence curves to transform the limestone porosity to that of basalt. Curves are available for sandstone and dolomite. The true sandstone porosity for a limestone porosity of 13 PU is 18 PU, and that of dolomite is 11 PU.