LITHOLOGIC CYCLES AND PALEO FLUID FLOW CHANNELS IN OLD OCEANIC CRUST FROM GEOPHYSICAL LOGS AT ODP SITE 418A

by

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ABSTRACT

Using some new processing of the multichannel sonic (MCS) log data from Site 418A, the resulting P, S, and Stoneley wave velocity estimates and apparent attenuation were integrated with the natural gamma, spectral gamma, resistivity, neutron, density, and caliper logs and core lithology information for interpretation of lithologic cycles and possible paleo fluid flow intervals. These data indicate the presence of multiple breccia or rubble zones in the lower portions of the borehole. These zones are interpreted as the last stages of eruptive cycles as described by Hyndman and Salisbury (1984). The results of permeability (packer) tests and temperature gradient measurements at Sites 395A and 504B indicate that fluid flow in the crust at those sites is localized to brecciated zones which occur below massive flow basalts. By analogy, the breccia zones interpreted at Site 418A may have acted as fluid flow channels at an earlier time. Six major paleo fluid flow zones are interpreted at Site 418A. These breccia zones have low velocities (P, S, and Stoneley), increased apparent attenuation, and an increase in gamma activity. These intervals are interpreted as permeable pathways which may have been altered by the second stage of oxidizing alteration as described by Holmes (1988). Breccia units occur just below massive basalt flow units. The massive basalt flow units are also easily identified in the MCS data. The resistivity log data suggest that each major eruptive cycle trend is made up of several smaller sub-cycles. The MCS data provides much insight into the variations in lithology in ODP boreholes. The trace energy provides a stable measure of apparent attenuation which may be related to alteration, fracturing, or permeability (if there are open fractures). Velocity

estimates for P, S, and Stoneley waves provide useful information about lithologic variability if interpreted in detail.

INTRODUCTION

ODP Site 418A penetrated 110my old crust south of the Bermuda Rise. This site was part of a transect designed to investigate the changing nature of the oceanic crust as a function of age. Houtz and Ewing (1976) were among the first to postulate the existence of a low velocity layer (Layer 2A) at the top of the oceanic crust based on seismic velocity evidence. The thickness of Layer 2A decreases with the age of the crust and is missing completely at Site 418A. This layer is postulated to be a fractured interval in which ocean water circulates. With passing time, the basalt in Layer 2A is increasingly altered with fractures and pore space becoming in-filled with alteration products (e.g., clay, calcite, zeolites). The alteration products increase the velocity of the layer until it can no longer be identified by a low seismic velocity. At Site 418A, the interval between 388 and 514 mbsf (meters below sea floor) was identified by Broglia and Moos (1988) as the paleo Layer 2A based on an analysis of geophysical logs obtained during Leg 102. This interval had a high natural gamma ray response which is due to the presence of palagonite and potassium-rich clays formed during extensive low-temperature oxidative alteration of the basalts (Holmes, 1988). These findings support the interpretation of paleo fluid flow throughout this interval. The natural gamma ray activity drops off dramatically below 514 mbsf, with several isolated intervals of moderately elavated readings occuring between 514 and 780 mbsf (Figure 1). In this paper we will present the results of an interpretation of the lower portions of this hole in an effort to make inferences about other zones of possible paleo fluid flow. In addition to utilizing the geophysical logs and core geochemical data, we will also use the results of some new processing of the multichannel sonic (MCS) data collected during Leg 102.

BACKGROUND

Fluid flow in oceanic crust is controlled primarily by fractures. In young crust, such as at Site 504B, temperature profiles, in situ permeability (packer) tests, geochemical studies, and logging measurements such as the borehole televiewer, porosity logs, and MCS logs, indicate that the shallow crust (upper 100 m or so) contains many open fractures. This fractured interval at Site 504B is an aquifer of high permeability (approximately 60 md) which is underpressured (Anderson et al., 1982). This zone, interpreted as Layer 2A, is not, however, present in old oceanic crust, such as Site 418A. Alteration products seal the fractures reducing the permeability. The geochemical makeup of these alteration products provides information about the nature of the paleo fluid flow.

Holmes (1988) reconstructed the alteration of the crust at Site 418A based on X-ray and SEM analysis of clay material obtained from the core samples. His results indicate general low-temperature oxidative alteration which took place in two stages. The initial stage of oxidation resulted in the precipitation of iron oxides, followed by potassium-rich clays. The high gamma ray readings in this hole are generally due to these potassium-rich clays (Figure 2). A second stage of oxidative alteration took place in zones of high permeability due to the circulation of a second, oxidizing fluid influx. The evidence for this second stage is the alteration of saponite to iddingsite. Potassium feldspar is also associated with this stage and is responsible for some increase in gamma ray readings in these sections of the lithologic column (Holmes, 1988). A number of these paleo fluid flow zones can be interpreted from the geophysical logs from Site 418A. In general, these zones occur just beneath massive basalt flows. This observation coincides with the hypothesis put forth by Hyndman and Salisbury (1984) in regard to the Site 395A data. The geophysical logging data at Site 395A showed distinct reponse patterns which can be related to chemical variations in the core. For each lithologic unit at Site 395A, the resistivity log decreases steadily from the bottom (low porosity massive flows and pillows) to the top (high porosity flow breccia and rubble). Other logs show similar trends (Figure 3). Hyndman and Salisbury (1984) hypothesized that these chemical changes and log trends could represent units emplaced by an eruptive cycle from a particular source or magma chamber. The trend from a low porosity massive flow to a high porosity flow breccia or rubble could be the result of increasing viscosity of the lava. Each eruptive cycle contains massive flows and pillow basalts capped by a rubbly, brecciated interval. Each cycle is then truncated by another massive flow which marks the start of another cycle. The downhole temperature measurements Site 395A indicate that the downhole fluid flow occurs below these massive flow intervals, that is, the brecciated zones are the most permeable (Figure 4). Permeability (packer) tests support this conclusion. At Site 504B, packer tests also indicate that the fluid flow is controlled by impermeable massive flows which act as a caprock (Zoback and Anderson, 1983; Leg 111 Scientific Party, 1988; Figure 5).

The log data from Site 418A can also be interpreted in terms of basalt emplacement cycles and the brecciated intervals can be identified. These brecciated zones are interpreted as possible paleo fluid flow channels analogous to those identified at Sites 395A and 504B. In addition to the interpretation of the geophysical log data presented by Broglia and Moos (1988), we also utilize some new processing of the multichannel sonic (MCS) log data. Multishot processing (MSP; Hsu and Chang, 1987) was performed on the Site 418A MCS data. This method improves velocity estimates by increasing the signal-to-noise ratio (S/N) via stacking of subsets of the array data, and increasing the vertical resolution by using shorter subsets of the total array. The resulting P, S, and Stoneley wave velocity estimates were integrated with the natural gamma, spectral gamma, resistivity, neutron, density, and caliper logs and core lithology information for interpretation of lithologic cycles and possible paleo fluid flow intervals.

MCS PROCESSING

The multichannel sonic log is an array-type sonic tool which records the entire waveform at 12 receivers from each source firing. The use of multiple receivers allows array processing techniques (such as semblance) to be used to obtain more stable and accurate velocity estimates than conventional two receiver sonic tools. In order to try to improve the depth resolution of the velocity estimates obtained with the semblance technique, multishot processing (Hsu and Chang, 1987) was applied to the data. This method increases the signal-to-noise ratio (S/N) via stacking of subsets of the array data, and improves the vertical resolution by using shorter subsets of the total array. For the MCS tool, the receiver array spans a distance of 1.65m (12 receivers at a spacing of 0.15m), while the normal recording speeds result in subsurface sampling intervals (source firing intervals) of 0.1m - 0.5m in general. With such dense coverage of the subsurface, there is a great deal of overlap between subsequent source positions. The MSP method breaks the data set up into subarrays to take advantage of the tremendous sampling density present in the logging data set. The MSP method consists of three steps: 1) divide the data into subarrays, 2) perform semblance processing on each subarray, and 3) stack the semblance calculations by projecting the semblance values onto the slowness axis. The selection of subarray lengths is dictated by the desired vertical resolution and by the data acquisition parameters (e.g., the logging speed). In processing the 418A MCS data, 4 subarrays of 6 receivers each were found to give the most stable results. This combination provides velocity estimates averaged over a 0.75 m interval in depth. Tests on 5 subarrays of 4 receivers each proved unsatisfactory, probably due to an insufficient number of traces for semblance analysis.

In order to estimate slowness values in the MSP method, the semblance method is used (Kimball and Marzetta, 1984). Semblance analysis is used in conventional processing of MCS data from the ODP (Moos, 1988; Leg 102 Shipboard Scientific Party, 1986; Leg 109 Shipboard Scientific Party, 1988; Leg 111 Shipboard Scientific Party, 1988), and the method is reviewed in most of these references. The resulting plot of semblance values as a function of arrival time T0 and slowness S for a "fast" formation, such as the oceanic crust, contains major peaks corresponding to P, S, and Stoneley waves. Since each subarray corresponds to different offset ranges, the arrival times will vary for the different modes within different subarrays. The slownesses for each mode, however, will be the same (averaged over the subarray length). The stacking process used to combine these data is to project the semblance values onto the slowness axis (Hsu and Chang, 1987). Plots of the computed P, S, and Stoneley wave velocities computed using MSP processing are shown in Figure 1.

In addition to utilizing the P, S, and Stoneley wave velocity values, a measure of the energy present in each trace of the MCS data is also used in the interpretation. The trace energy is simply a normalized sum of squared amplitude values for an entire MCS trace. The energy values plotted as a function of depth provide a qualitative measure of attenuation. It should be kept in mind that such a measure contains all forms of attenuation, such as intrinsic, scattering, and fluid flow. Because of the large amplitude Stoneley waves which are present in the 418A data set, the trace energy values are quite sensitive to changes in the Stoneley wave amplitudes. The trace energy, then, can be regarded as a qualitative measure of the changes in Stoneley wave attenuation as a function of depth in the crust. The Stoneley wave attenuation is sensitive to the borehole fluid attenuation, formation shear wave attenuation, variations in the borehole diameter, and fluid flow losses (Cheng et al., 1982, 1987). The caliper log indicates fairly uniform hole diameter at site 418A, and it is safe to assume that the borehole fluid attenuation is relatively constant throughout the borehole. Therefore, the trace energy can be interpreted as a qualitative measure of formation shear wave attenuation, fluid flow losses, or scattering in a highly fractured interval. The inverse of the trace energy is plotted as a function of depth in arbitrary units and labeled as apparent attenuation (that is, decreasing energy = increasing apparent attenuation). Figure 6 shows the MCS analysis results. This figure includes the apparent attenuation, smoothed P, S, and Stoneley wave velocities, and an iso-offset section of the MCS data.

INTERPRETATION AND RESULTS

The log data at site 418A consists of 3 major intervals which are visually apparent (Figure 1). The interval between about 380 and 514 mbsf shows natural gamma ray activity which is higher than any other section of the hole. This interval was interpreted in detail by Broglia and Moos (1988) and identified as a highly altered paleo Layer 2A. The section between about 515 and 600 mbsf has highly variable resistivity, neutron, and density log responses. The MCS data has lower amplitude (Figure 6) and therefore higher apparent attenuation. The P, S, and Stoneley wave velocities are variable but generally higher in this interval. The third major zone seen in the data is the bottom portion of the well (below 600 mbsf). In this lower portion of the borehole, the logs show varying structure and the MCS traces have lower apparent attenuation.

The upper portion of the data (320–514 mbsf) was extensively reviewed by Broglia and Moos (1988). They interpreted this section to be the remnant Layer 2A in which original fracture porosity has been replaced with potassium-rich clays. These clays cause the high gamma ray readings and are responsible for the increase in velocity in this layer such that the low velocity Layer 2A is not present. The middle interval of the borehole (515–600 mbsf) may be a fractured interval of pillow basalts. Broglia and Moos (1988) reported borehole roughness problems and attributed the highly variable resistivity, neutron, and density log responses to this. The increase in apparent attenuation in conjunction with the hole roughness and variable log responses suggests the presence of fractures. However, there is no increase in gamma ray activity, which implies little alteration in this interval. In the remainder of this paper, the lower portion of the borehole will be analyzed.

Before presenting an interpretation of the lithologic cycles and paleo fluid flow zones, the log responses for two key units for which core samples exist will be reviewed. The two units are the breccia unit (Unit 6A) at 514 mbsf, and the massive unit (Unit 10) at about 680 mbsf (Figure 1). The breccia unit is clearly seen on all log responses. This unit is identified by its low resistivity, high porosity, increased gamma ray acitivity, and low density. On the MCS data the breccia zone is clearly seen and can also be identified by the low P, S, and Stoneley wave velocitiesand high apparent attenuation (Figure 6, breccia unit B6). The massive unit is also seen on all log responses. This unit has high resistivity, low porosity, low density, low gamma ray acitivity, and is clearly visible in the MCS data. The P, S, and Stoneley wav velocities are high and the apparent attenuation is low for this massive unit (Figure 6, massive unit M3).

Using the log responses outlined above, the log data can be interpreted in terms of lithology. Figure 6 shows the locations of four massive basalt units (labeled M1 – M4) and six breccia zones (labeled B1–B6) as interpreted from the MCS data. Figure 7 shows the lithologic cycles interpreted from the resistivity log. The solid lines indicate the position of lithologic cycles marked by a trend from massive flows to breccia zones (Hyndman and Salisbury, 1984; Leg 111 Shipboard Scientific Party). The resistivity log data suggests that each major trend highlighted in Figure 7 is made up of several smaller sub-cycles. Because of the highly variable data in the 514–600 mbsf interval and the possible borehole roughness problems (Broglia and Moos, 1988), the lithologic interpretation is only carried up to about 600 mbsf. Figure 4 shows the lithologic cycles interpreted for Site 395A. Permeability and temperature gradient measurements from Sites 395A and 504B indicate that most fluid flow is taking place in breccia or rubble zones which mark the end of an eruptive cycle. A massive basalt flow of an overlying cycle acts as a caprock at these sites (Figures 4 and 5).

DISCUSSION AND CONCLUSIONS

The geophysical logs from site 418A indicate the presence of multiple breccia or rubble zones in the lower portions of the borehole. These zones are interpreted as the last stages of an eruptive cycle as described by Hyndman and Salisbury (1984). The results of permeability (packer) tests and temperature gradient measurements at Sites 395A and 504B indicate that fluid flow in the crust at those sites is localized to brecciated zones which occur below massive flow basalts. By analogy, the breccia zones interpreted at Site 418A may have acted as fluid flow channels at an earlier time. Six major paleo fluid flow zones are interpreted at Site 418A and they are labeled B1-B6 on Figure

6. Zone B6 is the major breccia interval at a depth of 514 mbsf. Three other breccia intervals are of particular interest. B2 and B3 occur below the massive basalt flow unit M3 in Figure 6. These breccia zone have low velocities (P, S, and Stoneley), increased apparent attenuation, and an increase in gamma ray activity. This interval is interpreted as a permeable pathway which may have been altered by the second stage of oxidizing alteration as described by Holmes (1988). The interval labeled B5 consists of a number of breccia units in close proximity as seen in the MCS data (Figure 6). Each unit has low velocity and resistivity as well as higher apparent attenuation and higher gamma ray activity. The massive basalt flow units are also easily identified in the MCS data. Four massive units are labeled in Figure 6 (M1–M4). Note that the breccia units occur just below these massive units.

The P, S, and Stoneley wave velocity estimates obtained by MSP help delineate the lithologic cycles in general, and the paleo fluid flow zones in particular. The Stoneley wave velocity estimates are very useful in this regard. The plot of trace energy provides a robust measure of general attenuation as a function of depth. Note that the brecciated zones correspond to decreases in the trace energy. Because of the high amplitude Stoneley waves present in this data, this measure is most sensitive to variations in the Stoneley wave energy or attenuation. The Stoneley wave attenuation is most sensitive to the borehole fluid Q value, the formation shear wave Q value, the borehole diameter, and the permeability at the borehole wall. We can safely assume that the fluid Q value is quite high and is constant throughout the borehole. Likewise, the borehole diameter is fairly constant in the interval below about 300 mbsf. Therefore, the changes in trace energy may be related to variations in the shear wave Q value of the formation, the permeability of the borehole wall, or increased scattering due to the presence of fractures, all of which may be indicative of fluid flow or paleo fluid flow capacity. Therefore, the relative decrease in the energy value for the different brecciated intervals may provide a measure of relative paleo fluid flow capacity. Zones B2, B3, B4, and B6 all have similar energy levels, while the B5 interval has a much higher apparent attenuation. This suggests a more highly fractured interval at this depth, and a higher paleo fluid flow capacity.

By looking at the MCS data itself much insight can be gained into the variations in lithology in ODP boreholes. The trace energy provides a stable measure of apparent attenuation which may be related to alteration, fracturing, or permeability (if there are open fractures). Velocity estimates for P, S, and Stoneley waves provide useful information about lithologic variability if interpreted in detail. The use of the MSP method is useful in providing stable velocity estimates. This is particularly true for the shear and Stoneley wave velocity estimates.

ACKNOWLEDGEMENTS

The authors would like to thank Dave Goldberg of Lamont-Doherty Geological Observatory for providing tapes of the geophysical logging data which was used in this study. Discussions with Roy Wilkens of Hawaii School of Ocean and Earth Science and Technology were very helpful in formulating our ideas. The work is supported by NSF Grant OCE-89000316 and the Full Waveform Acoustic Logging Consortium at M.I.T..

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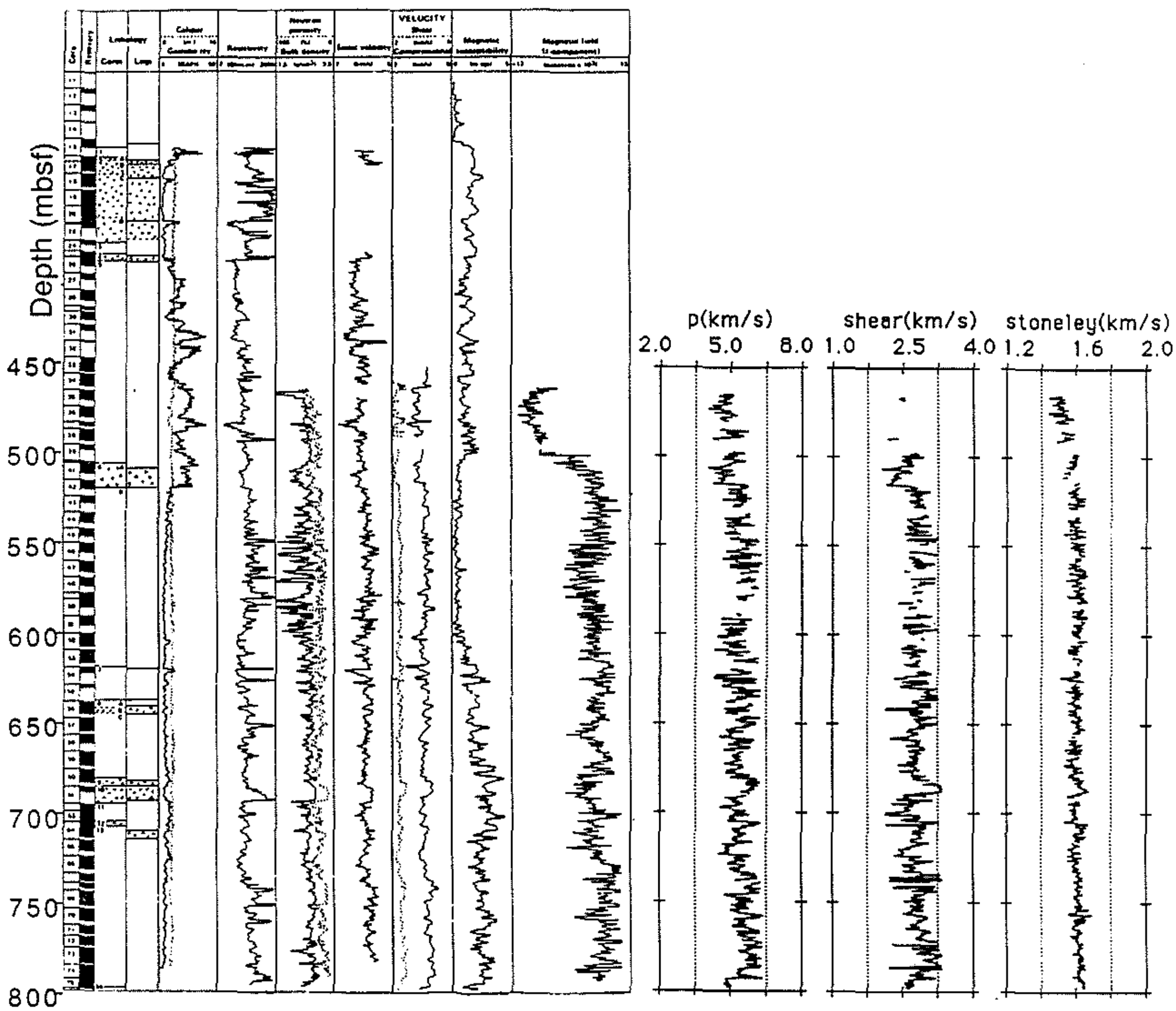

Figure 1: 1 Geophysical log data from Site 418A (from Leg 102 Shipboard Scientific Party, 1986), and the P, S, and Stoneley wave velocities computed using multishot processing on the multichannel sonic log data.

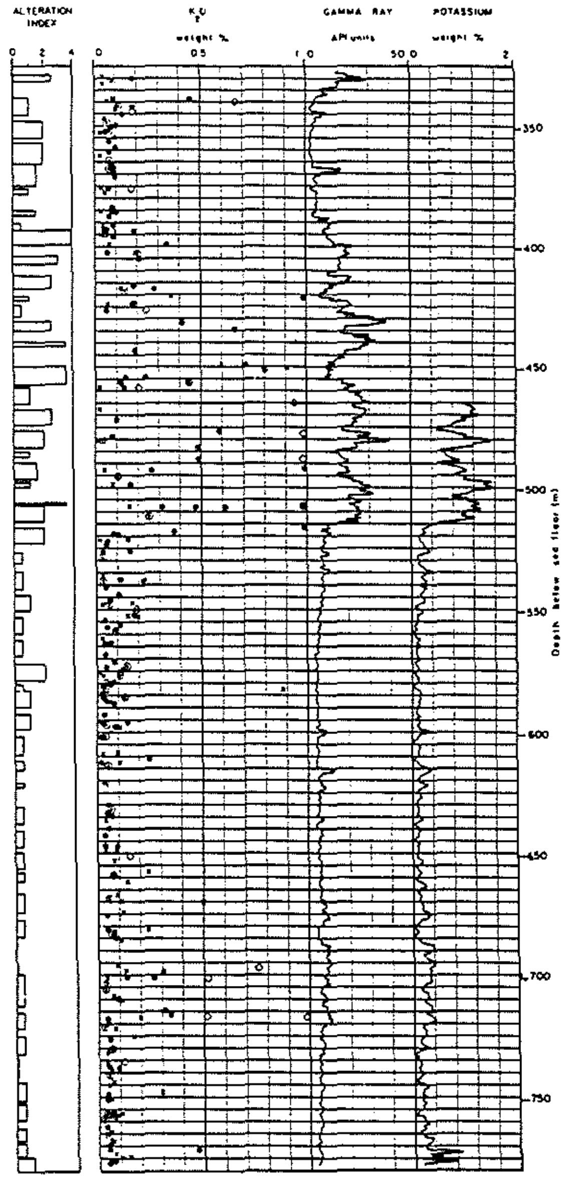

Figure 2: Core measured K_2O values and the natural gamma ray and spectral gamma ray (potassium) logs from Site 418A (from Broglia and Moos, 1988).

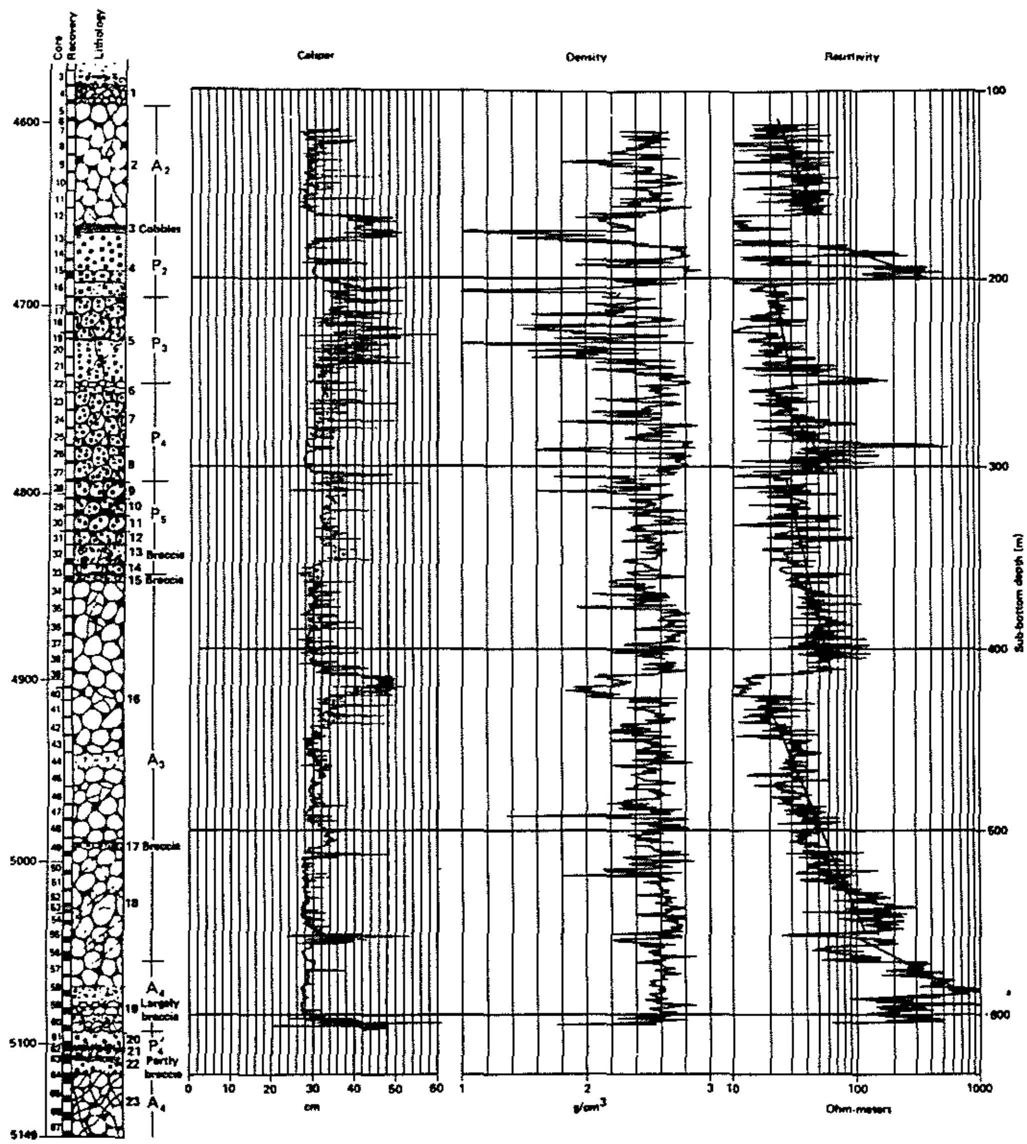

Figure 3: Geophysical log data and core lithology information from Site 395A. The resistivity log shows the interpreted lithologic cycles (from Leg 109 Shipboard Scientific Party, 1988).

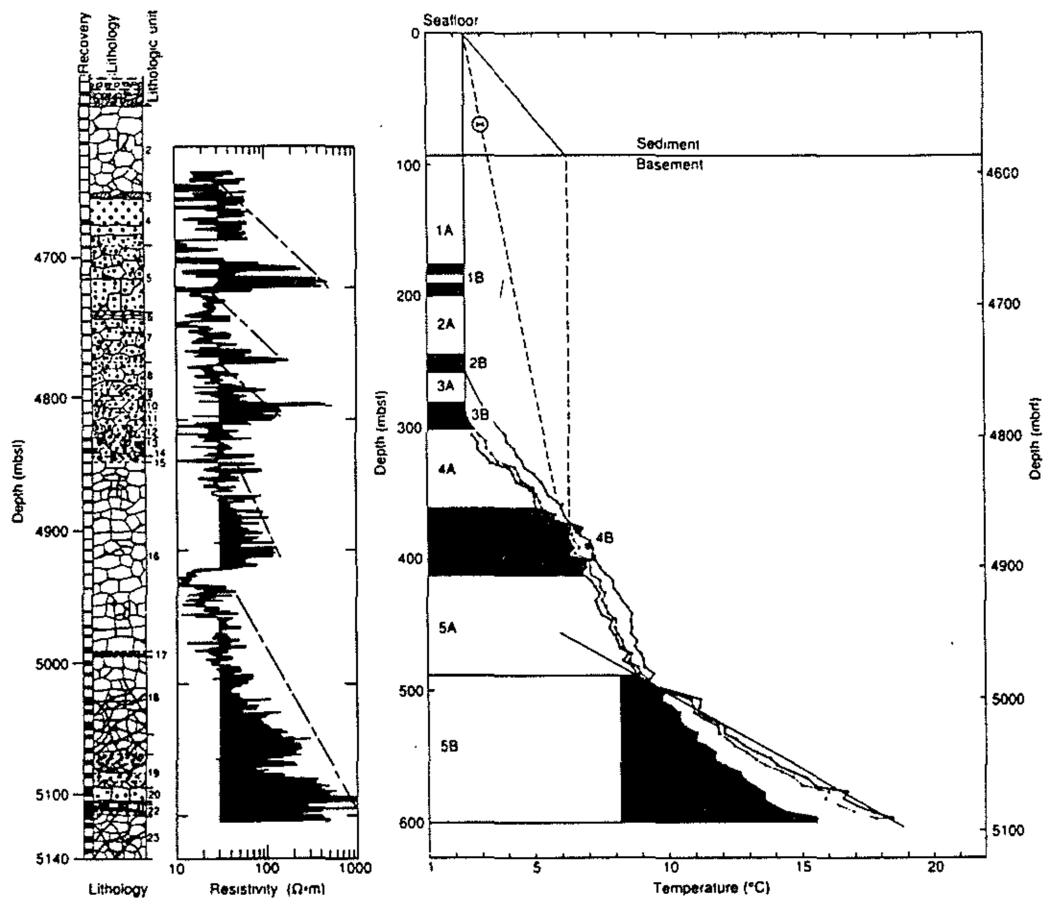

Figure 4: Site 395A resistivity log with interpreted lithologic cycles and the downhole temperature log data. Changes in the temperature gradient occur in the breccia or rubble zones directly beneath massive flow units (from Leg 111 Shipboard Scientific Party, 1988).

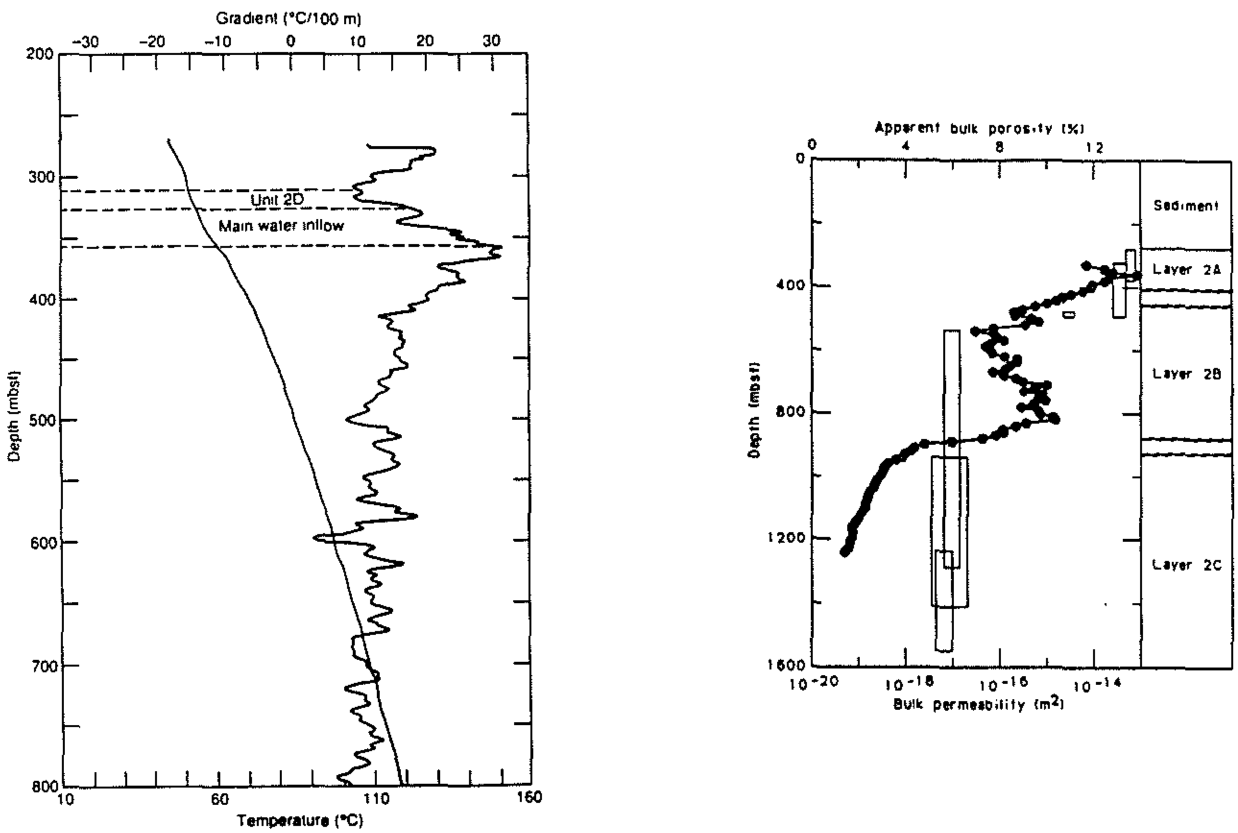

Figure 5: Temperature gradient, porosity, and permeability data from Site 504B. High permeability and water inflow occur below massive basalt unit 2D (from Leg 111 Shipboard Scientific Party, 1988).

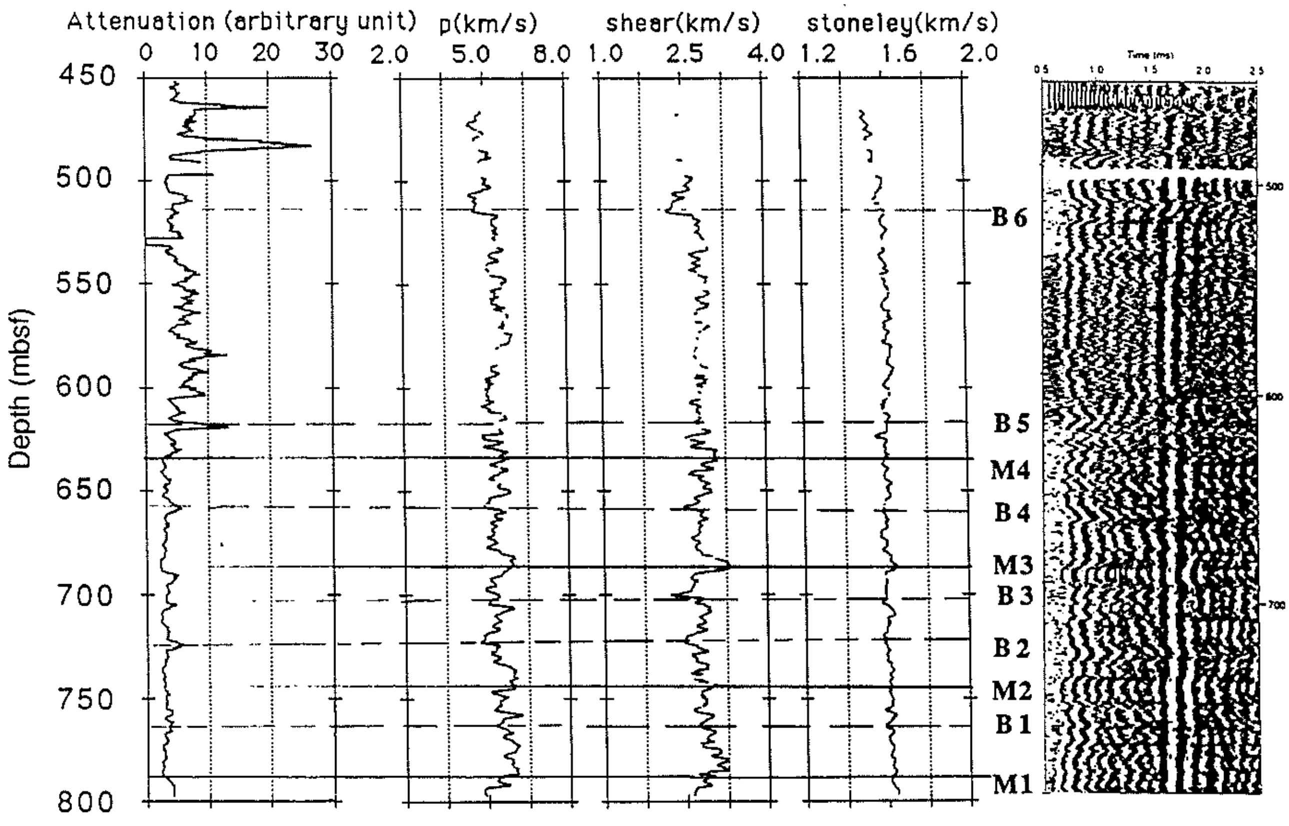

Figure 6: Results of the multichannel sonic log processing. The trace energy measure is plotted as apparent attenuation. The smoothed P, S, and Stoneley wave velocities were computed using multishot processing. The isooffset section is from Moos (1988). The interpreted breccia units are labeled B1 - B6 and indicated by dashed lines, while the interpreted massive flow units are labeled M1 - M4 and indicated by solid lines. The breccia units are identified by low velocities, increased apparent attenuation, and delayed P wave arrival times on the MCS data. The massive units have early P wave arrival times on the MCS data, high velocities, and low apparent attenuation.

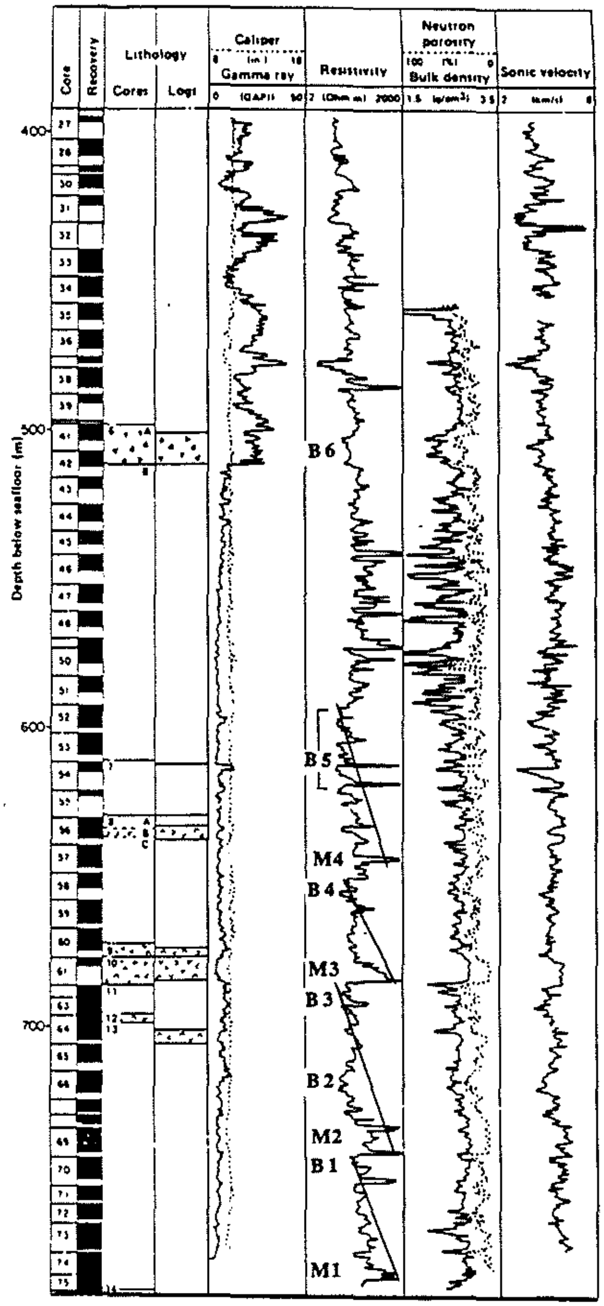

Figure 7: Site 418A geophysical logs and core lithology. Lithologic cycles are interpreted from the resistivity log. Note that each cycle could be further subdivided into subcycles. The cycles grade from massive flow units at the base to breccia or rubble zones ar the top. Based on the MCS data interpretation (Figure 6), the massive units are labeled M1–M4 and the breccia units are labeled B1–B6. Note the increase in gamma activity in the breccia zones.