OCEAN DRILLING PROGRAM

Wireline Logging Manual

Volume 1

The Basic Physical Principles of Well Logging

Borehole Research Group
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York 10964

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Chapter 1. The Basic Physical Principles of Well Logging

The major problem we face in the Ocean Drilling Program (ODP) is the use of downhole tools designed to detect hydrocarbons for something quite different: subsurface geology. Geology has little in common with either hydrocarbons or water confined within the pore space of a rock, and the tools themselves do not detect oil, gas or water directly. Consequently, combinations of different tools are necessary to determine either the lithology or the type of fluid in the formation. It is very important to always keep in mind the physics behind each type of logging tool because we must understand what these tools are actually measuring when they are lowered into the ODP's unusual environments such as basalts with under 10% porosity or sediments with over 60% porosity.

Density and Neutron Porosity Logs

In order to test how much of the physics of downhole measurements we really understand consider a standard set of logs: gamma ray, bulk density and neutron porosity (Figure 1). The density tool uses a cesium source to bombard the formation with gamma rays; these are scattered through the rock and gradually losing energy. The tool measures the energy level of the gamma rays returned to a NaI crystal with a photo multiplier, which measures flashes of light emitted as each gamma ray impacts the crystal. A simple geiger-counter does the same thing, except that it emits a "click" rather than storing the energy level. The drop in gamma ray energy occurring during the scattering process through water, rock matrix, and hydrocarbons, is strictly related to the electron density of the formation and in turn to the bulk density of the rock. Thus, the physical measurement made by the density tool does not discriminate the density of the rock matrix from that of the pore fluid. Therefore, other measurements are necessary to detect the differences among water, oil, and gas in the pore space of the rock.

The neutron porosity tool employs a chemical source (Am-Be) to bombard the borehole and the formation with neutrons. Neutrons collide with the molecules in formation and lose energy with each collision, just as gamma rays do. But neutrons lose energy most effectively when they hit something their own size. Neutrons are closest in size to hydrogen atoms present in the fluid and rock. In order to better understand this physical principle consider the case of a cue ball hitting the snooker ball versus the bowling ball. If your neutron (the cue ball) hits a hydrogen atom (the snooker ball) which is the same size, significant energy transfer occurs. If a neutron hits any other element in the formation or fluid (a bowling ball), the neutron loses less energy. In conclusion, the response of the neutron tool depends on the hydrogen concentration in the formation, and because water and hydrocarbons have different hydrogen indexes, the neutron porosity device allows us to discriminate among the types of fluid in the rock.

Water is densely packed with hydrogen atoms. Hydrocarbons are complex organic molecules of very large size, thus hydrocarbons do not ordinarily have as much hydrogen per unit volume because the molecules are much larger than H₂O molecules. If the pore
fluid is a heavy oil, it could have almost as many hydrogens as water but if it is a light oil, or gas, it will have a lower hydrogen index.

In the sandstone reservoir from 2500 to 2550 feet in Figure 1 gas, oil, and water can be discriminated by using both density and neutron logs. While the neuron log yields a very different response for the three types of fluid (with the typical crossover to low density-low porosity in the gas-bearing interval), the density log exhibits similar low density values over the gas and oil zones, thus indicating the presence of a very light oil.

In the example of Figure 1 the neutron log exhibits the highest values over clay-rich zones (shale). These high porosity readings, however, are only apparent; in fact, because of its sensitivity to all the hydrogens present in the formation. The neutron tool "sees" the bound water associated with clay minerals, and translates it into additional porosity. The amount of bound water varies with the clay type, and is inversely related to its hydrogen index. Corrections based on the volume of clay present and on the response to the clay type in the formation are required to estimate the "true" porosity of the rock.

Natural Gamma Ray Log

The addition of a measure of the natural radioactivity of the formation further contributes to the ability to find oil and gas. Natural radioactive decay from potassium, uranium and thorium produces gamma rays that can be measured by a NaI scintillation detector. In sedimentary formations the gamma ray log reflects the shale content of the formation, because radioactive minerals concentrate in clays. Igneous rocks can also exhibit high radioactivity levels, due to the presence of potassium-rich minerals. In the example in Figure 1 the gamma ray log allows us to recognize the shales from the "clean" sandstone intervals.

While potassium is chemically bound into the shale, uranium is electrically attracted to slots occupied by oxygen in the clays. If millions of years after burial the shale is swept by an oxygenated ground water, the uranium will be leached away and deposited elsewhere. The concentration of uranium in the sediments will be controlled by depositional environment and diagenetic processes, thus adding information on the geologic history of the well.

Acoustic Logs

Another useful physical measurement is acoustic velocity. While this measurement can be effectively used for gas identification (where it corresponds to a large reduction in compressional velocity) it does not provide any help when we try to separate oil and water. If we bang a hammer on a table, the acoustic energy travels through the table, regardless of the presence of fluid on the top. The velocity measurement is thus primarily made to separate the matrix from the fluid. If both shear and compressional velocities are measured, then we can describe the elastic parameters of the rock.

Of course, another important reason to measure sonic velocities is that the well was sited based on seismic reflection profiling. Velocity times density gives seismic impedance which is used to generate synthetic seismograms to tie well-depths to seismic times.
Figure 1. Example of the typical response of standard logs in a sandstone gas- and oil-bearing reservoir.
Electrical Resistivity Logs

The resistance of a rock to the passage of an electrical current provides significant help in determining the pore fluid composition. The transmission characteristics of an electrical current are the opposite of those of an acoustic wave; unlike sound energy, an electrical current moves primarily through the pore fluid. Water is the most conductive fluid; its conductivity is directly proportional to salinity and, to a lesser degree, to temperature. In fact, the presence of Na$^+$ and Cl$^-$ ions promotes the flow of electrons, while a temperature increase increases their mobility.

One of the major problems in reservoir analysis based on well logs is that clays can greatly contribute to an increase of the conductivity of a reservoir; in fact, all clays have negative charges because of electrostatically unbalanced substitutions within their lattice or of broken bonds on the edges of the silica-alumina units. These charges are partially balanced by absorption on the clay surfaces of counter-ions, which are exchangeable with other cations in aqueous solutions. The amount of this cations is called cation exchange capacity (CEC) and is responsible for the additional conductivity observed, for example, in shaley sands.

Hydrocarbons have low conductivity (high resistivity) because they do not contain many free ions within their huge, complex organic molecules. In the sandstone of Figure 1 the hydrocarbons are recognized by the high resistivity values between 2495 and 2515 ft, with gas being more resistive than oil.

Table 1 summarizes the typical responses to gas, oil, water, and shale of the logs commonly used in the oil industry. See Volume 2 for more detail about how these geophysical logs are used in oil exploration.

Geochemical Logs

The measurement performed with the geochemical logging tool (GLT) is more complicated than that of physical properties such as bulk density or porosity. It uses a pulsed-neutron accelerator, called a "minitron" to bombard the formation with fast neutrons. The "minitron" was developed by NASA to measure the chemical composition of the moon by remote sensing. The Apollo capsule shot neutrons at the surface of the moon and measured the energy level of gamma rays returned from the surface. The gamma rays emitted by interaction of the fast neutrons with the nuclei in the formation are measured in the geochemical logging tool by a spectrometer consisting of a NaI detector and a 256-channel analyzer. Each gamma ray that randomly hits the NaI crystal (similar to that employed in the natural gamma ray spectrometry tool) makes a flash of light of a certain "color" which is a function of the energy of the gamma ray that has just collided with the crystal.

Unlike the GLT, gamma ray spectroscopy experiments carried out in a laboratory utilize a germanium crystal. This is not used for logging because it must be maintained at cryogenic temperatures; in fact these crystals are clear at temperatures near -270°C, whereas they become "cloudy" at room temperature. The advantage in using a germanium
Table 1. Response of well logs commonly used in oil/gas detection.

<table>
<thead>
<tr>
<th></th>
<th>Gamma Ray</th>
<th>Resistivity</th>
<th>Neutron Porosity</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td>low (1)</td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>OIL</td>
<td>low</td>
<td>high</td>
<td>medium-high (2)</td>
<td>medium-high (3)</td>
</tr>
<tr>
<td>WATER</td>
<td>low</td>
<td>low</td>
<td>medium-high</td>
<td>medium-high</td>
</tr>
<tr>
<td>SHALE</td>
<td>high (4)</td>
<td>low</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>

(1) assuming a "shale-free" reservoir
(2) depending on the oil hydrogen index
(3) depending on the oil density
(4) assuming K-rich shales
crystal is an enhanced sharpness in the "color" of the flash of light, though the brightness is slightly lower. On the other hand, the sodium iodide crystal works at temperature as high as 150°C, above which it also becomes "cloudy".

The geochemical logs of the well displayed in Figure 2 provide the elemental abundances of iron, silica, calcium, and aluminum from induced gamma ray spectroscopy, as well as the concentration of thorium, uranium, and potassium from natural radioactivity. The combination of these chemical curves allows for a precise definition of lithology. In the example of Figure 2 two sandstone intervals, separated by a "shale" layer, can be identified between 2300 and 2500 ft. They are characterized by high silicon content, and low concentration in the radioactive elements. The lower interval exhibits an increase in iron and aluminum, which might be related to the presence of abundant feldspars. The shales are seen by their high aluminum, iron, potassium, uranium, and thorium content. Also, they display lower silicon content than the sandstones above. The calcium curve in Figure 2 leaves no doubt about the presence of two limestone layers at 2750 and 2900 ft.

The Ocean Drilling Program

"The Ocean Drilling Program is the world's largest and most successful multinational earth science research effort. By drilling deep beneath the sea floor, scientist can reconstruct the fundamental mechanisms that have led to formation of ocean basins, island chains, and mountain ranges. The ODP provides researchers with data essential to understanding the history and structure of the earth's slowly changing surface, and the evolution of its climate" (from "A record of our changing planet", Joint Oceanographic Institution).

The program employs a 143-meter long drilling ship, the JOIDES Resolution, to drill holes in waters as deep as 4-5,000 meters. Drilling is routinely performed with one way fluid circulation, (no return of fluid and cuttings to the surface), by lowering the drill pipe freely through the water column (Figure 3). At the beginning of some holes a re-entry cone is drilled into place and cemented with a short casing string. This allows scientists to re-enter the hole during subsequent legs by using a television camera, located at the bottom tip of the pipe. Unlike the oil industry, where selected hole intervals are sampled by sidewall coring, continuous coring is a standard practice in the Ocean Drilling Program. However, in most of cases continuous coring does not result in 100% core recovery; well logs are effectively used to fill these gaps.

When discussing logging within the ODP, it is very important to always keep in mind the basic physical principles behind each measurement, because the logging tools are used in scientific environments very different from those encountered in oil exploration (see above). Several improvements of tools and techniques have been necessary to solve some problems related to the unusual ODP logging environment for example, ship's heave. Because there is no "riser" connection to the sea floor the ship's heave is transmitted as movement onto the logging cable, thus affecting all measurements to various degrees. To solve the problem, L-DGO-BRG contracted Schlumberger to design a wireline heave motion compensator (WHC) for the logging cable. After an independent engineering report
Figure 2. Geochemical logging results compared with analyses made on sidewall core samples from the Conoco Test Well in the Anadarko Basin. Standard deviations between core and log results are shown at bottom.
Figure 3. Schematic drawing of logging operation on the JOIDES Resolution.
determined that the design was effective, the compensator was installed on the starboard side of the winch cab. During logging operations the logging cable is run from the winch to the rig floor, then back through a piston-mounted sheave on the heave compensator, and back again to the rig floor. As the piston extends, the length of cable between the winch drum and the rig floor is reduced by twice the amount of extension. The ship's heave is sensed by an accelerometer mounted near the rig floor, and the signal is transmitted to a computer which computes the effective motion. The piston-mounted sheave is then driven in or out to compensate for vertical motions of the drilling vessel. Tests of this system on ODP legs indicated that in operation the heave compensator improved log quality and reduced the primary components of ship's heave by more than 50%.

Another major problem encountered when logging for the Ocean Drilling Program is the bad hole conditions, mainly caused by the use of seawater as drilling fluid. In soft sediments seawater causes clays to swell, thus producing bridges that have often limited or prevented the logging program in the well. Besides the introduction of additives such as KCl or, less often, bentonite in order to inhibit clay swelling, we have adapted a part of the oil industry's horizontal logging capabilities called a Sidewall Entry Sub (SES). The drill pipe is first lowered into the hole and then the logging tool is lowered into the top of the drill pipe through the SES. The logging cable travels from the winch outside the drill pipe to the SES, where it passes inside the pipe to connect to the logging tool. This SES is then lowered with the drill pipe; the logging tool is pushed through the bottom of the drill pipe: and the tool and pipe are pulled upward simultaneously during logging. As you might guess, communication and coordination are difficult, and ODP has lost two logging tools so far using this technique. On the other hand, many ODP wells have been logged successfully with this technique.

Conclusions

Table 2 summarizes the major differences between ODP and oil industry data acquisition cultures. In the oil industry, sidewall coring is carried out solely in the hydrocarbon-bearing intervals, and only selective analyses are performed. Neglecting the rest of the hole means missing important information about the geology of the well (for example about the aquifer and the water replacement system of a reservoir delivering oil or gas to the surface).

In the ODP, we continuously core by wireline and have an extensive sampling and analysis program, both on the ship and on shore. A full array of measurements is routinely carried out on board (e.g. X-ray fluorescence and diffraction, pore fluid analysis, physical and magnetic properties, and biostratigraphy).

Finally, as you will see in the following volumes, the logging suites run in the Ocean Drilling Program are more complete than those run in in the oil industry. In fact, logging for the Ocean Drilling Program is the most technically complete downhole measurement program operated on a routine basis in the world. In succeeding volumes of this logging manual, the methodology for scientific well logging will be presented in more detail.
Table 2. Comparison of data acquisition cultures.

<table>
<thead>
<tr>
<th>OIL INDUSTRY</th>
<th>ODP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SELECTIVE CORING</td>
<td>CONTINUOUS CORING</td>
</tr>
<tr>
<td>VERY SELECTIVE ANALYSIS</td>
<td>VERY RIGOROUS ANALYSIS</td>
</tr>
<tr>
<td>ONLY RESERVOIR ANALYSED</td>
<td>ALL MATERIALS ANALYSED</td>
</tr>
<tr>
<td>GENERALLY MORE LIMITED LOGGING SUITES</td>
<td>VERY DIVERSE LOGGING SUITES</td>
</tr>
</tbody>
</table>
OCEAN DRILLING PROGRAM

Wireline Logging Manual
Volume 2

Exploration Well Logging:
A Historical Perspective

Borehole Research Group
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York 10964

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Exploration Well Logging: A Historical Perspective

Within the Ocean Drilling Program (ODP), there is often confusion as to what benefits will come from having an arsenal of downhole measurements run in a well when one could use the rig time to obtain more core material. One of the basic differences between ODP and the oil industry is that the ODP cores continuously. The oil industry's primary method for finding oil in a well is wireline logging, and consequently, it tries to minimize core because it is very expensive. Within ODP, the situation is reversed; because obtaining cores is your primary objective, there is a certain amount of reticence to use precious rig time for logging. But most ODP scientists now appreciate the added value of logging:

1) logging measurements are made at \textit{in situ} conditions,
2) logging measurements are made on a continuous basis throughout the well with no missed section, and
3) logging sample size is many times larger than cores.

These are the distinct advantages of downhole measurements within the ODP, as well as in the oil industry. Below, we will review the development of exploration well logging from the oil industry perspective. A perspective of where logging came from may help the scientist to better realize the strengths and weaknesses of logging when used to solve strictly geological problems. At the end of this volume, we should be to the point where the jargon, definitions, and perspective are out of the way so that subsequent volumes can discuss how to apply well logs to scientific objectives.

The Early Logs

The very first well log was an electrical log run in 1927 by the Schlumberger brothers in the Paris basin, France (Figure 1). In those days, the first logs were done in stationary mode: that is, the cable was stopped for several minutes at fixed points in the well in order to make the measurement (logs are now run continuously uphole).

The simplest of the early logging tools, which emerged in the early 1930's, and which is still part of the standard logging suite today, is the self potential (SP) log. The SP log is basically a single electrode pulled up the hole. It measures the "natural voltages" in the subsurface through an earth return. These "natural voltages" are, in fact, completely unnatural because they would not exist if the hole was not there. But the SP is still useful because it gives information about permeable zones. Electrochemical cells are established at boundaries between sands and shales, assuming that there is a salinity contrast between the borehole and the formation fluids. The SP log provides a very qualitative picture of the permeability in the formation.

The normal resistivity device, which came into use around 1932, is still offered today by a number of contractors and is used widely in other industries, for example for water resource evaluation. It was the first continuous measurement of the resistivity of the
Figure 1. The first log was an electrical log recorded by the Schlumberger brothers in 1927.
subsurface. These electrical logs could be used to determine bed thickness because resistivity changes from one bed to another. Also, high resistivity gave indication of the presence of hydrocarbon-bearing zones.

As we entered the era just before the Second World War, the practice of formation evaluation using downhole measurements was simply of correlating these electrical logs between wells and of trying to locate permeable zones with the SP log.

Archie's Law

This qualitative approach was dramatically changed in 1941 by the work of Gus Archie from Shell, who put together the "formation factor" concept from work of a number of previous investigators (in fact, the formation factor concept, now called "Archie's Law" was introduced by a Swede, Karl Sundberg, in 1932). Archie's Law (Table 1) contains the basic quantitative definitions of how to find hydrocarbons using resistivity logs. Basically, Archie put different electrolytes into the pore system of a rock in the laboratory and observed that the ratio of $R_o$ (the resistivity of a rock 100% saturated with water) to $R_w$ (water resistivity) remained nearly constant for resistivity of the electrolyte $< 1 \, \Omega m$. Therefore, the ratio was not a factor of the fluid; it was a factor of the formation. Called the "formation factor", Archie developed this into the partially saturated domain by observing that the more you de-saturated the rock, the more resistive it became. The ratio of $R_o$ to $R_i$ (formation resistivity), called the "water saturation index" ($S_w$; Table 1), was intuitively linked to the amount of water versus hydrocarbon in pores. These two equations (formation factor and $S_w$) have become known as the first and second Archie's laws.

Archie's first law, which related formation factor to porosity was essentially empirical (he observed that there was a logarithmic relation, Figure 2). He called the gradient "m" the "cementation factor" or the cementation indicator. These days people use it as a pore geometry exponent. The second law relates the resistivity index to the water saturation - the fraction of the pore space that is actually filled with electrolyte as opposed to fluids such as gas or oil. Again these were found to be exponentially related. The gradient "n" was called "saturation exponent." The first law has never been proved theoretically, though it has been established empirically in the laboratory in numerous formations, including basals and other fractured media. It is used extensively within the ODP to calculate porosity from resistivity.

Interpretation Philosophy - 1945

If we move to 1945, we can begin to see modifications made to Archie's Law. We are already approaching the philosophy of log evaluation as it is today in the oil industry.

Resistivity logging tools of 1945 measured $R_i$ and $R_w$, allowing the formation factor to be calculated from Archie's first law. Measurement of formation resistivity from sidewall cores would then allow the calculation of porosity. If you didn't know "m", you would assume it to be equal to two. But there was no way of separating the porosity effects
Table 1. Archie's Laws (1942) for clean (no clay present) sands.

\[
\phi = \left( \frac{a}{F} \right)^{1/m} = \left( \frac{R_w}{R_o} \right)^{1/m}
\]

\[
S_w = \left( \frac{1}{l} \right)^{1/n} = \left( \frac{FR_w}{R_t} \right)^{1/n}
\]

\(\phi\) = porosity

\(F\) = formation factor

\(m\) = cementation factor

\(a\) = empirically determined constant

\(R_w\) = formation resistivity (100% water-saturated)

\(R_o\) = formation water resistivity

\(R_t\) = formation resistivity

\(S_w\) = water saturation (% of pore space occupied by water)

\(l\) = resistivity index

\(n\) = saturation exponent

soft formations: \(a = 0.62\) \(m = 2.15\)

\(a = 0.81\) \(m = 2\)

hard formations: \(a = 1\) \(m = 2\)
Figure 2. Formation resistivity factor - porosity correlation from different laboratories (after Hook, 1983).
caused by lithology changes from those created by the occurrence of the hydrocarbons, so the practice was to assume constant porosity throughout the possible reservoir intervals. That is, you could measure porosity in the water zone through this new empirical facility of Archie, but you couldn’t find it in the hydrocarbon zone. If you then measured the formation resistivity of the hydrocarbon zone, \( R_w \) from a sample of water, and the formation factor of the water zone, then you could calculate a resistivity index (I; Figure 3). If you measured the value of "m" (and if you did not know it, you assumed 2 again), you could then calculate \( S_w \) from Archie’s second law. The relationship between I and \( S_w \) is shown in Figure 4. Combined with the bed thicknesses, \( S_w \) told you the total amount of recoverable hydrocarbons in the well.

Tool Developments - 1945-1970

By the end of the Second World War, the quantitative approach in well log interpretation was established, but some important technical and interpretation problems were still waiting for a solution. Among them, the need of resistivity tools with different depth of investigation, able to provide a measurement in both the shallow "flushed" zone (invaded by the drilling mud filtrate) and the deep "virgin" zone, unaffected by the mud filtrate. Such tools would provide a key to a better estimate of the porosity (allowing for a correction for the effect of hydrocarbons), of water saturation, and of movable and irremovable hydrocarbons.

So the tool development of the next twenty five years was directed at filling these gaps (Table 2). First we saw the emergence of the microlog, a pad-device consisting of two switchable arrays of electrodes several centimeters apart. Because they are sensing resistivity variations only very close to the hole, they are very much influenced by the mudcake. The mudcake forms when the formation is permeable; if there is no mudcake, we presume there is no permeability because there has been no mud filtrate invasion. Where the mudcake is thick, the two microlog electrodes respond differently and the measured resistivity curves separate.

Because of its very shallow investigation, the microlog was not the answer to the porosity problem (Figure 4). In the early 1980's, Schlumberger tried to withdraw it from the market, but there was pressure from oil industry customers to maintain it because it provided unambiguous information about the location of permeable zones.

In response to the porosity problem several non-electrical porosity measurement tools were designed in this period, such as the neutron porosity, gamma ray density and continuous velocity tools. There are now algorithms relating the responses of all these tools to porosity. In the latter two cases, the algorithms are conceptual, while in the former, they are empirical.

The other major developments during this time were the deep sensing resistivity logs. These focused tools were specifically designed to investigate the virgin zone, that is the zone uninvasive by the mud filtrate. The development of electrical induction devices, guard logs, and laterologs allowed for the first time a precise measurement of the bulk resistivity of the formation.

At this point we saw the emergence of the same interpretation philosophy that is in use today (Figure 5). We could now measure porosity from nuclear logs and the resistivity of
Figure 3. Resistivity index - water saturation correlation (after Hook, 1983).
Table 2. Tool developments in the 1945-1970 period.

- **Microlog**
  - Micronormal
  - Microinverse

- **Porosity**
  - Neutron–Neutron Log
  - Continuous Velocity Log
  - Gamma–Gamma (Density) Log

- **Deep Resistivity**
  - Induction Log
  - Guard Log
  - Laterolog
Figure 4. 1945 interpretation philosophy in clean unconsolidated formations.
Figure 5. 1945-1970 interpretation philosophy in clean formations.
the rock in both flushed and virgin zones. Note that in Figure 5 Archie's first law is now being used backwards. The original intention of Archie was to move from resistivity to porosity, and then to hydrocarbon concentration. What happened by 1955 was that we measured neutron and density porosity in the hydrocarbon zone and used that to calculate a formation factor independent of resistivity. It's in this reversal of Archie's law that the shaley sand problems of the 1960's became evident (see below).

The basic problem is that shaley sands with water in the pore space look very much like oil-bearing reservoir rocks (Figure 6), and as such it remains one of the major technical difficulties that the oil industry faces today. Shaley sands are sandstones that contain intermixed clay minerals. In a shaley sand, the resistivity values are lower than what you would expect from the electrolyte distributed in the rock pore space (Figure 7). This effect is caused by the surface interaction between clay minerals and the electrolyte in the pore fluid; whenever clay mineral surface conduction effects are present, they have an impact on the determination of resistivity-derived porosity.

In terms of the ODP, there are also clear situations where data have been misinterpreted because clay mineral products over altered zones produce the same effects on resistivity data as in oil reservoirs. One must be careful that Archie's law not be applied indiscriminately. Archie said, "My law only works for clean situations" (Journal of Petroleum Technology, 1953).

After 1960, we moved into the era of the logging tools as we know them today. Dual and multi detector tools started to be developed in order to overcome some of the problems related to the borehole environment (such as mudcake). Also, many realized that perhaps Archie's original experimental assumptions were not quite as valid as were thought of at the time. In fact, Archie had specified quite clearly that the relationship was valid for limestones and sandstones with very little clay-mineral content and high salinity, and that his "law" was applicable only over certain ranges of porosity. If you look at the shaley-sand literature, it appears that in 1951 clay minerals suddenly began growing in abundance in the reservoir rocks, only to stop in 1960 when another generation of logs was introduced.

The Interpretation Philosophy into the 1970's

In shaley-sands, the formation factor \(R_s/R_w\) drops fairly steeply as the volume of clay increases. To take this into account the literature now offers 50 different equations (see Appendix II) that all attempt to evaluate this extra conductivity, called "\(X\)" in Figure 8. For Archie's original laws, there are now correction factors for each term. Unfortunately, each equation provides a different answer. However, a way to test which equation is most appropriate for a specific situation is to check the value of water saturation \(S_w\) in the water-bearing zone (dashed line in Figure 8), where it should be equal to 100%.

New Technologies of the 1980's

The standard logging suite in the oil industry in the 1970's consisted of caliper, gamma ray, sonic, density, neutron porosity, and various resistivity logs, each with different
\[ \begin{align*}
\Delta t_{sh} & \quad \rho_{sh} \\
\text{Clay Bound Water} & \quad \{ \text{Porosity} \}
\end{align*} \]

\[ \begin{align*}
R_{sh} \\
\text{Electrochemical Effects (CEC)} & \quad \{ \text{Resistivity} \}
\end{align*} \]

\[ \begin{align*}
\Delta t_{sh} &= \text{shale transit time} \\
\rho_{sh} &= \text{shale bulk density} \\
R_{sh} &= \text{shale resistivity}
\end{align*} \]

Figure 6. Problems of shaley sands.
Figure 7. Effect of shaliness upon Archie's relationships.
depths of investigation. This set of measurements, integrated with laboratory measurements, allowed us to solve the porosity and water saturation problems.

Things have dramatically changed since then because of a technological revolution. Because of the complexity of the function in Figure 8, there have been efforts to bypass the calculation of $S_w$ and measure oil directly. For example, high frequency dielectric tools have been developed to measure the difference in dielectric constant between oil and water, but they have limited depth of investigation. They investigate the flushed zone only, that is the portion around the borehole where the hydrocarbons are displaced by the mud filtrate. Carbon-oxygen tools have been constructed that use the bombardment of fast neutrons to directly measure the carbon-to-oxygen ratio in the formation. But these tools have been shown to have uncertainties as big as the range of $S_w$ error.

Advances in digital data acquisition and processing, both downhole and uphole, have allowed for downhole computers that could transmit data digitally to the surface. By the end of the 1970's the introduction of digital computers at the well site made it possible to look at the raw logging data in real-time, providing better quality control, calibration, and more efficient operation. Enormous advances in pulse electronics, high data rate sensors, and multiple telemetry systems opened the door to a new generation of logging tools:

Natural Gamma Ray Spectroscopy Log

Instead of the gamma ray tool which was developed in 1939, a natural gamma ray spectroscopy tool was introduced that measures the three most abundant components of the natural radioactivity of the rocks, K, U, and Th. The reason for separate determination of K, U and Th was to provide greater insight into lithology identification and clay typing. Charts like that in Figure 9 which maps clay mineral variations by relating thorium versus potassium, have been heavily criticized because they are too simplified. This correlation is likely to break down if you look in detail at the complex compositions of different clay types but it pointed the way to better quantitative understanding of the geology of a well.

Lithodensity Log

At the beginning of the 1980's the lithodensity tool replaced the old density tool. The new generation of tools added a diagnostic capacity for detecting lithology to the density log, by measuring the so-called "photoelectric absorption index". Unlike the old tool, they measure the entire gamma ray spectrum (Figure 10), including the low-energy region where the tool response is a function of the lithology. Originally, low-energy gamma rays were not taken into account because the primary objective was to obtain information about the density of the formation, not the lithology. The photoelectric absorption index allows for a better identification of the lithology and therefore a better quantification of the clay content; this, in turn, yields a more precise estimate of the porosity and water saturation in the formation.
Figure 9. Thorium versus potassium can be used to classify radioactive minerals via spectral gamma ray. Because of the variability of the thorium and potassium content of clay minerals, this plot should be used as a guide, not as a definitive interpretation to the possible clay minerals present on the rock.
Figure 10. Gamma ray detection in the low and high energy region of the spectrum recorded by the lithodensity tool.
Induced Gamma Ray Spectroscopy Tool

The determination of lithology was raised to an entirely new level with the development of pulsed-neutron tools. They record the full spectrum (256 energy channels) of the gamma rays emitted by capture of the bombarding neutrons by individual nuclei in the formation. Through a comparison of the recorded spectrum with a library of standard responses for different elements it is possible to calculate the actual elemental composition of the formation around the borehole.

Multichannel Sonic Log

Another exciting development was the emergence of sonic waveform measurement, instead of just measuring the compressional wave velocity. Waveform recording gives us the ability to calculate amplitude, frequency and velocity of shear as well as compressional waves, which provide useful information about the elastic properties of the rocks, and indirectly, about the lithology. One of the biggest drives in the industry now is the integration with surface seismic reflection profiling. Everybody is talking of the need to integrate data from downhole with that from the surface to build a complete description of the reservoir.

Logging in the Ocean Drilling Program

One very important point differentiates the scientific logging done by the Ocean Drilling Program from that used in the oil industry. The oil industry is very conservative and, surprisingly, does not like risk. Drilling requires risk, thus the industry does not add to those risks by using technology which is not well established. The industry will be ready to adopt new technologies only when they have been sufficiently tested in different situations. In the ODP this problem is not addressed, because we use the most recent logging technology and take the inevitable risks related to tool failure and to the different logging conditions. Taking these risks has brought the Ocean Drilling Program considerable advancement in logging techniques, such as geochemical logging.

The package of logs routinely used in the Ocean Drilling Program and the so-called specialty tools go some way beyond the logging suites that are commonly used in the oil field. In acoustics, we provide sonic waveform measurements and ultrasonic acoustic imaging from the borehole televiwer. In terms of electrical measurements, a wide array of tools is available: the phasor induction, the dual laterolog, the spherically focused log, and the Formation MicroScanner (in the four pad form specifically developed for ODP use). Only very recently have four pad FMS's become available in the oil industry as well. Borehole magnetics figure prominently in ODP, whereas they are hardly used in exploration. In terms of mechanical measurements, major thrusts within ODP are sampling good pore fluids, and conducting permeability measurements through wireline packer tests (another tool designed for ODP). As to nuclear measurements geochemical composition, density, and porosity are provided by pulsed-neutron, neutron-porosity, and lithodensity tools. Thermodynamics measurements are represented by an accurate pressure and
temperature logging tool (again designed for ODP) which can be attached to the bottom of both Schlumberger and specialty tools for multiple temperature runs. In summary, only optics are missing from the ODP logging arsenal; optical borehole television systems are available on the market, but none of them has yet been used within ODP.

The way these different logging tools are combined for each lowering in the well is summarized in Figure 11 (also see Volume 3, Chapter 2 for further details). The quad-tool logging string consists of: a) sonic waveform log; b) dual induction and spherically focused log; c) the natural spectral gamma ray log; d) lithodensity log for density and lithology determination; e) neutron porosity log, and f) caliper log to determine hole size.

The biggest departure between ODP and oil industry logging is that instead of a tool combination which traditionally looks at fluids (water and movable and irremovable hydrocarbons) we run a geochemical tool string (Figure 11). This string has three components: a) an induced gamma spectral tool operated in capture mode to give us elemental analysis of nine elements (Si, Fe, Ca, S, Ti, Gd, K, H, and Cl); b) an aluminum activation tool which provides a measurement of the aluminum content in the formation, and c) the natural gamma spectral tool, which measures the concentrations of potassium, thorium, and uranium, in addition to the natural radioactivity of the rock.

The third tool string is the Formation MicroScanner, which is combined with a gamma ray tool for depth correlation.

New Directions in Logging in the 1990's

The problem areas to be faced in the near future concern parameters, algorithms, and environment. In terms of parameters, despite the new arsenal of logging tools, we still do not know how to handle complex lithologies. A complex lithology is a rock other than a sandstone, limestone, and dolomite (which are the only three lithologies on the Schlumberger logging charts).

In terms of algorithms, we are still investigating Archie's law, as we are facing more and more situations where it is not directly applicable (i.e., oceanic basalts). We have learned a great deal about how to make resistivity measurements on the recovered cores, but we still have to find a way to keep the core structure intact before it gets into the laboratory. We must find a way to sample lithologies such as unconsolidated sands so that the pore geometry remains undisturbed; a possible solution, freezing the cores at the wellsite, raises the question of how to defrost them in the laboratory without bursting the liner, and altering the pore structure.

There has been a tendency to extrapolate algorithms well established in one geographic area to others as well. For example, the Indonesia formula, an algorithm devised to overcome a particular problem of shaley-fresh-water sands in Indonesia, has been indiscriminately used around the world.

Finally, in terms of environment, despite the fact that a fair amount of attention has been paid to improving the resolution of logging tools, we do not have a uniform approach to enhance the resolution in finely laminated reservoirs. Also, we still cannot measure the invasion profile. Logging in pressured zones is a very important safety issue, and logging of deviated wells is an interesting area in its own right. A deviated well introduces the question of anisotropy; anisotropy has been shoved under the carpet for years, and the
Figure 11. Schematic configurations of the Schlumberger tool strings operated in the Ocean Drilling Program
geophysicists with their seismic interpretations are as bad as log analysts in pretending that the problem does not exist. But times are changing now, and we will probably see more people paying attention to quantitative solutions of the problems introduced by formation anisotropy.

Conclusions

As far as well logs are concerned, we use them because they provide a continuous and in situ characterization of a larger volume of the subsurface than cores. We see them as complementing the cores, and therefore we must use use both intelligently.

Logging is beginning to appear in all the geosciences, such as continental drilling, hydrology, and climate change research. Whereas in the oil industry the logs provide a commercial legacy (and actually have a dollar trading value), we try to see them within the Ocean Drilling Program as a scientific legacy. Suppose we don't fully understand the logging results from a certain well. In a few years somebody may come back to the same area with a fresh understanding and say: "Aren't there any continuous in situ data in this area that I could now look at?". Consultants in the United States make very good livings by looking at old logs and finding oil that wasn't seen at the time because we didn't fully understand the measurements.

As you will see in the other volumes of this Logging Manual, logs have already provided a strong scientific input to the Ocean Drilling Program. But the full potential of this input has not yet been realized. Data integration is going to be the hallmark of the geosciences in the 1990's, and people who allow themselves to concentrate only in special fields without looking outside are going to miss an important piece of information. There is no room for isolationists in the 1990's, and that goes for academic and government scientists as well as for those in the industry.

Finally, - remember that "too much data poorly understood is often worse than not enough data". We have tried to get this message across in the Ocean Drilling Program as well. We feel that fewer holes studied thoroughly are better than more holes studied imperfectly. Also, it is too easy to catch the enthusiasm of the latest technology and neglect the basics. If the industry is going anywhere, it is to return now to ask questions about some of the basic physics and chemistry that are not totally understood. All the major logging tool developments that will be used in the next decade are available to us now, so we have the possibility of trying to understand more fully what logging data are telling us about subsurface geology.
OCEAN DRILLING PROGRAM

Wireline Logging Manual

Volume 3

The Logging Service

Borehole Research Group
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York 10964

SEPTEMBER, 1990
Introduction

Lamont-Doherty Geological Observatory, as the prime logging contractor for the Ocean Drilling Project, provides JOIDES scientists with a full suite of geophysical and geochemical services which involve the acquisition, processing, and presentation of in-situ logging measurements. Our charge is to supply state-of-the-art logging customized to the scientific needs of JOIDES scientists, plus certain specialty logs which are of particular usefulness to scientific logging. We also provide data interpretation and dissemination services so that JOIDES scientists can use the logs to help solve their particular scientific problems.

To direct us in these duties, the JOIDES Planning Committee has designated the Downhole Measurements Panel to plan long-term tool and services development, to assist in the identification of new technology and in recruiting scientific logging scientists to participate in each ODP leg, and to coordinate and integrate the L-DGO logging services with other downhole measurements programs planned for ODP legs.

Volume 1 of this Wireline Logging Manual is subdivided into three chapters. The first chapter provides an overview of shipboard operations and of the responsibilities of the logging personnel. The next section acquaints the reader with the various types of logging measurements by describing the physics behind each measurement, the form in which the preliminary data is displayed, and its primary applications. The final chapter discusses logging times and provide equations for their estimate.
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Chapter 1. The Logging Service

Structure of the Logging Service

The Borehole Research Group at Lamont-Doherty consists of the personnel and management structure shown in Table 1-1. In our research effort we are involved in a wide array of scientific logging investigations on the continents, as well as with the Ocean Drilling Program. This broad scientific scope benefits JOIDES logging services in two direct ways. First, tools and techniques developed throughout the logging industry are examined for their applicability to ODP needs often long before they become commercial products. Consequently, the JOIDES RESOLUTION is presently equipped with the most advanced multi-element geochemical logging technology, high Resolution borehole imaging, and multi-channel sonic logging capability. Secondly the land program provides us the crucial opportunity to field-test tools and processing techniques before they become operational on the JOIDES RESOLUTION.

As the prime logging contractor for ODP we subcontract Schlumberger, the industry leader, to supply and operate their state-of-the-art logging tools on every leg of ODP. In addition, we provide some specialty tools such as the Borehole Televiewer and the Multichannel Sonic tools, which are operated by Borehole Research Group personnel. Also, we have recently developed a self-contained temperature tool that can be attached to the bottom of a host drilling string. Each year, we hope to bring on-line a new specialty tool to add to the scientific logging capability aboard the ship. Finally, a log analysis center at Lamont-Doherty has computer processing, log analysis and interpretation services ready for the ODP scientists' use after leaving the ship. This center is designed to provide the JOIDES scientist with the interpretive skills and tools to solve his/her geological problems with the assistance of in-situ measurements.

Data Acquisition Overview

In the Ocean Drilling Program, geophysical log data are recorded using probes which are lowered on the end of a wireline into the previously drilled borehole. The depth at which the measurements are made is determined primarily by measuring the length of cable run into the hole. Small but significant errors in this depth measurement can result from cable stretch, small horizontal offsets of the ship and wave motion. Because much of the analysis of wireline logs depends on the ability to compare at each depth the results from different lowerings of the various tool combinations, each tool string includes a measurement of the natural radioactivity of the formation. In general, different logging runs can be depth-shifted using this common measurement. Once the depths have been corrected to a common point, identifiable horizons such as the sediment/basement contact or the
BOREHOLE GROUP PERSONNEL

Director of Operations: Dr. David Goldberg
Overall responsibility of BRG operations and ODP logging.
Chief Scientist: to be named
Long-term planning of ODP logging program in cooperation with ODP planning structure.
Project Scientist: Dr. Peter DeMenocal
Interpretation and evaluation of ODP logs; paleoecological interpretation.
Project Scientist: Dr. Chuan Yin
Development of scientific applications and interpretation of ODP logs.
Program Manager: Ms. Katherine Rodway
Management of LDGO-BRG operations and ODP contracts and subcontracts.
Database and Log Analysis Manager: Ms. Cristina Broglia
Supervision of database and data distribution, and of shore-based log analysis.
Log Analyst: Ms. Elizabeth L. Pratson
Geochemical and FMS processing and interpretation.
Database and Log Analysis Assistant: Ms. Debbie Barnes.
Database implementation and data distribution.
Computer Systems Manager: Mr. Michael Hobart
Design and maintenance of computer systems operated by the BRG on the ship and on shore.
Manager of Technical Operations: Mr. Frank Filice
Supervision of downhole systems operations and development.
Logistics Coordinator: Mr. Larry Sullivan
Procurement, shipping, and inventory management of ship and shore operations.
Research Engineer: Mr. Alex Meltzer
Downhole systems design, electrical and computer engineering.
Secretary: Ms. Janice Gittings
Graduate Students: Mr. Gilles Guerin, Mr. Craig Wilkinson.
bottom of the drill pipe can be used to relate the log depth to the drilling depth. As the length of the logged section is usually small compared to the water depth, slight residual cable stretch will not degrade the correlation between log and drill depth. Because core recovery is seldom 100%, however, the exact relationship between core samples within a given coring run and log data recorded over the cored interval is ambiguous. The correlation can be improved by running a gamma-ray or velocity log on the core before sampling.

Two types of logging tools are currently operated in the Ocean Drilling Program: Schlumberger tools and specialty tools. Each of these tools is described in some detail in the next chapter. Unlike specialty tools, Schlumberger tools can be stacked so that each type of measurement does not require a separate lowering. Log data are recorded whenever the logging sonde is moving in the open hole. Downgoing logs are recorded both to ensure that the tool string has not stopped at a hole constriction (to prevent tangling of the logging cable) and to ensure that if the tool fails during its ascent some data will have been recorded. Data recorded uphill, however, are more reliable, as tool motion is less erratic. An exception to this is temperature logging, which must be done on the down-going pass.

All logging tools operate continuously, but the data can be recorded and averaged only in discrete steps, in the Schlumberger logs at half-foot (0.1524-m) intervals. An exception is represented by the Formation MicroScanner, whose sampling rate is every 0.1 in (3 mm). However, if data need to be sampled as a function of time (for instance, to invert tool motion data to monitor the performance of the heave compensator) slow logging speeds increase the length of time between samples. For example, a logging speed of 300 feet/hour yields data points at one-minute intervals.

**Shipboard Operations**

**Shipboard Personnel**

To carry out the program at sea, there are three persons on each ODP leg: a logging scientist from the JOIDES scientific community, a Schlumberger field engineer to operate the tools, and a L-DGO-BRG logging scientist to assist the co-chiefs and co-chief scientists in the design, implementation and subsequent interpretation of the logging program on each leg. The JOIDES logging scientist is selected by Texas A & M, from applicants approved by the Downhole Measurements Panel.

The L-DGO-BRG logging scientist oversees the operate of the Schlumberger engineer to ensure that the log data are properly recorded. He/she also works with the JOIDES logging scientist to prepare a logging plan for each borehole, and attends the pre-cruise meeting to present the co-chiefs a description of the log measurements and the logging plan with time estimates, to allow the logs to be integrated into the overall cruise plan. The L-DGO-BRG logging scientist also operates the Lamont specialty tools and the logging computer. Postcruise data archiving, distribution, and display for the ODP Proceedings
volumes. Initial Reports Volume is the responsibility of the L-DGO-BRG database and log analysis personnel, in cooperation with the logging scientist on that cruise.

The JOIDES logging scientist is the person on the ship who is primarily responsible for the dissemination of the logging results to the scientific party, scientific log interpretation, and, in concert with the LDGO-BRG logging scientist, for the preparation of the logging chapters of the shipboard and later scientific reports.

Equipment Used During Logging Operations

Logging operations on the JOIDES RESOLUTION depend on a wide variety of equipment. Figure 1-1 shows the location on the ship of the primary components of the logging system. The logging winch, the Schlumberger logging cabin, and the wireline heave compensator are located at the end of the pipe racker. The Downhole Measurements Lab, (DML) just forward of the rig floor on top of the lab stack, houses the L-DGO logging computer, electronics lab, and tool storage. Space in the DML is shared with the re-entry tools. Specialty logs brought on board by individual scientists are staged from this area, and the logs themselves are run from a lab which provides a window looking over the rig floor. Due to space constraints, Schlumberger logging tools are stored on the roof of the lab stack, from which they are easily moved for logging operations. The nuclear sources used during Schlumberger logging are stored in shielded containers below the pipe racking system and are installed in the tools just before they are run into the hole.

Logging Winch

The logging winch system is the responsibility of SEDCO. It contains almost 10 km of 7-conductor logging cable. The cable is terminated with a torpedo connection which can be quickly connected to pigtails terminated with a variety of logging heads. The Schlumberger engineer maintains pigtails for connection to his tools. Pigtails terminated with a Gearhart-Owen 1 1/2 in. 7-conductor logging head are provided for the specialty logs and for wireline re-entry. In theory, this method allows the use of any cable-head which can be connected to a 7-conductor cable. However, no other termination schemes are currently supported on the JOIDES Resolution.

The winch can operate at any speed between about 100 m/hr and the safe maximum working limit set by the ODP Operations Manager. Depth in the hole is determined by measuring the length of cable run into the hole. The Schlumberger depth counter transmits 120 pulses per foot and is used during standard and L-DGO specialty operations. The TAMU depth counter delivers 500 pulses per foot and is used primarily for reentry.

The upper end of the cable is terminated at the TAMU winch cab. A connection panel there allows the signals to be transmitted either to the Schlumberger cab, the DML or the Underway Geophysics Lab. A second patch panel in the DML reroutes the signals to different areas of that lab or to the dynamic positioning shack above the bridge. Each of these connections is made using a Schlumberger A-K connector.
Figure 1-1. Location of the primary components of the logging system aboard the JOIDES Resolution.
Schlumberger Cyber Service Unit (CSU)

The Schlumberger cabin houses a wellsite digital computer system called Cyber Service Unit. This system overcomes many of the problems related to the stacking of many measurement sensors into one logging string, and expedites some field operations such as tool calibration. The CSU contains two complete computer systems each with CPU, 4 Mb RAM memory, and hard disk in order to make sure that there is always a functional system available during the logging run. The data are recorded on magnetic disk and then played back on magnetic tape for archiving and transfer to other computer systems. Selected data can be printed out on a thermal printer during the logging runs, so that logs can be made available for immediate examination. Additional logs are played back to the film recorder or to a graphic printer after the run. The CSU is powered by a 12 Kva generator.

In 1991, the present CSU will be replaced by MAXIS (Multi Task Acquisition and Imaging System). In addition to being directly connected to the other computers on the ship, MAXIS will allow for interactive computer graphics on two color terminals for both logging engineer and scientist, color display and printed output, integration of Formation MicroScanner data with standard logging curves, and log quality control and printing while logging.

Weight indication

Line weight is determined by a load cell which measures the tension on a sheave mounted on the rig floor. Using the line weight indicator, the winch operator can usually determine whether the probes are sticking during descent or ascent. Line weight, however, varies with ship heave which complicates this determination. As a matter of ODP policy TAMU has decided that all logging tools must weigh at least 200 lbs. (90 kg) if they include bowstring centralizers. Most lighter tools can be run by adding an above-tool sinker bar that is available on the ship.

Wireline Heave Compensator

Experience during DSDP demonstrated that ship heave can seriously degrade the quality of logging measurements. Although the relationship between ship motion and the motion of a downhole instrument is not simple, a significant amount of heave was being transmitted to the logging probe. Therefore, L-DGO contracted Schlumberger to design a heave motion compensator for the logging cable. After an independent engineering report determined that the design was effective, the compensator was installed on the starboard side of the winch cab.

During logging operations the logging cable is run from the winch to the rig floor, then back through a piston-mounted sheave on the heave compensator, and back again to the rig floor. As the piston extends, the length of cable between the winch drum and the rig floor is reduced by twice the amount of extension. Ship's heave is sensed by an accelerometer mounted near the rig floor, and the signal is transmitted to a computer which computes the effective motion. The piston-mounted sheave is then driven in or out to compensate for vertical motions of the drilling vessel. Tests of this system on ODP legs indicated that in
operation the heave compensator improved log quality and reduced the primary components of ship's heave by more than 50%.

**Sidewall Entry Sub**

Bridges within soft sediments have been a constant problem. The amount of logged hole in Eocene or younger sediments was consistently less than 50% of the cored depth prior to our adaption of horizontal hole logging technologies to ODP use. A special Sidewall Entry Sub (SES) was designed which attaches to the drill-pipe to allow the cable to be run outside the pipe (see Figure 1-2). This sub is installed with the open end of the pipe above the top of the interval to be logged, and tools are then run into the hole as usual with the cable passing through the SES. The pipe is run back to total depth. Open hole logs are recorded as pipe is simultaneously pulled back up and hole is exposed. This significantly improves the recovery of logs in soft sediments. A TAMU-designed second-generation SES with improvements based on operational experience was installed on the ship in 1990.

**Communications**

Communications between the Downhole Measurement Lab, winch cab, Schlumberger cab, and the rig floor are accomplished by a special intercom system not connected to the shipboard telephones. Thus critical communications between these areas are not affected by standard telephone traffic. Good intercoms do not insure good communications, however. It is imperative that these areas communicate well with each other during logging operations.

**Shipboard Computers and Log Analysis Facilities**

Preliminary log analysis is routinely undertaken on board the JOIDES RESOLUTION, followed by the full complement of log analysis after each cruise. Also, interactive computer work stations at Lamont are available for post-cruise log analysis by interested scientists. As further analysis techniques are developed, these are implemented and tested first at Lamont and then incorporated into the shipboard log analysis system. Figure 1-3 provides an overview of the shipboard computers and log analysis facilities described in the text.

The computer systems available in the Downhole Measurements Laboratory (as of the fall of 1990) are a Masscomp MC-5500 Unix-based system, a Digital VAXStation 3200 running the VMS operating system, an Apple Macintosh SE, and a Compaq Portable running the MS-DOS operating system. *Various enhancements to these systems are being planned, so interested scientists should contact the Borehole Research Group for the latest information.*

Numerous additional computers are available for use on the JOIDES RESOLUTION as part of the support and operational facilities provided by ODP/TAMU. These include several Digital VAXes operated in a VAXCluster configuration, numerous Apple Macintosh computers, numerous MS-DOS computers, several Digital DECPros, two
Figure 1-2. Sidewall entry sub (a) installed with the open end of the pipe just above the top of the logging interval; (b) with the pipe run to total depth along with the logging tool; and (c) recording open hole logs as pipe is simultaneously pulled up and hole is exposed.
Figure 1-3. Sketch of the ship logging computer facilities.
additional Masscomps, and others. Contact the computer support staff at ODP/TAMU for further details on the current computers which they support on board ship.

MASSCOMP MC-5500 (Figure 1-4)

L-DOO-BRG specialty logs (BHTV, MCS) acquired on the ODP drillship are controlled by and recorded on a MASSCOMP 5500 data acquisition and display system. The MC-5500 is a 32 bit Unix-based minicomputer system designed specifically to facilitate real-time operations. The computer has 3 Mb of RAM memory, a high-resolution graphics display, and 85 Mb and 165 Mb hard disk drives. Two 1600 bpi 9-track tape drives are available (they are ONLY capable of 1600 bpi, there are NO facilities on the ship to read 6250 bpi tapes). An Ethernet controller is installed and TCP/IP and NFS software packages are installed. Three RS-232C serial ports are available, though one of them is almost always in use with the Macintosh SE. An independently controlled subsystem performs the data acquisition tasks, and a separate graphics processor simultaneously displays the acquired data in real-time. In addition, an integral array processor/floating point processor combination enhances computational performance, enabling the MC-5500 to compute Fast Fourier Transforms quickly and to handle the sophisticated image processing required for interpretation of BHTV images. Hard-copy output of the results of these calculations is provided by a Versatec V-80F electrostatic plotter.

As mentioned above, programs have been developed to run the MCS and BHTV logs, as well as general-purpose data acquisition routines to record the data from a wide variety of experimental logs. These include a continuous logging program and programs to record data from hydraulic fracturing experiments and flow tests. The primary reason for installation of the MC-5500 in the downhole measurement lab is to provide a general-purpose, flexible system which can be used to record data from any experiment which can be run from a wireline. For this purpose, we expect to be able to work closely with scientists interested in running unique experiments which would benefit from the real-time capabilities of the MASSCOMP system.

As the MC-5500 is fully programmable in Fortran or C, additional analysis routines can be developed easily while on the ODP drill ship. With adequate advanced warning, a specific applications package including data acquisition, display and analysis can be developed before the ship sails for any specialty experiment.

Terralog Log Analysis System

TERRALOG is an interactive system of log analysis routines which operates in real-time, using a menu-driven approach. It is a proprietary commercial product developed by TerraSciences, Inc. As with any log analysis system, it has immediate application to the petroleum industry, but it can also be used effectively in the evaluation of other subsurface problems for which borehole geophysics provides useful information. Even though TERRALOG has been designed to operate with geophysical logs, other data, such as geochemical measurements or core analyses can be handled. The package can import and
Figure 1-4. Setup of the Masscomp Computer on the JOIDES Resolution.

Figure 1-5. Vax Station for Formation Microscanner Data Processing.
export data in ASCII format, in addition to importing the various standard log data formats. The programming language is Fortran, in order to allow the user to modify and/or add routines (although this is not normally done due to the complexity of the package.)

TERRALOG is installed on the Masscomp and utilizes a Versatec V-80F for tape mapping and graphic display. The Macintosh SE is often used as a graphics display terminal with TERRALOG, since it supports Tektronix compatible graphics terminals or terminal-emulation programs.

The data are loaded from Field Edit tapes prepared by the Schlumberger engineer in the Cyber Service Unit. Once a data tape has been loaded onto the system the L-DGO and JOIDES scientists perform the preliminary analyses and interpretation needed for the preparation of the logging chapter of the shipboard report.

Corpac Data Correlation Package

The CORPAC data correlation package developed by Doug Martinson at L-DGO has been installed on the Masscomp MC-5500. This package allows the correlation of different logs, time series, core data sets, and the description of their correlations via transfer functions. It has many features and extensive built-in contextual help. It is run from the Macintosh or other graphics terminal since it does not directly support the Masscomp native graphics mode.

Specialty Log Processing

The specialty log processing is accomplished using programs developed at L-DGO and Stanford University which are run on the MASSCOMP logging computer. For the BHTV these include the calculation of a 3-D caliper log, a hole volume log (useful for analysis of slug-type permeability), a surface roughness log, and an oriented ellipticity log, which can be used to determine the orientation of the horizontal principal stresses acting on a borehole. Image enhancement techniques to improve the BHTV images and to quantitatively determine fracture properties are also available. For the MCS log, analysis and display software includes calculations of compressional, shear and Stoneley velocities using a modified semblance technique, estimations of energy and frequency content for the primary borehole modes, and frequency-domain and slowness filtering to enhance particular arrivals. Estimates of amplitude and frequency content of the arrivals can be obtained which can be related to fracturing and attenuation near the wellbore.

The range of analysis techniques is limited only by the scientific interests of the shipboard party. Cross-correlation of the Schlumberger logs with borehole televiweer fracture, void and bedding information and the multi-channel sonic data allow identification at sea of such geological targets as over- and under-pressure zones, fault zones, dip changes, geophysical boundaries such as reflector horizons imaged by surface multi-channel seismic profiling, etc. (see other volumes of this manual).
Schlumberger Cyber Service Unit (CSU)

This computer is designed primarily for data acquisition and display of all primary Schlumberger log curves (as discussed above). In addition, it can run preliminary analyses of the data to obtain a "quick look" at computed values.

VAXStation 3200 (Figure 1-5)

A Digital VAXStation 3200 has been put on the ship to process data acquired by the Formation MicroScanner (FMS) Tool. It runs Digital's VMS operating system (version 5.3 as of the summer of 1990) and uses DECwindows (DEC's version of X-Windows) on its 19" grey scale display. The system has 8 Mb of main memory, two 760 Mb hard disc drives, an Ethernet interface, and a TK-50 cartridge tape drive with 95 Mb capacity. DECnet software is installed to permit communication with the ODP/TAMU VAX computers and TCP/IP software is installed to permit communication with the Masscomp and the Macintosh. NFS server software is also installed on this system. An array processor is attached to the system to speed computations and a Versatec interface is installed to permit it to use the V-80F printer/plotter described above.

The primary analysis software on this computer is the proprietary Schlumberger Log Operating System (LOGOS) package. ODP/TAMU computer technicians are being trained to operate this package for the routine processing of FMS data. This will avoid the problems caused by having to train a new person in the use of this package for each leg. The Lamont and JOIDES loggers can instead concentrate on the scientific analysis of the data.

Macintosh SE

An Apple Macintosh SE along with an Apple Imagewriter is provided in the Downhole Measurements Laboratory. This is normally connected to the Masscomp MC-5500 as an additional terminal. An Ethernet card is installed along with TCP/IP software for high-speed data transfer and communications. The Macintosh has a 20 Mb hard disk and 1 Mb of RAM memory (as of the summer of 1990, an upgrade to 4 Mb of RAM memory is planned for the fall of 1990). Various standard word-processing, data-analysis, and data-presentation packages are installed on the computer.

Numerous additional Macintoshes are available on the ship, as are several Apple Laserwriter printers and an Apple Scanner.

Compaq PC

A Compaq portable PC running MS-DOS is available in the lab. (Actually there are two of these machines, but one is sometimes back at L-DGO). These are primarily intended for use with the Wireline Packer tools, but are otherwise available for use. They have 640 kB of RAM memory. One has a 10 Mb hard disk and the other has a 20 Mb hard disk. Various standard utilities are installed, but not a wide selection, since these are primarily intended to be dedicated machines for use with the specialty tools.
Numerous PC and PC/AT style MS-DOS machines are available on the ship and are supported by ODP/TAMU. Several of these have AppleTalk cards installed so that they can use the Apple Laserwriters.

A more advanced PC style machine will be added to the lab to support the new German Digital Borehole Televiewer system. Contact the Borehole Research Group for further details on what will be included and when it will be available on the JOIDES Resolution.

On-shore Computers and Log Analysis Facilities

Masscomp computer systems and the software described above are also available on shore at the Borehole Research Group laboratory at L-DGO. There are also two dedicated log analysis systems, one developed by Energy Systems, Incorporated, and the other by Schlumberger.

Energy Systems

The Energy Systems' package is a user-friendly, menu driven, interactive graphic system which provides an accurate analysis of the logging data. Data can be entered via tape, digitizer or manually (core data); they can be interactively adjusted for errors occurring during logging operations, depth shifted, and corrected for environmental conditions. Because the system was designed for the oil industry, it also offers a selection of analysis programs to estimate porosity, shaliness, and fluid saturation of a formation. Finally, the system provides the user with the capability of developing his own programs by using a simple programming language which combines features of Fortran and Pascal. We are running version 4.1L of this software (see below).

The equipment used at L-DGO-BRG consists of the following components: a DEC PDP-11/23 processor, a Kennedy 9800 dual density (800 and 1600 bpi) tape drive, a Calcomp 9000 digitizer, a Versatec V-80F printer/plotter, a Tektronix 4696 color printer, and two Tektronix 4107 color terminals. An RS-232C link to the Masscomp computers has been installed. Primary data storage consists of a 96 Mb hard drive with a 16 Mb cartridge drive. It is likely that this system will be upgraded to a MicroVAX II based system in the fall of 1990. This will be accompanied by a major upgrade in the software.

Energy Systems is largely used for editing, depth shifting, displaying for the ODP Proceedings, and for data distribution.

Schlumberger Elite 1000 Workstation

All Schlumberger software available to any oil industry client also resides at the BRG in the form of a CLIC (Client Log Interpretation Center) and is run on a small VAXCluster. The primary unit of the VAXCluster is a MicroVAX II computer which has all of the disk storage and input/output devices attached to it. A diskless VAXStation 3100 is also part of the cluster (see below). A second diskless VAXStation 3100 will be added to the cluster in the fall of 1990.
The MicroVAX II has 16 Mb of RAM memory, along with two 380 Mb and three 760 Mb hard disks. Input and output are accomplished with a 1600 bpi 9-track tape drive, a TK-50 cartridge tape drive, and a Benson (now Oce) B-90 printer/plotter driven by a Versatec interface. A Tektronix 4105 terminal is attached to the system, and it shares the Tektronix 4696 printer with the Energy Systems' system described above. It can also utilize the Energy Systems' or the Masscomp's Versatec V-80F as an output device. An auxiliary array processor is attached to the system.

The operating system is VMS (version 5.3 as of the summer of 1990) and the system supports DECwindows, though there are no graphics devices directly installed in the MicroVAX II. DECnet software is used to communicate within the VAXcluster. TCP/IP and NFS (server/client) software will be installed in the fall of 1990.

The proprietary Schlumberger Log Operating System (LOGOS) is the main data analysis package on the system. The MicroVAX II is primarily used to reduce and interpret the geochemical logs.

VAXstation 3100

A VAXstation 3100 has been added to VAXcluster for land-based FMS log data reduction and analysis. This system has a 19" color monitor running DECwindows and has 16 Mb of local memory. It does not have a local disk and is linked via ethernet to the MicroVAX II.

A similar diskless system will be added in the fall of 1990 to provide more processing power for the geochemical log analysis.

Other Computer Systems

There are various other computer systems available to aid in the analysis of the logging data. Our goal is to link as many of these systems together via Ethernet, TCP/IP and NFS as possible. The Borehole Research Group has several Apple Macintosh and Macintosh II computers linked together on an AppleTalk net along with a laser printer and an AppleTalk-Ethernet gateway. An 386SX, color graphics, MS-DOS computer will be added in the fall of 1990 with a CD-ROM drive so that the NGDC (National Geophysical Data Center) CD-ROMS of DSDP data and their associated programs can be used. Additional Masscomp computers with greater processing power and larger disk storage than the shipboard system are available in the BRG. A system which is similar to the shipboard system is maintained in our logging truck. An IBM PC/RT system with the Landmark Graphics software system is located in the BRG building and is linked into the net via an Ethernet connection. This has extensive 3-D graphics capabilities, a large digitizer, and an 800/1600/3200/6250 bpi tape drive.

The computer network in the BRG building is linked into the Lamont-Doherty network via a fiber-optic cable link. There are numerous other computers available at Lamont-Doherty, including Sun machines. The Lamont-Doherty net is linked to the Columbia University campus and to the NSFNET via a T1 class connection. Internet electronic mail, telnet services, and ftp file transfer are available through these connections. Direct modem dialup is also available worldwide.
Please contact us for further information about logging onto and using our computer facilities, and for updates to the facilities when they become available.

Data Distribution

All logging data acquired on each leg of the Ocean Drilling Program are available to each member of the scientific party. Practical limits to data distribution on board are such that some time is required to process, correct, and display the data in a form appropriate for preliminary science.

Once the data are returned to L-DGO, they are archived and composite logs are prepared for distribution to the members of the shipboard party. They also receive a form to request additional analog and/or digital data (the latter usually become available about 2 months after the end of the leg). When requests are received, the zdata are plotted or copied to magnetic tape in the desired format and sent to the individual scientist. Schlumberger data are available on tape in either LIS (Log Information Standard) or ASCII format, with density of 800 or 1600 bpi, on 3.5" diskettes in ASCII format, or in MS-DOS format. Schlumberger sonic waveforms and well seismic data are both available in LIS format; the former are available in binary format as well.

Multichannel Sonic data are available in BRG or binary format (1600 bpi); a guide to reading the former will be provided along with the data. Borehole Televiewer data are available in analog form only (photographs).

As per ODP data distribution policy the rest of the scientific community has access to the logging data from each leg beginning one year from the sailing date of that leg. In addition, certain other data distribution occurs after one year. The National Geophysical Data Center receives data tapes from each leg after one year, and logging tapes are deposited with the appropriate agencies in JOIDES non-U.S. member countries. For more information contact Dr. Mike Lovell at the University of Leicester, United Kingdom.
Chapter 2. Logging Tools

This chapter provides a description of the physics behind each logging measurement, the form in which the data is generally presented, and its primary applications. Table 2-1 presents a complete list of the Schlumberger and specialty logging tools currently used in the Ocean Drilling Program. As mentioned before, all logging tools operate continuously, but the data can be recorded and averaged only in discrete steps, at half-foot (0.1524-m) intervals in the Schlumberger logs (Table 2-2). An exception is represented by the Formation MicroScanner, whose sampling rate is every 0.1 in (3 mm). If data needs to be sampled as a function of time (for instance, to invert tool motion data to monitor the performance of the heave compensator) slow logging speeds increase the length of time between samples. For example, a logging speed of 300 feet/hour yields data points at one-minute intervals.

Table 2-2 provides a list of the sampling rates and vertical resolutions of most of the logging tools used in the Ocean Drilling Program. It is defined as intrinsic vertical resolution the thinnest bed in which the logging tool can provide a true reading. This depends mostly on the sonde geometry: for example, the closer the source and the detector in a nuclear tool, the higher the vertical resolution. In general, the vertical resolution is also inversely related to the depth of investigation. The vertical resolution reported by the log, instead, is a function of the tool's intrinsic vertical resolution, the sampling rate and data averaging at the well site.

Schlumberger Tools

The Schlumberger logging tools are the tools most commonly run in the Ocean Drilling Program. They are combined into multiple-tool strings for efficiency of operations (see Table 2-1 and Figure 2-1). Due to the stacking process and the finite separation between individual measurement points, however, a few meters at the very bottom of the hole cannot be logged completely. The maximum length of hole for which data is lost is different for each measurement and depends on the position of the tool in the logging string (Table 2-3).

We presently operate the following three tool combinations: the quad-tool string, the geochemical string and the Formation MicroScanner string. Sometimes, however, a seismic-stratigraphic and a litho-porosity combination are run instead of the quad-tool string. Each logging run includes a measurement of the natural radioactivity of the formation, which can be used later to depth-shift the logs to a common point. An additional sonde component which measures vector magnetic field, hole azimuth, and hole deviation can be run with each of the tool strings.

Most Schlumberger tools can be run in boreholes with pressure and temperatures as high as 20,000 psi (1400 bars) and 350 °F (175 °C) respectively. The temperature rating for the gamma spectrometry tool (GST) is 300 °F (150 °C).
<table>
<thead>
<tr>
<th>TOOL</th>
<th>ACRONYM</th>
<th>PRINCIPLE</th>
<th>Usable Through Pipe</th>
<th>Combinable</th>
<th>Synthetic Seismogram (2)</th>
<th>Lithology Mineralogy (3)</th>
<th>Porosity</th>
<th>Geochemistry Elements</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonic</td>
<td>LSS/SDT</td>
<td>travel time of sound (2 receivers)</td>
<td>N</td>
<td>1</td>
<td>G</td>
<td>F</td>
<td>F</td>
<td>G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BHC/SDT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistivity shallow</td>
<td>SFL</td>
<td>focused current</td>
<td>N</td>
<td>1</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>VG</td>
<td></td>
</tr>
<tr>
<td>medium</td>
<td>ILM</td>
<td>induced current</td>
<td>N</td>
<td>1</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>VG</td>
<td></td>
</tr>
<tr>
<td>deep</td>
<td>ILD</td>
<td>induced current</td>
<td>N</td>
<td>1</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>VG</td>
<td></td>
</tr>
<tr>
<td>Caliper</td>
<td>MCD</td>
<td>hole diameter</td>
<td>N</td>
<td>1</td>
<td>P</td>
<td></td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual Laterog Neuron</td>
<td>DLL</td>
<td>resistivity to current</td>
<td>N</td>
<td>1</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>VG</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>CNTG</td>
<td>absorption of bombarding neutrons</td>
<td>Y</td>
<td>1/2</td>
<td>P</td>
<td></td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral γ-ray</td>
<td>NGT</td>
<td>natural γ-ray emissions</td>
<td>Y</td>
<td>1/2/3/4</td>
<td>P</td>
<td>VG</td>
<td>K, Th, U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density</td>
<td>HLDT</td>
<td>absorption of bombarding γ-rays</td>
<td>N</td>
<td>1/2/3</td>
<td>G</td>
<td>G</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Induced γ-ray Spectroscopy</td>
<td>GST</td>
<td>capture of bombarding neutrons</td>
<td>Y</td>
<td>3</td>
<td>F</td>
<td>VG</td>
<td>F</td>
<td>Cs, Si, Fe,S, Ti, Gd, H, Cl</td>
<td></td>
</tr>
<tr>
<td>Aluminum Clay Tool</td>
<td>ACT</td>
<td>absorption of bombarding neutrons</td>
<td>Y</td>
<td>3</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>Al, Mn</td>
<td></td>
</tr>
<tr>
<td>General Purpose</td>
<td>GPIT</td>
<td>oriented magnetic field including inclination</td>
<td>N</td>
<td>1/2/3/4</td>
<td>P</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclinometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Microscanner</td>
<td>FMS</td>
<td>focused micro-current</td>
<td>N</td>
<td>4</td>
<td>P</td>
<td>P</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-Channel Sonic</td>
<td>MCS</td>
<td>travel time of sound (12 receivers)</td>
<td>N</td>
<td></td>
<td>VG</td>
<td>F</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole Televiewer</td>
<td>BHTV</td>
<td>travel time + reflectivity of borehole wall</td>
<td>N</td>
<td></td>
<td>P</td>
<td>F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>TLT</td>
<td>formation temp.</td>
<td>Y</td>
<td>1/2/3/4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) usefulness of tool for application: VG=very good; G=good; F=fair; P=poor
(2) logs other than sonic and density can be converted to pseudosonic/density, based on known log responses to lithology and porosity
(3) percentages of minerals with abundance > 3% are determined from simultaneous inversion of several logs
(4) quality control for other logs
(5) magnetic reversals, stratigraphy, fault zones
(6) detailed mapping of fractures, faults, foliations, and formation structures; analysis of depositional environments; formation dip
(7) shear velocity, apparent attenuation
(8) stress directions, fracture orientation, structural dip, formation morphology
<table>
<thead>
<tr>
<th>MEASUREMENT</th>
<th>INTRINSIC VERTICAL RESOLUTION</th>
<th>SAMPLING INTERVAL</th>
<th>VERTICAL RESOLUTION ON THE LOG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phasor Induction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>5-6 ft / 1.5 m</td>
<td>0.5 ft / 15 cm</td>
<td>5-6 ft / 1.5 m</td>
</tr>
<tr>
<td>Deep</td>
<td>7-8 ft / 2 m</td>
<td>0.5 ft / 15 cm</td>
<td>7-8 ft / 2 m</td>
</tr>
<tr>
<td>Spherically Focused Log</td>
<td>2.5 ft / 76 cm</td>
<td>0.5 ft / 15 cm</td>
<td>2.5 ft / 76 cm</td>
</tr>
<tr>
<td>Dual Laterolog</td>
<td>2 ft / 61 cm</td>
<td>0.5 ft / 15 cm</td>
<td>2 ft / 61 cm</td>
</tr>
<tr>
<td>Digital Sonic Tool</td>
<td>2 ft / 61 cm</td>
<td>0.5 ft / 15 cm</td>
<td>2 ft / 61 cm</td>
</tr>
<tr>
<td>Borehole Compensated Sonic Tool</td>
<td>2 ft / 61 cm</td>
<td>0.5 ft / 15 cm</td>
<td>2 ft / 61 cm</td>
</tr>
<tr>
<td>Compensated Neutron Tool</td>
<td>1.25 ft / 38 cm</td>
<td>0.5 ft / 15 cm</td>
<td>1.5 ft / 46 cm</td>
</tr>
<tr>
<td>High Temperature Lithodensity Tool</td>
<td>1.25 ft / 38 cm</td>
<td>0.5 ft / 15 cm</td>
<td>1.5 ft / 46 cm</td>
</tr>
<tr>
<td>Natural Gamma Ray Tool</td>
<td>0.75-1 ft / 20-31 cm</td>
<td>0.5 ft / 15 cm</td>
<td>1.5 ft / 46 cm</td>
</tr>
<tr>
<td>Gamma Ray Spectrometry Tool</td>
<td></td>
<td>0.5 ft / 15 cm</td>
<td>1.5 ft / 46 cm</td>
</tr>
<tr>
<td>Formation MicroScanner (1)</td>
<td>0.2 in / 5 mm</td>
<td>0.1 in / 2.5 mm</td>
<td>0.2 in / 5 mm</td>
</tr>
<tr>
<td>Stratigraphic High Resolution Dual Dipmeter</td>
<td>0.4 in / 1 cm</td>
<td>0.1 in / 2.5 mm</td>
<td>0.4 in / 1 cm</td>
</tr>
<tr>
<td>12-Channel Sonic Tool</td>
<td>0.5 ft</td>
<td>0.5 ft / 15 cm</td>
<td>5.5 ft / 1.68 m</td>
</tr>
<tr>
<td>Borehole Televiewer</td>
<td></td>
<td></td>
<td>0.5 in / 1.27 cm</td>
</tr>
</tbody>
</table>

(1) acceleration and magnetometer data acquired every 1.5 in. (3.8 cm)
Figure 2-1. Schematic configurations of the Schlumberger tool strings operated in the Ocean Drilling Program. For the exact location of the measure point of each tool sensor refer to Table 2-3.
Table 2-3. Sensor Measure Points of the Schlumberger Tools (height above bottom of tool string) (1)

<table>
<thead>
<tr>
<th>STRING</th>
<th>TOOL</th>
<th>SENSOR MEASURE POINT (in m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad-tool combination</td>
<td>NGT</td>
<td>30.61</td>
</tr>
<tr>
<td></td>
<td>LSS/SDT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CNTG</td>
<td>17.30 (E), 17.81 (T) (2)</td>
</tr>
<tr>
<td></td>
<td>HLDT</td>
<td>10.36 (N), 10.49 (F) (3)</td>
</tr>
<tr>
<td></td>
<td>CALI</td>
<td>10.31</td>
</tr>
<tr>
<td></td>
<td>DIT (deep)</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>SFL</td>
<td>1.98</td>
</tr>
<tr>
<td></td>
<td>DIT (medium)</td>
<td>1.83</td>
</tr>
<tr>
<td>Geochemical</td>
<td>NGT</td>
<td>16.87</td>
</tr>
<tr>
<td></td>
<td>CNTG</td>
<td>12.04 (E), 12.55 (T)</td>
</tr>
<tr>
<td></td>
<td>AACT</td>
<td>10.57</td>
</tr>
<tr>
<td></td>
<td>GST</td>
<td>2.84</td>
</tr>
<tr>
<td>Formation Microscanner</td>
<td>NGT</td>
<td>9.83</td>
</tr>
<tr>
<td></td>
<td>CALI</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>GPIT</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>FMS/SHDT</td>
<td>0.33</td>
</tr>
<tr>
<td>Seismo-stratigraphic</td>
<td>LSS/SDT</td>
<td>17.73 (N), 18.03 (F) (3)</td>
</tr>
<tr>
<td></td>
<td>CALI</td>
<td>13.08</td>
</tr>
<tr>
<td></td>
<td>NGT</td>
<td>11.79</td>
</tr>
<tr>
<td></td>
<td>DIT (deep)</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>SFL</td>
<td>1.98</td>
</tr>
<tr>
<td></td>
<td>DIT (medium)</td>
<td>1.83</td>
</tr>
<tr>
<td>Litho-porosity</td>
<td>NGT</td>
<td>13.08</td>
</tr>
<tr>
<td></td>
<td>CNTG</td>
<td>8.77 (E), 8.26 (T) (2)</td>
</tr>
<tr>
<td></td>
<td>HLDT</td>
<td>0.64 (N), 0.79 (F) (3)</td>
</tr>
<tr>
<td></td>
<td>CALI</td>
<td>0.81</td>
</tr>
</tbody>
</table>

(1) if a temperature tool is attached to the bottom of the tool string add 1.52 m
(2) E=epithermal detectors, T=thermal detectors
(3) N=near detector, F=far detector
Quad-Tool String (Figure 2-2)

When the logging plan does not allow any time for extra logging runs this string permits the running of five tools in one lowering (from top to bottom): Natural Gamma Ray (NGT), Long Spacing Sonic (LSS) with a cartridge from the Digital Sonic Tool (SDT), Compensated Neutron Porosity (CNT-G), High Temperature Lithodensity (HLDT) with Caliper, and Phasor Dual Induction (DIT) tool (Figure 2-2). With the quad-tool combination, however, the sonic tool response recorded in real-time is often unreliable, due to the lack of centralization. Because a hole size reading is now provided by the caliper mounted on the lithodensity tool (eccentered), the three-arm caliper originally located above the sonic tool has been eliminated, along with the centralization of the tool itself. As a consequence, the sonic pulse does not radiate symmetrically, and the measurements do not come from all sides of the hole simultaneously. On the other hand, the neutron porosity tool needs to be eccentered and in contact with the borehole wall in order to reduce the attenuation of the signal by the borehole fluid. Routinely, the eccentralization is accomplished by a bow spring which is not used on the quad-combo because it would increase the risk of getting stuck in the 5-inches diameter pipe. In conclusion, in order to obtain good quality sonic and neutron porosity data, the quad-tool combination is sometimes separated into two logging runs (Figure 2-1), the seismic-stratigraphic and the litho-porosity combinations (see below), which meet the requirements for a proper sonic and neutron recording.

Geochemical String (Figure 2-3)

This string utilizes three modes of gamma ray spectroscopy to obtain a detailed elemental analysis of the formation. Natural (no nuclear source) spectroscopy with the Natural Gamma Ray tool (NGT) yields the concentration of the naturally occurring radionucleides in the formation K, Th, and U. Neutron-induced activation analysis performed with the Aluminum Activation Clay tool (AACT) provides an absolute measurement of Al concentration. Finally, induced capture spectroscopy measurements made with the Gamma Spectroscopy tool (GST) can be used to determine the concentration of Si, Ca, Fe, S, H, Cl, Ti, and Gd.

Formation MicroScanner String (Figure 2-4)

The Formation MicroScanner (FMS) provides oriented, two-dimensional, high-resolution images of the variations in microresistivity around the borehole wall. The string also includes a general purpose inclinometer tool (GPIT) which allows for the orientation of the microresistivity measurements from accelerometry measurements and from the declination and inclination components of the earth’s magnetic field vector. The FMS also provides precise measurements of the borehole diameter in two orthogonal directions, while a natural gamma ray measurement permits correlations with other logging runs.

Among the applications of the FMS are the following: correlation of coring and logging depth; orientation of cores and location of the cored sections when recovery is less than 100
Figure 2-2. Typical log dataset recorded with the quad-tool string.
LEG 128: HOLE 798B
Oki Ridge (Japan Sea)

Figure 2-3. Example of logging dataset recorded with the geochemical tool string. Both the original and processed data are displayed. Because in this section of the hole the sediments consist almost entirely of siliceous oozes and the CaCO₃ measured on cores is less than 1%, the computation of CaCO₃ from the logs was omitted, as it would introduce noise into the other estimates.
Figure 2.4. Logging data recorded with the Formation Microscanner tool string.
%; mapping of fractures, faults, foliations, and formation structures; analysis of depositional environments; definition of stress directions.

Seismic-Stratigraphic String

The seismic stratigraphic combination includes the Long Spacing Sonic (LSS) with a cartridge from the Digital Sonic Tool (SDT), the Phasor Dual Induction (DIT), the Natural Gamma Ray (NGT), and the 3-arm caliper (MCD) tools. The Borehole Compensated Sonic tool (BHC) is also on the ship as backup tool, to replace the Long Spacing Sonic in case of tool malfunction. The value of this combination to seismic stratigraphy is that it directly measures compressional wave sound velocity and indirectly measures the two variables that most often affect velocity: porosity and clay mineral content.

Litho-Porosity-Gamma Ray String

This combination includes Natural Gamma Ray (NGT), High Temperature Lithodensity (HLDT), caliper, and Dual Porosity Compensated Neutron (CNT-G) tools. It provides measurements of formation porosity and density as well as an estimate of the proportions of the primary radioactive elements (U, K, and Th).

Dual Laterolog

Resistivity induction logging probes do not produce reliable results in highly resistive formations such as oceanic basalts. To record these data we must run in a separate pass the Schlumberger Dual Laterolog (DLL). This tool can be combined with the NGT (Natural Gamma Ray) tool.

Well Seismic Tool

The WST is a wellbore clamped single-component geophone used to record vertical seismic profiles in a borehole. It provides a measure of formation velocity at seismic frequencies by measuring the travel-time between a surface seismic shot and the wellbore geophone. Estimates of depths to reflectors below the total depth can be made with this experiment. These data are useful in depth correlating reflectors on nearby seismic lines. The WST is not routinely aboard the JOIDES Resolution but is available for individual legs.

Calibration of Schlumberger Tools

Schlumberger standard logging tools are calibrated for optimum response in sedimentary rocks. In order to verify operation in other lithologies, the ODP Schlumberger density, neutron, spectral gamma, resistivity, and sonic tools were run in hard rock test pits at the Denver Federal Center of the United States Geological Survey. All log responses were within the range of core measurements. The data recorded with the geochemical tools can be calibrated at each site using core measurements.
Specialty Tools

The Borehole Research Group at LDGO provides three types of logging tools, the Borehole Televviewer (BHTV), Multichannel Sonic (MCS), and the temperature tool (TLT) which are operated by the L-DGO-BRG logging scientist. While the temperature tool is virtually run on each logging run, the BHTV and MCS are run on selected legs only, after time is approved by the Downhole Measurements Panel and ODP Planning Committee.

Specialty Tools by Shipboard Scientists

A wide variety of other measurements have been made in boreholes on land. Many of these have also been obtained on the JOIDES Resolution by members of the scientific party during various legs. These include: large scale resistivity (leg 102, 109, and 128), precision temperature (leg 109, 111, and 118), magnetic susceptibility (leg 102, 109, and 118), 3-axis magnetometer (leg 102, 109, 111, 118, 120, 123, and 125), vertical seismic profile (leg 101, 102, 104, 111, 118, 123, and 129), and drillstring packer (leg 102, 109, 111, 118, and 123) to mention some. Measurements that have been made on land but have not yet been recorded in ODP boreholes include non-linear complex resistivity, induced polarization, and circumferential acoustic logs.

There are several restrictions which should be noted by prospective logging investigators. These include the TAMU minimum weight restriction (100 lbs. floating for uncentralized tools and 200 lbs. floating for tools with centralizers), the limitations in cable speed (100 m/hr lower limit), the specifications of the cable (7 conductors, 170 Ω line resistance, G-O cable-head or your own pigtail), the determination of depth (500 pulls per foot quadrature signal), the amount of space available for tool storage and setup, and the computer space to record and process the data (severely limited).
Phasor Dual Induction - Spherically Focused Resistivity (DITE-SFL)

The Phasor Dual Induction - Spherically Focused Resistivity tool provides measurements of spontaneous potential (SP) and three different resistivity values: IDPH (deep induction), IMPH (medium induction) and SFLU (shallow spherically focused resistivity). Since the solid constituents are orders of magnitude more resistive than pore fluids in most rocks, resistivity is controlled mainly by the conductivity of the pore fluids and by the amount and connectivity of the pore space. The spontaneous potential is a measure of the streaming potential generated by differences between borehole and pore fluid electrical properties; these result in both membrane and liquid junction potentials due to differences in the mobility of ions in the pore and drilling fluids. As such, it has generally been assumed to be uninteresting in ODP boreholes; recent results, however, suggest that it may be responding both to the presence of fractures and to the electromagnetic properties of basalts.

The induction sonde consists of a series of transmitter and receiver coils mounted on the sonde axis. To facilitate the principle understanding Figure 2-5A considers a simplified sonde with only one transmitter and receiver coil. The high frequency, alternating current of constant intensity sent through the transmitter coil produces an alternating magnetic field which in turns induces currents in the formation around the borehole. These currents flow in circular ground loops coaxial with the sonde and because the alternating current sent by the transmitter coil is of constant frequency and amplitude, they are directly proportional to the formation conductivity. They also produce a magnetic field which induces a voltage in the receiver coil, which is in turn proportional to the ground loop currents and therefore to the resistivity of the formation. The operating frequency of the induction arrays can be selected at 10 kHz, 20 kHz, or 40 kHz, but the default frequency is 20 kHz. Because the signal from an element of formation increases with the square of the transmitter frequency, operation at 40 kHz yields four times the signal that operation at 20 kHz, thus improving the signal-to-noise ratio at high resistivities. In addition to the usual inphase (R-signal) induction measurement, the Phasor Induction Tool provides a high quality measurement of the induction quadrature signal (X-signal). The combination of these two signals along with improvements in signal processing provide higher vertical resolution logs, fully corrected for shoulder and borehole effects.

The resistivity measured by the induction log is quite accurate for low resistivities, but in formations with resistivity higher than 100 Ωm the error can be as high as 20%. In these rocks the Dual Laterolog (see page 2.7) produces more reliable results.

In the spherically focused resistivity sonde the measure (i₀) and focusing currents (iₐ) are sent into the formation from electrode A₀ (Figure 2-5B). The former returns to the cable armor while the latter return to electrodes A₁ and A'₁ on the sonde. The focusing currents are adjusted so that the potential between M₀ and the midpoint between M₁ and M₂ is constant; thus, iₐ flows into the borehole and i₀ into the formation. This system produces two equipotential spheres around the sonde which are 9" and 50" away from the current electrode, while a constant 2.5 mV potential is maintained between the two surfaces; the
Figure 2-5. Sketch of the resistivity devices used in the Ocean Drilling Program: (A) Dual Induction Tool (DIT), (B) Spherically Focused Resistivity Tool (SFL), and Dual Laterolog (DLL; courtesy of Schlumberger).
intensity of the current flowing through the volume between these two spheres is inversely proportional to the resistivity of the formation.

**Depth of Investigation and Vertical Resolution**

In homogeneous formations with resistivity higher than 100 $\Omega$m the average radial depth of investigation is about 5 ft (1.5 m) and 2.5 ft (76 cm) for the deep and medium induction curves respectively, and 1.25 ft (38 cm) for the SFL. This drops to 4 ft (122 cm) and 2.2 ft (66 cm) at 0.1 $\Omega$m resistivities.

Thanks to an enhanced signal processing technique and to a real time correction for the effect of adjacent formations (shoulder effect) the thin bed resolution over a full range of formation conductivities has been greatly improved. Vertical Resolution is 5-6 ft (1.5 m) and 7-8 ft (2 m) for the medium and deep induction and 2.5 ft (76 cm) for the spherically focused log.

**Log Presentation**

Deep (ILD or IDPH) and medium induction (ILM or IMPH), and spherically focused resistivity (SFLU) are usually plotted in $\Omega$m on a logarithmic scale along with caliper, gamma ray, and sonic data (Figure 2-6).

**Environmental Effects**

The Phasor Dual Induction tool provides a set of corrections for different environmental effects, which can be performed in real time during logging. These include corrections for adjacent formations, borehole signal, and invasion. In general, invasion is not a problem in the boreholes logged in the Ocean Drilling Program, because seawater is used as drilling fluid, but can occur in land wells. In fact, depending on the type of drilling mud used and on the permeability of the formation, invasion of the mud filtrate into the formation adjacent to the borehole can lead to differences in the response of shallow and deeper resistivity devices. On the other hand, invasion can provide useful information about formation permeability and pore fluid electrical conductivity. Differences in the temperature of drilling fluid compared to undisturbed formation temperatures can also generate this effect, as conductivity in ionic fluids such as seawater is strongly temperature dependent.

**Principal Applications**

- **porosity estimate.** In sediments which do not contain clay or other conductive minerals, the relationship between resistivity and porosity has been quantified by Archie’s Law, which relates the resistivity to the inverse power of porosity. This relationship has also been used to estimate an apparent porosity in oceanic basalts.

- **density and velocity reconstruction.** Archie’s equation has been used effectively to create “pseudodensity” and/or “pseudovelocity” logs from porosity over intervals where no such logs were recorded or were totally unreliable. In some instances velocities derived from resistivity logs can be used to depth-tie seismic reflectors.
Figure 2-6. Typical display of resistivity data (ILD), ILm, SFLU) along with acoustic data (DT and DTL), gamma ray (GR), and caliper (CALI). Both resistivity and transit time were used to define lithologic boundaries where core recovery was poor and to detect grain size variations, (e.g. the fining-upward sequence between 3770 and 3740 mbrf). The difference between the three resistivity measurements is due to invasion by drilling fluid less saline that formation water; only the deep resistivity device "sees" the true formation resistivity.
lithologic boundary definition and textural changes. Resistivity, along with acoustic and velocity logs, is a very valuable tool in defining lithologic boundaries over intervals of poor core recovery, as shown in Figure 2-6. Also, in this example, the decrease in resistivity towards the top of the unit at 3740-3770 mbrf, coupled with a decrease in velocity, allows one to interpret this unit as as a fining-upward sequence in mostly carbonatic sediments. Similar saw-tooth patterns in the resistivity response can also be observed in oceanic basalt units where they are related to porosity changes towards the top of each unit (Volume 6, Figure 3-9).

Dual Laterolog (DLL)

The Dual Laterolog provides two resistivity measurements with different depths of investigation into the formation: deep (LLd) and shallow (LLs). In both devices, a current beam 2 ft-thick (A0) is forced horizontally into the formation by using focusing (also called bucking) currents (A1-A2, A'-A'2 in Figure 2-5C); two monitoring electrodes (M1, M2, M'1, M'2) are part of a loop that adjusts the focusing currents so that no current flows in the borehole between the two electrodes. For the deep measurement both measure and focusing currents return to a remote electrode on the surface; thus the depth of investigation is greatly improved, and the effect of borehole conductivity and of adjacent formations is reduced. In the shallow laterolog, instead, the return electrodes which measure the bucking currents are located on the sonde, and therefore the current sheet retains focus over a shorter distance than the deep laterolog.

The Dual Laterolog response ranges from 0.2 to 40,000 Ωm, thus permitting a good characterization of highly resistive rocks such as oceanic basalts and gabbros.

The DLL is usually run in combination with the Natural Gamma Ray Tool (see below).

Depth of Investigation and Vertical Resolution

The depth of investigation of the laterolog depends on the resistivity of the rock and on the resistivity contrast between the zone invaded by the drilling fluid and the virgin (uninvaded) zone. The vertical resolution of both LLd and LLs depends on the geometry defined by the focusing electrodes: this is about 2 ft (61 cm).

Log Presentation

The LLd and LLs curves are displayed on a resistivity logarithmic scale on tracks 2 and 3, along with the gamma ray log on track 1 (Figure 2-7, left).
LEG 111: HOLE 504B
Costa Rica Rift (Pacific Ocean)

Figure 2-7. Estimate of total porosity and fracture distribution using the Dual Laterolog. LLD > LLs because of predominance of vertical fractures.
Environmental Effects

For the LLd the borehole effect is small for hole diameters up to 16 in, while the LLs provides good readings in holes not exceeding 12 in. Corrections are available for holes up to 20" in diameter.

Principal Applications

- **Porosity Estimate.** Because of the inverse relationship between resistivity and porosity, the dual laterolog can be used to estimate the porosity of the rock from Archie's equation if the sediments/rocks do not contain any clay or if the contribution of surface conduction to the signal is negligible.

- **Fracture Porosity Estimate.** This can be estimated from the separation between the deep and shallow measurements based on the observation that the former is sensitive to the presence of horizontal conductive features only, while the latter responds to both horizontal and vertical conductive structures (Figure 2-7, right).

Natural Gamma Ray Tool (NGT)

The NGT utilizes a sodium-iodide scintillation detector to measure the natural gamma ray radiation of the formation and 5-window spectroscopy to resolve the detected spectrum into the three most common components of the naturally occurring radiation: potassium, thorium, and uranium. The high-energy part of the spectrum is divided into three energy windows, each covering a characteristic peak of the three radioactivity series. The concentration of each component is determined from the count rates in each window. Because the high-energy region contains only 10% of the total spectrum count rates, the measurements are subject to large statistical variations, even using a low logging speed. The results are considerably improved by including the contribution from the low-energy part of the spectrum. Filtering techniques are used to further reduce the statistical noise by comparing and averaging counts at a certain depth with counts sampled just before and after. The final outputs are the total gamma ray (SGR), a uranium-free gamma ray measurement (CGR), and the concentrations of potassium (POTA, wt. % or decimal fraction), thorium (THOR, ppm), and uranium (URAN, ppm).

Depth of Investigation and Vertical Resolution

The radius of investigation depends on several factors: hole size, mud density, formation bulk density (denser formations display a slightly lower radioactivity), and on the energy of the gamma rays; (a higher energy gamma ray can reach the detector from
deeper in the formation). The vertical resolution on the log is about 1.5 ft (46 cm; Table 2-2).

**Log Presentation**

The NGT log is routinely recorded with each logging string for correlation between logging runs. To this purpose SGR and CGR are usually displayed along with other curves (resistivity, sonic, density etc.; Figure 2-2, 2-3, 2-4). A full display of the data, with SGR and CGR in track 1, and THOR, URAN, and POTA on track 2 and 3 is usually provided separately (Figure 2-8).

**Environmental Effects**

The NGT response is affected by borehole size, mud weight, and by the presence of bentonite or KCl in the mud. In ODP boreholes KCl is often added to the mud to stabilize fresh-water clays which tend to swell and form bridges. This procedure takes place before logging operations start, and even though KCl is probably diluted by the time the tool reaches total depth, it can still affect the tool response.

All the above effects are accounted for during the processing of the NGT data on-shore.

**Principal Applications**

- **Clay typing.** Potassium and thorium are the primary radioactive elements present in clays; because the result is sometimes ambiguous, it can help combining these curves or the ratios of the radioactive elements with the photoelectric effect from the lithodensity tool.

- **Mineralogy.** Carbonates usually display a low gamma ray signature; an increase of potassium can be related to an algal origin or to the presence of glauconite, while the presence of uranium is often associated with organic matter (see Volume 3, Figure 5-3).

In sandstones with very low potassium signature sudden rises in thorium and uranium can be indicative of heavy mineral concentrations (which may be confirmed by the occurrence of positive kicks on the lithodensity log) or of feldspars mixed into terrestrial sands.

In igneous rocks the combination of potassium with the SiO₂ weight fraction from the GST tool and/or bulk density and photoelectric effect logs provides an easy determination of the rock type (Figure 2.9). Generally, the content of thorium and uranium decreases from acidic to ultrabasic rocks. In oceanic basalts an increase in potassium may be related to the presence of voids and fractures filled with K-bearing alteration minerals formed by interaction of basalt with seawater (see Volume 4, Figure 3-11).
Figure 2-8. Typical display of natural gamma ray data recorded with the Natural Gamma Ray Spectrometry Tool (NGT).
Figure 2-9. The potassium concentration (POTA) measured by the Natural Gamma Ray Tool, along with the bulk density (RHOB) and photoelectric effect (PEF) measured by the Lithodensity Tool have been effectively used to identify the different lithologies drilled at the Cajon Pass Scientific Drillhole.
Long-Spacing (LSS/SDT) and Borehole Compensated (BHC) Sonic Tools

Sonic tools are designed to measure the elastic compressional-wave velocity of the formation surrounding the borehole. In essence the sonic tool can be thought of as a miniature seismic refraction experiment carried out within the cylindrical borehole. The tool is centered in the hole by means of centralizers, and contains one or more sources and receivers. A source fires acoustic energy which is transmitted into the borehole fluid. When the wavefront impinges on the borehole wall, a refracted compressional wave is generated. If formation shear velocity is higher than the acoustic velocity of the fluid, a refracted shear wave will also be generated. The refracted waves travel along the borehole wall, re-radiating energy into the fluid. Energy arrives at receivers on the logging tool at a time which is linearly proportional to their offset from the source. Thus formation elastic-wave velocities can be determined by differencing the arrival times at two receivers a known distance apart.

The Borehole Compensated Sonic tool (BHC) consists of an upper and lower transmitter arranged symmetrically on either side of two pair of receivers (Figure 2-10, left). The spacing $T_1-R_1$ and $T_1-R_3$ are 3 and 5 apart as well as the spacings $T_2-R_4$ and $T_2-R_2$. The transit time of the compressional wave in the formation, measured in microseconds per foot is given by

$$\Delta t = \frac{1}{2} (T_1 R_3 - T_1 R_1 + T_2 R_2 - T_2 R_4).$$

The Long Spacing Sonic sonde (LSS), which utilizes a cartridge from the Digital Sonic Tool (SDT) contains two acoustic sources spaced two feet apart located eight feet below a pair of receivers also spaced two feet apart (Figure 2-10, right). This provides source-receiver offsets of 8, 10, 10, and 12 feet. The measurement relies on the "depth derived" borehole compensation principle. Compensation is achieved by memorizing the first $\Delta t$ reading and combining it with a second $\Delta t$ reading measured after the sonde has been pulled the appropriate distance along the borehole. The symmetry of the sources and receivers allows travel-time measurements for 8 combinations of sources and receivers. Four of these are reversed by source-receiver reciprocity.

The tool needs to be run centralized in order to obtain reliable readings: the upper centralizing spring provides the hole diameter using a linear potentiometer to measure leavespring extension.

The LSS tool records the full waveform for each source-receiver pair, in addition to its automatic determination of arrival time. The sonde can be run in two modes to either correct downhole gains for variations in amplitude or to maintain a fixed gain. As arrival-time is determined automatically using a threshold detector, the variable gain mode often produces better travel-time logs, although the waveforms will no longer be at fixed gain.
Figure 2-10. Sketch of the Schlumberger acoustic devices used in the Ocean Drilling Program: Borehole Compensated Sonic (BHC; left) and Long Spacing Sonic (LSS; right).

T = Transmitter
L = Lower  U = Upper
R = Receiver
Depth of Investigation and Vertical Resolution

The depth of investigation cannot be easily quantified: it depends on the spacing of the detectors and on the petrophysical characteristics of the rock such as rock type, porosity (granular, vacuolar, fracture porosity), and alteration. For source-detector spacings of 3-5”, 8-10”, and 10-12” the depth of investigation ranges from 2” to 10” (altered/invaded and undisturbed formation, respectively), 5” to 25”, and 5” to 30”. The vertical resolution is 2 ft (61 cm).

Log Presentation

DTI and DTL are interval travel-times in microseconds per foot for the near and far receiver pairs, respectively (Figure 2-6). In very slow formations DTL provides the only valid measurement, as the refracted wave is not seen at the near receivers. The sonic waveforms can also be displayed alongside the travel-time curves, and the individual travel-time measurements in microseconds (TT1 to TT4) are also available. Pips on the log plot indicate integrated travel-time to depth for crude seismic correlations.

Environmental Effects

One common problem is cycle skipping: a low signal level, such as that occurring in large holes and soft formations, can cause the far detectors to trigger on the second or later arrivals, causing the recorded Δt to be too high. This problem can also be related to the presence of fractures.

Transit time stretching appears when the detection at the further detector occurs later because of a weak signal. Finally, noise peaks are caused by triggering of detectors by mechanically induced noise, which causes the Δt to be too low.

Reprocessing programs that can eliminate the aberrations described above are available both at sea and on-shore.

Principal Applications

- **porosity and "pseudodensity" log.** The sonic transit time can be used to compute porosity by using the appropriate transform (Figure 2-11), and to estimate fracture porosity in carbonatic rocks. In addition, it can be used to compute a "pseudodensity" log (Figure 2-11) over sections where this log has not been recorded or the response was not satisfactory.

- **seismic impedance.** The product of compressional velocity and density is useful in computing synthetic seismograms for time-depth ties of seismic reflectors (Figure 2-12).

- **sonic waveforms analysis.** If a refracted shear arrival is present, its velocity can be computed from the full waveforms, and the frequency content and energy of both compressional and shear arrivals can also be determined.
LEG 124: HOLE 768C  
Sulu Sea (Pacific Ocean)

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<th>SONic POROSITY (%)</th>
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Figure 2-11. Estimate of porosity and pseudo-density logs from acoustic data recorded in basaltic crust. Note the good agreement with core measurements (solid squares).
Figure 2-12. Impedance curve and synthetic seismogram computed from density and velocity data.
fracture porosity. Variations in energy and frequency content are indicative of changes in fracture density, porosity, and in the material filling the pores. In some cases compressional-wave attenuation can also be computed from the full waveforms.

Lithodensity Tool (HLDT)

The HLDT consists of a Ce\textsuperscript{132} radioactive source and two detectors mounted on a shielded skid which is pressed against the formation by a hydraulically-activated eccentricing arm (Figure 2-13). The 662 keV gamma rays emitted by the source into the formation experience two types of interaction with the electrons in the formation: Compton scattering and photoelectric absorption. The former is an elastic collision by which energy is transferred from the gamma ray to the electrons in the formation. This interaction forms the basis of the density measurement; in fact, because the number of scattered gamma rays which reach the detectors is directly related to the the number of electrons in the formation, the tool responds to the electron density of the rocks, which is in turn related to the bulk density.

Photoelectric absorption, instead, occurs when the gamma rays reach a low energy (< 150 keV) level after being repeatedly scattered by the electrons in the formation. The photoelectric effect index is determined by comparing the counts from the far detector in the high energy region, where only Compton scattering occurs, with those in the low energy region, where the count rates depend on both reactions. The far detector is used because it has a greater depth of investigation. The response of the short-spacing detector, which is mostly influenced by mudcake (not present in ODP boreholes where a seawater-based drilling fluid is used) and borehole rugosity is used to correct the density measurement for these effects.

Depth of Investigation and Vertical Resolution

Like in the case of the sonic tool, the depth of investigation of the lithodensity tool cannot be easily quantified; it is in the range of tens of centimeters, depending on the density of the rock. In highly permeable formations the lithodensity tool may only investigate the zone invaded by the drilling fluid.

The vertical resolution is 16 in (38 cm).

Log Presentation

The primary curves are: bulk density (RHOB, in g/cc), photoelectric effect (PEF, in barns/electron) density correction (DRHO, in g/cc), and caliper (CALI, in in); Figure 2-14. They are usually displayed along with the neutron porosity curve NPHI. Also, DPHI (density porosity) can be computed and displayed by assuming a constant grain density of
Figure 2.13 Schematic drawing of the density and porosity devices used in the Ocean Drilling Program (courtesy of Schlumberger).
Figure 2-14. Typical display of bulk density, photoelectric effect and neutron porosity data. At this site, density, porosity and gamma ray data complemented the cores for a precise definition of the thickness of the basaltic flows versus the interbedded volcaniclastic sediments.
the matrix. DRHO is useful for quality control of the data; if the tool is operating correctly it should be less than 0.1 g/cc.

**Environmental Effects**

A reliable density measurement requires good contact between pad and formation. Because a caliper measurement is made during the recording, it is possible to check the quality of the contact. In the lithodensity tool the presence of mud cake and hole irregularities are automatically accounted for using a "spine and ribs" chart based on a series of laboratory measurements. The "spine" is the locus of the two counting rates (short and long spacing) without mudcake and the "ribs" trace out the the counting rates for the presence of mudcake at a fixed formation density. The short and long spacing readings are automatically plotted on this chart and corrected for their departure from true value.

**Principal Applications**

- **Porosity estimate.** If grain density is relatively constant, porosity can be calculated from the density log. Alternatively, porosity and density logs can together be used to calculate grain density.

- **Seismic impedance calculation.** The product of velocity and density can be utilized as input to synthetic seismogram computations.

- **Lithology and rock chemistry definition.** In combination with the neutron porosity log, the density log allows for the definition of the lithology and of lithologic boundaries (Figure 2-14). Because each element is characterized by a different photo-electric factor, this can be used, alone or in combination with other logs, to determine the lithologic type (Figure 2-9). Both density and photoelectric effect index are input parameters to some of the geochemical processing algorithms used on-shore.

**Compensated Neutron Dual Porosity Tool (CNT-G)**

The CNT-G tool employs a chemical source (Am-Be) to bombard the borehole and the formation with fast neutrons (4.5 MeV) and two pairs of sensors to detect the number of neutrons (count rates) in the epithermal (100 eV-0.1 eV) and thermal energy range (< 0.025 eV; Figure 2-13). In the scattering process the neutrons interact elastically with the atoms in the formation, are slowed down, and loose part of their kinetic energy at each collision; when they reach the thermal energy level, they are absorbed by the surrounding nuclei. The amount of energy lost by the neutrons depends on the relative mass of the nuclei with which they interact. Because the greatest energy loss occurs during the collision with hydrogen atoms - which have a mass almost equal to that of neutrons - the slowing-down
and capture processes are mainly controlled by the hydrogen concentration in the formation. By taking the ratio of count rates at each pair of detectors, a measurement of the porosity of the formation, compensated for borehole parameters, is provided.

The response at the thermal detectors can be greatly affected by elements with large thermal neutron capture cross section, such as chlorine, boron, gadolinium, and samarium; these are usually present in very small quantities in the borehole fluid or in clay or alteration minerals, yet they can cause the porosity of the formation to be overestimated. The epithermal detectors, instead, are less sensitive to these neutron absorbers and provide a more reliable measurement of the true porosity of the formation over clay-rich intervals. Because the epithermal neutron count rate is about one order of magnitude less than that for the thermal neutrons, the detectors are placed closer to the source in order to improve statistical variations.

**Depth of Investigation and Vertical Resolution**

The depth of penetration of the neutrons is inversely related to the porosity of the formation, but also depends on the source-detector spacing. In general we can say that for porosity ranging from 0 to 30% the depth of investigation varies from 2 ft (61 cm) to about 6" (15 cm).

The vertical resolution is 1.5 ft (46 cm).

**Log Presentation**

The CNT-G provides and epithermal (ENPH) and thermal neutron porosity (NPHI) measurement. The porosity curves are presented either in decimal units or in percents along with the bulk density.

**Environmental Effects**

Eccentricization of the tool by a bow spring is the most important requirement to obtain reliable porosity measurements. The lack of contact of the tool with the borehole wall during the recording results in the attenuation of the formation signal by the borehole fluid and, in turn, the overestimate of the true porosity of the formation.

Hole size also affects the neutron log response; the formation signal, particularly for the epithermal count rates, tends to be masked by the borehole signal with increasing hole size.

In liquid-filled holes the influence of the borehole fluid depends on its salinity - chlorine is a strong neutron absorber - and density: the addition of weighting additives such as barite will yield a lower porosity reading.

In the Ocean Drilling Program, the neutron tool is sometimes recorded through the drilling pipe and the bottom hole assembly. Because iron is a strong neutron absorber, the effect will be of an increased porosity reading depending on the thickness of the pipes.

**Principal Applications**

- **porosity.** In reservoir engineering its importance is quite evident; in the study of the volcanic rocks that make up the upper oceanic crust, a good *in-situ* porosity
measurement is most important to the correct understanding of the crustal structure. First, because it samples both the small-scale (microcrack, vesicle) porosity seen in the cores and the large-scale fractures not sampled by drilling, and secondly because other properties such as density, seismic velocity, and permeability, depend strictly on porosity variations and on the geometry of the pore space. In the presence of clays or hydrous alteration minerals a correction is required to account for the presence of bound water (Figure 2.15).

- **lithologic determination.** Because the hydrogen measured by the tool is present not only as free water but also as bound water in clay minerals, the porosity curve, often combined with the density log, can be used to detect shaly intervals, or minerals such as gypsum, which has a high hydrogen index due to its water of crystallization. Conversely, the neutron curve can be used to identify anhydrite and salt layers (which are both characterized by low neutron readings and by high and low bulk density readings respectively).

Geochemical Tool String: Natural Gamma Ray (NGT)-Gamma Ray Spectrometry (GST)-Aluminum Activation Clay (AACT) Tool

The geochemical tool string was originally developed by Schlumberger to measure all the major elements needed in determining clay mineralogy. However, because these elements are among the major constituents of most of the minerals forming sedimentary and igneous/volcanic rocks, geochemical logging has proven to be a very powerful complement to the traditional X-Ray Fluorescence (XRF) measurements obtained from cores.

A sketch of the geochemical tool string is shown in Figure 2.16. The tool string is configured with a Natural Gamma Ray tool (NGT) at the top that measures the gamma ray spectrum of Th, U, and K before the formation is activated by the neutron and gamma spectroscopy tools. Next, the neutron porosity tool (CNTG) is used as a source carrier for a Ca\textsuperscript{252} source. Californium is used instead of the conventional AmBe source because its spectrum has a much lower energy (2 MeV instead of 4.5 MeV), thus reducing the number of fast neutron reactions which would interfere with the aluminum activation measurement. Aluminum activation is caused by thermal neutron capture by Al\textsuperscript{27} and produces an Al\textsuperscript{28} nucleus. This decays with a half life of 2.3 minutes and emits 1.78 MeV gamma rays.

The Aluminum Activation Clay tool (AACT) is a modified NGT - the spectrometer includes three more windows for a more detailed analysis of the spectrum - which measures the gamma ray spectrum of the activated formation. By combining this measurement with that from the NGT tool, a reading of the formation Al concentration is obtained.

Finally, a Gamma Ray Spectrometry tool (GST) is located at the bottom of the string. The GST measures the relative contribution (yield) of gamma rays resulting from the interactions of neutrons emitted by a source with the elements present in the formation.
Figure 2-15. At ODP Site 735 the neutron porosity data were corrected for the abundant hydrous alteration minerals present in the gabbroic rocks. This yielded a corrected porosity value which is in good agreement with core measurements. The results from different tools (Borehole Televiewer, Multichannel Sonic) confirm that discrepancies between the two are probably related to the presence of fractures not sampled by coring.
Figure 2-16. Configuration of the geochemical logging string operated on the drillship JOIDES Resolution. For the exact position of each tool sensor see Table 2-3.
source consists of a pulsed neutron accelerator which generates 14 MeV neutrons. Through scattering interactions with the atoms in the rock surrounding the borehole, the neutrons progressively lose energy until they reach the thermal energy level in which they can be captured by elemental nuclei in the formation. When this occurs, the nucleus emits a γ-ray of characteristic energy. The emitted gamma rays are measured by a spectrometer consisting of a sodium iodide detector and a 256-channel analyzer. Because each element has a unique emitted spectrum, the comparison of the spectra recorded downhole with a library of standard spectra provides an estimate of the elemental composition of the formation. The GST can operate in two timing modes: inelastic, which mainly measures the neutron reactions in the high energy range, and capture-tau mode, in which the capture gamma ray emissions are detected. In ODP wells the GST is run in a capture-tau mode, which allows the calculation of the elemental proportions of six elements: Ca, Cl, Si, Fe, H, and S. The measurement accuracy is largely determined by statistics; the slower the logging speed the more accurate the results. The GST can be run inside the logging pipe, but corrections for the effect of the pipe are not always conclusive. The data, however, can be used from a qualitative point of view, and offer useful information about the formation geochemistry in holes that otherwise could not be logged due to well-bore instability.

Log Presentation

The standard presentation of the geochemical logging string data includes the elemental yields (CCA, CSI, CSUL, CFE, CHY, CCHL) along with the formation capture cross section (CSIG), and the aluminum counts (ALUM) from the Aluminum Activation Clay tool (Figure 2-3). Also displayed are the ratios of the elemental yields: IIR (iron indicator ratio), PIR (porosity indicator ratio), LIR (lithology indicator ratio), SIR (salinity indicator ratio), and AIR (anhydrite indicator ratio) in anhydrite or gypsum-bearing formations.

Environmental Effects

Since the GST investigation depth is rather limited (12.7-20.3 cm in capture mode) attention must be paid to invasion and borehole effects. Invasion affects the salinity readings; this effect is negligible in cased holes in which case the iron yield will be affected.

Principal Applications

- **geochemistry.** Because the elemental yields represent the relative contribution to the measured signal of some of the major elements present in the rocks, a complex processing technique, which requires data recorded with the natural gamma ray and aluminum activation clay tool as well, is routinely used on-shore to compute new elemental yields (that include titanium, potassium and gadolinium; Figure 2-17) and finally absolute dry weight fractions of the major oxides (Figure 2-18).

- **mineralogy.** The oxide concentrations can be inverted using a correlation matrix to estimate the volumes of the main mineralogical constituents of the rock (see Volume 5, Figure 3-17).
Figure 2-17. Example of recomputed geochemical yields in gabbroic rocks.
Figure 2-18. Comparison between log-computed oxides and core measurements from the Palisades Sill. Th and U from the NGT tool are also displayed.
lithologic determination. It is possible to perform a preliminary analysis of the data at the well site simply using the ratios of the elemental yields (see Volume 6, Figure 6-2) and/or the Al measurement. The analysis of GST results in sediment is relatively straightforward, as elemental concentrations vary markedly with lithology. The variations in the lithology indicator ratio (LIR) and/or in the Al curve can be correlated with the calcium carbonate values routinely measured on-board, (Figure 2.19) or with some of the mineral proportions estimated from the smear slides (clays, siliceous/nannofossil ooze, calcite). The iron indicator ratio can help detect Fe-rich clay intervals (see Volume 6, Figure 6-2), whereas the presence of sulfur can be related to the occurrence of anhydrite and/or gypsum. Also, K, Th, and U concentrations form the NGT tool can help in clay-type characterization.

porosity, salinity. The porosity indicator ratio shows porosity variations, whereas the chlorine/hydrogen ratio yields an estimate of the salinity of the borehole and formation fluids (see Volume 5, Figure 5-4).

lithologic boundaries. In basement, variations in elemental concentrations will help delineate flow boundadries, characterize alteration vein-filling, and provide an extension of the core analyses to the entire (continuous) logged section.

Elemental Yield Ratios Mnemonics

<table>
<thead>
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<th>Ratio</th>
<th>Mnemonic</th>
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<td>Si/(Si + Ca)</td>
<td>lithology indicator ratio</td>
</tr>
<tr>
<td>Fe/(Si + Ca)</td>
<td>iron indicator ratio</td>
</tr>
<tr>
<td>S/(Si + Ca)</td>
<td>anhydrite/gypsum indicator ratio</td>
</tr>
<tr>
<td>H/(Si + Ca)</td>
<td>porosity indicator ratio</td>
</tr>
<tr>
<td>Cl/H</td>
<td>salinity indicator ratio</td>
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</table>

Formation MicroScanner (FMS)

The Formation MicroScanner sonde consists of four orthogonal imaging pads each containing 16 microelectrodes which are in direct contact with the borehole wall during the recording (Figure 2-19). The tool also includes a General Purpose Inclinometry Cartridge (GPII) which provides accelerometer and magnetometer data which allow one to define the tool position and spatial orientation during the recording. The button current intensity is sampled every 0.1 in (2.5 mm), while the two-arm caliper, magnetometer, and acceleration measurements are sampled every 1.5 in (3.8 cm). The tool works by emitting a focused current from the 4 pads into the formation. The current intensity variations are measured by the array of buttons on each of the pads.

Processing transforms the current intensity measurements which reflect the microresistivity variations of the formation into high resolution grey or color images of variable intensity. Black and white (darkest or lightest color) indicate low and high microresistivity respectively. In Figure 2-20 (left), the interface between a silt layer and the silt/sand layers below is a sharp change from black (silt) to the alternate banding of dark
Figure 2-19. Sketch of the four-pad Formation Microscanner sonde redesigned for use in the Ocean Drilling Program (modified after Ekstrom et al., 1986).
Figure 2-20 Display of Formation Microscanner images in a silt/sand sequence (A) and in an andesite breccia (B) from the basement section of ODP Hole 793B.
(silt) and light (sand). The mottled black and white image of Figure 2-20 (right) is an FMS image of andesite breccia.

**Depth of Investigation and Vertical Resolution**

In smooth boreholes with very homogeneous bedding the depth of investigation is about 10 in (25 cm). The vertical resolution is 0.2 in (5 mm).

**Log Presentation**

FMS images are commonly plotted with identical vertical and horizontal scales to see features without exaggeration. To display the images, we use an oriented plot, also called an azimuthal plot, because the images are positioned according to their orientation in the borehole with N in the center and S on both edges. Images from two passes of the tool can be merged and plotted together (Figure 2-21). The calipers can be plotted alongside the images as well.

With an additional processing step on the VAXstation, dipmeter plots can be generated. Standard dipmeter plots consist of borehole drift, calipers, dip angle and direction (tadpoles), azimuth frequency plots, and pad traces (Figure 2-21).

**Environmental Effects**

To produce high-quality FMS images, the pads must be pressed firmly against the borehole. The maximum extension of the caliper arms is 15.0 inches. In holes with a diameter larger than 15 inches, the pad contact will be inconsistent and the FMS images will be blurred. The maximum borehole deviation that can be recorded with this tool is 10°, although the tool itself works well in horizontal wells with the Schlumberger Tough Logging Condition (TLC) system.

**Principal Applications**

- detailed correlation of coring and logging depths.

- precise positioning of core sections where core recovery is less than 100%.

- core orientation.

- mapping of fractures, faults, foliations, and other formation structures and dip determination.

- analysis of depositional environments.

- identification of stress directions.
Figure 2-21 Two passes of the Formation Microscanner tool have been merged and both sets of images are plotted together (left) along with a dipmeter plot (right).
Well Seismic Tool (WST)

The WST measures seismic velocities by recording the time required for a wavelet generated by a seismic source hung outside the ship to reach a sidewall clamped geophone located at a series of depths within the hole (Figure 2-22). The anchoring system includes two multi-spiked arms which are opened and retracted by an hydraulic system. The electrical signals produced by the geophones are amplified and transmitted to the surface instrumentation. The waveforms arriving from the downhole equipment are sampled, digitized and stored in the computer memory. Source time is determined using a surface hydrophone. The geophone and hydrophone signals are displayed on a screen where the complete waveform can be checked and stacked. The stacking technique allows a number of shots to be combined, in order to reduce any random noise and to increase the signal-to-noise ratio.

Log Presentation

A wellsite preliminary processing can provide correction of measured depths and transit times for well geometry, acquisition configuration, and formation characteristics. Also, it can produce the following types of display of the data (Figure 2-23):

- WST shot and stack plots. Stacked shots at each levels are displayed with amplitude and transit time. Upon request, the corrected, stacked data can be converted to a standard SEG-Y format for further processing.

- two-way time plot of stacked data, corrected to the surface reference datum and to true vertical depth

- WST depth versus time and time versus depth velocity curve.

Further processing can provide a vertical seismic profile of the well surroundings.

Principal Applications

- sonic log calibration. The calibrated sonic log becomes the basic seismic reference and allows a surface seismic section to be scaled to depth.

- determination of depth of seismic reflectors. Interval velocities, and characteristics of the formation through reprocessing of full VSP surveys can be obtained using standard seismic techniques.
Figure 2.22. In the Well Seismic Tool, a sidewall-clamped geophone located at different depths in the wellbore records the arrivals of an acoustic wave generated by a seismic source towed by the ship.
Figure 2-23 Different types of display available for the data recorded with the Well Seismic Tool (courtesy of Schlumberger).
Mechanical Caliper Devices (MCD)

Caliper is a measure of wellbore size. The Schlumberger 3-arm caliper log is run at the top of the seismic stratigraphic combination and also serves to centralize the sonic tool. Three bow-springs are mounted 120 degrees apart, and the extension of these moves a contact along a potentiometer. Changes in resistance of the potentiometer are linearly proportional to hole size. In case of elliptical holes, the measurement provided by this caliper is intermediate between the short and long axis. The caliper has a maximum extension of 16 inches, so larger diameter "washouts" are not measured accurately.

Log Presentation

The caliper trace (CALI) is usually displayed in the left-hand track with a scale from 6 to 16 inches. Often, bit size is also plotted for comparison.

Principal Applications

- **log quality control and borehole correction.** The caliper curve indicates the portions of bad hole where other logs may read inaccurately, and is used to correct the logs whose response is sensitive to hole size even when variations are less severe.

- **indication of lithologic variations.** For instance, in zones with swelling clays, hole constrictions are observed where caliper reads less than the bit size. Also, as hole conditions are in general a consequence of rock properties, variations in hole size may correlate with lithologic changes.

Borehole Televiewer (BHTV)

The borehole televiewer (BHTV) is an acoustic device which scans the wall of a borehole, producing an image of the reflectivity of the rock surrounding the wellbore as a function of depth and azimuth. The BHTV is manufactured by SIMPLEC under license from Mobil Oil Corp., and is operated on the ODP drill ship by the L-DGO logging staff.

Details of BHTV mechanical design and operation are shown in Figure 2-24. The BHTV log is obtained while logging uphole at a rate of approximately 1.5 meters/minute with the sonde centered in the hole by means of bowspring centralizers. A piezoelectric transducer mounted on a central shaft rotates 3 times per second and transmits a high-frequency acoustic pulse 600 times per revolution. Two transducers are mounted on this shaft, allowing the operator to select either a 1.3 MHz or a 400 kHz source pulse. While the
higher frequency source reveals more of the details of the wall surface, the lower frequency source has better penetration and can produce a cleaner image if the surface of the borehole is rough. When the source pulse is transmitted, it travels through the borehole fluid, reflects from the borehole wall and returns to be received at the transducer. This returning signal is transmitted uphill and recorded on a specially-formatted video cassette recorder and its amplitude is simultaneously displayed as brightness on a the z-axis of an oscilloscope. The oscilloscope image is thus an acoustic picture of the reflectivity of the borehole wall, where the azimuth varies along the horizontal axis and depth varies along the vertical axis (Figure 2-25). A film of the oscilloscope screen is exposed which is aligned (along the left-hand edge) with magnetic north using a sweep generator triggered by a downhole fluxgate magnetometer. This film exposure can be adjusted to compensate for reflectivity (amplitude) variations due to changes in hole size or opacity of the borehole fluid, such as from suspended cuttings, to show the fine-scale detail of the interior of the borehole wall (Figure 2-26).

In addition to obtaining a film image of the borehole reflectivity, the signal recorded on video cassette can be digitized by the L-DGO MASSCOMP computer and processed in a variety of ways to enhance the image and improve the results. These digital televiewer logs can be analyzed quantitatively, where previous analyses of BHTV images were at best only qualitative. For example, the BHTV data can be processed to obtain a picture in which the image intensity is proportional to the travel-time of the reflected pulse. Figure 2-26 shows two processed intervals which have high angle fractures (dark sinusoidal lines) intersecting the borehole. Such travel-time information can also be processed to create a three-dimensional wire mesh image of the shape of the borehole (Figure 2-27). As shown here, the borehole size can be presented as a function of depth and azimuth in the well, and from three different perspectives, which can be very useful for fracture identification and interpretation. The fracture shown in Figure 2-26 is dipping 50 degrees W-NW with apparent offsets due to tool sticking.

**Principal Applications**

- **location and orientation of fractures intersecting the wellbore.** Structural features such as bedding in sediments, and the character and distribution of pillow basalts in the ocean crust can be determined from oriented amplitude images of the borehole wall.

- **measurement of borehole diameter.** Wall surface roughness and ellipticity, the characteristics of borehole breakouts, and the orientation of the principle horizontal stress from cross-sectional images of the borehole dimensions are measured.

Although the BHTV log has wide applications, it does have some limitations, which should be considered before recommending its use in a given situation. First, as the BHTV log is effectively a point measurement, ship heave often results in jerky tool motion and a degradation of the images (Figure 2-26). Even operating with a heave motion compensator in moderate seas, this motion may prove to be a problem. Second, severe borehole deviation or ellipticity will degrade the image, because the acoustic beam is no longer perpendicular to the borehole wall at all azimuths. Usually, this effect can be recognized
Figure 2-25. Borehole Televiewer log recorded in fractured West Texas Precambrian formation (Zemanek et al., 1969).
Figure 2-26. Digitally processed BHTV amplitude (left) and travel time (right) images. Tool decentralization appears as diffuse vertical banding (right). An isolated fracture at 1020 mbbl shows up as a dark sinusoidal band that dips about 73° west-southwest.
Figure 2-27. Cylindrical net projections at three viewing angles (90, 210, and 330°) showing the intersection of a dipping fracture with the borehole at 1024.5 mbrf.
and corrected in the time-domain image (Figure 2-25). Third, the BHTV cannot recognize features which do not affect either the roughness, reflectivity, or radius of the borehole. Hence, subtle sedimentary variations usually will not be detectable.

Multi-Channel Sonic (MCS)

The multi-channel sonic log (MCS) is a multi-receiver, single-source sonic logging tool which records 12 sonic waveforms at each recorded depth. The MCS tool is configured with a magnetostrictive source above the receiver string, separated by a variable-length spacer assembly (Figure 2-28). The receivers are spaced 15 cm apart, resulting in a 1.65-m receiver array, and form a vertical geometry analogous to a surface refraction survey. The energy which ultimately arrives at the receiver array travels from the source as a compressional pulse in the borehole fluid, refracts at the borehole wall, propagates through the wall rock, and refracts back into the borehole fluid. While logging, the MCS tool must be centered in the borehole by means of bowspring centralizers to insure simultaneous arrival of the signal around the tool. Additional guided modes are typically produced in the borehole environment, and their propagation is controlled largely by the coupling of energy between the formation and the fluid-filled borehole.

The MASSCOMP computer controls the tool during logging, allowing the operator to select the depth increment between recorded source firings as well as the number of receivers to be used. MCS waveforms are digitized by the MASSCOMP and recorded on magnetic tape during the logging run. The MCS log is usually recorded while logging uphole at a rate of about 3 m/min, although the rate depends on the depth increment and number of receivers selected. Typically, 0.3-m depth increment and 12 receivers per source depth are used providing data at each source depth like that shown in Figure 2-29 (top).

MCS waveforms, such as in Figure 2-28, can be analyzed at each source depth to yield compressional, shear and Stoneley wave velocities in moderate to hard formations. The MCS log output includes the various velocity logs and full waveform displays, both plotted using a Versatec (Figure 2-29, bottom). In addition, variations in frequency content and amplitude of the individual wave modes can be computed from MCS data and used for fracture evaluation.

Principal Applications

- **lithology and Poisson's ratio** can be determined from compressional and shear wave velocities.

- **porosity and pore aspect ratio** can be estimated from Vp/Vs and theoretical models.
Figure 2-28. Schematic drawing of the Multichannel Sonic Tool.
Figure 2-29. Multichannel Sonic waveform display. Top: 12-channel array recording in a diorite formation at Kent Cliffs, NY. On the left, compressional, shear, and Stoneley wave modes are displayed and noted; on the right, the compressional and shear arrivals are shown in greater detail at an expanded time scale. Bottom: Variable Density Log (VDL) for one receiver recording over 450' in a shale-limestone sequence in Oklahoma. Compressional, shear, and Stoneley wave modes are observed as coherent arrivals with varying arrival times in each formation.
structural analysis and fracture location can be obtained by amplitude and frequency evaluation of MCS data

Although the standard Schlumberger sonic logs can provide accurate compressional velocities, the additional information available from the MCS log enables determination of the elastic properties of the formation and a qualitative estimate of fracture transmissivity. As MCS logging requires an additional pass, adequate time must be allocated only when information beyond that provided by the Schlumberger sonic log is desired. With recent advances, the MCS log can be adapted for use with a multipole source which enables accurate shear wave velocities to be measured in all formations.

Temperature Tool

Because of the high cost of operation time on the JOIDES Resolution, a separate logging run dedicated solely to heat flow measurement is not economically feasible. To solve this time constraint problem the Borehole Research Group at LDGO has designed a self contained tool that can be attached to the bottom of any of the Schlumberger strings or to the specialty tools from BRG. Fast and slow response thermistors measure the temperature every 1 and 2.5 seconds respectively, while pressure is measured every 3.5 seconds by a transducer. The pressure transducer also turns on the tool when the recording depth (100 m above the mudline) is reached, thus preventing battery drain. The data are recorded and loaded at a 9600 baudrate by an onset tattle tale data logger which operates in a TTBASIC language. Tattle tale has a memory capacity of 132 Kb which allows logging for up to nine hours.

The power supply comes from two lithium batteries which power the electronics cartridge and the pressure transducer.

Soon after the logging operations the data is dumped from the tool memory onto the Masscomp to be processed. Data processing first involves extracting the data from a raw data file and then converting it into readable temperatures and pressure as a function of time. Further processing, such as converting hydraulic pressure into depth, or merging temperature versus time with time versus depth data from Schlumberger logs, is needed to produce temperature logs (Figure 2-30).
Figure 2-30. Temperature data versus depth. The temperature tool was run through pipe at Hole 808C and through casing and openhole at Hole 808E.
Chapter 3. Logging Time Estimates

The following logging time estimates were written in November, 1989. You may wish to depart significantly from the steps and times shown in Table 3-2 (e.g. the Operations Superintendent may want to do a different hole preparation; the tool string is run more slowly to collect better data; through-pipe logging requires slower logging speeds than openhole logs). It is advisable that you prepare an estimated time breakdown (Table 3-1) and keep track of whether you are ahead of or behind schedule; this can influence operational decisions.

Total logging time at any site includes not only the time for collecting data but also time for hole preparation, logging tool rig-up, and other logging-related activities (Tables 3-2 and 3-3). Based on previous ODP logging operations, most aspects of logging can be estimated with reasonably good accuracy. Total logging time depends primarily on four variables: the tools to be run, whether or not the sidewall entry sub (SES) is used, water depth, and subbottom depth of the hole.

The logging tools that are routinely available on the JOIDES Resolution are listed in Chapter 2 of this volume, Table 2-1. The first 14 log types listed in the table are Schlumberger logs, run by the Schlumberger engineer. The last three logs are ODP specialty logs, run by the LDGO logging scientist. In order to save logging time, many of the tools are run at the same time, in tool combination strings, as explained in the previous chapter.

Two "standard" Schlumberger tools strings are run at virtually every logged hole: the quad-tool and geochemical combinations. The former includes the sonic, resistivity, gamma ray, lithodensity, neutron, and caliper tools. The geochemical combination includes the natural spectral gamma ray, induced gamma ray spectroscopy, and aluminum clay tools. Table 3-2 lists all logging operations times involved in hole preparation and running both standard Schlumberger combinations. To improve the quality of the recording sometimes the tools of the quad-tool combination are separated into two logging strings, the seismo-stratigraphic (sonic-resistivity-gamma ray) and the litho-porosity (density-neutron porosity-gamma ray) strings. Logging times for the lithoporosity and seismo-stratigraphic combinations are not specifically shown in either Table 3-2 or 3-3, but they are approximately equal to the times listed there for the multichannel sonic tool.

One additional Schlumberger strings is also often run. The Formation MicroScanner (FMS) string includes the FMS (a high-resolution dipmeter), general purpose inclinometer, and spectral gamma ray tools. Logging times for the FMS are shown in Table 3-3. Table 3-3 also lists the times required to run the borehole televiewer, magnetometer / susceptometer, wireline packer, and dual laterolog. Note that these times for the six tools assume that the standard Schlumberger logs of Table 3-2 have been run, so Table 3-3 does
not include hole preparation and general rig-up/rig-down times that are already included in Table 3-2.

The geochemical combination is the only tool string that collects useful data through drill pipe. Normally, the pipe is pulled to a depth of 50-100 mbsf prior to logging, so that nearly the entire drilled interval can be logged open-hole. In the calculations that follow, we assume that pipe ends at 75 mbsf. Variations from this 75 mbsf assumption cause very minor changes to total logging time. Most times in Tables 3-2 and 3-3 are functions of either pipe length or openhole length, and of either tool speed or pipe pulling speed. For example, the time to run the tool down to base of pipe when using the SES (Table 3-2) is \((WD+75)/2200\), that is a distance equal to water depth plus 75 m at a speed of 2200 m per hour.

Prior to Leg 112, the major uncertainty in logging time estimates involved delays associated with bridges. A bridge is a constricted-hole interval that the logging tool may not be able to get past, while the tool is on its way down through open hole. Nearly all ODP bridges are found in sedimentary sequences and are caused by clay swelling after drilling. Bridges can also form in heavily fractured formations, but these have been much rarer. Deep basalt holes virtually never exhibit bridging. Bridging is very difficult to predict before a leg begins. Even after drilling and before logging, the likelihood of bridges cannot always be estimated reliably.

In the past, one only had two choices if a bridge was encountered that stopped the logging tool. First, one could just log the interval above the bridge and cancel plans to log beneath the bridge. Second, one could pull the logging tool out of the hole and up onto the ship, set pipe through the bridge, then lower the logging tool again. Nearly always, the much heavier drill pipe can punch through bridges that had stopped the lighter logging tool. This second option requires about 3-4 hours for each bridge, in addition to the logging times shown in Tables 3-2 and 3-3 in the column "Time, no SES."

To-date, more than half of the ODP sediment holes have encountered bridges. To prevent lost time or lost logs associated with bridges, the JOIDES Resolution now has the capability of using a sidewall entry sub (Figure 1-2) during logging. The SES was tested successfully on Leg 108 and a new, streamlined design has been built for Leg 132. When inserted into the drill string, it allows one to add or remove drill pipe while a logging tool is downhole. The SES strategy is to lower pipe to near the bottom of the hole, lower the logging tool into open hole just beneath the pipe, then log up while simultaneously pulling pipe at the same speed. In this way open hole logs are obtained without allowing enough time between pipe removal and logging for bridges to form. Even though one usually hopes not to need the SES, it is prudent to estimate logging assuming that it will be used. If the SES is planned for but not needed, logging operations will take 1-12 hours less than planned at a site. Tables 3-2 and 3-3 include separate logging time estimates for programs with and without SES.

In order to estimate the logging time for a site, it is not necessary to use Tables 3-2 and 3-3. The times required for the many steps for each logging run can be combined into a
Table 3-1 - Site 731 Operations

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<td>RIH (run into hole) seismo-strat. combo.</td>
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<td>1750</td>
<td>resistivity calibration &amp; down log</td>
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<td>1904</td>
<td>log up</td>
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<td>2102</td>
<td>POOH (pull out of hole)</td>
</tr>
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<td>2215</td>
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</table>

* available for reduced time if necessary
Table 3-2 - Logging Times (hrs) for "Standard" Schlumberger Logs (Quad-tool and Geochemical Combinations)

<table>
<thead>
<tr>
<th>OPERATION</th>
<th>TIME USING SES</th>
<th>TIME, NO SES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulate mud</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Wiper trip</td>
<td>$1 + 2(SD-75)/667$</td>
<td>$1 + 2(SD-75)/667$</td>
</tr>
<tr>
<td>Release bit</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pull up to 75 mbsf</td>
<td>$1 + (SD-75)/667$</td>
<td>$1 + (SD-75)/667$</td>
</tr>
<tr>
<td>Rig up (WHC, seismo-strat. combo, possible SES)</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>Run tool down to base of pipe</td>
<td>$(WD + 75)/3000$</td>
<td>$(WD + 75)/3000$</td>
</tr>
<tr>
<td>Log down to T.D.</td>
<td>-</td>
<td>$(SD - 75)/1000$</td>
</tr>
<tr>
<td>Lower pipe and tool to T.D., reaming bridges</td>
<td>$(SD - 75)/600$</td>
<td>-</td>
</tr>
<tr>
<td>Exit pipe with tool (probably using circ. head) and position for logging</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Log up (while pulling pipe if SES used)</td>
<td>$(SD - 75)/300$</td>
<td>$(SD - 75)/300$</td>
</tr>
<tr>
<td>Run tool up pipe to ship (slow last 100 m)</td>
<td>$(WD - 25)/3000$</td>
<td>$(WD + 75)/3000$</td>
</tr>
<tr>
<td>Rig down seismo-strat. combo and rig up geochemical combo</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>Run tool down to open hole</td>
<td>$(WD + 75)/3000$</td>
<td>$(WD + 75)/3000$</td>
</tr>
<tr>
<td>Test and calibrate tool</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Run tool down to T.D.</td>
<td>-</td>
<td>$(SD - 75)/1000$</td>
</tr>
<tr>
<td>Lower pipe and tool to T.D.</td>
<td>$0.5 + (SD - 75)/600$</td>
<td>-</td>
</tr>
<tr>
<td>Log up (while pulling pipe if SES used)</td>
<td>$(SD - 75)/200$</td>
<td>$(SD - 75)/200$</td>
</tr>
<tr>
<td>Log up through pipe</td>
<td>85/50</td>
<td>85/150</td>
</tr>
<tr>
<td>Move pipe 5 m, lower tool to open hole</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Log up through pipe</td>
<td>85/150</td>
<td>85/150</td>
</tr>
<tr>
<td>Run tool up pipe to ship (slow last 100 m)</td>
<td>$(WD - 110)/3000$</td>
<td>$(WD - 10)/3000$</td>
</tr>
<tr>
<td>Rig down (WHC, geochemical. combo, possible SES)</td>
<td>3.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

TD = total depth (m); WD = water depth (m); SD = sub-bottom depth (m)  
SES = sidewall entry sub
<table>
<thead>
<tr>
<th>OPERATION</th>
<th>TIME USING SES</th>
<th>TIME, NO SES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rig up tool</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Run tool down to base of pipe</td>
<td>((WD + 75)/3000)</td>
<td>((WD + 75)/3000)</td>
</tr>
<tr>
<td>Run tool down to T.D.</td>
<td>-</td>
<td>((SD - 75)/1000)</td>
</tr>
<tr>
<td>Lower pipe and tool to T.D.</td>
<td>(0.5 + (SD - 75)/600)</td>
<td>-</td>
</tr>
<tr>
<td>Log up (while pulling pipe if SES used)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>borehole teviewer</td>
<td>(LI/90+(SD-75-LI)/1500)</td>
<td>(LI/90+(SD-75-LI)/1500)</td>
</tr>
<tr>
<td>magnetometer/susceptometer</td>
<td>(LI/300+(SD-75-LI)/1500)</td>
<td>(LI/300+(SD-75-LI)/1500)</td>
</tr>
<tr>
<td>Formation MicroScanner (FMS)</td>
<td>((SD-75)/500)</td>
<td>((SD-75)/600)</td>
</tr>
<tr>
<td>wireline packer</td>
<td>(8 + (SD-75)/500)</td>
<td>(8 + (SD-75)/1000)</td>
</tr>
<tr>
<td>multichannel sonic or temp. log</td>
<td>((SD-75)/180)</td>
<td>((SD-75)/180)</td>
</tr>
<tr>
<td>dual laterolog</td>
<td>((SD-75)/500)</td>
<td>((SD-75)/1600)</td>
</tr>
<tr>
<td>Run tool up pipe to ship (slow last 100 m)</td>
<td>((WD - 25)/3000)</td>
<td>((WD + 75)/3000)</td>
</tr>
<tr>
<td>Run tool up pipe to ship (slow last 100 m)</td>
<td>(100/200)</td>
<td>-</td>
</tr>
<tr>
<td>Rig down tool</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

TD = total depth (m); WD = water depth (m); SD = sub-bottom depth (m)
LI = length of interval to be logged (m); SES = sidewall entry sub
single equation. Table 3-4 lists these equations derived from the previous two tables. To estimate total logging time for a site, follow these simple steps:

1. decide whether or not the sidewall entry sub is likely to be used (probably, yes)  
2. calculate the total logging time for each logging tool (or tool string) planned, by inputting water depth and subbottom depth of penetration into the equation for that tool  
3. add the times for the various runs.

For example, suppose that the standard Schlumberger (seismic stratigraphic and geochemical combinations) and FMS tool strings are to be run at a site in 3000 m water depth, with 1000 m subbottom penetration, and that the SES will be used. The time for hole preparation and running the "standard" Schlumberger logs is

$$19.2 + .00147 \times 3000 + .0178 \times 1000 = 41 \text{ hours}$$

The additional time for the FMS is

$$3.0 + 00073 \times 3000 + .004 \times 1000 = 9 \text{ hours}$$

Thus, all logging operations at this site require about two days and obtain almost all of the logs shown in Table 1-2, or about 30 different types of log curves.

Table 3-4, as well as Tables 3-2 and 3-3, generally assumes that the entire interval below 75 mbsf is logged, with some exceptions. The times for the geochemical combo include not only the openhole interval but also two logging passes through pipe for the uppermost 75 mbsf. The borehole televiwer and magnetometer/susceptometer are normally run over only part of the hole (e.g. basement). Thus the equations for these two tools include a third variable: length of interval to be logged. The wireline packer is a station tool rather than a continuous logging tool. At each station, packers are inflated and a formation fluid sample is taken. The wireline packer times shown in Tables 3-3 and 3-4 assume one wireline packer trip and four fluid samples, but this tool is so new to ODP that the times are only very rough estimates.

The logging time equations in Table 3-4 are good working estimates, but they do not include four contingencies:

1. time required to punch through bridges or change to the sidewall entry sub if one starts logging without the SES  
2. for reentry holes in which it is not permissible to drop the bit at the bottom of the hole, time to pull the drill string, take off the bit, and reenter the hole  
3. time beyond 1 hour to drop the bit, due to problems with the bit release  
4. tool or cable breakdown, which occurs at about 10% of sites and requires 1-3 hours extra to deploy a backup tool or cut off faulty cable.

The preceding discussions of logging times consider all logging tools that are routinely available on board the JOIDES Resolution. For individual legs, scientists may bring
### Table 3-4 - Logging Time Equations

#### Using SES

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Standard&quot; Schlumberger</td>
<td>( t = 19.2 + .00147 \times WD + .0178 \times SD )</td>
</tr>
<tr>
<td>Formation MicroScanner</td>
<td>( t = 3.0 + .00073 \times WD + .004 \times SD )</td>
</tr>
<tr>
<td>Dual Laterolog</td>
<td>( t = 3.0 + .00073 \times WD + .004 \times SD )</td>
</tr>
<tr>
<td>Wireline Packer</td>
<td>( t = 11.8 + .00073 \times WD + .004 \times SD )</td>
</tr>
<tr>
<td>Multichannel Sonic or Temp. Log</td>
<td>( t = 2.7 + .00073 \times WD + .0079 \times SD )</td>
</tr>
<tr>
<td>Borehole Televiewer</td>
<td>( t = 3.1 + .00073 \times WD + .0026 \times SD + .0114 \times LI )</td>
</tr>
<tr>
<td>Magnetometer/susceptometer</td>
<td>( t = 3.1 + .00073 \times WD + .0026 \times SD + .0029 \times LI )</td>
</tr>
</tbody>
</table>

#### Without SES

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Standard&quot; Schlumberger</td>
<td>( t = 10.5 + .00146 \times WD + .0163 \times SD )</td>
</tr>
<tr>
<td>Formation MicroScanner</td>
<td>( t = 0.9 + .00073 \times WD + .0029 \times SD )</td>
</tr>
<tr>
<td>Dual Laterolog</td>
<td>( t = 1.0 + .00073 \times WD + .0018 \times SD )</td>
</tr>
<tr>
<td>Wireline Packer</td>
<td>( t = 9.8 + .00073 \times WD + .0022 \times SD )</td>
</tr>
<tr>
<td>Multichannel Sonic or Temp. Log</td>
<td>( t = 0.6 + .00073 \times WD + .0072 \times SD )</td>
</tr>
<tr>
<td>Borehole Televiewer</td>
<td>( t = 1.0 + .00073 \times WD + .0018 \times SD + .0114 \times LI )</td>
</tr>
<tr>
<td>Magnetometer/susceptometer</td>
<td>( t = 1.0 + .00073 \times WD + .0018 \times SD + .0029 \times LI )</td>
</tr>
</tbody>
</table>

\( t = \) total logging times (hrs); \( WD = \) water depth (m); \( SD = \) sub-bottom depth (m); \( LI = \) length of interval to be logged (m); \( SES = \) sidewall entry sub
their own logging tools (e.g. magnetometer, vertical seismic profile tool). Estimation of logging times for these tools requires consultation with those scientists.
OCEAN DRILLING PROGRAM

Wireline Logging Manual

Volume 4

Scientific Logging (1989-1990)

Borehole Research Group
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

SEPTEMBER, 1990
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## Chapter 4

Chapter 5

Chapter 1. Introduction to Scientific Uses of Wireline Logging

Wireline logging within the Ocean Drilling Program (ODP) provides fundamental observations of the physical and chemical state of the Earth's crust by making *in situ* acoustic, electrical and nuclear measurements in ODP boreholes. The combination of core samples returned to the surface and downhole measurements adds a new dimension to the pursuit of global geoscience problems into the 1990's.

As defined by the JOIDES COSOD I, and particularly, II documents, the major geological thematic objectives of the ODP are listed in Table 1-1, with examples of the contributions of wireline logging to the solutions of problems within these themes. Below, we present recent examples from Legs 123-131 of logs used to solve problems from this thematic list. Further, more extensive ODP examples of the utility of logging data directed at the solutions to these thematic problems are given in Volume 5 (covering ODP Legs 111-121) and Volume 6 (covering ODP Legs 101-111).

**Paleoenvironment**

The geophysical and geochemical logs recorded in ODP boreholes provide the only continuous record throughout the well from which to examine the impact of climatic changes on the sedimentological record of the past. Consider, for example, the variations in natural radioactivity (natural gamma-ray emissions from the decay of potassium, uranium, and thorium) of the sediments from Hole 798B (Leg 128) in the Japan Sea (Figure 1-1).

The cyclicity observed in the gamma ray log is caused by the variation of the wind-blown, continentally-derived dust component of the sediments called loess (see detailed discussion in Chapter 3, below), as can be seen from the correlation of zones with high natural gamma-ray emission and high aluminum content recorded by the geochemical logging tool. The continentally-derived loess contains clays and feldspars that are abundant in both radioactive elements and aluminum. These wind-blown deposits are massively eroded during major dry periods in Asia, and deposited in the Sea of Japan. When the climate of Asia becomes wet, the major deposition in the Japan Sea comes from local, river-bourn sources that are much lower in radioactive elements and aluminum. The period of the gamma ray log caused by this climatic variability agrees nicely with the 41,000 year variation in the Earth's orbital tilt predicted by Milankovitch (Figure 1-1).

Because the continuous nature of logs allow them to be treated as time-series, it is possible to define the periods of the cyclicity information they contain. The power spectrum of the gamma-ray log can be precisely calculated (Figure 1-2); the gamma-ray log tuned to the orbital tilt driving function produces a dramatic spectral peak at 41,000 years. This "tuning" predicts the fine-scale sedimentation rate changes that would be required to bring the logging cycles into complete agreement with an orbital tilt driving function for the signal observed in the log. These sedimentation rates are then observed to be consistent with, but
Table 1-1.

MAJOR ODP THEMES AND LOGGING CONTRIBUTION TO EACH

PALEOENVIRONMENT

a. Cyclicity
b. Geologic connection to orbital parameter changes

BIOSTRATIGRAPHY

a. Sedimentation rate
b. Ties to sequence stratigraphy from surface seismics

PHYSICS AND CHEMISTRY OF THE OCEANIC CRUST

a. Geochemical reference holes and mass balance during subduction
b. Chemical exchange during hydrothermal alteration
c. Geophysics of normal and back-arc basin crust

STATE-OF-THE STRESS IN THE EARTH'S CRUST

a. Direction of maximum horizontal compression
b. Thermal versus driving forces
c. Stress distribution in subduction zones
d. Plate rotation
Figure 1-1. Correlation of gamma ray logs from the Japan Sea with (left) the magnetic reversal time scale (left), the 41,000 year period of changes in the earth's orbital tilt (center), and the aluminum log showing increases caused by terrigenous sedimentation (right).
much more detailed than either paleomagnetic or biostratigraphic datums derived from the core recovered from this site (Figure 1-2). Note that the 23,000 year Milankovitch cycle is too fine-scale at these sedimentation rates for the gamma-ray log to detect, because this logging tool does not have sufficient vertical resolution. The observation of one Milankovitch cycle in the log predicts the locations of other detectable periods and there is considerable power in the proper location for the 100,000 year cycle seen in Figure 1-2 (again, see Chapter 3, next).

The gamma-ray log from the only hole yet to penetrate Jurassic sediments (Leg 129, Hole 801B; Figure 1-3) also shows cyclical variations in natural radioactivity that are related to Milankovitch climate cycles. Because the sedimentation rates are very low (approximately 10 m/Ma), only the 106,000 and 410,000 year Milankovitch periods are evident in spectral analyses of the gamma-ray log from Hole 801B. The Formation MicroScanner images of the fine-scale resistivity variations promise to reveal the shorter period sedimentological responses to Jurassic climate change, but these have yet to be analysed. This illustrates a powerful contribution of logs to paleoclimatic determinations because they record the variations in physical and chemical properties of the sediment, regardless of its age. The variations in the relative contributions of the various orbital parameters to past global climates are poorly understood far into the past.

Biostratigraphy

Well logs provide a record of the stratigraphic impact of major sequence changes caused by not only short-period climatic variations, but also longer period, sea-level and tectonic changes that allow for the fine-tuning of age-depth relations in ODP boreholes. The "tuning" of the gamma-ray log to adjust sediment ages to precise 41,000 cycles, allows for the determination of a sedimentation rate curve (Figure 1-2) that is considerably more accurate than that determined from biostratigraphy of the limited core recovered from this site. A new nuclear magnetic resonance logging tool for sediments that is to be tested on Leg 134 offers further hope of age-identification capabilities from logs. We have never before had the ability to determine absolute ages that will come from the tie to the magnetic reversal time-scale, but the determination of climatic periods is already giving us relative age determinations.

One important result of such age determinations is that precise ties to the "Vail" sea-level curve can be made between logs and seismic sequences derived from surface reflection profiling. Further examples of the age-dating and sequence correlation capabilities of logs are given in Chapter 3 of this volume.

Physics and Chemistry of the Oceanic Crust

Geochemical logs are the only continuous record of the chemical variations in the crust. (see Chapter 4). The usefulness of such a complete record can be seen from an examination of the geochemical logs from the Java Trench "geochemical reference site" in the Indian
Figure 1-2. Continuous correlation ("tuning") between the gamma ray log of Figure 1-1 and orbital obliquity variations provides very high-resolution data in the entire logged interval (bottom), consistent with but much more detailed than paleomagnetic and biostratigraphic datums. The biostratigraphic datums are determined from core-catcher samples, and therefore have a 9.5 m spread (error bar) in either direction. The relatively minor sedimentation rate changes resulting from "tuning" the gamma ray log to the orbital time series dramatically increase the 41,000 year power (top).
Leg 129, Hole 801B
Milankovitch climate cycles in Jurassic sediments from the Western Pacific

Figure 1-3. Cyclical variations of the gamma ray log recorded in the Jurassic sediments of Hole 801B appear to have detected the Milankovitch eccentricity periods of about 410,000 and 106,000 years.
Ocean, Hole 765D (Leg 123; Figure 1-4). The chemical composition of the upper 1.5 km of the crust in the Argo Abyssal Plain of the eastern Indian Ocean provides bounds for the composition of crust being subducted beneath the Java Trench to the north.

The compositional variability of the sediments and crust being subducted must be known before the volcanic processes active in the Island Arcs behind the subduction zone can be fully understood. For example, the amount of potassium to be subducted when this crust moves north in the near future is generally low in the upper 500 m of the sedimentary section and throughout the basement. However, an increase in the abundance of aluminum-rich clays (particularly in a layer found from 580 to 640 mbsf) raises the potassium content of the lower 500 m of the sedimentary column. The horizontal and vertical extent of this interval, with its >5 % K₂O, would obviously influence the amount of potassium available for incorporation into island-arc magmas after subduction.

The compositional variability of these island-arc volcanics is poorly known, so that the discovery of high potassium andesites beneath 700 m of high mafic-content boninites in the Izu-Bonin forearc at Hole 786B (Leg 125; Figure 1-5) was a big surprise. These andesites are compositionally variable, with high silica magmas containing virtually no iron (true rhyolites) overlying dacites with similar silica contents to the rhyolites, but with higher iron contents. These silicic rocks contain about 5% K₂O. Thus, a significant source for potassium must have been subducted beneath the Bonin Trench within the last 5 Ma. The source for this abundant potassium could be from the subduction of an extensive area of clay-rich sediments similar to those found in the lower sedimentary column in the Argo Abyssal Plain.

Geophysical logs provide the benchmark observations with which to integrate fine-scale core analyses with large wavelength, remote sensing techniques, such as seismic reflection, gravity, and magnetic mapping of the upper oceanic crust. The most extensive set of geophysical and geochemical logs into back-arc basin crust was recorded during Leg 124, at Holes 768C in the Sulu Sea and Hole 770C in the Celebes Sea (Figure 1-6). The true back-arc basin crust found in the Sulu Sea Hole 768 contains a magnetic reversal at 1068 m below the sea floor. Both pillow basalts and massive flow units below this boundary are reversely polarized. The trapped normal MORB oceanic crust from the Celebes Sea Hole 770C was found to contain a single reversely polarized sill within the otherwise normally magnetized pillow basalts of the rest of the hole.

State-of-Stress in the Earth's Crust

Logs provide the only mechanism for routine measurement of the orientation and magnitude of the tectonic stresses that drive the surface plates of the Earth. Both the Borehole Televiewer (BHTV) and the Formation MicroScanner (FMS) record the direction of maximum horizontal compressive stress by imaging the orientation of wellbore breakouts, failure caused by hoop stresses along the wall of the newly cut hole. Extensive wellbore failure produced the acoustically absorptive (black) stripes observed in the BHTV logs from Hole 765D in the Argo Abyssal Plain (Figure 1-7). The least compressive
Figure 1-4. Geochemical logs from Hole 765D were obtained through casing in the sedimentary section of the hole and openhole in the basaltic basement. Geochemical logging allows for the determination of the total geochemical budget in ODP boreholes, a critical ingredient for geochemical reference holes such as Hole 765D.
Figure 1-5. Four of the geochemical logs obtained for the island-arc volcanics of Hole 786B. One aspect of geochemical reference holes is a comparison of geochemistry between subducted materials and arc volcanism. The major geochemical change at the bottom of the hole could reflect a change in composition of subducted sediments.
Figure 1-6. Geophysical logs from two back-arc basins near the Philippines. The geophysical properties of back-arc crust at Hole 768C are actually more like those of typical oceanic crust than are the anomalously dense properties of "normal" crust trapped in the Celebes Sea at Hole 770C. At both sites magnetic reversals are evident in the magnetic logs.
Figure 1-7. Borehole televiewer record of basement at Hole 765D shows strong and consistent pattern of breakouts indicating approximately E-W minimum compressive stress seaward of the Java Trench.
horizontal stress direction in the Argo Abyssal Plain is east-west, indicating that the maximum compressive stress direction is north-south. This direction is consistent with predictions from plate driving force models of the Indian Plate based upon an evaluation of the relative importance of the pulling force of the Java Trench, the pushing force of the Southeast Indian Ridge, and the resistive force of the collision of India with Asia.

Stress directions were recorded at a total of eight sites in the Western Pacific during Legs 123, 124, 126, 127, and 128 (Figure 1-8). Compression oriented perpendicular to the subduction zone was found in all these sites. However, four stress directions that were recorded within a small area of the Bonin Fore-Arc indicate that the local stresses near the trench are more complex than previously thought. The maximum compressive stress direction rotates from 020° in FMS images from Hole 792E to 040° in BHTV logs from Hole 786, to 065° in FMS images from Hole 793B, to 090° implied by structural constraints in the newly rifted Bonin back-arc at Site 790 (Figure 1-8).

These present-day rotational forces within the fore-arc landward of the Bonin trench were also present in the past, as can be seen from the 90° rotation found in middle Oligocene sediments from Holes 792E and 793B (Figure 1-9). Here, viscous magnetization directions from normally polarized sediments from Hole 792 agree with paleomagnetic measurements from reversely polarized core oriented by the FMS log at Hole 793B. Both indicate that sediments now oriented east-west have been rotated by movement of the Philippine plate since the Oligocene. Such rotational forces are just now being recognized as important deformational processes in continental as well as oceanic plate boundaries (c.f., the England and Molnar and McKenzie articles in the March 12, 1990 issue of Nature on the rotation of eastern Tibet).

Further discussions of the determination of plate stresses from well logs are given in Chapter 5.

Summary.

Below, we detail new logging technologies recently added to the ODP arsenal of downhole measurements and show examples of how they can be used to do science (Chapter 2). We then describe in considerable detail how to use well logs 1) to do paleoclimate research with well logs (Chapter 3), 2) to determine the chemical exchange that has occurred between the oceanic crust and the ocean during hydrothermal alteration (Chapter 4), and 3) to map intraplate stresses within the oceanic lithosphere (Chapter 5).
Figure 1-8. Some of the first intraplate stress directions from the Western Pacific (circled at left and blown-up for the Philippine Plate at right), from FMS and televiewer breakouts, show unexpected lateral gradients in stress direction. Stars on the map of Pacific stress orientation data show the locations of possible CEPAC ODP sites; stress information from these "targets of opportunity" would clearly fill large gaps in our knowledge of broad intraplate stress patterns.
PHILIPPINE PLATE MOTION
FROM ORIENTED CORES
MIDDLE OLIGOCENE

HOLE 793B
FMS DIP
DIRECTION

HOLE 792E
VISCIOUS MAG
DIRECTION

ODP LEG 126

Figure 1-9. Paleomagnetic studies of oriented ODP cores have the potential for solving a long-outstanding problem of rotation of the Philippine Plate. Cores from Hole 793B could be oriented by comparing structural dips within cores to the in situ dip direction from the FMS. Paleomagnetism of these oriented cores indicates a clockwise rotation of about 90°; a similar but less reliable result was obtained by viscous magnetization orientation at Hole 792E.
Chapter 2. New Logging Technologies in the Ocean Drilling Program

Recently, the wireline logging program has made major technological improvements in the measurements made in ODP holes that have significantly advanced our ability to achieve a greater understanding of the mechanisms that affect the thematic processes outlined above in the oceans.

Formation MicroScanner

The most important addition to the ODP logging program is the deployment of the electrical Formation MicroScanner (FMS), a four-pad dipmeter with 16 resistivity-measuring electrodes per pad (see text and Figure 2-19 in Volume 3 for further detail). This tool gives oriented, high-resolution images of the electrical conductivity variations along the wellbore wall, and allows for the first time the exact location-in-depth and orientation of the cores recovered in ODP wells. FMS data are acquired at logging speeds that are the fastest of the entire Schlumberger suite (about 900 m/hour), whereas the other ODP imaging tool, the Borehole Televiewer (BHTV), acquires data at the slowest speed (100 m/hr). The eventual combination of BHTV and FMS images in each ODP well will yield acoustic and electrical images of comparable resolution to optical images of recovered core. The three imaging techniques are complementary since color (optical), reflectivity (acoustic), and conductivity (electrical) are each controlled by different physical and chemical processes in the rocks.

The FMS provides vertical resolution of about 5 mm, allowing the imaging of features of the wellbore wall that are more than three orders of magnitude finer than from any other logging tool except the ultrasonic Borehole Televiewer. For example, the images from the turbidite sequence drilled in Leg 126, Hole 793B (Figure 2-1), show the fine-scale layering and gradual grain size changes that can be observed only from core and in outcrop, on land. It is reassuring to see from the comparison of the FMS images and the more traditional induction log that the long wavelength peaks and troughts characteristic of the poorer vertical resolution of the induction log can be seen clearly in the FMS logs, as well. The combination of significant core recovery and continuous FMS logs allowed the construction of the most complete sedimentary description of this hole yet achieved within ODP (Figure 2-2). Laminations, cross-bedding, fluid-escape pillars, cobbles and pebbles, were imaged and used to locate the precise depths of core within the turbidite sequence.

As of September, 1990, the FMS has been deployed in 14 ODP wells in the Western Pacific, with about 6 km of cumulative log recorded. The images, as well as strike and dip of resistive beds in the formation, are oriented using a downhole, 3-component, fluxgate magnetometer. As shown by dipmeter results from Leg 128, Hole 798B in the Japan Sea (Figure 2-3), the strike of beds dipping 5-20° is predominantly to the northeast above a
Figure 2-1. Formation MicroScanner images allow the identification of several turbiditic sequences at Hole 793B. The high resolution image is compared to the conventional resistivity log; the high resistivity layer detected by standard logs at 1234 mbsf consists of thin beds visible on the FMS image.
Figure 2-2. Preliminary version of the sedimentary log derived from the combination of FMS data and cores from a turbiditic sequence at Hole 793B (after Hiscott et al., 1990).
LEG 128: HOLE 798B, Oki Ridge (Japan Sea)
Dipmeter and Borehole Images from FMS

Figure 2-3. Example of the information provided by the Formation MicroScanner. From left to right: hole deviation as a function of depth (shown as open-headed tadpoles); caliper measurements along two perpendicular directions (used to detect stress-induced breakouts); tadpole plots of local dip magnitude and direction (used to determine sedimentary facies and structural dip); resistivity logs (used to determine porosity variations); and a small portion of the FMS images.
subtle unconformity at 340 m subbottom, whereas the beds below strike south-southeast and dip from 0 to 10°. The hole ellipticity recorded by the four-arm caliper from 100 to 160 m subbottom indicates a maximum compressive horizontal stress striking east-west (orthogonal to the least compressive stress direction that causes the ellipticity of the wellbore).

The FMS provides much more than dipmeter information, however. The fine-scale images from 224 to 229 m show low resistivity (black) to high resistivity (white) cyclicity that varies with a 41,000 year period (4 m cycles), and with <1 m cycles (Figure 2-3). Even finer-scale laminations, fractures, and features directly recognizable in the core recovered from this same depth interval allow the core's location in true-depth, and more importantly, the orientation of the core to be determined.

The usefulness of the FMS images in basalts from the oceanic crust can be seen from Leg 127, Hole 794 in the Japan Sea (Figure 2-4). Two passes of the borehole wall produce extended coverage from the FMS, allowing the observation of resistive 'banding' caused by cumulative layering within a massive flow unit in the upper basaltic crust. Extensive fracturing of the basalt is also evident. The strike and dip of the layering and the imaging of the fractures allows the basaltic core to be oriented at this site, as well. Pillow basalts were also successfully imaged in Leg 130, Hole 807 on the Ontong Java Plateau (Figure 2-5).

Boron Sleeve for Geochemical Logging Tool

Another major improvement in ODP logging has been the introduction of a boron sleeve onto the Geochemical Logging Tool (see text and Figure 2-16 in Volume 3), which allows further isolation of borehole effects and subsequent improved sensing of formation chemical changes. Because the Schlumberger boron sleeve is >5 inches in diameter, we designed a slim-hole version which would fit in ODP boreholes.

The added sensitivity of the Geochemical Logging Tool allowed the recording of variations in elemental abundances of the sediments surrounding the frontal thrust of the Nankai Trench off southern Japan in Leg 131, Hole 808C (Figure 2-6). At this site the hole conditions were so bad that the drillpipe itself was in considerable jeopardy. Open-hole logging was therefore impossible, and the logs shown in Figure 2-6 were recorded through the drillpipe; as a result, the signal is greatly attenuated. By using elemental ratios to enhance the geochemical variations (Figure 2-7), both the frontal thrust and several surrounding intervals were found to be zones with high clay content. The abundant hydrogen, aluminum, potassium and thorium abundances relative to that of silica, and the high thorium and uranium concentrations are characteristic of the presence of clay minerals.

The combination of FMS imaging and geochemical logging provides geophysical and geochemical characterization of the formation never before possible from logs. Consider for example the diagenetic changes found in Leg 127, Holes 794B and 797C in the Japan Sea (Figures 2-8 and 2-9). Geophysical logs record major physical property changes related to the opal-A/CT and CT/Quartz phase transitions that occur in the laboratory at 36-55° and 49-64° C, respectively (Figure 2-8). The aluminum weight percent log from the Geochemical Logging Tool indicates an increased clay content across these reaction fronts
Figure 2-4. Raw (left) and processed (right) FMS images of basement rocks at Hole 794B. Though these black and white display provide only a small fraction of the information contained in the many gray-levels of the original images, fracturing and the sinusoidal pattern of dipping cumulate layers are still evident.
LEG 130: HOLE 807C
Ontong-Java Plateau (Western Pacific)

RESISTIVITY (ohmm)

1300
1350
1400
1450
1500

SEDIMENTS

 BASALTS

PILLOW BASALTS

1495
1496
1497
1498
1499
1500

Figure 2-5. Pillow basalts at Hole 807C. FMS images and electrical resistivity logs in the pillow basalts of Hole 807C, Leg 130, Ontong Java Plateau.
Figure 2-6. 808C. Geochemical logs recorded through drillpipe from the Nankai accretionary prism, Hole 808C, Leg 131.

Spikes are pipe joints not yet corrected for steel.
Figure 2-7. Hole 808C. Elemental ratios from geochemical logs (see Figure 2-6) from the Nankai Trough, Leg 131. Blackened peaks are clay-rich zones.
Figure 2-8. Diagenetic boundaries were logged by a complete geophysical suite in Hole 794B in the Japan.
IMAGING CHERT BANDS AND DIAGENESIS BOUNDARIES
JAPAN SEA
LEG 127, HOLE 797C

Figure 2-9. A wealth of diagenetic information was obtained from a single fully-logged hole such as Hole 797C, whether one looks at geophysical versus geochemical log variations at a broad scale (left), core recovery versus log-based lithology at a scale of tens of meters (center), or laminations at a scale of centimeters (right).
as well, and brightness bands from the FMS images identify chert bands forming within the opal-rich horizons (Figure 2-9). Core recovery was clearly affected by these chert bands.

Lamont Temperature Tool

The use of the Lamont Temperature Tool on the bottom of each Schlumberger tool string run into ODP holes has now become routine (see Volume 3). Multiple runs allow for the precise mapping of fluid flow disturbances, as well as the calculation of changes in heat flow in ODP wells. At Hole 792E (Leg 126), the fault zone encountered just above the sediment/basement contact (Figure 2-10) would have gone undetected without the observation of borehole cooling from the loss of drilling fluid into the highly permeable fault zone.

Wireline Packer/Fluid Sampler

The Wireline Packer-Fluid Sampler is in the final stages of testing prior to deployment on the drillship (Figure 2-11). The WLP inflates two straddle packers against the formation, then draws fluid through a test chamber using a powerful downhole pump. Pressure, temperature, chlorinity, pH, sodium, and calcium content of the tested fluid is displayed in real-time at the surface. When the operator is satisfied that borehole fluid has been flushed and formation fluid is being sampled, four sample bottles can be filled. These fluids are then delivered to the surface under pressure. We anticipate full operational use of the tool for the drilling in the eastern pacific in 1991.

WBK Digital Borehole Televiewer

The BHTV has, with the advent of the wireline heave compensator, acquired excellent data in hard sediment and basement rocks. Among their scientific applications, these data provide delineation of formation contacts, fractures, and intraplate stress directions (See Chapter 5). The borehole televiwer will hopefully be transformed from our least reliable tool to one that realizes its full potential with the replacement of our obsolete analog tool with digital BHTV's leased from the German WBK. These state-of-the-art ultrasonic imaging tools send a digital record of the reflectivity and precise size of the borehole at 600 points per rotation within the borehole. One of the new BHTV's will be able to operate at the relatively high-temperature of 250°C.
Figure 2-10. Down- and up-going temperature logs are now routinely obtained on most ODP logging runs, thus providing information on both thermal gradients (broad trends) and fluid flow (local anomalies). This example shows the comparison between two runs at Hole 792E (Leg 126). The steeper thermal gradient of the second run was obtained after the hole had approached thermal equilibrium. In both runs anomalously low temperatures were recorded at an inferred fault zone just above the top of the basement.
Figure 2-11. Schematic drawing of the three connecting portions of the wireline packer. Inflation of the upper and lower packer (bottom right) isolates a short interval of borehole; *in situ* fluids from this interval are sucked through the filter (bottom right) first into a test chamber (center left) for real-time transmission to the surface, and then into sample bottles (middle right) for later laboratory analysis.
High Temperature Slim-Hole Logging

Among the slim-hole logging tools identified by the JOIDES Panels for deployment in the high temperatures of the East Pacific drilling programs which use the Diamond Coring System (DCS) are temperature, fluid resistivity, and fluid sampling. ODP must develop a high-temperature, slim-hole logging capability in the near future. Options are to lease a temperature, fluid pressure, flowmeter tool from JAPEX, or to procure this tool and a fluid sampler from Sandia National Laboratories, where their Office of Continental Drilling has developed capabilities to make temperature logs and fluid samples in wells with temperatures up to 400° C.

In addition, there are longer-term requirements within ODP for a full, conventional logging capabilities for the high-temperature, DCS holes. The double dewing of electrical resistivity, and then possibly gamma-ray and sonic logging tools (assuming new crystals and transducers are not required) will be attempted in 1991. Prior to their deployment in ODP wells these re-packaged slim-hole tools will be evaluated in land wells in order to test the accuracy of their measurements versus that of conventional, larger diameter tools.

Summary

Below, we go into more detail about the scientific applications of these new technologies. In subsequent volumes of this logging manual you will find that significant new insights have already been made utilizing these tools within ODP. Their use, along with the enhanced drilling and station-keeping capabilities of the JOIDES Resolution, are the major technical advance from the Deep Sea Drilling Project to the Ocean Drilling Program.
Chapter 3. Cyclicity in Logs and Paleoclimate

Introduction

Cycles in the Earth's climate have been known for hundreds of years. The causes must be derived from variations in the energy input the earth receives from the sun. It is not likely, however, that the sun itself has flickered, or in other ways wavered in its energy output, particularly over periods of tens- to hundreds-of-thousands of years that appear to have been driving climatic changes such as glacial cycles. Milankovitch first recognized that it was changes in the Earth's orbital parameters themselves that have caused the energy input to vary periodically over our geological past. It is still unclear how the ellipticity of the Earth's orbit, the obliquity of that orbit to the sun, or the precession of the Earth's tilt axis have changed in relative importance as driving forces of the Earth's climate far into the geological past.

In order to fully understand the ultimate causes of climatic variation, we must also determine the geological responses to that climatic change. The effects of climatic change do not have to be either linear or the same everywhere on the Earth's surface, and their ties to external energy input may not be clear. For example, a major shift in the locations of the continents caused by plate tectonic movements likely cooled the high latitudes, producing the last ice ages, with or without orbital variations. We must first understand the geological responses to climatic change and then determine the effects such change might have on logging data before we can address fundamental questions of the long term variations in the paleoclimate of the earth.

As a result of such an understanding, logs may be used to identify variations in porosity or elemental abundances that are caused by climatic periodicities. These log-derived cycles can then be used for quick age-control, particularly when core recovery is poor. Sedimentation rates, unconformities, and ages themselves can be determined from logs for the first time using this correlation to the Earth's climatic variations.

Climate Cycles and Milankovitch Orbital Parameter Variations

First, the earth does not spin around its axis with a perfect spiral. It wobbles slightly on its axis, because of the gravitational pull of the sun and moon on the equatorial bulge of the earth. The axis precesses; it moves slowly around a circular path and completes one revolution every 19,000-23,000 years. Second, the angle of tilt of the earth, called obliquity, changes with a period of 41,000 years. Third, the orbit of the earth varies from about 5% eccentric, to just about a perfect circle with a period of about 100,000 years. The obliquity and precession signals are modulated by the eccentricity variation with periods of
approximately 400,000 years (Figure 3-1). Therefore, there are significant variations in the amplitude of the energy flux as well as in the period of the changes.

These orbital variations must be integrated to determine the energy flux at any time in the past. At present, the earth is closest to the sun at winter solstice. 5,500 years ago, the Earth’s tilt was 9 degrees from vertical. 11,000 years ago, the closest approach to the sun was at the summer solstice. Then, a larger amount of solar energy was entering the northern hemisphere in the summer.

The energy flux is also dependent upon latitude, as we all know. The flux at the highest latitudes is dominated by the obliquity cycle, whereas at low latitudes, the precession cycle is more important because it is closer to the sun in the summer. This orbital variation in energy flux at any given latitude is only about 10%, however, because even though the amplitude is higher at lower latitudes, the mean is also much higher. Though 10% appears small, it was enough of a change to bring the ice sheets down over the entire northern United States only 18,000 years ago.

In fact, increasing the areal cover of ice on the Earth’s surface reflects more solar energy, amplifying the effect. Complex feedback mechanisms clearly are of great importance. Also, the degree of change in the orbital parameters over the geological past is poorly known. The day has been lengthening through time because of the drag of the moon’s tide on the earth. Both tilt and precession have been changed by this slow movement of the moon away from the earth, and we know of few methods for tracking the change in eccentricity back in time. The hope is that logging results from the Ocean Drilling Program will provide an entirely new data set to track the variations in these fundamental orbital parameters back into the Mesozoic.

Log Responses to Climatic Change

Orbital parameter variations produce periodic changes in the overall climate of the earth resulting in local climatic changes that can be observed as mineralogy or porosity changes in a drillhole (Table 3-1). For example, clay type and abundance can be affected by aridity and humidity cycles; grain size, mineral type and abundance can be related to wind pattern changes; and biogenic abundance and compositional changes can be caused by ocean temperature and upwelling variations.

As a case study, consider the log responses recorded during Leg 128 at Hole 798B on the Oki Ridge in the Sea of Japan (Figure 3-2). The Sea of Japan is interesting because of what’s happening upwind. The stippled region in Figure 3-2 indicates the extent of Chinese loess deposition. Loess is a silty soil deposited over vast regions of the Chinese plateau by winds carrying silt and clay released by the drying up of glacial streams. The Chinese loess deposits contain a 3 million year record of glacial aridity from mainland Asia. These deposits are cyclical in China, where they appear as a repeated loess-soil sequence. The loess represents glacial times and the soil represents humid interglacial times. Very good magnetic stratigraphy exists in the Chinese deposits, with the Matuyama/Gauss, the Olduvai, the Jaramillo, and the Brunhes/Matuyama reversals clearly evident in these samples. This sequence of loess/soil alternation correlates very well with the marine oxygen-isotope record over a period of 41,000 years (Figure 3-3), leading to the inference that the loess deposits are a continental record of ice development in Asia.
Figure 3-1. Variations over the last 3 m.y. of the three major components of the Earth's orbit around the sun: eccentricity, obliquity, and precession. Precession is shown as the precessional index $e \sin w$, which incorporates the modulating effect of eccentricity.
Table 3-1. The sequence of cause-and-effect between Milankovitch orbital parameter changes and log responses. Changes in eccentricity, obliquity, and precession cause changes in the amount of the Sun's energy to hit the planet. This, in turn, causes cycles in aridity/humidity, wind and ocean current patterns, and sea-surface temperatures. These changes cause cycles of clay type and abundance, grain size, mineralogy, and composition and abundance of organisms that die to form deep sea sediments. The logs respond differently to several of these changes producing a complex interaction of geophysical and geochemical responses to climate change.
Figure 3-2. Location of Hole 798B, drilled and logged during ODP Leg 128 in the Japan Sea.
Figure 3-3. Correlation of Xifeng loess deposits to marine record (core V21-146). a) Lithologic column I uses susceptibility model to define time scale of loess deposition, b) Column II shows refined ages of loess sedimentation based on correlation to aeolian flux record, c) Aeolian flux record of the North Pacific, d) δ¹⁸O stratigraphy of core V21-146, and e) δ¹⁸O stratigraphy of Specmap global record.
The Oki Ridge in the Sea of Japan is like an inverted cup which collects sediments that are not subjected to down slope transport. The sedimentation rates are extremely high (about 12 centimeters per thousand years) and the sediments have very good paleomagnetic stratigraphy, as well as several thick ash layers that can be used for depth control.

There are two main benefits from the use of logs for paleoclimate work. Paleoclimate studies in general are based on measurements made on discrete samples taken from whatever core material is available. Also, you are limited by the number of samples you can actually process in a reasonable amount of time. Logs are continuous and quick.

The sediments sampled at Hole 798B on the Oki Ridge are composed of only two components: a) about 20 to 40% opal in diatomaceous clay, and b) silt and clay size, loess-like terrigenous material. From a visual inspection of the core, there are cycles about every 4 meters from dark layer to light layers. The dark layers are organic-rich, opal-rich sediment with organic carbon content of up to 5%. Ash layers as little as 3 centimeters thick were both cored and imaged by the Formation MicroScanner, and they proved critical for establishing core-log correlations. The Formation MicroScanner image of that interval also shows a 4 meter wavelength variation in the electrical resistivity of the formation in Hole 798B (Figure 3-4). Dark indicates conductive, opal-rich units while light corresponds to the more resistive, terrigenous-rich units. The core recovery, which looks relatively good in Figure 3-4, is deceiving. One of the problems with having organic-rich sediment is that the gas exploded little bits of mud all over the rig floor, so that the core recovery is fragmented, and the section is expanded and disturbed.

Cyclicity is apparent in all the logs from Hole 798B (Figure 3-4). Increases of gamma ray are interpreted as reflecting terrigenous content; increases in bulk density are reflecting the fact that terrigenous material is denser than opal because opal tends to enhance porosity and decrease density; and increases in resistivity reflect the fact that the terrigenous-rich levels are less porous than the opal-rich intervals. These sympathetic variations in all three logs can be correlated with the amount of terrigenous material observed in the cores (Figure 3-5).

We can then use the paleomagnetic stratigraphy to assign age levels to the logging data. Then the logs can be directly compared to the δ18O record from the oceans, a very high resolution indicator of variations in northern hemisphere ice volume (Figure 3-4). Both the logs and the δ18O record have monotonic, 41,000 year variation. Even the fine-scale variations in the δ18O record are duplicated by the logs. Just above the Matuyama/Gauss boundary, the sharp increase in oxygen isotope values, which documents the inception of northern hemisphere glaciation, is seen in the gamma ray curve as a decrease in radioactivity.

Variations in the supply of terrigenous material to the Sea of Japan are reflecting variations in aeolian dust which has its source in the loess deposits in China. When accumulating loess on a Chinese plateau, some of it is also being blown by the westerlies in the Sea of Japan, which is what happens today. Loess is a health hazard in Korea and Japan. Logs have provided a remote sensing method of detecting past variations in Asian aridity from marine sediments.
Figure 3-4. Downhole logging at Hole 798B. Logs and paleomagnetic time scale correlation shown at left. See for details of correlation between FMS and core (center) and gamma ray logs versus oxygen isotopes (right).
Figure 3-5. Gamma ray, bulk density, and resistivity logs compared to terrigenous content of cores at Hole 798B, ODP Leg 128.
Determination of Sedimentation Rate

As the above example has shown, periodic changes in depositional environments due to Milankovitch astronomical-climate cycles can cause cyclic patterns in sediment properties as recorded by logging data. Spectral analysis of logging data can identify these regular cycles and be related to the known Milankovitch periodicities, thereby providing actual sedimentation rates. Where accumulation rates are variable, application of a close-spaced series of sliding windows through the logging signal can detect variations and discontinuities in rates of sedimentation.

Sedimentation rates are generally determined by estimating the elapsed time between biostratigraphic events identified in the section. This procedure requires an absolute time scale and will generally yield a minimum sedimentation rate due to the difficulty of compensating for hiatuses. However, sediments contain an internal "clock" created by the systematic variation of depositional facies in response to periodic changes in the Earth's climate. These periodic climatic cycles are commonly recorded in sediments as variations in clastic grain size and abundance, biogenic constituents, organic carbon preservation and sedimentary structures; later diagenesis can enhance these variations. As we have seen above, resolution and separation of periodic components requires a spectral analysis of the temporal variation of some sedimentary factor, such as the clay content, gamma ray variation or oxygen-isotope ratio.

Spectral analysis of a time-series is a common technique in geophysics: high-pass and low-pass filters are applied to the signal to remove long-period trends and high-frequency noise. A "window taper" is applied to eliminate discontinuities across the ends of the signal interval. Fourier transforms of this processed signal are then displayed as spectral plots of the amplitudes of this constituent frequency components.

The response of depositional environments to Milankovitch climatic cycles is periodic in time. In contrast, the observed sedimentary record is a function of depth. If a sediment has a relatively constant long-term rate of accumulation, then the variation of its constituents with depth (expressed as cycles/meter) will approximate their variation with time (expressed as cycles/million years). In such cases, spectral analysis of the depth-series will detect temporal cycles. This may be done in either of two ways. In the example from the Sea of Japan, we estimated the periods of the sediment cycles by applying a sedimentation rate estimated from the available magnetostratigraphic and biostratigraphic data. The computed periods were similar to those of climate cycles, so the corresponding Milankovitch periods were used to "tune" the sedimentation rate.

An alternate technique is to compare the ratios of the observed sediment cycle wavelengths to the ratios of Milankovitch time-periods. For example, if the spectral analysis of a formation displays three main cycles having ratios of wavelengths nearly identical to the ratios of the 413-123-95 k.y. set of major eccentricity cycles, then these cycles are probably a reflection of those eccentricity cycles. This ratio technique requires neither precise biostratigraphy nor a tie to an absolute time scale. Often these two methods must be combined, so that the available biostratigraphic data as a constraint on the interpretation of the Milankovitch orbital periodicities, because some ratios are not unique...
(the ratio of the 123/95 k.y. eccentricity cycles is very similar to that of the 23/19 k.y. precession set).

The ability to detect Milankovitch cycles within logging data depends on the resolution of the tool and spacing of measurements relative to the sedimentation rate -- to detect cyclicity using Fourier analysis of such signals requires at least two points per cycle. Therefore, a resistivity-log signal having a 1-meter resolution requires a sedimentation rate of at least 20 m/m.y. to detect the suite of eccentricity cycles (95, 123, 413 k.y.) or at least 100 m/m.y. to detect precession cycles (23-19 k.y.). The natural gamma-ray logging tool has a resolution of 0.3 m, and therefore can detect the eccentricity cycles if the sedimentation rate is greater than 6 m/m.y. The Formation MicroScanner, with resolution down of 1 millimeter, should provide the ultimate cycle-detection logging tool.

Geophysical and geochemical logs of Ocean Drilling Project (ODP) holes have been used to identify periodic lithologic changes corresponding to Milankovitch climatic cycles in many sedimentary sequences from ODP boreholes. For example, sonic, resistivity and U/Th logs indicate fluctuations in porosity and clay content induced by bottom-water currents in the Labrador Sea and Baffin Bay (Leg 105), responding to Milankovitch cycles during the Pleistocene. Geochemical logging of Meteor Rise (Leg 114) detected obliquity and possibly eccentricity cycles. Obliquity and eccentricity cycles were also observed in gamma-ray, resistivity and sonic logs of upper Tertiary sediments on the Antarctic continental margin (Leg 113).

**Sliding-Window Spectral Analysis to Compute Sedimentation Rate Curves**

Sedimentation rates are rarely constant over multi-million year intervals, and therefore the vertical wavelengths of periodic sedimentary cycles will shift. However, if those cycles are reflections of Milankovitch orbital cycles, then the relative spectral ratios of power peaks within those wavelengths will remain constant. If spectral analysis were applied to the entire depth-series signal from a log from such a location, the result would either be broadband peaks or inconclusive cyclicity. Therefore, if subsets ("windows") of this depth-signal were analyzed, the individual results might display well-defined cyclicity, but there would be a consistent relative displacement of the peak-wavelengths between windows. Such displacements would be an indication of changing sedimentation rates, provided the spectral ratios of peak-wavelengths remain constant.

This sliding window comparison of spectral peak ratios is also a valuable supplemental technique to demonstrate the presence of Milankovitch cyclicity. If the windows yield shifting peaks which do not retain a constant ratio, then it is possible that the cyclicity may be due to non-Milankovitch-related variations such as diagenetic segregation, turbidite frequency or other sedimentary phenomenon.

Window size is adjusted according to the approximate spacing of the longest-period cycles of interest. A smaller window is more accurate for determining sedimentation rate variations, but will have poorer resolution of cycles. Use of narrow windows can also result in aliasing of the spectra; a problem that can be partially reduced by application of multiple window tapers.

Spectral analysis of overlapping windows can also be used to precisely determine the depth where discontinuities in sedimentation rate occur. A sharp change in sedimentation rate will result in the replacement of one set of peaks by another set with different
wavelengths, which retain the same ratio among wavelengths. The level at which a discontinuity or rapid change in sedimentation occurs can be approximated from the depth of the window in which the amplitudes of the "underlying" and the "overlying" sets of peaks are nearly equal.

High-speed workstations provide the ability to slide a selected window at close-spaced intervals through the logging signal and display the series of spectral analysis results as a three-dimensional plot of depth vs. cycle-wavelength vs. peak-intensity. An example of sliding-window spectral analysis applied to a gamma-ray log of Upper Jurassic-Lower Cretaceous radiolarian mudstones of Pacific ODP Hole 801B (Figure 3-6) is shown in Figure 3-7 to illustrate the progressive shifting of peaks. The spectra from the logs can be used to locate the sedimentation rate change even more precisely by increasing the number of windows chosen across the boundary (Figure 3-8). Splitting from one peak as the new peak is formed across the disconformity can be observed.

The final sedimentation rate curve computed by this sliding-window procedure for these radiolarian mudstones is displayed in Figure 3-9. The major discontinuity in sedimentation rate corresponds to a sharp change in the chert/clay ratio, which was also observed in geochemical and Formation MicroScanner logs. The available radiolarian biostratigraphy, coupled with low core recovery, did not enable resolution of this discontinuity.

Summary

Many types of marine and continental sediments record periodic changes in depositional environments caused by Milankovitch climatic cycles. Spectral analysis of logging data of these sediments can enable resolution of Milankovitch climatic cycles, thereby providing rates of sedimentation. It is important to verify that the ratios of the wavelengths of such cycles are the same as the ratios of the periods of the corresponding Milankovitch cycles; and preferably at least three such cycle periods should be identified and correlated. Plots of a series of such spectral analyses generated from overlapping sliding windows can be used to identify both gradual changes and sudden discontinuities in sedimentation rates. As sedimentation rate changes, the locations of spectral peaks shift, but the relative ratios within each spectra must remain constant. Use of Milankovitch cycles to compute sedimentation rates removes the need for precise biostratigraphic control for detailed age correlation in marine sediments.
Figure 3-6. Location of Hole 801B drilled and logged during ODP Leg 129 in the Western Pacific.
Power spectra

Figure 3-7. Selected spectra as a function of depth (in meters below seafloor) for Upper Jurassic-Lower Cretaceous radiolarian mudstones of the Equatorial Pacific (ODP Site 801B). Trends and rapid changes or discontinuities in sedimentation rates are indicated by shifts in the wavelengths of eccentricity cycles.
Figure 3-8. Much finer step-interval of 1.1 m used to calculate spectra of gamma ray log across the postulated unconformity. The peak-splitting of the spectra indicates equal energy of old and new peaks at 373.3 m, thus determining the precise depth of the unconformity.
Figure 3-9. Computed sedimentation rates over the Lithologic Unit IV Interval of Hole 801B and relative errors between the 413-123-95 k.y. cycle sets.
Chapter 4

Geochemical Well Logging in Basalts:
the Palisades Sill and the Oceanic Crust of Hole 504B

Roger N. Anderson (1), Jeffrey C. Alt (2), John Malpas (3), Michael A.
Lovell (4), Peter K. Harvey (4), and E. Lewis-Pratson (1)

(1) Borehole Research Group of Columbia University, Palisades
(2) Dept. of Geological Sciences, University of Michigan, Ann Arbor
(3) Earth Sciences Dept., Memorial University, St. John's, Newfoundland, Canada
(4) Dept. of Geology, University of Leicester, Leicester, United Kingdom
Geochemical Well Logging in Basalts: 
The Palisades Sill and the Oceanic Crust of Hole 504B

ROGER N. ANDERSON,1 JEFFREY C. ALT,2 JOHN MALPAS,3 MICHEAL A. LOVELL,4 PETER K. HARVEY,4 AND E. LEWIS PRATSON1

Geochemical well logging provides a continuous record of the variations in elemental abundances of the major rock-forming oxides of Si, Al, Ca, Fe, Ti, and K, as well as S, Gd, U, Th, and the H and Cl in the formation and pore fluid. Through the additional measurement of the photoelectric capture cross section of the rock, the sum of Mg + Na can also be estimated. Though not as accurate as laboratory analyses of recovered core samples, the log-derived abundances are precise enough to define the degree and extent of alteration, to identify igneous lithostratigraphy, and to calculate integrated chemical exchange between the oceanic crust and seawater. In this paper, the elemental yields from geochemical logging in basalts are calibrated against extensive XRF analyses of cutting samples from the Lamont 2 test well into the diabases of the Palisades Sill, New York. Accuracy and precision of the log-derived analyses are determined in the lower part of the well, and calibration equations are derived, which are then tested against core-derived “standards” from the upper part of the well. The calibrated, log-derived, elemental analyses are within one standard deviation of the core-derived results (except for the Mg + Na curve, which is somewhat noisier). These calibrations are then applied to geochemical logs of the ocean crustal basalt of Ocean Drilling Program hole 504B, where core recovery was less than 20% of the section. The accuracy and precision of the calibrated, log-derived elemental abundances are tested against core-derived standards from seven dike and sill intervals. Then the corrected elemental analyses are used to derive a mineralogy model for hole 504B that shows the oceanic crust to contain secondary mineralization in the form of cements and smectites in the pillow basalts and chlorites in the dikes that are largely confined to fracture and breccia zones. Cyclicity in the Ai and other elemental logs was found to vary with the abundances of these alteration products and with eruption and intrusion event boundaries. The geochemical logging data are then used to estimate the integrated chemical exchange resulting from hydrothermal alteration of the oceanic crust that has occurred over the last 5.9 m.y. in hole 504B. The primary change is from Ca loss and Mg gain caused by the reaction of basalt with seawater. A large Si increase found in the transition zone between the pillows and dikes is attributed to precipitation of quartz during mixing of hot, upwelling hydrothermal fluids and cold, downwelling seawater at what was once a major permeability discontinuity. The present low-to-high permeability transition in hole 504B is found 500 m shallower. The K budget requires significant additional activity to the uppermost pillow basalts both from high-temperature depletion in the lower pillows and dikes and from low-temperature exchange with seawater. The geochemical logs further document that the total chemical exchange between the oceanic crust and seawater is as important to the long-term composition of the oceans as is the chemical input carried by rivers. Integrated “water/rock ratios” are then derived for the mass of seawater required to add enriched elements and the mass of hydrothermal fluid required to remove depleted elements in the oceanic crust of hole 504B. Whereas Ca, Mg, and K require relatively low water/rock ratios, high values for Si, Al, and Fe suggest that off-axis, ridge-flank exchange is as important to the total cation exchange budget as are ridge-axis processes.

INTRODUCTION

The exploration of the Earth’s crust has increasingly involved the direct testing of geophysical and geochemical models of structure, stratigraphy, and tectonic evolution by the drilling of wells. Successful scientific drilling requires a more complete description of the well bore rock and pore fluid than is required for economic drilling. These scientific drilling projects often involve coring programs that attempt to recover continuous samples of rock. As the Ocean Drilling Program (ODP) and its predecessor, the Deep Sea Drilling Project (DSDP), have all too well found, continuous coring does not result in continuous core recovery. And even when all the rock section is returned to the surface, it is not possible to analyze even a small percentage of the recovered core, particularly for geochemical variations. Consequently, geophysical well logging, in which a measurement device is placed directly into the well to make continuous in situ measurements of the electrical, nuclear, and acoustic properties of the rock, occupies an even more important role in scientific drilling than in industrial drilling.

A major addition to the in situ investigation of sedimentary basin well bores has recently been made with the invention of geochemical well logging, in which the elemental abundances of major and certain trace elements are determined continuously in a well in real time through the use of gamma ray spectroscopy. This promising new geochemical logging technology must be calibrated and tested carefully in environments other than the sedimentary basins for which it was designed before it can be fully utilized in scientific drill holes. In this paper, we first develop and test calibration equations for geochemical logging in basalts through comparisons with extensive laboratory analyses of cutting samples from a test
well into the diabases of the Palisades Sill, New York. Then we establish standards to correct log-derived elemental abundances from ODP hole 504B in the eastern equatorial Pacific. Once we have determined the accuracy and precision of the new geochemical logging technology in each well, we interpret variations in log-derived elemental abundances in terms of the lithostratigraphy and alteration state of the crust at each site.

THE PALISADES SILL WELL AND ODP HOLE 504B

In order to evaluate the accuracy and precision of geochemical log-derived elemental analyses in basalts, it is necessary to first calibrate the logging method in relatively fresh basalts of uniform composition and in a well for which extensive, precisely located samples exist for laboratory analyses and intercomparison. We use the intensely sampled lower portion of the Lamont 2 test well into the Palisades Sill to derive general calibration equations for geochemical logging in basalts. We then test these calibrations against "standards" from the upper portion of the well.

In the course of the log calibration experiment, useful geochemical information is derived for the lithostratigraphy of the Palisades Sill itself. The Palisades Sill, which outcrops along the western cliffs of the Hudson River along the northern New Jersey and southern New York borders (Figure 1), consists of more than 150 m of diabase (medium- to coarse-grained, basaltic igneous rock) that was intruded into the Triassic sandstones and shales of the Newark Basin Group approximately 200 Ma, during the rifting of North America away from Africa. The Palisades Sill is a classic example of closed-system, basaltic magma differentiation [Bowen, 1928], and as such, the chemical variation of the sill has been extensively studied [e.g., Walker, 1940; Walker, 1969; Shirley, 1987].

The geochemical logging technique is then extended to the poorly sampled oceanic crust, where the continuous nature of these observations can add significant new information to interpretations of the geology of the upper lithosphere. ODP hole 504B, which was drilled into the Nasca plate on the southern flank of the Costa Rica Rift (Figure 1), is the deepest penetration into the oceanic crust to date. As such, its structure, stratigraphy, alteration state, and composition form the standards for comparison to geophysical and geochemical models of the oceanic crust. Also, the core recovery in hole 504B has been less than 20% of the drilled section, with less than 12% of the deepest dikes recovered. Consequently, geochemical logging in this hole promises to yield much needed additional information.

Great emphasis has already been placed during DSDP legs 69, 70, 83, and 92 and ODP leg 111, upon geophysical logging to identify structure and stratigraphy and to locate the recovered rocks within their proper geological framework. The log-derived, physical properties of this young oceanic crust (5.9 Ma) which was generated at moderate spreading rates (3.3 cm/yr), have already yielded fundamental information about the formative mechanisms of mid-ocean ridges [e.g., Cann et al., 1983; Anderson et al., 1985; Becker et al., 1988].
derived results are reasonably accurate and precise, as claimed by Schlumberger. That is, all elemental abundances derived from the geochemical logs appear to be normally distributed about the means from the core analyses (accuracy), and the standard deviations are within the ranges quoted above (precision). In fact, Fe, Al, and K are somewhat more and Ca and Si are somewhat less noisy than the averages from all the field tests in sediments.

The Continental Deep Drilling Program of the Federal Republic of Germany (Kontinentale TiefBohrprogramm der Bundesrepublik Deutschland (KTB)) has completed the pilot hole for their ultradeep penetration of the European continental crust. A significant part of the experiments carried out in the pilot hole was the calibration of the geochemical logs in the metamorphic rocks of the Oberpfalz thrust belt of northwestern Bavaria (Draxler and Hanel, 1989). The large variations of major elemental compositions between the highly foliated gneisses, amphibolites, and metabasites encountered in just the upper 500 m of the pilot hole provide an excellent environment within which to calibrate the geochemical log-derived results (Figure 6). Cuttings were retrieved from the KTB well in an unusually effective manner because of the rapid circulation system, small borehole annulus, and thick isotropic drilling mud employed in this technically advanced drilling project. Cutting samples were collected over 1-m intervals and measured by XRF in the field laboratory adjacent to the well.

The calibration experiment in the KTB well shows that the correlation between log- and core-derived elemental abundances is linear for all the elements analyzed (Figure 6). Since the oxide abundances calculated from the geochemical logging measurements are forced to total 100% at each depth, slopes of core versus log-derived cross-plots are almost always less than 1:1. Thus it is necessary to calibrate geochemical log-derived measurements to 'standards' derived from laboratory analyses of samples from each well in order to produce quantitatively accurate major elemental analyses. However, relative changes between elements (ratios) are reasonably accurate even in wells without such calibration information.

**Calibration in Basalts of the Palisades Sill**

The direct application of geochemical well logging to igneous rocks is not straightforward, however. The distributions of oxygenics are different in igneous rocks versus those in sediments, particularly in carbonate versus silicate lithologies. Consequently, we have modified the oxygen distribution coefficients of Hertzog et al. [1987] from their CO3-based, sedimentary system to a silicate-based, igneous system, in order to produce accurate oxide determinations from geochemical logging in basalts.

Theoretically, elemental abundance calculations consistent with an igneous oxide model should produce measurements from the geochemical logging tool that standup well in comparison to chemical analyses of samples of basalts. The
comparisons below must assume that there are no errors in the depths assigned to either the core or log sample locations and that heterogeneities in rock composition do not make core measurements unrepresentative of the larger volume of the logging measurement [Grau et al., 1990]. We will also ignore measurement uncertainties of the core analyses done in the laboratory.

Geochemical logs were recorded in the Lamont 2 test well, which penetrates more than 200 m of the basal portion of the diabases of the Palisades Sill, so that the log-derived elemental abundances could be compared to XRF analyses of cuttings collected from the same well (this study) and from samples taken from outcrops farther south along the cliff face [Shirley, 1987] (Figure 1). The Lamont 2 well offers the almost perfect logging conditions of a shallow, cylindrical well bore of a 6-inch diameter well collected from high-velocity circulation using an air hammer drilling technique.

The geochemical logging tool induces the emission of gamma rays from the formation that come from a considerably larger volume of rock than that represented by individual rock cuttings. Consequently, we have collected virtually continuous cutting samples over the lower half of the Lamont 2 test well. These were then mixed into 1-foot (0.3 m) samples for shipment to the University of Nottingham, where XRF analyses were performed.

Elemental analyses from the geochemical logging tool were calculated both with and without the Mg + Na curve from the PEF measurement. In the latter case, the cutting-derived analyses of Mg + Na were input into the otherwise wholly log-derived oxide calculations, in order to produce a "lowest-noise-level-possible" data set (Figure 7). The degree of additional noise introduced throughout the major elemental suite by the PEF-differencing scheme is shown in histograms of the elemental oxides derived with, versus without, the PEF-produced Mg + Na curve (Figure 8). The means and normal distributions of the oxide abundances are not disturbed, but the standard deviations are increased. Elemental weight percentages of Al and K are measured

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**Fig. 7.** Elemental analyses (in dry weight percent oxides, except where indicated) from geochemical logs in the Lamont 2 test well. Before calibration (left) and after (right) calibration (see text), are plotted with XRF analyses (crosses) from cutting samples taken every foot over the lower 90–200 m interval and more sparsely from 30 to 90 m. Note the boundary between intrusion events marked by the increase in potassium, aluminum and thorium, at approximately 100 m depth, and the famous olivine-rich layer at 175-180 m.
directly by the logging tool, so their abundances are not affected by the inclusion of the Mg + Na curve. Though more noisy, the elemental abundances that are derived with the Mg + Na curve are of greater value to rock characterization studies because they present almost a complete major elemental oxide analysis at every 0.15 m throughout the well.

The calibration strategy which we will follow is analogous to XRF standardization procedures performed in the laboratory. We will first calibrate the instrument (the logging tool) by analyzing standards (the 90–200 m interval that was most intensely sampled). We will then apply corrections to the log analyses from throughout the well and test the calibrated abundances against samples of known composition from elsewhere in the well (the 30–90 m interval).

The comparison of the raw analyses from the geochemical log versus core-derived measurements within the 90–200 m interval show that though there are significant differences between laboratory and log-derived results, the correlations appear to be linear (Figure 9). Linear calibration equations to correct each element to values consistent with the core-derived results are easily calculated (Figure 9). The applications of these calibration corrections produce log-derived data that, though of considerably larger scatter than the laboratory analyses (less precise), are of sufficient accuracy to be of clear worth in determining the variations in chemical properties of the basalts of the Palisades Sill, as can be seen from the improvement in the fit of core- to log-derived abundances in the 30–90 m interval (Table 2 and Figures 7 and 10). The corrected, log-derived abundances from the 30–90 m interval are within one standard deviation of the core measurements for all elements except Mg + Na (Figure 10). The fact that this curve is reading so much higher than the lab analyses in this interval (11 versus 8% in Figure 7) suggests that large capture cross section, minor or trace elements that interfere with the PEF residual calculations may be more abundant in this portion of the well.

The calibration equations derived from the log-versus-laboratory intercomparison in the Palisades Sill well are proposed to be generally applicable to geochemical logs in basalts from scientific wells drilled under less favorable conditions. Of course, calibration tests with core “standards” from each well are required, but such are not always easy to locate to true depth in poor core recovery wells (as with most ODP wells). If such calibrations prove successful, geochemical well logging will add greatly to the chemical reconnaissance capabilities within basaltic drill holes, be-
cause the logs provide analyses that are fast and continuous with depth.

**Geochemistry of the Diabases of the Palisades Sill**

The Palisades Sill is most famous for the existence of a sharply defined, olivine-rich layer located just above the lower contact of the sill and for a steady increase in Al content upward from this basal layer, both of which were caused by differentiation in the magma of the newly forming sill [Walker, 1940, 1969]. The heavy olivine crystals sank to the bottom of the Sill as lighter plagioclase crystals floated toward the top. Abrupt increases in thorium content upward within the sill were used by Shirley [1987] to establish the existence of at least three distinct magmatic intrusion events that formed the sill. The Lamont 2 well is within the lowermost two of these intrusions.

The geochemical log-derived elemental abundances clearly locate both the olivine-rich layer at 550 feet (175-180 m) and the increase in Al content upward in the well (Figure 7). The olivine-rich layer is observed in all major elemental logging curves, with Fe and Mg increasing and Si, Ca, and Al decreasing. The increase in Al content upward in the hole was also recorded (Figure 7). The Al and thorium logs both display an abrupt increase at the appropriate stratigraphic height for the second intrusion. These changes, coupled with increases in log-derived gadolinium and potassium abundances and a decrease in uranium content, suggest a contact between intrusive events at approximately 100 m above the base of the sill.

The calibrated log analyses demonstrate that these differences are real and resolvable within the accuracy of the logging tool measurements (Figure 10). The average compositions of Al, Ti, and K are more than 1 standard deviation higher, and the Ca and Mg + Na are lower above versus below this contact (Table 2). The analyses from outcrop samples from 12 miles (19 km) to the south [Shirey, 1987] corroborate the existence of this boundary and place this intrusive contact at 90 m above the base of the sill. This small difference in depth can be accounted for by the increased stratigraphic dip of the sill at Lamont versus to the south.

The continuous nature of the geochemical log-derived analyses provides useful additional stratigraphic information, even when abundant samples can be taken from cut-
In addition, the location of hole 504B near the equator has resulted in the early deposition of a thick, relatively impermeable sedimentary blanket that has mostly sealed the crust to hydrothermal interchange with the ocean at an unusually early age [Anderson and Hobart, 1976; Hobart et al., 1985; Langseth et al., 1988]. The alteration recorded within the hole is from chemical reactions within a convective system which is in the process of sealing itself through deposition and precipitation of various zeolite, greenstone, and green-schist products [Alt et al., 1986a]. Only the uppermost pillow units remain highly permeable to hydrothermal circulation at this time [Anderson and Zoback, 1982; Anderson et al., 1985a; Becker et al., 1989]. Geochemical logs from hole 504B, when properly calibrated, will provide the first continuous description of the variations in chemical composition versus depth that resulted from the volcanic emplacement and subsequent alteration of this oceanic crust.

**THE GEOCHEMICAL WELL LOGGING TECHNIQUE**

Geochemical well logging (mark of Schlumberger Well Services) was recently developed for use in sedimentary basins by the oil industry and is only just beginning to be used for scientific investigations in drill holes through igneous and metamorphic rocks [Anderson et al., 1988a, b, 1990; Drexler and Hanel, 1989]. The geochemical logging tool string (Figure 2) is lowered into a well to make in situ, gamma ray spectroscopy measurements of the relative concentrations of 11 major and minor elements. In turn, continuous elemental and dry weight percent oxide abundances are derived at 0.15-m intervals throughout the well. As shown below and by Anderson et al. [1988a, b, 1989], the precision of geochemical log-derived measurements within a basaltic well is as good as that in sediments, although the accuracy is somewhat less than X ray fluorescence (XRF) analyses made on core or cutting samples in the laboratory, as expected.

The geochemical logging tool is, in fact, four different nuclear logs combined into one tool string for lowering into the well bore. First, a natural gamma spectroscopy (NGT) tool measures the abundances of the naturally occurring radionuclides potassium (K, in weight percent), uranium, and thorium (U and Th, in parts per million) by detecting naturally decaying gamma ray particle energy in the 180 keV

![Fig. 2. (opposite) Configuration of the geochemical logging tool (mark of Schlumberger) used in this study. At the top are the auxiliary measurement sondes (AMS), which determines temperature and cable tension, and the TCC or CCC (both of which telemeter digital information to the surface much as a complex telephone modem works). Potassium, uranium, and thorium are measured by the natural gamma ray spectrometer (NGT). The compensated neutron tool (CNT-G) measures porosity and activates aluminum with a californium 252 source. The aluminum clay tool (ACT) follows to measure Al concentration. The induced gamma ray spectrometer tool (GST) uses a nuclear accelerator as a source for controlled "bursts" of neutrons, then collects emitted gamma rays with a NaI crystal, scintillation detector for the determination of the concentrations of silicon, iron, calcium, titanium, gadolinium, sulfur, hydrogen, and chlorine. A lithodensity tool (LDT) then either follows, as in the Ocean Drilling Program, or is lowered separately, as on land, to measure density and photoelectric capture cross section (PEF) using a cesium source. Magnesium plus sodium is calculated as a residual abundance from the difference between the measured PEF and that calculated from the abundances of all the other elements measured above.](image-url)
to 3 MeV range, using a six-channel, NaI scintillation counter. Below this tool, a caesium-fluoride chemical source is carried within a compensated neutron tool (replacing the traditional americium beryllium source). This high-neutron-flux source of relatively low-energy neutrons (2.35 MeV) is used to activate aluminum in the formation (Al clay tool, ACT). Another natural gamma spectroscopy tool is then passed across the borehole wall to capture gamma rays emitted by Al activation with particle energies from 180 keV to 2 MeV. Then, an induced gamma spectroscopy tool (GST) carries a “mimiron” neutron accelerator that emits gain-controlled bursts every 100 µs that total 10^7-8 neutrons/s at energies higher than the Cf source (14 MeV) in order to activate iron, calcium, silicon, titanium, the rare earth elements gadolinium, and sulfur in the rock, and the hydrogen and chlorines in the borehole and pore fluid (Fe, Ca, Si, Ti, Gd, S, H, and Cl). A 256-channel spectrometer analyzer then records the energy levels from emitted gamma rays with particle energies ranging from 1.5 to 7.5 MeV which impact a large NaI crystal within the tool. The gamma ray spectrum is summed over repeated burst intervals, and digitally transmitted to the surface at 0.15-m intervals.

In order to add an estimate of the amounts of magnesium and sodium (Mg + Na) present in the rock (the only major elements not measured by the geochemical logging tool), a new interpretation technique is then applied to the density tool, which bombards the formation with gamma rays from a cesium source. Not only is bulk density recorded, but a photoelectric absorption factor (PEF) is also measured which can be indirectly related to the weight percentage of Mg plus Na in the rock. The PEF of each major element has been measured in the laboratory, and therefore the theoretical PEF of a formation can be calculated as the sum of the elemental components measured by the geochemical logging tool. The difference between the logged PEF curve and that calculated based upon the abundance of elements recorded by the geochemical logging tool can then be used to estimate the abundance of the sum of these two missing elements (Mg + Na). This calculation is only as accurate as the PEF measurement itself in the well bore, and since often the tool cannot be padded solidly against rugged boreholes common in basaltic drilling, the Ma + Na derivation becomes the most “noisy” component of the elemental abundance computation.

**Errors in the Geochemical Logging Technique**

The gamma ray spectroscopy measurements made in the well detect a fraction of the total spectrum for each activated element which is linearly proportional to the concentration of that element within the volume of the measurement. The geochemical logging tool produces neutrons that penetrate rock up to 1 m away from the sources, but the tool’s scintillation counters are detecting emitted gamma rays in that rock a few seconds after the source passes the locale of each burst (since the crystals are below each source and logging is done upward in the hole at rates of approximately 100 m/h). Consequently, rock near the borehole wall provides more detected gamma rays than rock far from the well bore. The relative yields from each depth are used to calculate elemental abundances which are, in turn, forced to sum to 100% at each sampling point. The variations in dry weight percent of the major elemental oxides are estimated by assuming that approximately 50% of all rock is oxygen by weight [Herron, 1986; Hertzog et al., 1987].

A significant contributor to the noise of induced gamma ray spectroscopy logging comes from the statistical variation in gamma ray counts returning to the crystals after each burst of neutrons. This statistical uncertainty caused by the logging measurements themselves can be calculated by beginning with $W_i$, which is the weight fraction of an element $i$ measured through thermal neutron capture [Grau et al., 1990]. $W_i$ is related to the total spectrum $Y_i$ by a sensitivity coefficient $S_i$ and a depth-varying normalization parameter $F_i$ that is applied to all the elements (i.e., $W_i = F_i Y_i S_i$). Aluminum and potassium weight fractions are calibrated directly from their measurement peak heights and so are not subject to the same uncertainties. Grau et al. [1990] showed that individual elemental uncertainties are essentially independent of the values of $Y_i$ by simulating 2000 spectra, each repeatedly perturbed by the application of statistical noise. Each was then analyzed as if it were an independent measurement. The standard deviations of the “measured” elemental concentrations were then used to estimate the statistical error for each measurement ($\Delta W_{measured}$). The calculated elemental uncertainties ($\Delta W_{i}$) were then compared to these measured standard deviations. The calculated relative errors of both the standard deviations and the elemental uncertainties were found to be less than 2%. These results, in absolute weight percentages, are shown in Table 1, together with an estimate of the uncertainty from just the induced gamma ray spectroscopy elements, shown as $FY/S$. The latter calculation ignores the effects of the forced closure relationship in going from spectral yields to elemental concentrations. The calculated uncertainties are in excellent agreement with the standard deviations from the simulated spectra for each element, though the statistical errors for Si and Ca are considerably larger than those for Fe and Ti. Typical statistical uncertainties under normal logging conditions are between 2 and 3 wt % for Si and Ca and a few tenths of 1 wt % for Fe and Ti. It is important to consider what happens to the measurement accuracy when borehole conditions deviate from the ideal. Considerable tool standoff from the borehole wall can occur when washouts force the 21-m-long, centered tool string away from the borehole wall. This standoff increases the number of gamma rays detected from the borehole fluid and decreases the number of elements in the rock (Figure 3). Even for the most extreme case yet analyzed by Grau et al. [1990], where the borehole is repeatedly washed out from 8 inches (20 cm) to as much as 18 inches (46 cm), the measured elemental concentrations are all equally affected.

### Table 1. Comparison Between Calculated Uncertainties and Measured Standard Deviations for 7.5-s Accumulation Times

<table>
<thead>
<tr>
<th>Element</th>
<th>$F_i Y/S$</th>
<th>$\Delta W_{meas}$</th>
<th>$\Delta W_{measured}$</th>
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<tr>
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<td>3.67</td>
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<td>2.76</td>
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<td>Ca</td>
<td>2.52</td>
<td>2.37</td>
<td>2.29</td>
</tr>
<tr>
<td>Fe</td>
<td>0.46</td>
<td>2.37</td>
<td>2.29</td>
</tr>
<tr>
<td>Ti</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Values are in absolute weight percent. From Grau et al. [1990].

*Uncertainties from induced gamma ray only (no Al, no K).

*Calculated uncertainties.

*Measured standard deviations.
Calibration in Sedimentary and Metamorphic Rocks

Although the elements measured by gamma ray spectroscopy make up almost all of the significant major oxides comprising most rocks, the technique was developed and calibrated in sediments which have very large differences in major elemental compositions between different lithologies. That is, a carbonate is easily distinguished from a sandstone or a shale based upon major element compositional variations (cf. Figure 3). Metamorphic rocks also have large differences in major elemental compositions among different lithologies because of the chemical variability of the hydroxyl-bearing alteration products they commonly contain. Before we test the applicability of the geochemical logging technique in basalts that have much smaller differences in major elemental compositions, we review the accuracy and precision of the geochemical logging tool in sedimentary and metamorphic rocks.

Several major oil companies have conducted independent field tests which collectively demonstrate that the geochemical logging tool measures elemental yields that can be accurately converted to dry weight percent oxides in sediments from a wide variety of geological and borehole environments [Hertzog et al., 1987; Grau et al., 1989; Herron and Herron, 1989]. ARCO [Pasternack and Herron, 1989], Chevron [Everett and Riek, 1989], Conoco [Hutchinson and Petersen, 1989], Exxon [Wendlandt and Bhuyan, 1989], and Statoil [Floto, 1989] have each conducted comparisons between measurements made by the geochemical logging tool and laboratory analyses from side wall cores from wells in the Anadarko Basin, Gulf Coast, Basin and Range, and North Slope of the United States, the North Sea, and the Middle East. The standard deviations of measurements from these field tests range from 1.6 to 6.5 wt % for Si (compositional ranges of 0–50%), 1.0 to 5.9 wt % for Al (0–15% range), 0.7 to 3.1 wt % for Ca (0–40% range), 0.2 to 0.6 wt % for Fe (0–10% range), and 0.1 to 0.3 wt % for K (0–5% range).

Consider, for example, the calibration results from the Exxon Production Research Sego Canyon 2 well in Utah [Wendlandt and Bhuyan, 1989]. XRF measurements were...
made on side wall cores taken in a sand-shale sequence to test the accuracy and precision of the geochemical logging tool's elemental abundance determinations (Figure 4). The sandstones at 100–400 and 600–800 feet (30–122 and 183–244 m) are distinguished by high Si contents and low Al, Fe, Ca, and K abundances. The shales at 400–600 feet (123–183 m) are high in Al, Fe, and K, and somewhat lower in Si contents. These elemental variations describe the stoichiometry of the clay minerals that make up the shales within this interval of the well. More subtle differences are also apparent in Figure 4. The 100–400 foot (30–122 m) sandstones have significant feldspars present, as can be seen from the higher Al, Fe, and K contents than in the clean sandstones found at 600–800 feet (183–244 m). Thin limestone stringers are found at 140, 220, and 780 feet (43, 67, and 238 m), as can be seen from the spikes of abundant Ca that correlate with the troughs of low Si content.

Histograms of the differences between core analyses and log-derived elemental abundances at each depth (core-minus-log values in Figure 5) demonstrate that the log-
TABLE 2. Geochemical Analyses of Palisades Sill Lamont 2 Well

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<td>Total number</td>
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<td>284</td>
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*Shirley [1987].

Geochemical Logging in Hole 504B

The correlation between core- and log-derived chemical analyses is considerably better in the Palisades Sill well than can be expected for hole 504B because of the more difficult logging conditions and poorer hole quality. The main differences are (1) the lack of a boron sleeve to isolate the formation from borehole fluid effects in hole 504B (used in the Palisades Sill well, but only after leg 125 in the ODP) will cause changes in the total induced gamma ray flux that will correlate with hole size determined by the caliper log (compare Figure 3), (2) the use of seawater as the drilling fluid will add Na cations from the borehole fluid to the measured major elemental abundances (since C) from the fluid is also measured but is not present in the rock, it is easy to correct for this effect), (3) the larger hole diameter of hole 504B will lower the rock-derived, gamma ray flux and increase the borehole fluid-derived flux (9+ inches (23 cm) versus 6 inches (15 cm) for the Palisades Sill well), and (4) the uncertainty of depth locations for the limited amount of core recovered from hole 504B will make the calibration more difficult. The cumulative effects should produce a decrease in the precision (increased noise) of the geochemical logs from hole 504B. On the other hand, the extensive metamorphic alteration of the basalts in hole 504B produces much stronger major elemental contrasts (more signal) than within the relatively fresh diabases of the Palisades Sill.

Below, we correct the log-derived elemental abundances from hole 504B using the calibration equations for basalts derived from the Palisades Sill analyses. Then we compare these corrected abundances with the laboratory XRF analyses from core recovered in seven of the best sampled and lithologically distinct portions of hole 504B (our “standards”). Major elemental variations observed from these corrected geochemical logs are then interpreted in terms of alteration and structural changes encountered in the well.

Structural and Stratigraphic Setting of Hole 504B

Hole 504B penetrates over 1.25 km of 5.9-m.y.-old oceanic crust on the southern flank of the Costa Rica Rift in the eastern equatorial Pacific Ocean, easily the deepest oceanic crust section yet drilled. The geophysical logging suite [Anderson et al., 1985b; Becker et al., 1988] reveals three distinct zones within the basement: (1) an uppermost, 150-m-thick pillow basaltic section of very low sonic velocity and resistivity and high porosity that perhaps corresponds to the seismic layer 1A, (2) a lower pillow basaltic layer of increasing sonic velocity, slightly higher resistivity, and somewhat lower porosity that may represent seismic layer 2B, and (3) a deeper zone of high sonic velocity and resistivity and low porosity that is composed of basaltic dikes thought to be the upper part of seismic layer 2C (Plate 1). The basalts in this deep zone are highly altered, as can be seen from the contrast between total and fracture porosities determined from shallow- versus deep-penetrating electrical resistivity logs (Plate 1) [Pezard, this issue]. Long spacing resistivity
Fig. 10. Means and standard deviations of log- and core-derived elemental analyses (Figure 7) from 90–160 m (3–5) and 30–90 m (1–3) depth intervals before (B) and after (A) calibration within the Palisades Sill (Figure 9). Except for Mg + Na, the corrected, log-derived means are within one standard deviation of the core analyses (Table 2).

measurements show that the "apparent" porosity of the formation drops from 15 to 0.3% from the upper pillows to the dikes, whereas the actual porosity varies from 5 to <1% (Becker, 1985). (Fracture porosity is thought to more correctly record the true porosity structure of the crust, with the difference between fracture and total porosity curves being "apparent" porosity caused by cation exchange capacitance of clays present in the formation [Becker et al., 1989; Pertz, this issue].)

Permeability measurements, as well, indicate that the dikes are much tighter, lower permeability rocks than the pillows [Anderson et al., 1985a; Becker, 1989]. Flow and pulse test measurements using hydraulic packers demonstrate that the permeability is high in the upper pillows but is constant and low within the lower pillows even though the "apparent" porosity is high [Becker et al., 1989]. This drop in permeability is also thought to be the result of the precipitation of clays that have clogged the plumbing system of the lower pillows.

Three stratigraphic zones of chemical alteration were defined in hole 504B, based upon the occurrences of secondary minerals in cores recovered from the well [Alt et al., 1985, 1986a]: (1) the upper half of the pillow section was altered by low-temperature (approximately 0°C, oxidizing, seafloor weathering; (2) the lower half of the pillow section was altered by low-temperature (<100°C), reducing react-
Plate 1. Geophysical and geochemical logs from hole 504B (Figure 1). Depths are in meters below the seafloor. At left, total-porosity and fracture-porosity derived from dual laterolog electrical resistivity measurements (left center) [Pezard, this issue]. "Apparent" porosity is the difference between these two porosities and is largely caused by cation exchange capacitance of clays that have been precipitated during hydrothermal alteration of the oceanic crust. Center, mineralogy model derived from geochemical logs (Table 5), with blowup of stockwork mineralization zone to right. Chemical alteration progresses from low-temperature, oxidative celadonite precipitation (white mineral in color plot) above 550 m, to smectites (orange) which are abundant to 900 m, and then to chlorite-rich greenschist metamorphism (green) in the dikes below 900 m. Far right, photo of core from stockwork located at 925-950 m. The stockwork is characterized within the mineralogy model by the abundance of pyrite (yellow) from the log and core (centimeter-sized crystals of which are evident in the core photo at far right) [Anderson et al., 1988b]. Bulk permeability was measured by impulse testing across packed-off intervals shown (center) [Anderson and Zoback, 1983; Anderson et al., 1985a; Becker et al., 1988]. Magnetic inclination was measured with a three-component, flux gate borehole magnetometer by H. Kinoshita (as cited by Becker et al. [1988]). (Reprinted with permission from Oilfield Review.)

...tions; and (3) the dike section was altered by greenschist-grade, hydrothermal metamorphism occurring at high temperatures (>250°C).

Within the pillow-dike transition zone at 925 m, a stockwork of sulfide mineralization was cored during leg 83 (Plate 1). Porosity shows an abrupt change across this zone [Becker, 1985]. Hot, upwelling, mineralized hydrothermal fluids once mixed with cold seawater at this depth in the crust to deposit the stockwork [Honnorez et al., 1985]. The mixing and precipitation likely occurred at the ridge axis as part of an axial hot spring system.

**Comparison of Corrected Logs With Core Standards**

The geochemical logs recorded in the basement of hole 504B, once properly calibrated, will allow the determination of the chemical variability of the oceanic crust, including the accumulated, bulk rock chemical changes caused by hydrothermal exchange between the oceanic crust and circulating seawater. The geochemical logs record the bulk chemistry of both the altered basalts and the secondary minerals filling fractures, pore spaces, and breccia zones, and they provide...
Fig. 11. Dry weight percent oxide concentrations of (from left to right) silica, aluminum, calcium, magnesium plus sodium, iron, titanium, and potassium from geochemical logs in hole 504B. Basaltic calibration corrections from the Palisades Sill (Figure 9) have already been made. Symbols are from core analyses by XRF. Depth given in meters below seafloor.

an integrated measurement of the compositional changes in the oceanic crust that have occurred over its 5.9-m.y. lifetime.

In spite of the complex alteration history encountered in hole 504B, it is possible to find examples in the recovered core samples of horizons where a considerable amount of primary basaltic rock still exists, including well-preserved chill margins of pillow basalts. These rocks have been taken as most representative of the primary composition of the basalts at hole 504B [Alt and Emmermann, 1985]. Several coherent flow units are found within the pillow basalts of the upper crust. These intervals have distinctively high electrical resistivities within the much lower resistivities of the altered pillow basalts (Plate 1). They are also some of the best recovered intervals within the pillow section of the well. Below, we use XRF analyses from cores from three of these internally coherent and well-sampled sills, along with four dike intervals with constant electrical resistivity, as "standards" for calibration of the corrected, geochemical log-derived analyses.

Comparisons between log- and core-derived analyses within the "standards" intervals are thought to be more
TABLE 3. Core to Log Calibration Analysis of Hole 504B
Freshest Basalts

<table>
<thead>
<tr>
<th>Core</th>
<th>Mean</th>
<th>s.d.</th>
<th>Log</th>
<th>Mean</th>
<th>s.d.</th>
</tr>
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<td></td>
<td></td>
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</tr>
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<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

Either coring operations selectively sample only the least altered basalts in the well or, more likely, the recovered rocks reflect the appropriate compositions of the basalts and alteration products, but they do not properly represent the relative abundances of basalts versus secondary mineralization filling fractures, pore spaces, and breccia zones.

Dry weight percent abundances of major elemental oxides were calculated from geochemical logging measurements in hole 504B. Then corrections were applied using the calibration equations derived for basalts from the Palisades Sill study, and the results compared to all of the core-derived analyses from hole 504B (Figure 11). The success of the geochemical log analyses in determining major elemental abundances were then tested by comparing and correcting to the "standards" from the seven relatively fresh silts and dikes in hole 504B (Table 3 and Figure 12).

The comparisons with the "standards" demonstrate that the log-derived abundances can be corrected to within one standard deviation of the core-based analyses for most depth intervals tested (Figure 12). The relative precisions of the log-derived analyses are displayed as histograms of core-minus-log-derived values (Figure 13). The scatter is normally distributed, and surprisingly, the standard deviations of the hole 504B analyses are similar to those observed in sedimentary rocks and in the Palisades Sill study (compare Figures 3; 5, 8, and 12) (also compare Tables 1, 2, and 3). It is clearly possible to derive representative elementals analyses from geochemical logging in oceanic basalts when core "standards" are available for calibration within that well.

ALTERATION OF THE OCEANIC CRUST OF HOLE 504B

The geochemical logging results show quite different trends when compared to core analyses from throughout hole 504B as opposed to just from the "standards" intervals. Cross plots show that systematic discrepancies clearly exist between the overall log- and core-derived analyses (Figure 14). For example, there is a general decrease in the log-derived values of Ca upward in the hole, which is thought to be the result of depletion in the crust caused by cation exchange with seawater during chemical alteration [Seyfried and Bischoff, 1979; Seyfried and Mottri, 1982]. The corresponding Mg increase consistent with Ca-Mg exchange observed during experimental seawater-basalt reactions at various temperatures is also present, though somewhat complicated by the fact that Mg + Na is measured by the logs.

Core analyses, in fact, show the opposite: a Ca increase and a Mg decrease upward in the hole [Alt et al., 1986a]. Alt et al. [1986a] interpreted these changes in the core analyses to reflect slight compositional variations of the freshest basalts which were preferentially sampled by the coring operations at hole 504B.

Systematic borehole size changes may accompany changes in the degree of alteration in hole 504B. If alteration minerals are confined to relatively soft breccia and fracture zones, the borehole may become more washed out in these areas. We have previously seen that such washout zones would lower the precision of the geochemical logging results but would not affect the accuracy of the measurements. Also, Francis [1982] determined that hole size changes observed in hole 495B in the Mariana Trough were caused by
Fig. 12. Cross plots of the means and standard deviations of corrected, geochemical log-derived elemental abundances versus core-derived XRF analyses (standards) averaged over seven sill and dike intervals with both adequate sampling density and relatively fresh basalt in hole 504B. See Table 3.

rhythmic drilling processes. Though these too would presumably be attributable to soft versus hard drilling conditions, they too could produce significant borehole size changes in hole 504B.

We can test whether elemental variations in hole 504B are related to any such physical changes in borehole size by calculating the correlation coefficients between all the various combinations of geochemical and geophysical logs within 200 m overlapping intervals throughout the well (Figure 15). The variations in these correlation coefficients between the various elemental abundance curves, porosity, and the caliper log recorded by the borehole televiwer and multichannel sonic logging tools (much more accurate than traditional mechanical arm calipers) show that there is no systematic correlation between borehole size and elemental abundances (Figure 15). In fact, large borehole size intervals correlate with zones of increased porosity (softer rock) and with increases in some elemental abundances (e.g., Si and Mg + Na), but with decreases in others (Al and Ca). In addition, an inverse correlation exists between Si content and the other elements (when Si abundances are high, all other elemental abundances are proportionally lower). Al correlates negatively with Mg + Na but positively with Ca. Fe is positively correlated with Ti.

These correlations are caused by the chemical changes accompanying the alteration of basalts to clays and the cementation of cracks by clays, which in turn, cause changes in the "apparent" porosity in the well. This relationship can be seen particularly well in the lower pillow units where variations in the abundances of alteration products correspond with changes in the porosity curve determined from the electrical resistivity log (Figure 16). Increased Si and Mg + Na and decreased Al and Ca correlate quite clearly with porosity because the plumbing system is clogged with alteration products, as can be seen from both the low permeability, but high "apparent" porosity and the correspondence between elemental abundance changes and the porosity curve (Figure 16). These elemental variations reflect the changes in stoichiometry accompanying the alteration of basalts to smectites and chlorites within pore spaces, fractures and breccia zones. Consider for example, XRF analyses of core samples of adjoining basalt and breccia zones which show similar elemental changes between fresh and altered basalts over very short distances in the well (Table
4. Mg increases and Ca decreases with increased porosity (Figure 16) mirroring the alteration of dikes to breccias (Table 4).

Cyclicity in the Oceanic Crust in Hole 504B

One of the puzzles revealed by previous geophysical logging in hole 504B was the detection of cyclicity down the well bore not correlated with borehole size changes. These cycles affect all the geophysical logs, including velocity, resistivity, and borehole telescope images [Newmark et al., 1985]. Cyclicity can also be seen in the elemental abundances recorded by the geochemical logging tool, particularly in the Al variation (Figure 17).

A spectral analysis of Al abundance and resistivity logs provides a quantitative measure of the variation with depth (Figure 17). The Al abundance log cycle is found to have predominant periods of 10 and 20 m in the upper pillows, decreasing to 5 and 9 m in the lower pillows, then increasing to 12–30 m in the dikes (Figure 17). While the short-wavelength energy might be from noise inherent in the geochemical logs (compare Figure 7), there is considerably more long-wavelength energy in the dikes than in the pillow units, (probably because of the vertical drill hole penetrating the nearly vertical dikes versus subhorizontal pillows and flows). This long-period cyclicity can be converted to an average thickness for individual dikes of 2–3 m if we assume an average dip for the dikes of 86°.

While the wavelengths of the lithostratigraphic units observed from core do not correspond exactly to those from the Al log, the frequency of changes observed in the core suggests a cause for the Al variability (Figure 17). Adamson [1983] (as cited by Becker et al. [1988]) was able to discriminate three phytic and one aphyric lithostratigraphic units (Figure 17). The compositional differences are associated with different lithostratigraphic units within the basalts. In fact, Emmermann [1985] identified changes in Al content between lithostratigraphic units that are at least as abrupt as similar changes observed in the Al log. However, the Al contents of adjacent lithostratigraphic units sometimes do not vary significantly, even though the phenocryst assemblages (upon which the units are distinguished) do change (compare 1270–1350 m, Figure 17). Therefore cycles derived from a single element (Al) cannot distinguish all the lithostratigraphic boundaries in hole 504B. Some Al units would appear thicker than the lithostratigraphic units, perhaps explaining the observed discrepancies in the lower portion of the hole (Figure 17).

The extrusion of relatively thin and geochemically distinct volcanic units within pillow basalts and the intrusion of individual dikes during the primary volcanic construction of the upper oceanic crust likely account for the primary cyclicity found not only in the Al log but also in the other geophysical and geochemical logs from the upper portion of hole 504B. That is, extrusions building the upper oceanic crust at hole 504B consisted of many thin flow units fed by intrusive dikes, some of which are of variable composition. Subsequent precipitation of alteration products along unit boundaries certainly enhanced the amplitudes of the observed cycles.

A Mineralogical Model for Hole 504B

The elemental abundances from the geochemical logs at hole 504B can be inverted using a correlation matrix to determine the distributions and abundances of alteration minerals that are present in the well [Hertzog et al., 1987]. In the hole 504B case, six mineral compositions were input as
end-members into an inversion matrix with the dry weight percent oxide compositions of Si, Al, Fe, Ca, K, Na − Mg, and S from the geochemical logs (Table 5). Only six minerals were used because the number of constraining elements available for the matrix inversion in hole 504B is seven. Ideal compositions of plagioclase (An₃₀), clinopyroxene, smectite, chlorite, celadonite, and pyrite were chosen to be representative of the mineral suite found in the core. Other minerals recovered from the well but not included in the model, such as olivine, palagonite, and anhydrite, can be safely excluded because nearly all the olivine is altered to smectite and chlorite, anhydrites and other sulfides are rare relative to pyrite, and palagonite can be approximated by the smectite composition (see Table 5 for sources of microprobe analyses used to select the appropriate composition of each mineral going into the model).

This ELAN (mark of Schlumberger) calculation is essentially a “cluster analysis,” in that the chemical analysis at each depth is fit within a seven-axis volume (one for each input element). The six ideal minerals form separate clusters within this volume. A serial calculation is performed to locate the nearest mineral clusters to each input of elemental abundances at the depth point. In much the same way that normative mineralogies are computed, the correlation matrix selects the amount of each ideal mineral that, when added together, would occupy a space closest to the elemental data within the volume. The amount of sulfur decides the amount of pyrite, the potassium is partitioned between celadonite and smectite, etc., as in Table 5.

Elements that have little contrast in abundance between ideal minerals (such as iron in Table 5), will have little influence on the mineral selection process, whereas those with large differences (such as aluminum in Table 5) will be very important. All errors propagate through the calculations as in normative analyses. However, at the end, reconstructions are created of the elemental abundances predicted by the mineral distribution chosen by the model. Comparisons are then made between this “best fit” elemental reconstruction and the original input analyses to estimate error.

The mineralogy model calculated for hole 504B, as limited as it is, still indicates that two major compositional components are present within the hole (Plate 1). Plagioclase and clinopyroxene form the bulk of the formation (this is the fresh basalt itself, in blue in Plate 1). A second component appears as large “spikes” of (1) K-rich celadonites (white) in the upper pillow basalts, (2) smectites (orange) in the upper and lower pillows, and (3) chlorites (green) in the dikes. The geochemical log-derived, mineral variations (Plate 1) agree nicely with those observed in core by Alt et al. [1986a] (compare our Plate 1 and Alt et al.’s [1986a] Figure 2). For example, the chlorite appears only below 600 m depth in
both the core samples and in the log-derived mineralogy model.

A pattern is evident in the abundances, as well as the compositions of minerals present in hole 504B. Volume percentages of high temperature chlorites present in the dikes average 10%, whereas lower temperature smectites fill up to 15% of the volume of the lower pillows. Celadonites and smectites fill only 5% of the upper pillow section in hole 504B.

The mineralogy model shows that abundant clay-rich fracture and breccia zones are found along the contacts of the lithostratigraphic units discussed above, (the characteristic spikes in Plate 1, see blowup). These elemental variations reflect smectite and chlorite precipitation in pore spaces within fracture and breccia zones found along the contacts between the lithostratigraphic units in hole 504B.

**Integrated Chemical Fluxes in Hole 504B**

Chemical reactions within submarine hydrothermal systems result in significant fluxes of elements between seawater and the oceanic crust, both at the ridge axes [e.g., Edmond et al., 1979; Jenkins et al., 1978; Von Damm et al., 1983] and on ridge flanks [Maris et al., 1984]. A volume of seawater equivalent to that of the entire oceans is thought to circulate through the ridge axes in approximately 7 Ma [Sleep and Wohletz, 1978]. Concomitant chemical exchange with basaltic not only alters the crust but affects the composition of the oceans as well. For the mass budgets of many elements in seawater, hydrothermal exchange is as important as river-input to the maintenance of a stable composition for the oceans over geologic time [e.g., Thompson, 1983].

Hot (~350°C), hydrothermal fluids exit the ridge axis at "black smokers," providing us with a view of active metallogenesis as metals, derived from reactions between seawater and basalts, are deposited as sulfides directly onto the seafloor [e.g., Ballard and Francheteau, 1983]. Helium 3 and methane gases that escape with the hydrothermal fluids provide chemical tracers with which to map the deep circulation patterns of the oceans [Lupton and Craig, 1983]. On the flanks of mid-ocean ridges, cold water circulation continues the chemical exchange between the oceans and the crust for several tens of million years [Anderson and Hobart, 1976; Anderson et al., 1977]. Moreover, the interaction of seawater with the oceanic crust produces secondary minerals that, when subducted, release fluids into the overlying mantle affecting volcanism above downgoing plates [e.g., Anderson et al., 1980].

Chemical fluxes between seawater and the oceanic crust have been calculated for many elements based upon the compositions of fluid samples taken directly from effluents. Hydrothermal vent fluids, sampled at several locations along the axial rifts, provide the most accurate estimates of axial fluxes to date [e.g., Edmond et al., 1979; Von Damm et al., 1983; Hekinian et al., 1983; Bowers et al., 1988]. Despite continued exploration of mid-ocean ridges and discoveries of additional high-temperature axial hydrothermal vents, problems still remain with quantification of chemical fluxes in seafloor hydrothermal systems. For example, Morton and Sleep [1983] estimate that only about one sixth of the convective heat loss from young oceanic crust occurs in high temperature, axial circulation systems, whereas the remainder occurs during lower temperature convection that occurs off-axis. Low-temperature, off-axis hydrothermal fluids have been sampled from pore waters of "hydrothermal mounds" at the Galapagos Spreading Center [Maris et al., 1984; Bender, 1983] and the Mariana Back-Arc Basin [e.g., Leinen et al., 1988], but only a primitive understanding of the chemical fluxes from these ridge flank systems presently exists.
Analyses of another source of direct sampling, sediment pore fluids, often indicates that basalt-seawater exchange has continued far off-axis, but again insufficient information is available from these data to place constraints upon the overall chemical mass balance [Mottil et al., 1983; 1985; Becker et al., 1989].

An alternative approach to the determination of the chemical exchange between seawater and the oceanic crust is to measure changes in rocks dredged and drilled from the seafloor and to estimate the distribution of the various alteration types [Staudigel and Hart, 1983; Thompson, 1983; Alt et al., 1986a]. This method has an advantage over the direct fluid sampling in that the rocks integrate the mineralogical and chemical effects of alteration processes that have affected the rocks throughout their residence time on the seafloor [e.g., Humphris and Thompson, 1978]. However, the problem remains of extrapolation of the processes observed in dredged and cored rocks to those occurring throughout the subsurface. Exposures of ophiolites on land allow complete sections of the old oceanic crust to be collected. However, conclusions from analyses of ophiolites are complicated by the often occurring overprint of metamorphism that accompanied emplacement and by variations in tectonic setting between

| TABLE 4. X Ray Fluorescence Analyses of the Elemental Abundances of Core Samples From Breccias and Dikes in Hole 504B |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Leg 83                                          | Leg 83                                          | Leg 83                                          | Leg 83                                          | Leg 83                                          | Leg 83                                          |
| Leg 83                                          | Leg 83                                          | Leg 83                                          | Leg 83                                          | Leg 83                                          | Leg 83                                          |
| Core 100-1                                      | Core 101-1                                      | Core 111, Core 142                              | Core 111, Core 142                              | Core 111, Core 142                              | Core 111, Core 142                              |
| 83-109 cm                                      | 109-114 cm                                     | 110-114 cm                                     | 110-114 cm                                     | 110-114 cm                                     | 110-114 cm                                     |
| Depth, m                                        | 1075                                           | 1076                                           | 1091                                           | 1090                                           | 1354                                           | 1353                                           |
| SiO₂                                            | 50.20 ↑                                         | 48.25 ↑                                         | 50.00 ↑                                         | 49.20 ↑                                         | 45.50 ↓                                         | 50.20 ↓                                         |
| Al₂O₃                                            | 13.20 ↓                                         | 16.20 ↓                                         | 13.90 ↓                                         | 15.10 ↓                                         | 14.70 ↓                                         | 15.10 ↓                                         |
| Fe₂O₃                                            | 12.40 ↑                                         | 9.40 ↑                                          | 10.60 ↑                                         | 9.96 ↑                                          | 14.40 ↑                                         | 10.70 ↑                                         |
| MgO                                             | 7.78 ↑                                          | 7.30 ↑                                          | 8.01 ↑                                          | 8.72 ↑                                          | 9.62 ↑                                          | 7.73 ↑                                          |
| CaO                                             | 7.61 ↓                                          | 12.40 ↓                                         | 10.60 ↓                                         | 12.80 ↓                                         | 9.26 ↓                                          | 12.60 ↓                                         |
| breccia                                        | dike                                            | breccia                                        | dike                                            | breccia                                        | breccia                                        |
| Arrows indicate the direction of change from dikes to breccias. Up is enrichment; down is depletion.
Fig. 17. (Left) Cyclicity in Al logs from hole 504B shown by variations in thicknesses of major units determined by abrupt changes in Al content and compared to lithostratigraphic unit thicknesses determined from phenocryst variations between cores (Adamson [1985], as cited by Becker et al. [1988].) Lithostratigraphic basalt types are 1, plagioclase-olivine phricic; 2 and 3, plagioclase-olivine-clinopyroxene phricic; 4, olivine-plagioclase phricic; and 5, aphric. (Center) Power spectra of the Al log (solid line) and resistivity log (dashed curve) over depth intervals indicated. Solid circles identify prominent wavelengths (indicated in meters) of coherent power in the Al log, open circles are peaks in the resistivity spectra. (Right) Core-derived (dots connected by solid line) and log-derived (dot-dashed curve) Al variations both show changes in composition between adjacent lithostratigraphic units in the oceanic crust.
TABLE 5. Mineral/Element Abundance Matrix Used for Mineralogy Model of Plate 1. Hole 504B

|          | Plagioclase
d| Clinopyroxene
d| Celsian
d| Chlorite
d| Smeectite
d|
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>49.0</td>
<td>52.0</td>
<td>49.5</td>
<td>28.0</td>
<td>50.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0</td>
<td>2.0</td>
<td>0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>28.0</td>
<td>3.0</td>
<td>2.0</td>
<td>20.5</td>
<td>2.0</td>
</tr>
<tr>
<td>FeO</td>
<td>2.0</td>
<td>20.0</td>
<td>20.0</td>
<td>16.0</td>
<td>15.0</td>
</tr>
<tr>
<td>MgO=Na₂O</td>
<td>5.0</td>
<td>1.0</td>
<td>8.0</td>
<td>22.0</td>
<td>27.0</td>
</tr>
<tr>
<td>CaO</td>
<td>12.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>K₂O</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*aKempson et al. [1985, Table 2].
*bKempson et al. [1985, Table 1].
*cHon老年es et al. [1983, Table 3].
*dAlt et al. [1985] near the average composition, Table 2.
*eKempson et al. [1985, Table 9].

Different exposures [e.g., Gillis and Robinson, 1985; Hon老年es et al., 1985].

Additional information about the variability and evolution of the chemical fluxes between oceanic crust and seawater can be gained from samples and measurements from drill-holes within the oceanic crust [e.g., Staudigel et al., 1979; Alt et al., 1986a]. Because the compositions of the basaltic glasses and the freshest rocks are remarkably uniform throughout hole 504B [Natland et al., 1983; Alt and Emmersmann, 1985], the geochemical log-derived elemental abundances can be used to calculate integrated fluxes that resulted from the exchange of cations between these basalts and seawater.

CHEMICAL FLUXES IN HOLE 504B

As noted above, the crustal section at hole 504B contains evidence of at least three different alteration processes that dominate separate stratigraphic intervals; seafloor weathering in the upper pillow basalts, low-temperature, reducing alteration in the lower pillows, and high-temperature, green-schist metamorphism in the dikes. Moreover, the rocks from throughout the section record the effects of time-varying alteration processes; from high-temperature processes at the ridge axis to low-temperature, off-axis hydrothermal circulation that has proceeded to the present time [Alt et al., 1986a]. In order to determine the integrated cation exchange between basalts and seawater from these different alteration processes, we must characterize the changes in elemental abundances between the freshest basalts (found in the deepest dikes) of hole 504B, and the crust that is more heavily altered (i.e., contains secondary mineral precipitates). By calculating the integrated cation exchange from the bottom to top of hole 504B, we do not intend to imply that no exchange has affected the lowermost basalts (our “datum” composition) or that only the uppermost oceanic crust contributes to the overall crustal exchange with seawater. We simply have no geochemical logs from either deeper in the section or from any significant distance away from this well bore, yet.

The elemental variations caused by alteration cannot be estimated simply by comparing the oxide weight percentages in the altered rock to those in our chosen protolith (the freshest, most unaltered dikes at the bottom of hole 504B). Either a constant-volume assumption must be made for the rock during alteration (a common assumption), or a constant mass must be assumed for an immobile element such as gadolinium throughout the hole. Data for heavy rare earth elements similar in chemical behavior to Gd indicate that these elements are immobile during both seafloor weathering to zeolites and green-schist metamorphism [Ludden and Thompson, 1979; Humphris et al., 1978]. Below, we make estimates of integrated chemical fluxes based upon both assumptions and interpret the differences between the two assumptions to be a fair representation of the error inherent in the method.

The first method used below to calculate the integrated chemical fluxes in the oceanic crust in hole 504B will be to assume that to the first-order, no volume change occurs during the alteration process. We begin by smoothing the log-derived, elemental oxide curves, then normalizing to the protolith composition of the freshest dikes at the bottom of the hole. We use the average composition of log values found in the 1450 to 1485 m depth interval from our “standards” analysis (Figure 18 and Table 3). This depth interval corresponds to rocks with the highest resistivity and density, the lowest porosity and potassium content, and presumably, the freshest basalts recovered by the coring operation (also identified as the visibly least altered by J. Sparks and S. Uhlig (as cited by Becker et al. [1988]). We use the log-derived rather than the core-derived composition over this interval since it is the log-derived differences at other depths that are of interest. We recognize that any systematic errors between the log-derived elemental abundances and the true composition of the protolith will produce errors in the integrated cation fluxes which increase or decrease continuously with depth (the vertical, zero lines in Figure 18 would be moved to the left or right). The disadvantage of using the less accurate, log-derived elemental abundances for the calculation of elemental fluxes is more than offset by the advantage that these geochemical logging measurements are made continuously throughout the well.

CHEMICAL EXCHANGE IN HOLE 504B

To quantify the total chemical exchange that has occurred in hole 504B between basalts and seawater, a correction must be made for “apparent” volume changes that accompanied alteration (assuming first that we have constant volume in hole 504B). As noted above, a significant percentage of the porosity of the well measured by electrical resistivity logs is, in fact, “apparent” porosity caused by the added cation exchange capacity of alteration products [Pezard, this issue].

From Lesher et al. [1986], after Gresens [1967], the total integrated mass flux (Fi) of each element i over the depth interval of the basement section of the well (dz) is then

\[ F_i = \int \rho_i (X_{i}^b - X_{i}^s) \{(1 - \phi_b)/(1 - \phi_s)\} dz \]  

(1)

where \(X_{i}^b\) is the weight fraction of element i in the altered rock (b), and \(X_{i}^s\) is that in the fresh basaltic protolith (s). Dry bulk density (\(\rho_i\)) is measured at each depth by the geophysical logs [Anderson et al., 1985b]. The constant-volume correction is estimated as the difference between the total porosity (\(\phi_b\)) and the porosity of fresh basalt (\(\phi_s\)) at each depth in the well (from Pezard [this issue], as indicated above). Integrated fluxes are shown in Figure 18.
Error is introduced into the integrated flux calculations from two different assumptions. First, the protolith composition may be incorrectly determined by the geochemical logs. This introduces an error which rotates each accumulated flux-versus-depth curve in either the enrichment or depletion directions from a "pinned" beginning point at the bottom of the hole in Figure 18. The most extreme change in protolith composition that we believe reasonable comes from selection of the average, log-derived, elemental composition for the entire dikes interval (from 925 to 1500 m), instead of that for the basal dikes (from 1450 to 1485 m). This error in the flux calculations is indicated as the lower bound for each element in Figure 18, since significant alteration is clearly included within the "protolith." The other assumption which introduces error into the integrated flux calculation is the constant volume assumption itself. Consequently, we have also calculated integrated fluxes based upon the assumption of immobility of Gd:

$$ F_i = \int \rho_s (X_i^b - X_i^a) (I_b/I_a) \, dz $$  (2)

The integrated flux calculations for each cation based upon immobile Gd are displayed as the maximum error estimates in Figure 18. $I_b/I_a$ is the ratio of the concentration of Gd in the altered rock versus that in the protolith. The assumption of constant Gd in a protolithic composition given by the log-derived Gd value in the lowermost dikes does not quite produce no Gd flux when equation (2) is calculated for Gd itself. Therefore a further correction was made at each depth to force the total Gd flux to zero throughout the well. This produces the most extreme fluxes of Figure 18.

A compilation of experimental and total rock fluxes of Ca and Na versus Mg by Mott (1983) can be used to estimate the relative contributions of Na and Mg to the log-derived Mg + Na flux. Mott (1983) found an approximate -1 molar relationship between Ca and Mg, and an inverse-linear relation between Na and Mg. Given the measured Ca flux of -9 to -11 g/100 g of basalt, the observed Mg + Na flux of 3.6-4.9 g/100 g can be separated into a Mg flux of 5.9-7.2 g/100 g and a Na flux predicted to be -1 to -2 g/100 g. Such an estimate will obviously add additional error to estimates of the cation fluxes in the crust.

**Implications of the Integrated Chemical Flux Calculations**

There have been significant mass fluxes of all the major cations within hole 504B (Figure 18) (total fluxes of the elements per 100 g of basalt available in hole 504B are shown in Figure 19). The major fluxes observed in hole 504B are Mg gain above 900 m and Ca loss from 1100 to 600 m (Figure 18). This Mg increase and Ca decrease is caused by the exchange
of cations during chemical reactions between seawater and basalt [Bischoff and Seyfried, 1978; Mostl et al., 1979]. The observed Si enrichment in the crust from 100 to 800 m (Figure 18) is corroborated by observations from core samples from within this depth interval, where abundant quartz was found filling fractures (particularly from 850 to 1050 m) [Alt et al., 1986a].

The Fe loss from the pillows may be due to reactions occurring during low-temperature, off-axis fluid circulation, such as those causing the Fe-rich hydrothermal deposits of the Galapagos [Bender, 1983] and Mariana mounds [Leinen et al., 1988]. Alternatively, a relative increase in the Fe content of the dikes over that in the fresh basaltic composition may have been caused by the addition of chlorite to the bulk rock chemistry measured by the geochemical logs. In that case, the Fe flux (Figure 18) should be rotated to the right to indicate more enrichment in the dikes (since most of the chlorite is found in the dikes), rather than depletion in the pillows.

Still another alternative for the Fe flux can be seen in its covariance with the Ti loss (Figure 18). These elements generally covary in igneous processes, with Fe and Ti becoming enriched in the melt as tholeiitic magmas evolve or become more fractionated. Since Ti is thought to be much more difficult to move by hydrothermal processes than Fe, the complementary Fe and Ti loss may reflect primary igneous compositional changes relative to the protolithic composition.

The large K gain in the upper pillows becomes even more evident when viewed in percentage terms, because there is not a large amount of potassium in basaltic systems (Figure 19). It appears that almost 10% of the K is missing from the dikes, whereas almost 50% more K (than in fresh basalt) resides in the upper pillows. The transfer of K from both the dikes (accounting for the K loss there) and cold seawater is required to balance the increase observed in the upper pillows.

The magnitude of the Al loss is surprising, particularly since very little Al is found in black smoker hydrothermal fluids gushing at the ridge crest. While some Al can be leached from basalt by hydrothermal fluids, most is thought to be reprecipitated locally as clays (or epidote, chlorite, and actinolite in the gneisschist facies section of the hole). Staudigel and Hart [1983] estimate that whereas 1.3 g/100 g of Al are released during the alteration of fresh basaltic glasses, 0.6 g/100 g are retained in smectites.

The presence of significant amounts of Al-rich precipitates in some seafloor massive sulfide deposits [Alt et al., 1987] and of hydrothermal Al-hydroxide precipitates coating basalts at mid-ocean ridges [Howard and Fisk, 1988] both indicate that Al mobility can occur on the scale of meters to tens of meters in the oceanic crust and that significant amounts of Al have been released through hydrothermal vents. Most of the Al loss in hole 504B occurs from 800 to 1000 m (Figure 18), which could be a “passive” loss caused by the cementation of breccias by Al-poor smectites in this zone. The smectites are also Ca-poor and Mg- and Si-rich in this zone (where the “apparent” porosity, or smectite content increases significantly) (Figure 16). Thus the Al loss could be related to Mg and Si gain through the filling of pore spaces with smectite, causing a dilution of Al and Ca. The constant-Gd assumption should eliminate any such passive chemical changes, however, and the decrease in Al is present in this calculation as well.

There is another possible explanation for the Al flux, in that the Al variation in Figure 18 might be a long wavelength change in the lithologic cyclicity discussed above. Al loss would appear in units with less primary Al than the protolith.
at 1450-1485 m and would be caused by primary compositional variations of the basaltic units themselves. The depth interval from 800 to 1000 m would simply have a greater number of Al-poor lithologic units than the protolith composition. The Gd and constant volume normalizations would both show this effect since both are normalized to the same fresh interval. Using the entire dike section as the protolith should reduce this effect, and it does (Figure 18). However, the core analyses from the lower pillow section do not support such a lower Al content than the dikes [Alt et al., 1986a], so we interpret this as a real crustal Al loss. In any event, caution should be used when normalizing to constant Al, as is often done in the oceanic crust. In most cases, such a normalization is probably reasonable, but given the evidence for Al fluxes from the geochemical logs, together with the above mentioned hydrothermal evidence for relatively large-scale mobility of Al, appropriate caution should be used with such normalizations.

If we assume that the observed fluxes in hole 504B are representative of the entire oceanic crust, we can calculate the overall chemical exchange between seawater and the oceanic crust. Though the crust is mostly sealed at a younger age in hole 504B than elsewhere [Anderson and Hobart, 1976; Hobart et al., 1985; Langseth et al., 1988], heat flow studies indicate that it is possible that all crust is eventually sealed because of hydrothermal precipitation [Anderson et al., 1977]. A calculation for fluxes in the entire, worldwide ridge system shows that the Si and Mg enrichment in the crust is of the same order of magnitude as the supply coming down all the rivers of the world [Thompson, 1983], as previously concluded by Humphris and Thompson [1978], Stakes and O'Neil [1982], and Bowers and Taylor [1983]. As much Ca is supplied to the oceans by the crustal alteration mechanism as is carried by rivers, and about the same amount of K is needed to account for the enrichment of the upper pillows as is supplied by rivers. More important than the absolute magnitudes of these changes is the fact that the geochemical logs locate the sites of elemental sources and sinks within the crust (Figure 18).

**Integrated Water/Rock Ratios**

"Water/rock ratios" are frequently used by geochemists to quantify the amount of material that has reacted in hydrothermal systems [e.g., Mottl, 1983]. The geophysical meaning of such "water/rock ratios" in the oceanic crust is problematic, however. Geophysical fluid flow models describe convection of water through a rock matrix in terms of velocity, permeability, and buoyancy forces. The "water/rock ratio" actually represents the reactivity of the fluid-rock system and hence is a function of flow rates and reaction rates.

To examine the possible implications of the log-derived, integrated chemical fluxes in hole 504B, we have calculated "water/rock ratios" in two ways. For the calculation of "water/rock ratios" of Si, K, and Mg into the crust, we have assumed that all cations come from seawater of the composition given by Rosenbauer and Bischoff [1983] (Figure 20). The calculated "water/rock ratios" are then the volumes of seawater required to completely supply Si, K, and Mg cations to basalt to account for the total addition of these elements to the crust observed in the geochemical logging results.

For fluxes of Al, Ca, and Fe leaving the crust, we have assumed the extreme case that they exited as "black smok-
Fig. 20. Total integrated water/rock ratio over the last 5.9 m.y. in hole 504B, calculated from the assumption that the source for cations going into the crust is from bottom seawater and the output from the crust is a fluid of the composition of “black smoker” hydrothermal vent fluid. Very large numbers for Si, Fe, and Al mean that large volumes of fluid are required to enrich Si and deplete Fe and Al in the crust because little Si is going into the crust from seawater and little Fe and Al is leaving in black smoker fluids. Other sources and sinks are likely: silica from deeper in the crust (see smaller water/rock ratio calculated for black smoker source for Si precipitated as quartz also shown above), and Fe and Al loss in low-temperature, ridge-flank convection systems. Alternatives for large Al and Fe sinks are primary igneous variations within the original basalts in the crust.

for two reasons: (1) the continuity of the data allows for the quantification of elemental variations in all rock in a well, not just that recovered by core, and (2) the vertical extent of the data allows for variations to be examined as a function of depth in the crust. We have calibrated the geochemical logging technique against an extensive set of rock analyses from the Palisades Sill. An olivine-rich layer and more subtle intrusive contacts were easily identified in the corrected, log-derived analyses. To demonstrate the usefulness of geochemical logs in the oceanic crust, we have first corrected the log-derived measurements of the bulk chemistry of hole 504B using “standards” from relatively well-recovered sills and dikes. We have then demonstrated that the geochemical logs record the chemical signature of multiple, volcanic extrusion and intrusion events and the integration of all subsequent alteration processes that have acted upon these basalts.

In the future, the rapid accumulation of geochemical logging data for a wide variety of oceanic and continental crustal drill holes will allow studies of the intrusive origin, alteration history, and integrated mass fluxes throughout the crust to be carried deeper and farther back in time than would be possible from surface or core sampling alone.

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Alt, J. C., P. Lonsdale, R. Haymon, and K. Muehlenbachs, Hydro-


J. Alt, Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109.

R. N. Anderson and E. L. Pratt, Borehole Research Group, Lamont-Doherty Geological Observatory, Palisades, NY 10964.

P. K. Harvey and M. A. Lovell, Department of Geology, University of Leicester, Leicester, LE1 7RH, England.

J. Malpas, Earth Sciences Department, Memorial University, St. John's, Newfoundland, Canada.

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Chapter 5

Utilization of Observations of Well Bore Failure to Constrain the Orientation and Magnitude of Crustal Stresses: Application to Continental, Deep Sea Drilling Project, and Ocean Drilling Program Boreholes

Daniel Moos and Mark D. Zoback

Dept. of Geophysics
Stanford University
Stanford CA
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DANIEL MOOS AND MARK D. ZOBACK

Department of Geophysics, Stanford University, Stanford, California

The conditions necessary for compressive and tensile failure of well bores drilled into crystalline rock can be adequately represented by simple elastic failure criteria, and analysis of well bore failure can provide constraints on the magnitudes of in situ stresses if the strength of the rock is known. When applied to several boreholes drilled into continental crust where there is relatively complete knowledge of stress magnitudes, these criteria enable us to predict the depth at which compressive failure of the well bores is observed. In oceanic crust, breakouts have been observed at depths below 700 m below sea floor in Deep Sea Drilling Project (DSDP) hole 504B, drilled into 5.9 Ma crust south of the Costa Rica Rift, and near the bottom of DSDP hole 395A, drilled into 7.3 Ma crust west of the Mid-Atlantic Ridge. In both cases the azimuth of maximum horizontal compressive stress is roughly perpendicular to the ridge axis. As the unconfined compressive strengths of basalt samples from DSDP hole 504B are generally above 200 MPa (Bauer and Handin, 1985), the existence of breakouts in DSDP holes 395A and 504B requires a highly compressional stress state, where $S_{min} = S_\sigma$ and $S_{max} \approx 100$ MPa at about 500 m subbasement. These results are consistent with the state of stress inferred from compressional (strike-slip and reverse faulting) earthquake focal mechanisms in young oceanic crust. As ridge push forces are relatively small in young oceanic crust, we concur with previous suggestions that the high horizontal compressive stresses result from the thermoelastic effects of a convectively cooled upper crustal layer overlying a conductively cooling lithosphere.

INTRODUCTION

Determination of the magnitude and orientation of in situ stress in the continents and oceans is important to understand lithospheric deformation and to evaluate models of a wide variety of plate tectonic processes. While many aspects of crustal deformation and plate tectonics can be adequately addressed from a kinematic perspective, data on the forces acting within plates are needed to provide constraints on the physical processes causing and resisting plate motion and deformation.

Compilations of stress orientation and relative magnitude data have become increasingly more complete over the past 10 years, and tectonic stress orientation can be reliably mapped in many parts of the world. In total, over 3400 reliable indicators of tectonic stress are now available to define global patterns of intraplate stress [Zoback et al., 1989]. The remarkable improvement in the quantity and distribution of in situ stress orientation data makes it possible to utilize such data to interpret tectonic processes in a number of important ways. However, there are still some very large data gaps in the stress maps, and there is almost a complete absence of stress magnitude data from depths greater than about 1 km [e.g., Rummel, 1986]. The lack of data on stress orientation and magnitude is especially severe in the oceans. While earthquake focal plane mechanisms help constrain the orientations and relative magnitudes of oceanic crustal stresses [e.g., Okal et al., 1980; Okal, 1984; Bergman and Solomon, 1984; Wiens and Stein, 1984; Bergman, 1986], intraplate events are rare, no direct measure of stress magnitude is obtained, and measurements of stress direction from a single earthquake focal mechanism are complicated by the fact that the earthquakes often occur on preexisting faults [McKenzie, 1969; Raleigh et al., 1972; Newmark et al. [1984] and Morin et al. [this issue] determined stress directions in oceanic crust from analysis of well bore breakouts. In this paper we expand on these two studies and consider the more general problem of utilization of well bore failure for evaluating stress magnitudes, with the potential for studying the state of stress throughout the ocean basins.

In general, borehole failure can occur as a result of either compressive or tensile stress concentrations around the well bore. Compressive stress failures at the azimuth of the least principal horizontal in situ stress (where the compressive stress concentration is greatest) are termed stress-induced well bore breakouts [Bell and Gough, 1979, 1983; Gough and Bell, 1981; Cox, 1983; Zoback et al., 1985] and have proven to be a reliable measure of stress orientation on land in many areas [Bell and Gough, 1979; Zoback and Zoback, 1980; Plumb and Cox, 1987; Zoback et al., 1987; Mount and Suppe, 1987; Zoback et al., 1989]. In this paper we show the range of conditions under which breakouts occur in both continental and oceanic boreholes and the manner in which information about stress magnitude can be obtained from the breakouts. Tensile failures around the well bore form at the azimuth of the greatest principal horizontal in situ stress (where the stress concentration around the well is least compressive). Tensile fractures may form adjacent to the well bore because of the localized stress concentration, and thermally induced tensile stresses due to cooling of the borehole wall by circulation of relatively cold drilling fluids also promote tensile failure. In these cases the fractures cannot propagate significant distances away from the well.
bore unless the well bore fluid pressure exceeds the least principal in situ stress [cf. Stock et al., 1985]. As is the case for well bore breakthroughs, observations of tensile failure of the well bore provide information about both stress orientation and magnitude. Our overall goal is to illustrate the simple fact that the presence (or absence) of compressive and/or tensile failure at the well bore can provide useful information about the magnitudes of in situ stresses.

**Frictional Strength of the Crust**

As suggested by Sibson [1974] and Brace and Kohlsstedt [1980], we assume that the ratio of the maximum to minimum effective stress cannot exceed that required to cause motion on preexisting faults that are optimally oriented to the principal stress field. We also assume that principal stresses ($S_1$, $S_2$, and $S_3$) in the upper few kilometers of the Earth's crust generally act in the vertical direction, corresponding to the weight of the overburden ($S_3$) and in two orthogonal horizontal directions ($S_{hmin}$ and $S_{hmax}$), corresponding to the least and greatest horizontal principal stresses. The validity of this assumption is borne out by the very small number of intraplate crustal earthquake focal mechanisms in which neither the P nor the T axis is observed to be within 10°–15° of horizontal or vertical [e.g., Zoback et al., 1989]. If these assumptions are correct, the limiting stress ratio can be written [after Jaeger and Cook, 1979] as

$$ (S_1 - P_d) / (S_3 - P_d) = [(1 + \mu^2)^{1/2} + \mu]^2 $$

where $\mu$ is the coefficient of friction of the preexisting plane of weakness and $P_d$ is the pore pressure. Thus the stress can range from lithostatic (in the absence of tectonic forces, [McGarr, 1988]) to the limit defined by (1).

A large number of in situ stress measurements in seismically active areas have shown this to be generally correct [McGarr, 1980; Brace and Kohlsstedt, 1980; Zoback and Healy, 1984]. As we are applying these results to the upper part of the crystalline crust, we assume that pore pressure is approximately hydrostatic, which is borne out from a number of drilling experiments in both continental crystalline crust [Kozlovsky, 1984; Rummel, 1986; Coyle and Zoback, 1988] and oceanic crust [Anderson and Zoback, 1982; Hickman et al., 1984a; Shipboard Scientific Party, 1985].

Figure 1 illustrates the range of allowable values for horizontal principal stresses in the earth's crust for normal-, reverse-, and strike-slip-faulting environments using (1) and Anderson's [1951] theory of faulting. For reference the figure is shown for a depth of 5 km in continental crust (average density of 2600 kg/m$^3$ and $\mu = 0.8$) and for a depth of 1 km into basalt in 4 km of water for the oceanic crust (rock density of 2800 kg/m$^3$ and $\mu = 0.8$). We choose these depths for illustration simply because they are within the depth range of scientific boreholes in the continents and oceans. By definition, the fact that $S_{hmin}$ ≤ $S_{hmax}$ requires all stress states to be above the line of unit slope in Figure 1. The vertical and horizontal lines corresponding to $S_3$ separate the fields of normal (NF), strike slip (SS), and reverse (RF) faulting as defined by Anderson. The vertical line constraining the lowest value of $S_{hmin}$ is the failure bound for normal faulting (i.e., (1) with $S_1 = S_2$ and $S_3 = S_{hmax}$). The horizontal line constraining the greatest allowable value of $S_{hmax}$ is the failure bound for reverse faulting (i.e., (1) with $S_1 = S_{hmax}$ and $S_2 = S_3$). The inclined line is the limit of the allowable stress states for strike-slip faulting (i.e., (1) with $S_1 = S_{hmax}$ and $S_3 = S_{hmin}$). In cases of incipient fault activity (a case that may be true of much of the upper crust) the expected stress state is found along one of these three limiting lines, depending on the style of faulting. It is clear in Figure 1 that principal stress magnitudes are appreciably lower in the oceanic crust than in the continental crust for the depths chosen. This has an important impact on the likelihood of well bore failure at the depths reached by drilling within the oceans. For reference to several specific cases the circles shown in Figure 1 correspond to simultaneous strike-slip and normal faulting, where $S_1 = S_{hmax} = S_3$ and $S_{hmin} = S_2$.

**Stresses Around a Borehole**

In the following discussion we continue to assume that the vertical stress is a principal stress, and we further assume that the well bore is drilled in the vertical direction and that the rock behaves elastically. We will present equations describing the magnitudes of the vertical, radial, and circumferential elastic stresses as a function of azimuth at the well bore; of the principal stresses; of fluid pressure differences between the well bore and the surrounding rock; and of the effects of temperature changes induced by the drilling fluid. These equations can be generalized for arbitrary stress and borehole orientations [e.g., Fairhurst, 1968; Martin, 1988].

For a cylindrical hole in a homogeneous, isotropic elastic plate subjected to effective minimum and maximum far-field principal stresses ($S_{hmin}$ and $S_{hmax}$), the effective radial ($\sigma_r$), circumferential ($\sigma_\theta$), and tangential shear ($\tau_{r\theta}$) stresses described by Kirsch [1989] reduce at the borehole wall to

$$ \sigma_r = \Delta P $$

$$ \sigma_\theta = S_{hmax} - S_{hmin} - 2(S_{hmax} - S_{hmin}) \cos 2\theta $$

$$ \tau_{r\theta} = 0 $$

where $\Delta P$ is the difference between the well bore fluid pressure and the pore pressure in the rock, $\sigma_\theta$ is from Fairhurst [1968], and $\nu$ is the static Poisson's ratio. Theta (\theta) is measured from the azimuth of the maximum horizontal stress. The circumferential stress is greatest at the azimuth of $S_{hmin}$ and smallest at the azimuth of $S_{hmax}$. Figure 2 shows the variation in $\sigma_\theta$, the circumferential stress, and $\sigma_{zz}$, the vertical stress, as a function of azimuth at the well bore for the stress states indicated by the circles in Figure 1. It is important to note the wide range of circumferential stresses for this stress state. For the case at 5 km depth in the continents, $\sigma_\theta$ varies from a point on the borehole at the azimuth of $S_{hmax}$ where the circumferential stress is quite compressive (35 $S_{hmax} - S_{hmin}$ = 220 MPa) to a point where, for the case shown, the well bore is in tension (35 $S_{hmax} - S_{hmin}$ = -25 MPa) at the azimuth of $S_{hmax}$. For the oceanic crust at 1 km below sea floor, $\sigma_\theta$ ranges from about 50 MPa to -5 MPa. The vertical stress has the same $\theta$ dependence as the circumferential stress. However, the range in vertical stress in crystalline rock is considerably less than the far-
Fig. 1. Allowable stress conditions based on the frictional strength of favorably oriented fault planes, assuming $\mu = 0.8$, for continental crust at 5 km depth and for oceanic crust at 1 km below seafloor. (Note the different scales.) $S_v$ is calculated from the weight of overburden, and pore pressure is assumed to be hydrostatic. The stress state is constrained to lie inside the polygon, because $S_{\text{Hmax}} \leq S_{\text{min}}$, by definition, and the ratio $(S_1 - P_0)/(S_1 - P_0)$ is bounded by friction (equation (1)). For reverse faulting, $S_1 = S_{\text{Hmax}}$ and $S_3 = S_v$, defining a maximum bound on $S_{\text{Hmax}}$. For normal faulting, $S_1 = S_v$ and $S_3 = S_{\text{min}}$, defining a minimum bound on $S_{\text{Hmax}}$. For strike-slip faulting, friction bounds the ratio $(S_{\text{Hmax}} - P_0)/(S_{\text{min}} - P_0)$. The circle represents in each case the stress state $S_{\text{Hmax}} = S_v$, with $S_{\text{min}}$ constrained by the frictional strength of normal or strike-slip faults.

Field stress difference for static Poisson's ratios <0.25 [e.g., Carmichael, 1982].

**Effect of Temperature Changes on Borehole Stresses**

Additional stresses are applied to the rock at the borehole wall if the well bore fluid is at a significantly different temperature than the rock. These stresses can be compressive or tensile depending on whether the temperature of the fluid is higher or lower, respectively, than the ambient temperature. The effect of temperature is time-dependent, in the sense that the longer the rock is in contact with the well bore fluid, the further away from the hole the temperature perturbation will propagate. Cossy [1990] presents a complete treatment of the problem for a Biot coupled thermo-poroelastic material, which requires for its solution detailed knowledge of rock properties such as permeability. However, if one assumes that the material is impermeable with no thermoelastic coupling, simpler integral equations can be written for the magnitudes of $\sigma_{\text{mm}}$ and $\sigma_{\text{rr}}$ as a function of
radial position $r$ and time $t$ (see, for example, Stephens and Voight [1982]). Although the exact solution for the temperature distribution near a constant-temperature well bore is a series expansion [Ritchie and Sakakura, 1956], solutions which approximate the temperature using the first two terms of the expansion give sufficiently accurate results close to the hole, and the stresses become

$$
\sigma_\theta = \frac{\alpha E \Delta T}{(1 - \nu)} \left[ \frac{1}{2r} - \frac{1}{r} \ln r \right] \frac{1}{2} [1 + \frac{1}{2r}] 
$$

$$
\sigma_r = \frac{\alpha E \Delta T}{(1 - \nu)} \left[ -\frac{1}{2r} + \frac{1}{r} \ln r \right] \frac{1}{2} [1 - \frac{1}{2r}] 
$$

(3)

where

$$
I_0 = \int_{-\infty}^{\infty} e^{-(\text{erf}^2 x)^2} \frac{1}{z} \frac{1}{z} \, dz
$$

Here $\alpha$ is the coefficient of thermal expansion; $E$ is the static Young's modulus; $\Delta T$ is the temperature difference between the well bore fluid and the rock surrounding the borehole; $\nu$ is the static Poisson's ratio; $\sigma$ is the stress; $\gamma$ is Euler's constant; $r$ is radial position normalized by the well bore radius $R$; and the parameter $\tau = k t R^2$ is the Fourier number. Here $k$ is the thermal diffusivity, and $t$ is the time during which the well bore fluid temperature is perturbed.

If the well bore fluid is colder than the rock, the thermally induced stresses are extensional. This will generally be true where drilling fluids exit the pipe, particularly in Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP) drill holes, as in situ temperatures are generally higher than the temperature of the drilling fluid. However, drilling fluids returning to the surface from greater depths may be somewhat warmer than the undisturbed temperature of the rock and thus may induce compressional thermal stresses. For the purposes of this paper we will consider only the case of the effect of cooling the rock at the drill bit.

Equation (3) is plotted in Figure 3 for various values of time, assuming a 15-cm borehole radius and a coefficient of
thermal expansion of $5.4 \times 10^{-6} \, ^\circ \text{C}^{-1}$ (values appropriate for DSDP and ODP boreholes penetrating oceanic crustal basalts). For these values and a thermal diffusivity $\kappa = 10^{-6}$ m$^2$/s the curves illustrate the effect of maintaining a $10^\circ \text{C}$ temperature reduction within the well bore for 19, 38, 75, 150, 300, and 600 hours (from less than 1 day to 25 days). For this case, well bore cooling applies 4.1 MPa of circumferential tension at the borehole wall. The thermally applied stress decreases rapidly with radial distance, and after 19 hours of circulation is confined to less than 1 borehole radius. As circulation time increases, the stress anomaly progresses further away from the well bore but even after several weeks of cooling is insignificant beyond about 10 borehole radii (1.5 m). The thermally induced radial stress is zero at the well bore, attains a most tensile value a short distance away from the hole, and decreases at greater distances. The peak of the radial stress anomaly migrates away from the well bore as circulation is maintained for longer times, but as in the case of the circumferential stress, the effect is still confined to within a few borehole radii. Times shorter than 19 hours are not accurately modeled by the simplified (3) above but have a similar form.

**Well Bore Failure**

In this section we consider the role of tectonic stress, applied fluid pressure and well bore temperature changes in
terms of the stresses required to cause compressive and tensile failure.

**Conditions for Breakout Formation**

As first suggested by Gough and Bell [1981] and Bell and Gough [1983], breakouts are spalled regions centered on the azimuth of the least horizontal far-field stress and are formed by compressive shear failure due to the large difference between the radial stress and the circumferential stress at that point. Zoback et al. [1985] extended this model to account for the shape of the breakout region, using a modified Mohr–Coulomb criterion for shear failure. They showed that breakout shapes are generally consistent with those predicted by the Mohr–Coulomb theory and proposed that information about the shape of breakouts could allow estimates of the horizontal stress ratio. This technique was successfully applied by Barton et al. [1988]. It is not our intent in this paper, however, to utilize breakout shape information to constrain the stresses.

In the simple elastic Mohr–Coulomb analysis, compressive failure will occur at the well bore wall due to differences between the circumferential and the radial stress when the stress concentration exceeds $C$, the strength of the rock, i.e.,

$$
\sigma_{\theta \theta} = S_{H_{\text{max}}} + S_{L_{\text{min}}} - 2(S_{H_{\text{max}}} - S_{L_{\text{min}}}) \cos 2\theta - 2P_0 \geq C
$$

(4a)

for failure due to differences between circumferential and radial stresses, and

$$
\sigma_{zz} = S_o - 2\nu(S_{H_{\text{max}}} - S_{L_{\text{min}}}) \cos 2\theta - P_0 \geq C
$$

(4b)

for failure due to differences between the vertical stress and the radial stress. Because $\sigma_o \sim 0$ (when $\Delta P \sim 0$) and $\sigma_{\theta \theta}$ and $\sigma_{zz}$ are both nonzero, the stress state around the well bore is polycrystalline. In general, rock is stronger under polycrystalline conditions than under uniaxial conditions, and as described by Wiebo and Cook [1968], the appropriate rock strength when only one principal stress is zero is between the uniaxial strength (where $\sigma_z = 0$) and the biaxial plane strength (where $\sigma_1 = \sigma_2$). Wiebo and Cook relate the biaxial plane strength to the uniaxial strength $C_0$ through the formula $C_o = C_0(1.0 - 0.6\nu)$, where $\nu$ is the coefficient of sliding friction on microcracks. For reasonable values of $\nu\approx 0.6$ (Byerlee, 1978), $C_o = 1.36C_0$. Therefore the stress strength for well bore failure lies within the range $C_0 \leq C \leq 1.36C_0$. In the remainder of the paper we shall assume that this range of values is appropriate for the study of breakouts.

Zheng et al. [1989] present a different model for breakout formation by extensional cracking (spalling) parallel to the well bore. As their spalling process requires some microcrack sliding to initiate the tensile cracks, the stresses necessary to initiate breakouts in their model are those required to promote sliding on favorably oriented microcracks. Thus the far-field stress magnitudes are similar to those necessary to cause compressive shear failure in the model of Zoback et al. [1985] using the Wiebo and Cook [1968] failure criterion. Laboratory results [Mastin, 1984; Haimson and Herrick, 1986, 1989] show that breakout formation generally occurs at stresses consistent with the Mohr–Coulomb criterion for shear failure as modified to include the effect of the intermediate stress, and although Haimson and Herrick [1989] observed features within breakouts that mimic spalling, the stress state for which the breakouts formed was similar to that of the Zoback et al. [1985] model. Vardoulakis et al. [1988] suggest an alternative failure criterion, based on a rigid plastic pressure sensitive dilatant rheology, and a bifurcation analysis to define failure development. This results both in a modification of the stress concentration at the well bore and a more complicated failure criterion. Unfortunately, this analysis has not yet been developed for unequal stresses acting perpendicular to the well bore and cannot be utilized for interpretation of field observations.

We now consider the in situ stress conditions under which (1) breakouts do not occur, (2) breakouts occur only near the azimuth of $S_{L_{\text{min}}}$, and (3) breakouts occur everywhere around the well bore. The boundaries between these three "fields" in horizontal stress space are determined by the strength of the rock and the differences between the far-field total stresses. In general, it is not necessary to evaluate the conditions for compressive failure due to the vertical stress, as in the region of the well bore the maximum circumferential stress ($S_{H_{\text{max}}} - S_{L_{\text{min}}} - 2P_0$) generally greater than the maximum vertical stress ($S_o + 2\nu(S_{H_{\text{max}}} - S_{L_{\text{min}}}) - P_0$), for reasonable values of the static Poisson's ratio ($\nu\approx 0.25$), except in the case of normal faulting where the two horizontal stresses are approximately equal ($S_o \gg S_{H_{\text{max}}} - S_{L_{\text{min}}}$).

For the present we assume that $\Delta P = \Delta T = 0$, but from the discussions above one can see that it is straightforward to vary these parameters and incorporate their effects.

In Figure 4 the fields in which breakouts do and do not occur are shown for an assumed rock strength $C = 200$ MPa for the same depths and conditions as Figure 1. As discussed below, $C = 200$ MPa is somewhat high for many crystalline rocks but comparable to the strength of basalt. The allowable stress states defined by the frictional strength of the crust that are shown in Figure 1 are also shown in Figure 4. The breakout fields in the figure are defined using (4a) by $S_{H_{\text{max}}} \geq C + S_{L_{\text{min}}} + 2P_0$, for failure only at the azimuth of $S_{L_{\text{min}}}$, and $S_{L_{\text{min}}} \geq C + S_{H_{\text{max}}} + 2P_0$, for failure occurring everywhere around the hole. For a strength of 200 MPa it is clear that at a depth of $5$ km on land, breakouts are to be expected under nearly all stress conditions except those of normal faulting, and in a highly compressive tectonic stress state, breakouts would be expected to occur nearly everywhere around the well bore. Conversely, at a depth of $1$ km in the ocean crust, breakouts would only occur at relatively high values of $S_{H_{\text{max}}}$ and a large horizontal stress difference, a reverse/strike-slip stress regime.

Breakouts have been found in many wells drilled on land, and the frequency of breakouts (and the likelihood that breakouts would be encountered) in a given well increases with depth. This can be understood by simply considering limits on the horizontal stresses in reverse-, strike-slip-, and normal-faulting regimes (where the values of $S_1$ and $S_3$ are limited by (1) and the coefficient of friction $\mu$) and the criteria for breakout formation due to the circumferential stress concentration (Equation (4)). The relationship between the rock strength and the minimum depth of breakout occurrence from these equations is illustrated in Figure 5. In this figure the vertical stress $S_o$ is equal to the weight of overburden, pore pressure is hydrostatic, and well bore fluid pressure is equal to the pore pressure. The value of the intermediate stress is conveniently defined in terms of a
parameter $\phi$, where $\phi = (S_2 - S_3) / (S_1 - S_3)$ [Angelier, 1979]. The figure shows, for the stress states defined by the respective faulting regimes and the value of $\phi$, the depth at which breakouts would form for a given strength. As seen in this figure, breakouts develop at much shallower depths in a reverse-faulting regime than in a normal-faulting regime, for a given rock strength. For example, for a rock strength of 200 MPa and $\phi = 0.5$, breakouts would occur below a depth of approximately 1.2 km in a reverse-faulting environment, but in a normal-faulting environment they are not expected until depths of more than 9 km.

Figure 6 presents an analysis similar to Figure 5 for the oceanic crust assuming a water depth of 4 km. In this case, breakout formation occurs roughly at the same depth below the seafloor as below the ground surface on the continents, for the same tectonic stress and rock strength. Unfortunately, wells penetrating more than a few hundred meters of the oceanic crust are extremely rare, and breakouts would be expected only if the level of compressive stress was quite high and the rocks were anomalously weak.

**Borehole Televiewer Observations of Well Bore Breakouts**

The borehole televiewer (BHTV) is an acoustic logging device which scans the interior wall of a borehole, as first
Fig. 5. Minimum depth of breakout formation due to the circumferential stress concentration around a well drilled into continental crust, plotted as a function of rock strength. For each stress state the stresses are at the limit constrained by a coefficient of friction $\mu = 0.8$ on favorably oriented fault planes.

described by Zemanek et al. [1970], to produce a magnetically oriented image of the reflectivity of the borehole wall as a function of depth and azimuth in the hole. Zoback et al. [1985] demonstrated that breakouts could be imaged with the BHTV and produced the first detailed study of breakout cross sections. Since that time, considerable improvement has been made in the analysis of borehole televiewer data [Barton, 1988], and travel times determined from digitized data are now used to determine borehole shape [e.g., Shamir et al., 1988; Morin et al., this issue].

Plate 1a shows breakouts imaged with the BHTV in the Cajon Pass research well [Shamir et al., 1988]. The images
Fig. 6. Minimum depth of breakout formation in kilometers below sea level due to the circumferential stress concentration around a well drilled into oceanic crust overlain by 4 km of water, plotted as a function of rock strength. For each stress state the stresses are at the limit constrained by a coefficient of friction $\mu = 0.8$ on favorably oriented fault planes.

on the left are borehole radius as a function of depth and azimuth. On the right, cross sections of the borehole are shown at various depths. Each cross section involves superposition of three transducer scans (spanning approximately 10 cm vertically). The breakouts appear in cross section as smooth enlargements on opposite sides of the borehole. The amplitude of the reflected signal is lower within the breakout, due to the rougher surface and the fact that the reflection within the breakout is scattered away from the transducer because of nonnormal incidence of the acoustic pulse. As a result, one finds that often a reflection is returned only from the back of the breakout. In the images on the left side of the figure the breakouts appear as irregular vertical bands spanning several meters along the borehole.

**Conditions for Tensile Failure**

The conditions for tensile failure have been discussed extensively in the context of hydraulic fracturing. In typical
Plate 1. (a) Observations of well bore breakouts at 3 km depth in the granitic rocks penetrated by the Cajon Pass well (data from Shamir et al. [1986]). On the left is an oriented, false color image of the well bore radius as a function of azimuth. The difference in radius between light blue and deep purple is about 0.6 cm in an ~8.5-cm-radius borehole. The cross sections on the right have somewhat enhanced borehole relief, to show the characteristic broad, flat-bottomed shape of the breakouts. These are typical of well bore breakouts observed by the borehole televiwer in crystalline rock. (b) Observations of well bore failure at 1.3 km below seafloor in sheeted dikes in DSDP hole 504B (data courtesy of R. Morin) are shown. The difference in radius denoted by the color change from blue where the hole is not enlarged to yellow within the breakouts is 1.4 cm. (c) Borehole televiwer data recorded during DSDP leg 78B in hole 395A, showing very small (incipient) breakouts at a depth of 603 mbsf, are illustrated.
Fig. 7. Stress conditions necessary to cause tensile fracturing at the azimuth of $S_{\text{Hmax}}$, for the stress conditions defined in Figure 1. The lines illustrate the stress values necessary to cause tensile failure for the given values of tensile strength, if the well bore fluid pressure is equal to the ambient pore pressure (i.e., $S_{\text{Hmax}} = 3S_{\text{Hmin}} - 2P_0 + T$). Tensile failure can occur under normal drilling conditions where the lines intersect the polygon constraining the stress state. For example, the stress state indicated by the circle will cause tensile failure if the tensile strength is zero, as shown also in Figure 2.

Hydraulic fracturing operations, increasing the fluid pressure in the well bore induces tensile failure in a vertical well bore at the azimuth of the greatest far-field horizontal principal stress. Hydraulic fractures will be produced when the pressure in the well bore exceeds the sum of the tensile strength and the circumferential stress concentration. Written in terms of the total stresses and the pore pressure, this condition [after Hubbert and Willis, 1957] is

$$P_0 = 3S_{\text{Hmin}} - S_{\text{Hmax}} - P_0 + T$$

(5)

where $P_0$ is termed the breakdown pressure and $T$ is the tensile strength.

Under certain tectonic stress conditions, however, tensile failure occurs during drilling simply because of the pressure of the fluid column in the borehole resulting in "drilling-induced" hydrofracs. At the Nevada Test Site (NTS), where
TABLE 1. Relationship Between Observed and Predicted Breakout Depths

<table>
<thead>
<tr>
<th>Well Name</th>
<th>$C_0$, MPa</th>
<th>$C_0$, MPa</th>
<th>Measured $\phi$</th>
<th>Stress Regime</th>
<th>Depth of Breakout</th>
<th>Predicted Depth</th>
<th>Predicted Range of $\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moodus</td>
<td>&gt;105*</td>
<td>&gt;105–143</td>
<td>0.5</td>
<td>R</td>
<td>~1.1</td>
<td>0.90–1.22</td>
<td>&gt;0.25</td>
</tr>
<tr>
<td>NTS</td>
<td>15–120†</td>
<td>15–163</td>
<td>0.35–0.6</td>
<td>N</td>
<td>~1.1</td>
<td>0.50–5.45</td>
<td>&gt;0.3</td>
</tr>
<tr>
<td>Cajon Pass</td>
<td>100–150*</td>
<td>100–204</td>
<td>1.0</td>
<td>N/SS</td>
<td>~2.7</td>
<td>2.30–4.47</td>
<td>&gt;0.9</td>
</tr>
<tr>
<td>Fenton Hill</td>
<td>124–176†</td>
<td>124–240</td>
<td>1.0</td>
<td>N/SS</td>
<td>2.9</td>
<td>2.88–5.58</td>
<td>&gt;0.85</td>
</tr>
</tbody>
</table>

* $C_0$ inferred from tensile strengths measured using the Brazilian test and the relationship between tensile and uniaxial compressive strength $C_0 \approx (8–12)\sigma_0$.  †Price and Bauer (1985).
†T. Dey (personal communication, 1987) [after Barton et al., 1988].

...the ambient pore pressure is appreciably subhydrostatic, the water used to fill the well bore during drilling frequently caused hydraulic fractures to occur [Stock et al., 1985]. Figure 7 illustrates the range of stresses that could lead to tensile failure at the well bore, if the well bore fluid pressure is equal to the ambient pore pressure. Tensile failure can occur for a given value of tensile strength if the stress state lies to the left of the indicated line. Drilling-induced hydraulic fracturing can occur whenever the horizontal stress ratio is close to the limit constrained by the strength of strike-slip faults (i.e., where the ratio of the effective principal horizontal stress is about 3). In some cases, as a consequence of the excess pumping pressure required to lift cuttings, the pressure at the bottom of a well during drilling can exceed the pressure due to the static fluid column by as much as 10 MPa. This is equivalent to reducing the “effective” tensile strength and would shift the lines of constant tensile strength to the right, making tensile failure more likely. Nevertheless, it is clear that the presence of drilling-induced hydraulic fractures would still constrain the possible stress state to be close to that associated with incipient strike-slip faulting.

Tensile failure at the well bore can also be induced by the thermal stresses associated with well bore cooling. Allison and Nielsen (1988) observed features in four-arm caliper (dipmeter) logs in geothermal wells which may be due to tensile fractures developed because of well bore cooling.

Similarly, tensile fractures were produced during drilling in geothermal fields in France and are suggested to have formed in the KTB (German deep drilling project) pilot hole (L. Mastin, written communication, 1989). The effect of thermal stresses is equivalent to that of the excess well bore pressure. Cooling the well would induce tensile thermal stresses, lower the apparent tensile strength, and promote tensile failure. Depending on the magnitude of the thermal stress, this could lead to failure within the oceanic crust even if the rock is fairly strong.

Thus although the presence of tensile cracks requires a large ratio of effective horizontal stresses and a strike-slip-faulting regime, it does not generally differentiate between cases in which $S_h = S_{h_{max}}$ (strike-slip and normal faulting) and $S_h = S_{h_{min}}$ (strike-slip and reverse faulting). Distinguishing between these cases requires observations related to compressive failure (breakouts).

APPLICATION TO CONTINENTAL CRUST

Over the past 5 years a number of wells have been studied in sufficient detail that data are available on the magnitude of in situ stresses, distribution of well bore breakouts, and compressive strength of the rock. This makes it possible either to utilize all of the data that are available from these wells to test the overall validity of the analysis, or to utilize only a portion of the available data in an attempt to place constraints on stress magnitudes simulating the general approach that we are suggesting for cases in which relatively complete information from a given well is not available.

Table 1 summarizes the key information from several wells in which the state of stress was found to be consistent with that predicted from the frictional strength of well-oriented faults (that is, in accordance with (1)) and for which information is available on the distribution of well bore breakouts and rock strength. Note that these four cases involve normal, normal/strike-slip, and reverse-faulting environments. Relatively continuous breakouts were observed in each case from the shallowest depth to the total drilled depth.

Utilizing (4a) and the information on stress and strength magnitudes in Table 1, we can calculate the range of depths below which “relatively continuous” breakouts would be expected in each well. The term relatively continuous refers to the fact that we want to consider failure of the well bore at representative stresses and rock strength values, not isolated and discontinuous breakouts that might be observed only in selected sections of the well bore where locally the rock might be unusually weak. We compare the observed depth below which breakouts are relatively continuous with the calculated depths. In each case the depth below which relatively continuous breakouts were observed is within the range predicted by the calculation. However, one must keep in mind the fact that the strength values are poorly constrained by laboratory measurements, particularly where unconfined compressive strength is calculated, rather than measured directly. In fact, the largest range of predicted depth (at NTS) is the one for which the largest range of strengths were assumed. The NTS wells were drilled into imbricated tuffs, for which the strengths depended on the degree of imbrication, which varied greatly from unit to unit. In general, breakouts were only observed in the weaker units, consistent with the known stress state. Aside from this case the depth of initiation observed is close to the lowest calculated value, suggesting that the appropriate stress is closer to $C_0$ than to $C_0$.

Alternatively, one can use the depth of breakout initiation to constrain the stress state. Table 1 shows the range of $\phi$ values predicted on the basis of the breakout distribution if the vertical stress and one limiting stress are known. In all cases the vertical stress was measured, and the stress magnitudes are at failure equilibrium; therefore (1) is valid for these data. The comparison between the calculated range of $\phi$ and the measured values illustrates our ability to predict one of the three principal stresses simply from knowledge of...
the depth range of compressive well bore failure and of the other two stresses. In each case the predicted range includes the known value of \( \phi \). The power of the method lies in its ability to restrict \( \phi \) and hence to place one bound (either a lower or an upper bound) on the intermediate stress. For example, for Moodus, where \( \phi \) was measured to be 0.5, the analysis constrains \( \phi \) to lie above 0.25. For NTS, where \( \phi \) is between 0.35 and 0.6, the analysis requires \( \phi \) to be greater than 0.3. At Cajon Pass and Fenton Hill, where \( \phi \) is close to 1, the analysis also predicts very large values for this ratio.

All of these results are limited by our knowledge of the appropriate value of rock strength. The large range of values for \( \phi \) result from the large range of possible values for \( C \). These uncertainties will persist until laboratory strengths can be determined for rock from within these wells both in intervals which contain breakouts and in those which do not.

### Application to Oceanic Crust

Although a large number of boreholes have been drilled into oceanic basement during the DSDFP and ODSP, only a small number of these have been logged with the borehole televinewar, and none have been tested by hydraulic fracturing. As described above, the presence of breakouts allows the determination of the orientation of the principal horizontal stresses and places a lower bound on the stress difference, whereas the absence of breakouts provides an upper bound on the stress difference. If tensile cracks are present, a further constraint can be placed on the ratio of the effective principal horizontal stresses.

We make the following assumptions in this analysis. First, we can reasonably assume that the in situ pore fluid pressures are close to hydrostatic. In fact, measured pore pressures in hole 504B [Anderson and Zoback, 1982], hole 395A [Hickman et al., 1984a], and hole 597C [Shipboard Scientific Party, 1985] indicate that pore pressures are within 1 MPa (2.5%) of hydrostatic. We also assume that \( S_z \) is a principal stress and is equal to the weight of the overlying rock and seawater.

To place constraints on the stresses necessary for well bore failure, we need to know the properties of the basalts. Table 2 shows typical values for the parameters necessary for these calculations [Clark, 1966; Carmichael, 1982]. With the exception of one anomalously low-strength sample, Bauer and Handin's [1985] measurements of \( E \) and \( C_{55} \) of basalts from DSDFP hole 504B lie within the range presented in this table.

There is considerable scatter in these data, particularly for the tensile and unconfined compressive shear strengths. The constraints presented below should therefore be considered in light of this fact and will have to serve until better information concerning the strength of specific oceanic basalts is available. For the purpose of this paper we will use the following (average) values of the properties tabulated above: \( T = 28.5 \) MPa, \( C_{55} = 200 \) MPa, \( \nu = 0.2, \ E = 60 \) GPa, \( \alpha = 5.4 \times 10^{-6} \ \text{°C}^{-1} \), and \( \kappa = 1 \times 10^{-6} \ \text{m}^2/\text{s} \).

#### DSDP Holes 504B and 501

Hole 504B was drilled over a succession of DSDFP and ODSP legs to a total depth of 1562 m below seafloor (mbsf) in 3460 m of water and penetrates over 1200 m of 5.9-Ma oceanic crust south of the Costa Rica Rift (Figure 8). Pillows and minor flows were encountered in the uppermost 671.5 m of basement, below which was a 209-m transition zone followed by sheeted dikes and massive units [Becker et al., 1989].

In hole 504B, Newmark et al. [1984] observed stress-induced well bore breakouts in the section of the hole drilled on legs 69 and 70. Morin et al. [this issue] digitized both the wellbores and the televiewer data from the leg 83 log and from a log recorded during leg 111. The digitized data cover a depth range from 440 mbsf to 1525 mbsf. The uppermost 170 m of basement could not be studied, as no data were recorded on tape during the log of this interval on leg 83. Morin et al. [this issue] identify a bimodal distribution of hole enlargements throughout the interval from about 700 mbsf to total depth and attribute the predominant azimuth of enlargement (117.5° ± 20°) to compressive failure (breakouts) and the secondary mode (about 27°) to tensile failure. The breakouts become nearly continuous below about 1.2 km below seafloor. The maximum compression direction inferred from these data (N27.5°E) agrees with the axes of focal plane mechanisms of nearby earthquakes [Bergman, 1986].

Plate 1b presents a short section of digitized televiewer data from leg 111. The leg 111 data contain clearly imaged well bore enlargements, over the interval 1294–1300 mbsf, within the intrusive section of sheeted dikes. Hole enlargements occur at 90° and 270° here, within the range of scatter of the measurements presented by Morin et al. [this issue]. Although the breakouts are not as regular or as well imaged in data from hole 504B as they are in holes such as Cajon Pass (Plate 1a), the fact that enlargements occur on both sides of the hole, and at a generally consistent azimuth, suggests that they are stress-induced.

DSDP hole 501 was drilled 400 m west of hole 504B through 264 m of sediments and penetrated 73 m of basement. Core recovery was moderate and indicated a mixed assemblage of pillows and massive units. Televiewer data were recorded in the uppermost 25 m of basement only, but data were recorded in almost the entire sedimentary section [Zoback and Anderson, 1982]. We analyzed these data in detail and found no breakouts, either in the sedimentary section or in the basement interval.

The presence of breakouts within the depths penetrated by hole 504B demonstrates that high horizontal stresses must exist at a relatively shallow depth of less than 1 km into young oceanic crust. To illustrate this, we present in Figure 9 schematic plots of two possible stress states at sites 501 and 504. In these figures we calculate \( S_z \) from the weight of the overlying rock and seawater; in Figure 9a, we assume that the stress regime is extensional, with \( S_z = S_1 = S_{\text{max}} \), and allow \( S_{\text{min}} \) to range between that value and the value limited by a coefficient of friction \( \mu = 0.8 \). In Figure 9b, we assume the stress regime is compressional, with \( S_z = S_1 = S_{\text{min}} \), and allow \( S_{\text{max}} \) to range between that value and the
value limited by a coefficient of friction $\mu = 0.8$. In each case, setting one horizontal stress equal to $S_3$ is equivalent to the most favorable stress state for the formation of breakouts. Lines are shown illustrating the value of rock strength \( C \) below which breakouts would occur for a given value of the unknown principal stress. It is evident in Figure 9a that breakouts cannot occur in an extensional stress environment at the depths penetrated by DSDP hole 504B unless the rock strengths were less than 75 MPa. This is a factor of 3 smaller than the average value of \( C \) of more than 200 MPa measured by Bauer and Handin (1985). We see in Figure 9b, however, that for a rock strength of between 200 and 272 MPa (\( C = 0.3C_0 \)), nearly continuous breakouts would be expected to occur at depths of about 1 km below seafloor, but only if the maximum horizontal stress was at the limit imposed by the strength of reverse faults and $\phi = 1$ (or $S_{\text{min}} = S_\alpha = S_3$).

As illustrated in Figure 9, Morin et al. [this issue] report relatively continuous breakouts in hole 504B below about 1.2 km below seafloor. Therefore $S_{\text{max}}$ must be quite high (close to the limit constrained by the frictional strength of the crust), and $S_{\text{min}}$ must be equal to $S_\alpha$. Short intervals with breakouts which occur above that depth can be explained simply by localized sections of the hole with lower than average compressive strength. Morin et al. [this issue] also report the presence of tensile failure in DSDP hole 504B. We can develop a similar set of criteria for tensile failure, to constrain the ratio of the horizontal stresses. However, in this instance the thermal stress and therefore the temperature difference due to pumping cold fluid into the well bore must be known.

Calculating the thermal effect of circulation is quite difficult as pumping rate, rotation rate, fluid viscosity, and the temperature profile outside the pipe all influence the heat transfer among the drilling fluid, the fluid outside the pipe, and the rock surrounding the hole. Furthermore, although drilling fluids exiting the bit may cool the bottom of the hole, returning fluids may warm shallower sections. However, estimates of the minimum temperature perturbation can be obtained from temperature logs run shortly after circulation ceased. Temperatures within hole 504B were recorded a number of times, either shortly after drilling or after the well bore had equilibrated during legs 69, 70, 83, 92, and 111 [Becker et al., 1989]. On the basis of the results of these measurements, drilling and circulating within hole 504B resulted in a minimum of 40°C cooling of the bottom of the well bore. During each circulation phase, shallower sections of the hole may have been warmed somewhat. As suggested by Morin et al. [this issue], temperatures were most strongly perturbed at the points where the fluid exited the pipe and for the periods during which the hole was deliberately cooled prior to logging. On the basis of 40°C cooling, the rock properties in Table 2, and (3), the minimum additional circumferential tensile stress applied during circulation within hole 504B is 16.4 MPa. Figures 10a and 10b are similar to Figures 9a and 9b and illustrate the stress conditions necessary to cause tensile failure at the borehole wall if well bore fluid pressure is equal to the in situ pore fluid pressure. The additional stresses generated by well bore cooling can be considered simply by reducing the tensile strength by the magnitude of the tensile thermal stress. In other words, a tensile stress of 20 MPa and a tensile thermal stress of 20 MPa are equivalent to a zero effective tensile stress. For the assumed average tensile stress of 28.5 MPa and a 40°C decrease in well bore temperature, the effective tensile stress is 12.1 MPa. For this strength and the reverse/strike-slip stress regime required for breakouts, tensile failure could occur at almost any depth below the top of basement. Thus the stress state required to produce breakouts would also produce tensile failure by well bore cooling, and it is therefore not surprising that such features were observed by Morin et al. [this issue].
Fig. 9. Schematic illustration of possible stress conditions at DSDP sites 504 and 501. Also shown is the incidence of breakouts in holes 504B [Morin et al., this issue] and 501. No breakouts were observed in 501, and breakouts were intermittent in 504B below about 700 mbsf, common below about 1.2 km below seafloor, and nearly continuous below about 1.5 km below seafloor. (a) A normal/strike-slip environment, with $S_{\text{Hmax}} = S_3$, $S_{\text{Hmin}} = S_2$, is shown. $S_{\text{Hmin}}$ can range from equal to $S_{\text{Hmax}}$ to a minimum value controlled by friction (equation (1)). The lines are $S_{\text{Hmax}} = \frac{1}{2} S_{\text{Hmax}} + P_{\text{g}} + C$, for the values of $C$ shown. (b) A strike-slip/reverse environment, with $S_{\text{Hmin}} = S_3$, $S_{\text{Hmax}} = S_1$, is also illustrated. $S_{\text{Hmax}}$ can range from equal to $S_{\text{Hmin}}$ to a maximum value controlled by friction (equation (1)). The lines are $S_{\text{Hmin}} = 3 S_{\text{Hmax}} - C - 2 P_g$ for the values of $C$ shown. In each case, breakouts will form only if the rock strength $C$ is below the contoured values. For strengths of 200–270 MPa, typical of samples from hole 504B [Bauer and Handin, 1985], breakouts would not be expected in a normal/strike-slip environment at any depth penetrated by hole 504B. The observations of breakouts are, however, consistent with a reverse-faulting regime with $S_{\text{Hmax}}$ close to the limit imposed by a coefficient of friction $\mu = 0.8$. 
Fig. 10. Schematic illustration of possible stress conditions at DSDP sites 504 and 501. The stress states are as described in the caption Figure 9. Also shown is the depth range over which tensile failure was observed in hole 504B [Shorin et al., this issue]. (a) The maximum values of $S_{\text{min}}$ for which tensile failure would occur at a given depth if the tensile strength of the rock is below the indicated values and the stress regime is transitional between normal and strike-slip faulting. (b) The minimum values of $S_{\text{max}}$ for which tensile failure would occur at a given depth if the tensile strength of the rock is below the indicated values and the stress regime is transitional between reverse and strike-slip faulting. In both cases it is assumed that the fluid pressure in the well bore is equal to the pore pressure in the rock and that the fluid temperature is equal to the ambient temperature. The intermediate value of tensile strength is the effective tensile strength computed assuming a 40°C decrease in well bore temperature during fluid circulation and a tensile strength of 28.5 MPa. Note that the presence of tensile cracks is only somewhat more likely for a reverse-faulting regime, but that in either a reverse- or normal-faulting regime the maximum horizontal stress difference (strike-slip equilibrium) is required.
DSDP HOLE 395A

DSDP site 395 is situated on the edge of a small sediment pond near the center of magnetic anomaly 4, at 22°45′N latitude, in 7.4 Ma crust between the Kane and the Vema fracture zones (Figure 8). Hole 395A was drilled to a total depth of 664 m below seafloor in 4493 m of water, through 93 m of sediments and 571 m of pillow basalts. A borehole televiwer log was obtained during DSDP leg 78B in the interval from 112 mbsf to 609 mbsf [Hickman et al., 1984b]. Well bore enlargements satisfying the criteria for breakouts (that is, that enlargements were observed on both sides of the hole over a series of successive scans) were observed only near the bottom of the hole. No indications of well bore failure in tension were observed within hole 395A.

Plate 1c shows an example of the breakout data within DSDP hole 395A. Although the breakouts are impossible to resolve in the panel on the left, the well bore cross sections on the right clearly reveal shallow, poorly developed well bore enlargements oriented at approximately N20°W and S20°E. These indicate a maximum compressive stress N70°E, about 60° to the trend of the mid-Atlantic Ridge. The fact that the breakouts are very small and occur only intermittently suggests that the stresses are barely large enough to cause failure, and then only for anomalously weak rock.

Figure 11 shows possible stress regimes at site 395, along with lines for breakout formation as a function of maximum stress for various values of rock strength. As in the case of hole 504B, no breakouts would be expected in an extensional regime (Figure 11a) unless the rock is extraordinarily weak. Furthermore, Figure 11b illustrates that for a rock strength of 200 MPa, breakouts would not be expected even near the bottom of the hole, regardless of the state of stress. The well bore enlargement seen near the bottom of the hole could only occur by compressive shear failure if the rock strength in that short interval is about 150 MPa and if \( S_{\text{Hmax}} \) was at the limiting stress for reverse faulting and \( S_{\text{Hmin}} = S_c \). These results are quite similar to those obtained at site 504, and together they suggest that in relatively young crust in both the Atlantic and the Pacific Oceans, very large compressive stresses are at a large angle to the ridge axes.

An attempted hydraulic fracturing experiment in this hole [Hickman et al., 1984a] was unsuccessful after attaining an excess well bore fluid pressure of 15.2 MPa. The experiment was conducted with the packer set at a depth of 582 mbsf, in competent rock near the bottom of the hole. Using the values for tensile strength from Table 2 (23–34 MPa), the fact that breakdown did not occur is not surprising. Even if the state of stress implied by the breakouts near the bottom of the hole is correct, the expected breakdown pressure would be over 50 MPa. Temperature profiles recorded during leg 78B [Becker et al., 1984] and during ODP leg 109 [Shipboard Scientific Party, 1988b] indicate that temperatures were essentially isothermal to 250 mbsf. Extrapolating a conductive gradient to total depth indicates a maximum thermal "shock" of less than 5°C, and thus the maximum applied circumferential tensile stress at the borehole wall due to this flow is about 7 MPa, much too small to substantially aid development of tensile cracks.

DSDP HOLE 597C

Site 597 is located at latitude 18°14′S, longitude 129°46′W, and is the westernmost site of an east-west transect of the southeast Pacific conducted during DSDP leg 92. DSDP hole 597C, drilled into 28.5-Ma crust (water depth 4160 m) generated at the Mendoza Rise, penetrated 52.5 m of sediments and 91 m of oceanic basalt; the hole has a reentry cone and therefore can be reoccupied and deepened in the future. Recovery was almost 54% and consisted largely of massive basalts [Shipboard Scientific Party, 1985]. Two complete BHTV logs were made in the hole within the basement interval. Newmark et al. [1984] reported the presence of intermittent breakouts throughout the total depth of the hole, from which a maximum horizontal compressive stress direction of N110°E ± 25° was determined. The presence of breakouts at such shallow depths is quite unusual, on the basis of both our experience and the theories presented above, and therefore we reanalyzed the data to confirm their presence.

No evidence of breakouts was found. Although the water depth and sediment thickness are slightly different at site 597 than those at sites 395 or 504, a figure similar to Figures 9 or 11 would reveal that breakouts could not develop at the depths penetrated by hole 597C (to 140 mbsf) even in a highly compressive stress regime, unless rock strength is extremely low. For a compressive strength of 200–270 MPa, this borehole would have to be drilled an additional 600 m before breakouts might be expected. On the basis of these considerations, measurements of stress orientation from well bore enlargements in hole 597C should be treated with caution.

DISCUSSION OF SITES 504B AND 395A

Summarizing the results of previous work and of the above analyses, breakouts were observed in DSDP hole 504B and in the bottom of DSDP hole 395A, and no breakouts were observed at shallow depths in DSDP hole 501 or in DSDP hole 597C. Tensile failure within hole 504B could have occurred only with the addition of large tensile stresses generated by well bore cooling. The orientation of maximum compression inferred from the breakouts in holes 504B and 395A is roughly perpendicular to nearby ridge axes, and in the case of hole 504B is parallel to that inferred from nearby earthquake focal mechanisms, as pointed out by Morin et al. [this issue]. In order for breakouts to occur at the depths penetrated by these wells, the stress state must be \( S_{\text{Hmin}} = S_c < S_{\text{Hmax}} \); \( S_{\text{Hmax}} \) must be large enough to cause reverse faulting on planes with a coefficient of friction \( \mu = 0.8 \).

The presence of thermally induced tensile fractures in hole 504B, and their absence in hole 395A, can be related to differences in the temperature profiles within the two holes. Heat flow at site 504 is about 200 mW/m² [e.g., Langseth et al., 1988; Becker et al., 1989], and the temperature gradient in hole 504B is also quite high. In contrast, heat flow in the sediments at site 395 is of the order of 37 mW/m², less than one fifth that at site 504 [Hussong et al., 1979]. The undisturbed temperature gradient within basement at site 395 is similarly quite low, a consequence of strong lateral convection within shallow basement [e.g., Becker et al., 1984; Kopietz et al., 1990]. Thus temperatures increase much more slowly with depth within hole 395A, and the likelihood of large thermal stresses generated by fluid circulation at equivalent depths in 395A is therefore much smaller than in 504B.

Figure 12a, which gives an overview of earthquake focal
Fig. 11. Schematic illustration of possible stress states at DSDP site 395, if stresses are controlled by the frictional strength of well-oriented fault planes. The figure is similar to Figure 9 but for the conditions in hole 395A. Note that for breakouts to occur at 0.6 km below seafloor within DSDP hole 395A the compressive strength of the rock must be less than 150 MPa, and the stress regime must be as illustrated in Figure 11b.
mechanisms within oceanic lithosphere as a function of crustal age as tabulated by Bergman and Solomon [1984], reveals that reverse faulting predominates at shallow depths in young crust and that at greater depths and as the crust ages, strike-slip and normal faulting become more common. Bratt et al. [1985] have proposed that this state of stress is generated by thermoelastic effects in a plate consisting of a convectively cooled lid over a conductively cooling half-space, as illustrated in Figure 12b. The differential stresses generated by thermoelastic effects can exceed 100 MPa at shallow depth, for crustal ages similar to those of sites 395 and 504. Ridge push forces cannot explain this stress distribution, as the horizontal stress generated by ridge push is zero at the ridge crest and increases with crustal age [e.g., Bott and Kuszniir, 1984]. Although various models for stress relief and the depth of hydrothermal cooling lead to differences in the age to which shallow compressional stresses persist, thrust faulting predominates to ages older than 5 Ma in every case examined by Bratt et al. [1985], and the maximum deviatoric compression is horizontal and perpendicular to the ridge axis. In Bratt et al.'s [1985] model, stress relief is a function of time. This is quite different than the model used here, where the frictional strength of suitably oriented faults controls the maximum stress difference. However, if we combine the thermoelastic stress model of Bratt et al. [1985] with the frictional constraint on stress magnitudes, then in young oceanic lithosphere a thrust-faulting regime should predominate at shallow depths with \( S_{H_{\text{max}}} \) maintained at a value constrained by strength and the (fixed) magnitude of the vertical stress, as in (1), and \( S_{H_{\text{min}}} \) approximately equal to \( S_{v} \) (there is no thermoelastic contribution to the horizontal stress parallel to the ridge axis), as required by the presence of breakouts within holes 504B and 395A.

As the crust ages, however, the model of Bratt et al. [1985] predicts that the importance of thermoelastic stress on the total lithospheric stress decreases. At an age of approximately 10–15 Ma, thermoelastic stresses are less important than the accumulated ridge push, and although the superposition of the two effects causes compressional stress normal to the ridge axis at all ages, the magnitude of the deviatoric compression is less than 50 MPa to ages of more than 35 Ma. Two implications arise from this observation. First, earthquakes and stress measurements within oceanic lithosphere
young than 15 Ma probably do not record plate-driving stress, and second, it is unlikely that in situ stresses in older oceanic lithosphere are large enough to allow their orientation to be established by observing well bore failure at depths less than 1 km below the seafloor. This second conclusion may be invalidated by the presence of additional stress sources such as midplate swells, seamounts, or bending stresses related to subduction. Unfortunately, these stresses would also obscure those related to plate-driving forces.

Conclusions

We have presented here a simple model describing the conditions necessary for compressive and tensile failure of well bores in response to far-field stresses and well bore temperature variations generated by circulation of drilling fluids to depth. Using a simple elastic model for the stress concentration around a borehole, we find that the presence or absence of breakouts allows reasonable constraints to be placed on the magnitude of the horizontal principal stresses. Comparisons of the model predictions and the measured stresses in boreholes drilled on land show that in most cases the relatively simple failure criterion enables us to predict the depths at which breakouts are actually observed. The single largest uncertainty lies in the large variation of stress in these rocks and the lack of precise values to use in this analysis.

The presence of breakouts in DSDP holes 504B and 395A requires very high horizontal compression in young (5.9 and 7.3 Ma, respectively) crust, with $S_{\text{Hmax}} > S_{\text{Hmin}} = S_{\tau}$. $S_{\text{Hmax}}$ is within 30° of the spreading direction in both cases and reaches a value of more than 100 MPa at depths less than 0.5 km subsaline. Our conclusion that the stress magnitudes must be large enough to cause reverse faulting on planes with a coefficient of friction $\mu = 0.8$ is consistent with the observation of reverse and strike-slip earthquake focal mechanisms within young oceanic crust.

Thermally induced stresses due to well bore cooling by drill fluid circulation can play a large role in the generation of tensile failure at the azimuth of $S_{\text{Hmax}}$ as seen in DSDP hole 504B. This is especially true where heat flow and the geothermal gradient are both quite high, either in young oceanic crust or in geothermal regimes on the continents, but is less important in the case of DSDP hole 395A, where the temperature increase with depth is more modest. The occurrence of thermally induced tensile cracks in hole 504B is consistent with the strike-slip/reverse-faulting regime indicated by the breakout analysis. These thermally generated tensile cracks do not propagate away from the well bore unless the well bore fluid pressure exceeds the minimum far-field principal stress, which is unlikely unless the formation is severely underpressured.

The compressive crustal stresses required by observations of breakouts in DSDP holes 504B and 395A are due to thermoelastic effects of plate cooling and are not associated with plate-driving forces. Measurements of stresses from observations of well bore failure in crust older than 25 Ma, where stresses are dominated by the forces which drive the plates, require boreholes with significant penetration below the seafloor. This is a consequence of the high strength of oceanic basalts and the fact that the horizontal stresses are limited by the vertical stress and the strength of the crust.

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OCEAN DRILLING PROGRAM

Wireline Logging Manual

Volume 5

Perspectives on Scientific Logging
from the Ocean Drilling Program

Borehole Research Group
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York 10964

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Chapter 1: Introduction to Perspectives on Scientific Logging

As of this writing, twenty-two legs of the Ocean Drilling Program (ODP) have been completed. Below, we present new methodologies for doing marine geoscience in the conceptual framework of the Second Conference on Scientific Ocean Drilling (COSOD II, 1987), using additional examples from ODP Legs 111-122. These examples are presented solely for educational purposes, as are those of the other volumes of this manual. Where appropriate, we have indicated in the section headers the articles upon which the examples and discussion are based. Logging data are proprietary to the shipboard scientific staff of each leg for one year after the end of each cruise. Those interested in the logging results from legs within the one year proprietary period should contact the JOIDES Logging Scientist or co-chief scientists of that particular leg.

We will begin with a synopsis of future uses of scientific logging from the most recent review of the ODP logging program prepared for the COSOD II report by Worthington et al. (1988). This "white paper" clearly spells out the current status and direction of the logging program.

We then place the logging effort into perspective within the newly emerging international scientific drilling and logging programs which are loosely coordinated through the International Lithosphere Program of the International Union of Geodesy and Geophysics (IUGG). Here we find deep scientific wells being drilled through the continental crust, the results of which complement the COSOD II goals of the ODP. In the USSR for example, eleven ultradeep holes are being drilled, each of which is aimed at a total penetration depth of at least 10 km. A worldwide survey of scientific drilling shows a clear view of how ODP and various continental drilling programs (Federal Republic of Germany, Japan, Sweden, United States, and USSR) contribute to a truly global movement toward in situ investigation of the earth's crust (Figures 1-1 to 1-3).

We end this introductory chapter with an example of the synergy between continental and oceanic drilling by describing the various inter-calibration studies being done on land between standard core analyses and the new geochemical logging techniques. Studies in a variety of geological environments, from granites to basalts to metamorphic and sedimentary rocks, provides the ODP with the "ground truth" required to calibrate geochemical logging measurements in ocean-floor rocks and sediments.
Figure 1-1. Locations of scientific drillholes in the Western Hemisphere discussed in Volume 5.
Figure 1-2. Locations of scientific drillholes in the Atlantic Ocean area discussed in Volume 5.
Figure 1-3. Locations of scientific drillholes in the Indian Ocean discussed in Volume 5.
JOIDES Downhole Measurement Panel White Paper for COSOD II: Conclusions and Recommendations

"An ODP borehole is a scientific legacy; it is not a mere relic of a core acquisition procedure. Scientific measurements in boreholes and on recovered core should be planned on the basis of their incorporation into a regional or global model, their future reinterpretation and, in some cases, the reoccupation of the drill site for further investigations. Core recovery is discontinuous and represents a small volume of sampled material. Core data are often used to calibrate the interpretation of wireline logs. Wireline well logs provide a continuous record of the succession and sample a volume about 100 times greater than that of recovered core. The cost of well-logging is small compared to the expense of drilling a hole in the first place. In terms of cost-effectiveness and the volume sampled, well-logging programs produce substantial returns. Well-logging is neither a replacement for core analysis nor is it a subordinate discipline. It provides complementary information which is often of a different type from that which can be determined by core analysis. Logging is not therefore a luxurious add-on to a drilling program. It is an integral part of data acquisition within any deep drilling program and has a specific and important role of its own. This premise has been proved time and time again outside ODP, at sea or on land, in pure geophysics or in the mining and oil industries."

Scientific Applications of ODP Logs (from Worthington et al., 1988)

Many marine geological discoveries of the past followed new technical developments in observational capability. For example, the revolutionary advances made by the Deep Sea Drilling Project (DSDP) were derived from analyses of samples from deep beneath the sea floor. The discoveries made during those early years of research drilling in the oceans were based substantially on qualitative descriptions of core material supplemented by laboratory measurements of chemical and physical properties of spot samples. The volumes sampled were therefore small and the vertical data records were discontinuous.

Earth science is now in the throes of another revolutionary phase, stimulated by important developments in downhole-measurement technology. These developments have made possible accurate in situ measurements of a broader range of chemical and physical properties. Unlike core material, which is often disturbed during acquisition, in situ measurements characterize the environment around the borehole and lead to the determination of chemical and physical properties in that environment. Furthermore, the resulting data in the form of continuous well logs relate to much larger sampling volumes than do core data, thereby providing an intermediate scale between core measurement and
surface geophysics. By using these logs, the interpretation of drilling results from the ODP can be placed on a much sounder quantitative footing than has been hitherto achievable.

Important Points about Logging Tool Response to Keep in Mind

First, logging tools provide a complete and representative response to changes in formation characteristics by sampling every 15 cm over the entire logged interval, regardless of lithology. In contrast, the effectiveness of core recovery is often controlled by those same formation characteristics, so that the degree of core recovery can be partially a function of rock type. Furthermore, in alternating lithologies, preferential core recovery of one lithology may give a non-representative sample. Core recovery averages 99% for hydraulic piston cores (usually the top 100-150m) but only 46% for rotary cores; of this latter amount, a significant proportion is disturbed and mixed by the drilling process.

Second, the usefulness of individual logs in evaluating mineralogy and porosity in different downhole environments also depends very much on the vertical resolution of the logging tools. This varies from a few millimeters to over a meter according to the physical principles and configurations of the different measurement systems. Most logging tools have a vertical resolution of about 0.5 m, i.e., a bed of thickness less than 0.5 m would not manifest itself sufficiently in logging tool response to be characterized.

Finally, nearly all logging tools respond primarily to changes in the mineralogy and porosity of the rock. The determination of porosity from logs inevitably requires a knowledge of the mineralogy. With the logging tools currently available, one can invert log responses and solve for the percentages of all minerals present in amounts greater than about 5%. The principal complication to such an inversion is that some clay minerals vary in composition (and therefore log response) as a function of both depth and locale; these variations degrade the accuracy of mineralogy determinations from logs.

Application of Downhole Measurements to Specific Scientific Topics of COSOD II

In the succeeding chapters of Volume 3, we will deal in detail with the mechanics of how to use logs to solve the specific thematic questions outlined in the Second Conference on Scientific Ocean Drilling (COSOD II) held in Strasbourg, France in 1987. These scientific themes to be addressed in future ODP logging are outlined below, again from Worthington, et al. (1988).

Theme: Global Environmental Changes

Rhythmic, cyclic and long-term environmental changes recorded in the mineralogy or grain size of marine sediments can be recognized in modern well logs provided that the sedimentation rate is high enough to produce resolvable events. Logs are especially well suited for addressing problems of environmental change since the solutions frequently require a continuous stratigraphic record in order that the effects of variations in climate and
ocean circulation upon sediment composition and texture can be recognized. Improvements in stratigraphic resolution should be most achievable through the combined use of seismic information, well logs, and bio- and lithostratigraphic data from core studies. The use of core data alone is not defensible for these studies since they are rarely sufficiently continuous.

Mineralogy or porosity changes can be caused by climatic variables such as aridity/humidity, wind patterns, eustatic sea level, water temperature, and oceanic upwelling:

a. Aridity/humidity changes affect clay type and/or clay abundance. Changes in clay type are apparent in natural gamma spectral, spectral density, and aluminum activation logs. Changes in clay abundance are apparent in gamma ray, natural gamma spectral, and the combination of neutron and spectral density logs.

b. Wind patterns affect the grain size and the abundance and type of minerals in pelagic sediments. Porosity is closely related to grain size for uncemented pelagic sediments and is very well determined from logs. Porosity is often the dominant variable controlling the responses of the sonic, resistivity and spectral density logs. Hydrogen content, a porosity indicator, is determined by the neutron and induced gamma spectral logs. The elements Ca, Si, Al, Mg, Ti, K, Fe, Mn, S, Th, H, Cl, U, and Gd are determined from the geochemical logs (the natural gamma spectral, aluminum activation and induced gamma spectral tools). Mineral abundance can be determined from inversion of either the geophysical logs (sonic, resistivity, spectral density and gamma ray) or the geochemical logs. ODP generally uses both.

c. Eustatic sea level changes, like wind pattern changes, affect the grain size and mineralogy of sediments. Log responses to these sedimentary changes have been described above. The logs alone cannot distinguish whether changes are caused by wind pattern or sea level variations, but sedimentological studies of cores often remove this ambiguity.

d. Changes in either water temperature or upwelling affect the type or abundance of biogenous sediment components. Biogenous components are determined in the same way as other minerals. Determination of calcite abundance is relatively straightforward; however, the logs do not distinguish whether the calcite is in nannofossils, foraminifera, or detrital grains. Determination of radiolarian and diatomaceous opal is more difficult, as most other minerals also contain silica. Changes in radiolarian and diatom contents are more often indicated indirectly by logs, through their effects on porosity.

A major issue to be addressed by ODP is the enhancement of stratigraphic resolution through the recognition of the Milankovitch climatic cycles in ocean sediments. These climatic cycles are believed to be driven by the earth's orbital variations. These orbital changes will often cause some type of cyclic variation in the local pelagic sequence, though the most important climatic fluctuations will vary regionally. Milankovitch (1941) recognized eccentricity changes at 95,000 year periods, obliquity changes at 41,000 years,
and precession changes at 19,000 and 23,000 years. Verification of these cycles is a principal ODP objective to which logging can make substantial contributions.

For the study of Milankovitch cycles in ODP holes, logs have two powerful advantages over cores: (1) continuous, uniform sampling throughout the drilling interval, independent of core recovery, and (2) measurement of a wide variety of variables that may be climatically influenced. Accurate sedimentation rates from cores are needed in order to determine the temporal frequency of log cycles. Virtually all studies of Milankovitch cycles in DSDP and ODP cores have been limited to the Plio-Pleistocene, because only hydraulic piston cores have sufficient core recovery and they seldom can be used deeper than 150 m. In contrast, continuous sampling by logs is not depth-limited.

Changes in depositional environment are often recognized on regional seismic lines rather than in cores. It is essential to have an accurate tie between core (or log) depth and seismic travel time, so that one can either recognize the location in cores of regional seismic reflectors or extrapolate regionally from the depositional changes recognized in cores. Most seismic reflectors are interference patterns caused by impedance variations over a 20-30 m interval; thus it is hazardous to try to tie core-depth to seismic-time based on either discrete physical property measurements or observed sedimentological changes. Instead, sonic and density logs are routinely used to calculate synthetic seismograms. Matching the synthetic to the seismic section yields a detailed and correct link between core-depth and seismic travel-time.

**Theme: Mantle-Crust Interactions**

Downhole measurements including wireline logging and special borehole geophysical experiments have already played a major role in furthering our knowledge of oceanic crustal structure. Logging is an essential element of crustal drilling programs because it provides a complete record of physical properties in the borehole, in contrast to the usually sparse recovery of core material in hard rock. Borehole geophysical experiments expand the scale of the information acquired from the borehole from a few meters to a few hundreds of meters or kilometers, which is the scale of typical marine geophysical surveys. In sedimentary sequences it is common to assume that the structure intersected by the borehole and sampled at a lateral resolution of less than a meter extends horizontally for at least hundreds of meters. This assumption is not valid in oceanic crust, where strong lateral heterogeneities can occur over length scales from centimeters to kilometers.

Because of the scale of sampling associated with ODP, almost any conceivable ocean crustal objective will require that drilling results be placed in a regional setting. Wireline logging and special downhole experiments meet this need.

For example, virtually all models of crust/mantle interaction are constrained by seismic structure which is, in turn, affected considerably by porosity and fractures. It became evident in the early 1970s that laboratory-measured velocities of cores could not be directly correlated with refraction velocities because of the presence of secondary voids. Since integrated sonic logs and oblique seismic experiments did take account of these voids, they agreed much better with seismic refraction data. Well logs and borehole seismic methods, therefore, have an important role to play in establishing the seismic stratigraphy of the oceanic crust, which is an essential indicator of crust/mantle interactions.
Theme: Fluid Circulation and Global Geochemical Budget

Drill holes provide unique opportunities to obtain invaluable data on the patterns of fluid flow and the physical properties that control such in oceanic sediments and crust. By carefully applying currently available logging and experimental technology in ODP holes, reasonable estimates can be made of vertical flow rates and the two critical, controlling properties, porosity and permeability.

As drilling penetrates deep into sediments and crust, it allows detailed measurements of temperature and thermal conductivity with depth. Concurrently, analyses of pore waters sampled in situ or from recovered cores yield complementary profiles of concentrations of important chemical species. Fitting the thermal and chemical data to one-dimensional advection/diffusion models yields independent estimates of vertical advection rates. A different kind of flow, in the form of vertical movement of fluids through the borehole column, provides important information relating to permeability and pore pressure within the drilled section. In stable holes, this kind of flow can be monitored by detailed temperature logs.

The properties that control fluid storage and flow in oceanic sediments and crust are porosity and permeability. Porosity involves pore spaces that range over several orders of magnitude in size. Permeability is a measure of the ability of fluids to flow through a rock and is related to that proportion of porosity which is interconnected.

Since the oceanic crust is a porous medium, nearly all of its bulk physical properties depend on porosity. Thus, most of the properties that are logged are sensitive to porosity, e.g. sonic velocities, electrical resistivity, density, neutron activation. However, nearly all the logs respond in different ways to porosity over different scales, and it is unclear which log(s) can be interpreted to yield the most accurate estimates of porosity. This is partly a consequence of calibration uncertainties in hard rock.

Present directions in log interpretation for porosity include: (1) multi-log evaluation to yield the "best" estimates of total porosity; (2) comparative analyses to try to separate the different components of porosity, particularly fracture porosity; (3) direct detection of fractures; and (4) analyses of neutron activation logs sensitive to geochemistry for the presence of alteration products that seal original porosity.

With present technology, permeability can only be measured in situ using a packer to isolate hydraulically the formation penetrated by the borehole. With such a hydraulic seal, the hydrological properties of the formation, including permeability and pore pressure can be tested by applying fluid pressure or flow to the formation.

Two drillstring packers have been developed during the first two years of ODP (see Appendix 1):

(1) A nonrotatable, single or straddle-packer that has worked reliably in stable re-entry holes in basaltic crust.

(2) A rotatable packer intended for use in a coring bottom-hole-assembly or in unstable sedimentary formations. The initial tests of this packer in 1986 showed that additional development work was needed.

In addition, ODP is purchasing an electrically-powered wireline packer to be run as a special logging tool starting in 1989. This packer will be intended primarily for
measurements of pore pressure and water sampling over short (one meter) straddled intervals.

Hydrothermal circulation in young oceanic crust is accompanied by chemical exchange between crust and seawater. The most dramatic examples of this exchange are black smokers which are the surface manifestation of the chemical scouring of iron, manganese, etc. from oceanic crust by seawater. Assessment of the volumetric extent of basalt/seawater exchanges requires continuous geochemical analyses as a function of depth in the oceanic crust. Core recovery in basalts, however, is usually only about 20% and may be biased in favor of the least altered rocks. Furthermore, core geochemical analyses are of very small volumes (about 1-5 cm) that may be unrepresentative. In contrast, geochemical logs provide a continuous record of major element changes throughout the drilled crustal section, with each data point representing an averaging over a rock volume of close to one cubic meter. Thus, geochemical logs might constitute the only viable approach to the estimation of the overall geochemical exchange between basalt and seawater.

**Theme: Brittle and Ductile Deformation of the Lithosphere**

The ODP's well logging and downhole measurement program provides continuous records of information which, in turn, permits hole-to-hole correlation of physical and chemical parameters pertinent to an improved understanding of the lithosphere. For investigations which involve documenting and accounting for brittle and ductile deformation of the lithosphere, three categories of information are available:

1. Data for establishing the tectonic history of the drill sites and their surrounding areas
2. Data bearing on the physical and chemical properties of the drilled section, and
3. Indications of ongoing tectonic activity.

The subsidence/uplift record of a drill site is deciphered largely from core-derived palaeontological, sedimentological and geochemical data. These insights can, however, be augmented and focussed by downhole logs. For example, the evaluation of decompaction and subsidence requires continuous and representative vertical records of density and porosity, parameters measured by logging tools on a routine basis. Logs can also provide lithological continuity where cores are lacking, pinpoint faults and unconformities, and often identify subtle stratigraphic cycles of tectonic significance, which are not immediately apparent from the samples. For example, past lithospheric flexure could have caused tectonic rotation or changed the bathymetry of an oceanic area through time. The former can be detected using a gyrostabilized borehole magnetometer. The latter may be reflected in the chemical composition of the sediments which were deposited, and this composition, in turn, may be detectable from well logs. Gamma ray spectral logs can directly identify some chemical variations such as Thorium or Uranium; others may become apparent when the responses of several logging tools are cross-correlated. In addition, thickness of the missing section at unconformities can sometimes be inferred from logs of porosity, density or acoustic velocity.

Perhaps the major contribution well logs make to unravelling tectonic history is in calibrating reflection seismic records, i.e., tying the travel-time of reflections to depth and
thereby to actual rock in the drill hole. The only way to do this with precision is to measure the acoustic properties of the section either with sonic logging tools or by means of a borehole seismic velocity survey. This type of information is essential for definitive interpretations of structural history from seismic records. Log-derived acoustic and density data can also be used for seismic modeling of problematic reflection configurations.

Physical properties which can be measured by ODP logging tools and downhole measurement devices, or which can be derived from their records, include: specific gravity, density, acoustic velocity, electrical resistivity, temperature, presence of fractures, elastic properties, shear strength, pore pressure, porosity, permeability, fluid content, rock composition, radioactivity, and magnetic intensity and susceptibility. In one application or another, all these variables have figured in investigations of lithospheric deformation. For example, provided the rock units are mechanically isotropic, their elastic constants can be derived from 'P' and 'S' wave velocities (from long-spacing sonic waveform logs) and density (given by gamma ray density logs). Borehole televiwer records can provide excellent documentation of fractures, borehole geometry and bed form. Modified drill-stern-test tools with packers can sample formation fluids and measure pore pressure.

Ocean bottom seismometers operating remotely in abandoned boreholes can provide virtually noise-free records of earthquakes for epicenter location and first motion studies. The greatest contribution to ongoing studies of lithospheric deformation is likely to come from ocean-bottom-seismometer arrays set up to monitor all scales of earthquake activity around areas such as plate boundaries. Proposals are in hand for ODP ocean-bottom-seismometer deployment near plate margins offshore of Japan.

At this time, there is particular interest in the geodynamics of accretionary prisms; the deployment of instruments to measure downhole temperatures, permeability, pore pressures, in situ stresses and a range of mechanical properties is currently at the planning stage. Without downhole measurements, we would have much more difficulty advancing our understanding of these active thrust wedges.

An interesting tectonic application of well logs is the determination of in situ stress orientations using the borehole televiwer, with an ultimate goal of producing a global horizontal stress azimuth map. Where regional tectonic stresses exceed the strength of the wall-rock around a borehole, and the horizontal principal stresses are anisotropic, failure will occur. The cavities so created are called "breakouts". Breakouts are detectable using the borehole televiwer. The orientation of breakout failure in a semi-vertical borehole is perpendicular to the direction of the larger horizontal compressional stress.

Theme: Evolution and Extinction of Oceanic Biota

Downhole geophysical logs have yet to contribute substantially to the study of evolution and extinction of oceanic biota in ODP. Logs have contributed only indirectly through their detection of environmental change in the sedimentary column. This approach to the history of biotic events is achievable through well logging provided that three important conditions are met. First, the emergence of a marine organic community changes in its diversity, and its ultimate disappearance must be attributable to physical and chemical processes or other environmental factors that are manifested in the oceanic sedimentary record. Second, these diagnostic physical-chemical characteristics of sediments must be
sufficiently distinctive in terms of electrical, nuclear or sonic properties that environmentally-governed sedimentary zones can be recognized definitively. Third, the time interval must be such that the characteristic sediments are sufficiently thick to be resolved by contemporary logging tools.

There are two ways in which future logging could make a powerful contribution to the study of evolution and extinction: (1) removal of the core-depth ambiguity, and (2) using Milankovitch cycles to greatly refine the age-dating of sediments.

Core-depth ambiguity results from incomplete core recovery. If a zone boundary is found in a 10-m core with only 10% recovery, then that boundary may actually occur anywhere within a 9 m interval. If the character of some property of the core can be correlated with a similar character in downhole logs, then the depth ambiguity is removed. The necessary prerequisites are similar high vertical resolutions (1-5 cm) in both core and log measurements, and a type of core measurement that is continuous, fast, and nondestructive. Two routine physical property measurements (density and velocity) are now run continuously on cores. Both properties depend primarily on porosity, and porosity-sensitive logging tools with similar 1-5 cm vertical resolution could eventually be introduced into ODP. However, the correlation problem would remain non-trivial because core disturbance can dominate the core porosity structure and make log vs. core comparisons difficult even with data of similar vertical resolutions. Furthermore, the ship’s heave can introduce additional uncertainties in correlation of logging and coring depths.

For many years the age-precision of each palaeontological datum was limited by the 5% uncertainty of potassium-argon ages. In fact, the length of a palaeontological zone could be uncertain by a factor of two. A major increase in the accuracy of the time scale occurred when palaeontological zones were linked to magnetic reversal stratigraphy. The next great increase in accuracy has already begun through the counting of Milankovitch cycles between magnetic reversals or between palaeontological zone boundaries. One must, of course, know the Milankovitch frequency being detected (19-23,000 years for precession, 41,000 years for obliquity and 95,000 years for eccentricity). Milankovitch cycles in logs, coupled with biostratigraphy and reversal stratigraphy of cores, offers the potential for substantially improving the yardstick against which evolution and extinction of oceanic biota are measured.

In the much longer term, two potentially useful logging tools for the study of sediment age and evolution/extinctions are at early stages of development: (1) a downhole magnetometer capable of determining reliably the reversal stratigraphy of weakly magnetized sediments; and (2) a cryogenic geochemical logging tool with high elemental resolution that might measure iridium concentration and other extinction boundary “tracers” directly. A finer spatial resolution for this tool is also essential.

The above COSOD II goals attainable with scientific logging are being complemented by thematic objectives studied by scientific logging in continental drillholes. The important point is that the same logging technologies are being used in both drilling programs.

Ironically, the success of DSDP and ODP is causing a shift in earth-science research back toward land. Although many mysteries remain for the marine researcher, the dynamics under the ocean seem simple compared with far more complex goings-on within the continents. We know that the continents have accumulated through repeated collisions with ocean plates or other continents, but beyond that simple details are hard to pin down. For example: how do sedimentary basins develop and subside? How is it possible that thin horizontal sheets of ocean crust (ophiolites) can overthrust deep into an existing continent? What are the controlling factors behind earthquakes or volcanoes?

To answer these and other difficult questions, several nations have developed on-land deep-drilling projects. The Soviet Union planned deep holes from the early 1960's and began drilling its first on the Kola Peninsula through solid granite and metamorphic rock in 1970 (Figure 1-2). The hole has reached 12,200 meters (40,000 feet), a world record, and is targeted for 14,000 meters (46,000 feet). The Kola hole, which is almost completely cored and logged, has provided several surprises (Figure 1-4). The formation at 12,000 meters (39,400 feet) appears much more hydrologically active than expected, with fluid movement and ore deposition in fractures where open permeability had been previously considered impossible. Also note the acoustic velocity inversion below 4500 meters (15,000 feet). Contrary to expectations, acoustic velocities decrease the deeper the depth in the Kola crust (Figure 1-4). Another well targeted deep into a sedimentary basin in the Soviet Republic of Georgia is currently at 7,600 meters (25,000 feet). The Soviets have begun drilling nine other super-deep wells.

Besides adding knowledge to earth science, the Kola well also spurred dramatic improvements in drilling and logging technology. The Soviets' logging arsenal at Kola includes: resistivity, acoustic (compressional and shear), natural gamma-ray spectrometry, neutron porosity, lithodensity, pulsed-neutron, multi-arm caliper, magnetic susceptibility, inclination, temperature, and vertical seismic profiling. Most of these logging tools are rated to 200 °C (400 °F), some to 250 °C (480 °F). The logging cable comprises several connected sections with repeaters to boost the electronic signal to the surface. Cable sections that reach near the bottom of the hole are relatively small in diameter and therefore light, but are resistant to high temperatures and pressures. Cable sections near the surface are larger diameter and strong enough to carry everything below. The Soviets use several devices to ensure successful fishing in the event of a cable break. To prevent cable wear against the hole, logging tools are lowered through drill pipe to just above the section being logged (the method also used by ODP).

Continental deep drilling is not without practical or even commercial applications, i.e., hazardous waste disposal and the harnessing of geothermal energy. In Sweden, a consortium including the Swedish State Power Board and the US Gas Research Institute is drilling a 7,500 meter (24,600 feet) hole to test a controversial and commercially interesting
Figure 1-4. Compressional and shear velocity logs run in the Soviet Union's Kola Peninsula drillhole. These are the deepest logs ever run into the Earth. Poisson's Ratio, Bulk and Young's Moduli are elastic properties of the rock determined from these velocity logs. Note the drop in velocities at 4.5 km depth. Lithologies are various forms of metamorphic rocks. Arrows at 9 km indicate mineralized, fluid flow zone encountered. This is deepest mineralization ever found.
idea of the astronomer, Thomas Gold (Figure 1-2). Gold claims that the earth contains vast untapped reservoirs of "abiogenic" gas, which is not formed from decayed organisms, but generated deep in the mantle.

The drilling site is on the rim of the large Siljan Ring meteorite crater (Figure 1-2). Gold contends that on impact the meteorite might have fractured the surrounding rock and allowed abiogenic gas to seep upward. Currently, the well is at 6,600 meters (21,700 feet). The hole produced some gas—methane, ethane, and pentane, but the biogenic composition of these gases has so far disproved Gold's idea. For a moment, when circulation was suddenly lost at about 6,000 meters, drillers thought they had hit a porous zone. A more likely explanation is that the heavy mud (1.6 g/cc or 13.5 lb/gal.) had induced a hydraulic fracture of the borehole wall.

The West German continental deep-drilling program, KTB, is federally financed and managed by the Geological Survey of Lower Saxony. Plans call for two wells in the Oberpfalz area of Northeast Bavaria (Figure 1-2). A pilot well, currently being drilled, will go to a depth of 3,000 to 5,000 meters (9,800 to 16,400 feet). A second well, to be located one hundred meters away from the first, is planned to go to 14,000 meters (46,000 feet). The West German scientists aim to study how continental crust was formed when the European and African plates collided long ago.

Deep continental drilling in the United States is supported by the National Science Foundation and planned by an organization called Deep Observation and Sampling of the Earth's Continental Crust (DOSECC). DOSECC teams up with the US Department of Energy for geothermal projects and the US Geological Survey (USGS) for earthquake studies. The major project of DOSECC is a well being drilled at Cajon Pass on the southern edge of the Mojave desert just 4 kilometers (2 1/2 miles) from the San Andreas fault where the Pacific and North American plates are sliding apart. Discovering the fundamental forces causing catastrophic earthquakes is the main objective.

One focus of logging research at Cajon Pass is the "heat flow-stress paradox." The problem is that there is no heat flow anomaly along the San Andreas fault, even though it is thought that heat flow must be elevated near highly stressed faults because of friction generated as the blocks grind across each other. The lack of a heat flow anomaly implies that the San Andreas is a low stress fault generating no extra heat; a fact that contradicts laboratory measurements of rock strength. Possible reasons for the lack of a heat flow anomaly are that frictional heat is being dissipated either by ground-water flow or through rock having higher than usual thermal conductivity. Scientists usually measure rock thermal conductivity directly from cores, but in the Cajon Pass project, they are also using geochemical logs to provide the rock's mineralogy. Established thermal conductivity values of minerals then permit an estimation of the rock's thermal conductivity. Radiogenic heat production from the rock can be measured from potassium, uranium and thorium concentrations measured by the natural gamma-ray spectrometry tool. These data, and also extremely precise temperature logs, are then used to calculate heat flow at every measurement interval in the well (Figure 1-5). The log-derived heat flow-versus-depth curve shows constant heat flow throughout the logged interval indicating that heat is mostly being dissipated conductively through the rock and not via the ground water, at least in the upper 1800 m (6000 feet) of the well. The Cajon Pass drillhole is targeted for 4900 m (16,000 feet). The heat flow-versus-depth log would have to remain constant to total depth
Figure 1-5. Heat Flow log from Cajon Pass (right) determined from thermal gradient from temperature log, thermal conductivity from geochemical logs, and radiogenic heat generation from natural gamma-ray spectroscopy log. Geochemical log (left) measures abundances of elements in the borehole wall. These, in turn, are inverted to estimate mineralogy (left, center). Major changes in thermal gradient at 3000 ft are caused not by fluid flow, but by thermal conductivity and radiogenic heat generation anomalies. The heat flow is generally constant with depth as would be expected in a conductive thermal regime.
to conclusively prove that the San Andreas is a low stress fault with little frictional heat being generated.

Another controversial explanation for the lack of a temperature anomaly is that, near the Cajon Pass hole at least, the rock is being compressed perpendicular to the San Andreas fault rather than parallel to it. Thus, the blocks are colliding rather than ripping apart, eliminating frictional shear heating. The hypothesis is supported by breakouts observed on the dipmeter-caliper and borehole televiwer logs--both show the direction of maximum stress always perpendicular to the fault. It remains to be determined whether other parts of the San Andreas fault are similarly stressed.

A Worldwide Scientific Logging Database

Scientists from different logging programs have cooperated directly with ODP scientists. The KTB project, for instance, is operated from the same geological survey in Hanover that coordinates the involvement of the Federal Republic of Germany (FRG) in ODP. With so many of the scientific logging activities on the continents operating in parallel with the ODP wireline logging program, it is only natural that strong synergism is rapidly developing. As an example, consider the effort being expended to calibrate the Geochemical Logging Tool (GLT) measurements of oxide weight percentages. If accurate, this logging tool will revolutionize the scientific return from the logging of any hole. The GLT tool operates by doing 256 channel spectral analysis of gamma rays stimulated by neutron bursts from a downhole accelerator. It provides a continuous elemental analysis of the rock and fluid composition of a drillhole at 15 cm intervals (Figure 1-6). More measurements of elemental abundances have been made on the ODP Legs 109-122 than have previously been done at all Joint Oceanographic Institution universities. The main problem with this tool is accuracy. The nature of the constraints on hardware and the harsh natural environment make these measurements an order-of-magnitude less accurate than laboratory measurements of core samples. Are these reconnaissance measurements accurate enough to yield geological information?

KTB

The best attempt to calibrate the geochemical logging tool measurements to date comes from the KTB project of the Federal Republic of Germany (Figure 1-2). As part of their ultradeep drilling effort, they took extensive cutting and core samples of the metamorphic rocks encountered in their pilot hole drilled in 1988. The geochemical logging tool (GLT) was then run into the hole and the results of chemical analyses compared (Figure 1-7). A very interesting result is the better agreement between the geochemical logging results and cutting analyses (Figure 1-8) than versus core analyses (Figure 1-9).

The GLT irradiates approximately one cubic meter of rock, a volume which more closely approximates that mixed during cutting-retrieval than that sampled by discrete core-plugs. These plugs are 3-cm in diameter, and even though they were cut every 1 meter along continuously recovered core, they indicate bias toward sampling away from Fe- and Ti-rich rock.
# Measurement Precision Elements

## Geochemical Logging Tool Nuclear Measurements

<table>
<thead>
<tr>
<th>Element</th>
<th>Tool</th>
<th>Source</th>
<th>Bombarding Particle, Energy</th>
<th>Interaction</th>
<th>Detected Particle, Energy</th>
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</thead>
<tbody>
<tr>
<td>C, O</td>
<td>Gamma Spectrometry (GST*) tool</td>
<td>Accelerator</td>
<td>n 14 MeV</td>
<td>Inelastic scattering</td>
<td>γ 1.5 to 7.5 MeV</td>
</tr>
<tr>
<td>Ca, Cl, Fe, H, S, Si, Ti, Gd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>Aluminum Activation Clay (AACT) tool</td>
<td>235Cl</td>
<td>n 2.35 MeV†</td>
<td>Thermal-neutron absorption activation</td>
<td>γ 180 keV to 2 MeV</td>
</tr>
<tr>
<td>Th, U, K</td>
<td>Natural Gamma Spectrometry (NGS*) tool</td>
<td>—</td>
<td>—</td>
<td>Natural radiation</td>
<td>γ 180 keV to 3 MeV</td>
</tr>
</tbody>
</table>

*Mark of Schlumberger  †Approximate mean energy

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Ca</th>
<th>Fe</th>
<th>K</th>
<th>Si</th>
<th>S</th>
<th>Th (ppm)</th>
<th>Ti</th>
<th>U (ppm)</th>
<th>Gd (ppm)</th>
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<tr>
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<td>0-40</td>
<td>0-10</td>
<td>0-5</td>
<td>0-50</td>
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<td>0-30</td>
<td>0-1</td>
<td>0-20</td>
<td>0-10</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.1-0.8</td>
<td>0.7-3.1</td>
<td>0.2-0.6</td>
<td>0.26</td>
<td>1.6-6.5</td>
<td>0.1-1.8</td>
<td>2</td>
<td>0.1-0.6</td>
<td>5</td>
<td>0.3-2.4</td>
</tr>
</tbody>
</table>

Figure 1-6. The Schlumberger Geochemical Logging Tool measures oxides using the nuclear sources and physical reactions shown in the top part of the figure. The accuracy in determinations for sedimentary rocks is given in the bottom part of the figure.
Figure 1-7. The most complete calibration experiment conducted to date is in the metamorphic rocks of the KTB drillhole, Federal Republic of Germany. Here, the dry weight percent oxide elemental abundances from X-ray fluorescence analyses of cutting samples are compared to the geochemical logging results.
Figure 1-8. Cross-plots of cutting analyses (vertical axes) versus logging analyses (horizontal axes) for the data from the KTB drillhole shown in figure 1-7. Open circles are comparisons to centrifuged fines from cutting for comparison of any possible biasing due to grain size selection. U and Th are analyses from core plugs. 1:1 slope is expected fit, other lines are least-squares regression lines to data. The geochemical logging results should be calibrated to correct for these differences in this well. Universal hard-rock calibration-corrections are being sought.
Figure 1-9. Geochemical log-derived chemical analyses from KTB drillhole do not compare as well to laboratory analyses from discrete core plugs. Some sampling bias is indicated by skewing of results away from mafic compositions. Clearly, care must be taken when calibrating geochemical logs, with a one cubic meter irradiation volume, to analyses from small volume core samples.
Another interesting result of the GLT-cutting comparison is that the GLT results are quite good, but small calibration shifts are necessary to move the fitted line relating cutting and log values to the proper 1:1 slope (Figure 1-8).

The misfit of aluminum is thought to be caused by abundant Mn in the rock. Although Schlumberger has been struggling to correct for Mn for some time, they have not yet been successful (Figures 1-7, 1-8, and 1-9).

Once the validity of the GLT elemental chemical analyses has been established, a matrix inversion can be performed to determine the most likely mineral abundances present in the well. Ideal mineral compositions must be assumed. These in turn can be compared with determinations of mineral abundances derived from x-ray diffraction analyses of thin sections. These were done every 1 m in the KTB well (Figure 1-10), with generally positive results. It is clear that the GLT provides excellent chemical reconnaissance of the KTB drillhole in metamorphic rocks.

Cajon Pass

A somewhat more elaborate calibration experiment was performed in granites as part of the DOSECC Cajon Pass Scientific Drillhole into the San Andreas Fault, California, (Figure 1-1). Here, cores of up to 1.7-m length were sliced vertically to remove a wedge-shaped sample of the entire length of the core. The entire wedge was then powdered and mixed. Several samples were then measured using x-ray fluorescence and the average composition compared to the GLT average over the same interval (Figure 1-11). The results are comparable to the KTB cuttings rather than to core analyses and point to the extreme care that must be taken when conducting log calibration tests with core. Special problems arise when, as in the ODP example, continuous coring only results in partial core recovery.

At Cajon Pass, mineralogy was determined as at the KTB site (Figure 1-5) and compared to modal analysis of thin sections, again with good agreement (Figure 1-12). The model results were then inverted to predict the beginning elemental composition. A comparison of these "reconstructed" curves with the original data provides a "goodness-of-fit" determination for the model-based mineralogy (Figure 1-13). When the model is good, as at Cajon Pass, the reconstructed curves overlay the original data.

Cajon Pass provides an excellent example of the usefulness of the calibrated GLT results for discriminating lithologies. Major lithologic units of granodiorite and granite are easily determined from simple cross-plots of elemental compositions such as TiO₂ and Gd vs. SiO₂ (Figure 1-14).

Palisades Sill

Basalts similar in composition to those of the oceanic crust have been cored and logged in the Palisades Sill of southern New York (Figure 1-1). GLT results easily identify trends in basalt fractionation identified on the samples (Figure 1-15). For example, the olivine layer near the bottom of the sill formed by the settling of these heavy crystals is easily seen on the Si, Al, Ca, Fe, Mg and Ti curves. The increase upward in light, plagioclase
Figure 1-10. Comparison between abundances of minerals determined from quantitative X-ray diffraction on cutting samples and mineral inversion results from geochemical logs at the KTB drillhole.
Figure 1-11. Calibration experiment in granites from the Cajon Pass drillhole. Here, continuous wedges were cut from long cores to more closely approximate the measurement volume of the geochemical logging tool.
Figure 1-12. Comparison between mineral inversion from geochemical logging analyses and point-counts from thin-sections of cutting samples in granites of Cajon Pass drillhole. The accuracy is affected by bad hole conditions (solid dot).
Figure 1-13. The mineralogy inversion of geochemical logging results from the Cajon Pass drillhole can itself be inverted to calculate, or "reconstruct", the ideal elemental compositions that would give the exact mineral abundances determined by the model. Since ideal mineral compositions were used by the model, the comparison of reconstructed abundances with log-derived abundances points out discrepancies with the real rock, and gives a qualitative feel for goodness-of-fit.
Figure 1-14. The elemental abundances determined from geochemical logging can be used to differentiate between different lithologies as demonstrated in the granitic rocks of the Cajon Pass drillhole. Here, granodiorites have higher Ti (above) and Gd (below) and lower Si contents than do granites.
Figure 1-15. Geochemical logging analyses from basalts of the Palisades Sill are compared to analyses from rock outcrops of the same formation taken from the Palisades Cliffs a few miles away. Shading indicates disagreement. The logs locate an increase in Th content from a later stage intrusion more precisely than do the outcrop samples. Disagreement in Gd, Al, and U at top of the well may be due to subtle stratification within the Sill itself. The enrichment zone at the bottom of the well is clearly delineated by the geochemical logs.
phenocryst content is seen in the increase upward in Al abundance. The discrepancies in Th, U, and Gd probably reflect bias in sampling rather than errors in the GLT. In fact, the location of a second intrusion event is more precisely located by the Th log than by sample analyses (A vs B depth in Figure 1-15).

The Palisades Sill Scientific Drillhole also provides the first basaltic test for the geochemical logging technology of the future: cryogenic-germanium-crystal spectroscopy recorded with a 4096-channel spectral analyzer. The USGS is developing such a tool, and they ran it in the Palisades Sill hole to compare with the Schlumberger GLT results. While the data analysis is not finished yet, several important results are available which point to the importance of high-resolution logging in the future using the Ge crystals.

As a synthetic spectrum of an ideal composition "Palisades Sill Basalt" shows in Figure 1-16, large major element peaks are evident in the 6-8 MeV energy windows. The actual geochemical log midway into the Palisades Sill (Figure 1-16) shows these peaks (heights give the abundances) and peaks of Ni and Sc, Cr, V, and Xr are seen in other energy windows as well. For the first time, the Ni/Al ratio in basalt has been determined with a logging tool (Figure 1-17). The Ni/Al ratio increases with depth toward the bottom of the hole because fractionation has caused the more mafic components of the basalt to sink as the light plagioclase floated as the sill cooled.

Anadarko Basin

Schlumberger designed the Geochemical Logging Tool for use in sedimentary basins and they have completed important calibration tests in sediments using side-wall cores for comparison. The Conoco test well in the Anadarko Basin in Oklahoma provides perhaps the best example of the usefulness of the GLT in sediments (Figure 1-18). Carbonates at 2750 ft are easily identified by the high Ca and U contents and low Fe, Si, Al, K and Th. Sandstones at 2450-2500 ft are easily distinguished from clays at 2500-2700 feet because of their higher Si and lower Fe, Al, and K contents. The core measurements agree with a precision of 1 to 2% in this test case (Figure 1-18).

A Gulf Coast sand-shale sequence was also used as a calibration test between side-wall cores and the GLT (Figure 1-19). The shale at 450-600 feet is easily distinguished from the sands above and below by the Si, Al, Fe and K curves. Schlumberger tested mineral determinations with abundances measured on cores and found excellent agreement (as seen earlier for granitic and metamorphic rocks; Figure 1-20).

Summary

In succeeding chapters, further scientific application of geophysical, as well as the new geochemical logging techniques will be demonstrated using ODP examples. The continental efforts will continue in parallel, of course, producing measurements from the same tool suite in complementary tectonic environments. We must always remember the importance of understanding how the whole earth works beneath both oceans and continents. As with seismology, logging provides a powerful data set to span the whole earth.
Figure 1-16. A cryogenic Germanium detector, geochemical log was also run in the Palisades Sill well. This tool provides enhanced sensitivity to the NaI crystal detector of the geochemical logging tool, but the logging speed must be 100 feet per hour or slower. Ni peaks (below) are identified in the Sill rock that were not present in the synthetic spectra (above). The Sc peak is likely measuring the composition of the steel in the tool itself.
Figure 1-17. The Ni/Al ratios determined from geochemical logs using the Ge-crystal tool in the Palisades Sill compare favorably with analyses from outcrop samples. The increase in Ni/Al with depth in the well indicated crystal fractionation has occurred in the Sill, with mafic crystal sinking and plagioclase crystals floating.
Figure 1-18. Geochemical logging results compared with analyses on side-wall core samples from the Conoco Test Well in the Anadarko Basin. Standard deviations between core and log results are shown at bottom.
Figure 1-19. Geochemical log-derived analyses from the U.S. Gulf Coast compared to analyses on sidewall cores. The increased "noise" in the geochemical logs are likely from thin-interbedding.
Log Minerals vs. Core

Figure 1-20. Mineral inversions from geochemical log results of figure 1-19 compared to quantitative X-ray diffraction results.
Chapter 2: Scientific Uses of Wireline Logs

A drillhole beneath the seafloor is a treasured natural laboratory for the recovery, measurement and monitoring of geophysical and geochemical properties of the geological past and present. It is expensive; but, if done properly, definitive. For example, the dating of sediments recovered during the DSDP is often cited as the irrefutable measurements that established the validity of plate tectonics. Who could question the recovery of core that repeatedly demonstrated that the oldest sediment above basement was the age predicted by magnetic anomalies?

The Ocean Drilling Program carries an additional arsenal of geophysical and geochemical weapons for determining the geology of the drillhole. It is important to recognize the differences between coring and logging of a hole. They are complementary, and together provide the most complete picture possible of the geology encountered by the drill bit. Below, we review the added information determined by ODP Logging.

Missing Section

The most obvious addition to the ODP program is the determination of in situ properties of the section of the borehole that was not recovered through coring. Continuous coring does not result in continuous core recovery. In fact, average recovery by techniques other than hydraulic piston coring is 50% in sediments and 40% in basement. The core that is recovered cannot be properly located stratigraphically because of the missing rock intervals. Logging measures a wide variety of geochemical and geophysical parameters at 15 cm intervals throughout the logged interval.

Site 719 (ODP Leg 116) in the mid-plate deformation zone of the central Indian Ocean provides an excellent example of the value of logging to fill a missing section (Figure 2-1). Here, core recovery was >75% in clays, but <10% in silts. Lithology determined from logs located the silts by higher gamma ray, high velocity, density, and resistivity, and lower porosity (black in the lithology column of Figure 2-1). The clays were easily distinguished by opposite features (white in Figure 2-1). The logs clearly show that the core recovery was highly successful in the clays but very poor in the silts. The fact that the distribution of these two lithologies is about equal in the hole would have gone unrecognized without the logs.

Geophysical and Geochemical Logs

It is important to recognize that not only are there differences between the information delivered by core versus logs, but there are major differences between the formation responses of the various logs run in a hole. The chemistry of sediments and basement rocks, and the physical changes caused by different geological processes can be quite different. Both data sets are much more informative than either alone.
Core recovery can be lithology-dependent: logs give continuous data

LEG 116: Site 719

Figure 2-1. The geophysical logs from ODP Leg 116, Hole 719 can be used to classify two lithologies--a clay with lower gamma ray, velocity, resistivity, and high porosity, and a silt with opposite features. The lithology log at right indicates lithologies picked from the logs (white-clay, black-silt). The coring program recovered the clay preferentially over the silt (left-hand column, black indicates core recovery). The logs are of obvious importance for filling in the gaps left by selective core recovery.
Consider logs from Site 731 (ODP Leg 117), a turbidite sequence on the Owen Ridge of the northwestern Indian Ocean (Figure 2-2). The turbidites are not very different one from the other in chemical composition, so the GLT elemental compositions are rather uniform throughout the sequence. Fe, Si, Ca, and K hardly change from top to bottom within each sequence (Figure 2-2). The geophysical logs, however, show dramatic changes related to the grain size changes that accompany turbidite deposition. The velocity log, for example, clearly delineates the different turbidite events (Figure 2-2).

In the interval just above the turbidites in the same well, the reverse phenomenon occurs (Figure 2-3). Here, an alternating sequence of chalks and oozes contains fine interlayers of carbonate and silica that produce large variations in the GLT measurements of Si and Ca. The geophysical logs show only slightly varying velocity and electrical resistivity that indicate that the major chemical changes produce rocks with rather uniform physical properties (Figure 2-3). It is important that ODP wells are logged with both geophysical and geochemical logging tools.

Core versus Log Comparisons and Synthetic Seismograms

A major use of core in the oil industry, particularly side-wall cores, is for the spot calibration of logs. The ODP methodology calls for the reverse - logs used to calibrate cores, particularly physical property measurements. Site 752 (ODP Leg 121), provides an excellent example of the similarities and differences between physical property measurements from core and logs (Figure 2-4). Density and velocity measurements are of similar character between core and log results, but the logs show much finer character, and locate precisely the boundaries within the well. This enhanced resolution is important for precise definition of the impedance of the sediment (velocity times bulk density), from which a synthetic seismogram can be calculated to tie the core to the seismic section (Figure 2-5). The onset of the dipping reflector sequence in this well would have been missed without the log-derived velocity contact identified at 170m depth. Also, the velocity and density are more precisely determined in situ than from measurements on cores because of disturbance during the recovery operation. The laboratory-derived velocities were somewhat lower than the logs, as shown in Figure 2-4.

Amplitude and Attenuation

Multichannel sonic logs determine in situ elastic properties of the rock that simply cannot be reliably measured on core. The propagation of acoustic energy from source to an array of receivers is similar in geometry to a refraction seismic experiment. The source energy level naturally falls as a function of distance from the near receivers to the far receivers (Figure 2-6, from Site 637, ODP Leg 103). As the tool moves across lithologic boundaries, fractures and alteration zones, additional decreases in amplitude can be identified. The sporadic core recovery in the serpentinite basement at the toe of the Goban Spur off Portugal did not allow for a characterization of either alteration state or degree of brecciation and fracturing. The latter cause low-amplitude compressional waves to be recorded that indicate the location of highly attenuating zones (Figure 2-7). Semblance,
Alternating silt and clay layers have large velocity changes but small chemical differences.

LEG 117: Site 731
Owen Ridge

Figure 2.2. Geochemical logs (center and right) from ODP Leg 117, Hole 731 show only small changes in composition within turbidites on the Owen Ridge that decrease in grain-size upward. The change in grain size produces a very large change in sonic velocity within each turbidite layer (left).
Figure 2-3. In the section just above the turbidite sediments in Hole 731 (figure 2-2), the alternation of carbonate-rich and silica-rich sediments produces large changes in the geochemical logs, but geophysical properties such as velocity and resistivity are very similar between the two lithologies. Geophysical and geochemical logs together provide a much more powerful geological interpretation than either alone.
Figure 2-4. Log-derived velocity (right) and density (left) fill in the detail, and calibrate the results from laboratory measurements on recovered core, as in this example from ODP Leg 121, Hole 752 on Broken Ridge.
Figure 2-5. Detail in velocity and density determinations from logs provides an excellent impedance log for the calculation of synthetic seismograms to compare with surface seismic profiles. The dipping reflectors of Hole 752 are precisely located in depth from such logs.
Figure 2-6. Multichannel sonic logs record the dissipation of sonic energy across several meters of borehole, as in this example from ODP Leg 103, Hole 637, drilled into the serpentinites at the toe of the Gobnan Spur off Portugal. The hard streak within the serpentinites at 240-245 m depth is evident from the increased energy recorded by the array at that depth.
Figure 2-7. A semblance analysis of slowness across the multichannel sonic array of figure 2-6 shows more coherence (greater semblance value) in the fresher rock such as that at 235-245 m depth. Higher amplitudes also delineate the fresher rock. Notice that the core preferentially recovered the breccia zones (black at right).
which measures the coherence of energy between receivers as another way of quantifying relative amplitudes, and velocity, are not as sensitive indicators of alteration as compressional amplitude changes (Figure 2-7). It is important to utilize the multichannel sonic log amplitudes of shear and Stoneley and compressional waves in addition to velocities for complete elastic characterization of a formation.

A Worldwide Database of Basement Lithostratigraphy

The use of the same geophysical and geochemical logging measurements in all ODP boreholes has resulted in the gradual development of a logging database in all oceans. In the oceanic crust, for example, velocity, resistivity, and density logs can be compared from crust of different ages and from ocean to ocean. Consider the crust sampled on ODP Leg 111, Hole 504B (5.9 million years old, medium spreading rate), ODP Leg 109, Hole 395A (7 Ma, slow spreading rate), and ODP Leg 102, Hole 418A (110 Ma, slow spreading rate, Figure 2-8). The thicknesses and transition zones between the seismic layers 2A, 2B, and 2C can be compared at these three sites. For example, seismologists have noticed that layer 2A thins with age and distance from the ridge axis. The logs from the various oceanic crustal holes indeed show that the high-porosity layer 2A is eventually altered into layer 2B as hydrothermal circulation on the flanks of ridges gradually clogs the plumbing of the fractured pillows by the deposition of alteration products (Figure 2-8).

The transition zones found between these layers are not well imaged by seismic profiling because of the long wavelengths of the seismic energy (20-30 m). Logs provide the detail missed by seismic techniques. The borehole televviewer, for example, is an ultrasonic imaging tool that delivers to the surface an acoustic image of the borehole wall. The transition zone between pillow basalts and dikes in Hole 504B was imaged with the BHTV (Figure 2-9), and pillows were seen well into the dike section of the hole, well below the depth of the last recognized pillow in the core. Observations in ophiolites show similar phenomena. The transitions from one layer to the next are zones in which a gradual change occurs from a stratigraphic predominance of one structure to another.

Imaging of Structure and Stratigraphy

The electrical resistivity of a wellbore wall can be imaged using the Formation Microscanner dipmeter (FMS; Figure 2-10). This tool provides 1-mm resolution and produces an image of the electrical conductivity anomalies found along the borehole wall. Faults, breccias, and fractures can be imaged to determine if they are open (filled with low resistivity water) or cemented (filled with high resistivity calcite, quartz or other alteration products; Figure 2-10). Sediment structures such as slumps, laminations and bedding can also be imaged with unprecedented resolution.

The tool essentially delivers to the surface an electronic core image. Fractures, for example, may not only be counted, but their "electrical permeability" quantified by measurement of the electrical current flowing into them (Figure 2-11). In the example from Cajon Pass, sealed fault zones can easily be distinguished from open, permeable ones.
Figure 2-8. Density, resistivity and velocity at three drillholes (Holes 504B from Leg 111, 395A from Leg 109, and 418A from Leg 102) show similar transitions and layering in the upper oceanic crust, although the thicknesses of each vary. Eventually, ODP will produce an archive of the physical and chemical properties of oceanic crust from around the world.
Figure 2-9. The Borehole Televiewer is an ultrasonic imaging device that is capable of discriminating pillow basalts from dikes, as in this example from Hole 504B. The image of an elliptical feature in the side of the wellbore is similar to shapes seen in shallow excavations of pillow flows in Hawaii.
Figure 2-10. The Formation Microscanner is a dipmeter with four orthogonal pads that are dragged up the wall of a borehole. Electrical current is pushed out from 16 finely spaced "buttons" on each pad to provide an image of the electrical conductivity of the formation. The tool is capable of imaging laminae, bedding, cementation in fractures, slumps and other fine-scale stratigraphic information that was previously only available from analyses of core.
Figure 2-11. (A) The natural gamma ray and the fracture porosity logs are displayed at the left. The latter is derived from the difference between deep and shallow penetrating electrical resistivity curves of the dual laterolog. (B) Fracture intensity determined by counting fractures imaged by the FMS. (C) Electrical conductivity due to fracturing is identified from the analysis of FMS images as zones of excess current that the tool must pump into the rock to produce an image. For (B) and (C), each curve represents the data recorded by one pad of the FMS, and both scales are in normalized, dimensionless units.
Dipmeter Determination of Structure and Stratigraphy

The Formation Microscanner also provides the traditional dipmeter information of orientation of bedding and fractures. In the Cajon Pass drillholes, dips were significantly different in two wells only 100 m apart (Figure 2-12). In addition, basement rocks were encountered 170 m deeper in one hole than in the other. These structural and stratigraphic features constrained the geometry such that a previously unknown thrust fault, dipping almost vertically, must be located between the two wells (Figure 2-13). The advantages of stratigraphic interpretation using the dipmeter are so important that it continues to be the most heavily used oil field logging tool in the world. Beginning on Leg 126, the FMS dipmeter will be part of the routine ODP logging suite.

Summary

In conclusion, the ODP logging program allows the measurement of geophysical parameters such as velocity, density, porosity, radioactivity and acoustic attenuation, and geochemical parameters such as elemental mass abundances of Si, Al, Fe, Mg, Ca, K, Ti, S, Gd, U, and Th continuously throughout a logged interval. These data complement core analyses for an enhanced geological interpretation. The Ocean Drilling Program makes logging measurements in holes that are exactly like those made in scores of continental scientific drillholes. The result is a truly global database of in situ measurements in the earth's crust.
Figure 2-12. (A) Dip angle and azimuth from dipmeter data in the Cajon Pass drillhole. The dots represent the dip angle, and the tails point in the down-dip direction. A rose-diagram summarizes the results for dip orientation every 25 m. (B) Dip angle and azimuth from dipmeter log in the adjacent Arkoma oil well. Note dip change even though wells are only 150 m apart. (C) Resistivity data recorded with electrical resistivity logging tools in the Cajon Pass and Arkoma drillholes.
Figure 2-13. Southwest-northeast cross-sections running through the Arkoma and Cajon Pass drillholes. (a) Data from dipmeter logs, and (b) interpretation of the thrust fault running between the two wells. There is no vertical exaggeration in these drawings.
Chapter 3: Ocean Crust, Fluids, and Volcanic Processes

Hole 504B is perhaps the most famous scientific borehole in the world, rivaling the Kola superdeep drillhole of the Soviet Union and the Bertha Rogers drillhole of oil industry lore. Hole 504B has penetrated to the deepest depths in the oceanic crust (1.5 km), as have Kola into the continental crust (14 km), and the Bertha Rogers into a sedimentary basin (10 km). It is important to realize the expenditure of funds already invested into science in Hole 504B - $16 M in rig-time alone - makes it perhaps our best hope for a permanent scientific observatory in the deep oceanic crust. A summary of logging and downhole experiments conducted in the hole during the five legs in which ODP and DSDP have occupied the site is presented below because Hole 504B exemplifies the power of integrated, multidisciplinary, downhole experimentation towards investigation of the oceanic crust.

Geophysical and Geochemical Logging in Hole 504B
(from Becker et al., 1988)

One of the most elusive objectives of JOIDES and ODP is to core as deeply as possible beneath the ocean floor at carefully-selected sites, simply to provide "ground-truth" for our models of the structure and evolution of the oceanic crust. With one notable exception, deep sea drilling to date has penetrated no farther than 0.6 km into the basaltic, upper layer of the ocean crust, which has often proven quite difficult to drill. Since pillow lavas extruded at the mid-ocean ridges and the overlying sediments generally constitute only 1-2 km of a typical 6 to 8 km thick crustal section, the greater part of the oceanic crust has never been directly sampled in situ and in section. Thus, much of our incomplete understanding of the deeper crust must be inferred from remote geophysical and geochemical investigations and from studies of ophiolites (subaerial sections of crust formed in island arc, back-arc, or mid-ocean ridge settings, that have been tectonically emplaced and incompletely represent in situ oceanic crust).

The only borehole that clearly penetrates through the pillow lavas into the underlying sheeted dikes is Hole 504B, which is located under 3460 m of water in Nazca Plate crust that formed 5.9 million years ago at the Costa Rica Rift (Figure 1-1). Here, five legs of DSDP and ODP have cored to a total depth of 1562.3 m beneath the seafloor (mbsf), more than 1200 m of which is into oceanic crust (over twice as deep into oceanic basement as any other hole), and scientists have conducted the most extensive program of logging and downhole measurements of any deep ocean hole. As core recovery has been relatively poor in the hole (< 20%) the remarkably comprehensive logging and downhole measurements have been especially important in resolving the state of the crust at Site 504.

Hole 504B has been logged with a wide range of logs and special experiments designed to continuously assess the downhole variation of several key geophysical and geochemical properties in situ, including temperature, sonic and seismic velocities, electrical resistivity, density, porosity, permeability, the magnetic field, lithology, and the state of stress. These logs and experiments were in many cases calibrated by laboratory measurements of...
physical and chemical properties of recovered basalts, including sonic velocity, density, porosity, electrical and thermal conductivities, and magnetic properties. The logs and experiments conducted in Hole 504B provide a remarkably comprehensive and consistent description of the physical state of the crust at the site.

Many of the logs and experiments in Hole 504B suggest the presence of a 100 to 200m thick geophysical Layer 2A in the porous upper pillow lavas, which is the only permeable interval in the entire cored section. Layer 2B apparently corresponds to the lower section of pillow lavas, which is partially sealed as a result of hydrothermal alteration. Nearly all of the logs show significant changes in situ at the transition zone between 900-1000 mbsf, some 100-200m deeper than a relict fault hypothesized from the results of the magnetic log. This indicates that the transition between pillow lavas and sheeted dikes in Hole 504B corresponds quite closely to that between Layers 2B and 2C.

1. Borehole temperatures and geothermal observations.

During the five legs that worked at Site 504, downhole temperatures were measured thirteen times, including one profile of sediment temperatures in Hole 504C and twelve logs of borehole temperatures in Hole 504B. Of the twelve profiles in Hole 504B, four were measured under equilibrium conditions, when Legs 70, 83, 92, and 111 initially reentered Hole 504B at long time intervals after the drilling on previous legs. These equilibrium temperatures are shown in Figure 3-1, along with the temperatures measured in the sediments at Hole 504C. Hole 504B is easily the hottest hole yet drilled by DSDP or ODP, with an equilibrium bottom-hole temperature of about 165 °C at the present total depth of 1562.3 mbsf.

Temperatures measured in the upper 400m of Hole 504B show the effect of a transient phenomenon that has been active only since the hole was drilled: ever since Hole 504B penetrated through the relatively impermeable sediment layer and into the upper 100m of basement, cold ocean bottom water has flowed down the 276.5m-long casing through the sediments and into the upper section of permeable, porous pillow lavas. This was inferred from depressed temperatures measured in the upper 400m (Figure 3-1) and was confirmed by actually sampling ocean bottom water as deep as 355 mbsf and by measuring pressures in the formation that were lower than hydrostatic (underpressured). The equilibrium gradient in the sediments in Hole 504C provided the essential initial and boundary condition that allowed the rate of downhole flow to be determined from the depressed temperatures in Hole 504B. The results indicate that the rate of downhole flow commenced at about 100m/hr (7000 l/hr) when the hole was first drilled, and decayed to less than 1% of this rate in the seven years between Legs 69 and 111.

The approach of temperatures at about 400m to the undisturbed conductive profile indicates that the downhole flow of bottom water extends no deeper, but instead must be exiting the borehole into the upper 100-125m of pillow lavas. Flow tests using a drillstring packer showed that this section of basement was underpressured by about 1 MPa, so that the ocean bottom water was literally being sucked down the hole and was not circulating hydrothermally. A total of about $10^8$ kg of ocean bottom water has been drawn into this underpressured reservoir; the decay of the downhole flow suggests that the reservoir is of limited lateral extent and/or that the underpressures have been quenched by the total flux of seawater.
Figure 3-1. High-precision temperature logs (above) from several legs over the last ten years are shown for Hole 504B. The drop in temperatures in the upper 400 m of Hole 504B temperatures versus Hole 504C is due to drawdown of ocean bottom water into an underpressured reservoir that is the upper oceanic crustal Layer 2A. The steady increase in temperatures with time in this interval is evidence that the reservoir is being slowly filled to equilibrium. A reservoir model assuming lateral continuity of measured permeabilities produces a prediction of the drop in inflow into the crust that closely matches observed rates, and that predicts future temperatures to be found in the zone. The next test will be in 1991-92.
Similar observations of downhole flow have been made in several other DSDP holes, notably holes penetrating sediment ponds in young Atlantic crust, e.g., Holes 335 and 395A. The results in these holes and in Hole 504B suggest that the upper pillow lavas in sedimentered young oceanic crust may commonly be underpressured. The underpressures in Hole 504B result from hydrothermal circulation in the oceanic crust, which the detailed surface heat flow measurements also require. Models of such circulation beneath an impermeable sedimentary cap rock have been quite successful at simulating the observations of underpressures and downhole flow in Hole 504B.

2. In situ permeability and porosity

Hole 504B is one of only four DSDP/ODP holes (395A, 504B, 735B, and 765B) in which the key property that controls circulation - permeability - has been directly measured in situ. These measurements were made utilizing drillstring packers to isolate various sections of basement and to determine bulk permeabilities of these zones by applying differential fluid pressures. In the upper 100-200 m of the pillows lavas, bulk permeabilities are on the order of 200 millidarcys. In the remaining section, which comprises over one kilometer of sealed pillow lavas and sheeted dikes, bulk permeabilities are orders-of-magnitude lower, on the order of 10 microdarcys (Figure 3-2). The uniformity of the low permeability of the entire lower kilometer penetrated by Hole 504B was unexpected, given that this section spans the transition between pillow lavas and sheeted dikes, but it confirms that the lower 400 m of pillow lavas are truly sealed. The only section penetrated by the hole that is presently permeable to hydrothermal circulation is the upper 100-200 m, which is the zone into which ocean bottom water has flowed since the hole was drilled, and which corresponds closely to seismic Layer 2A.

While permeability is very difficult to measure directly, it is much easier to estimate a related property, the porosity of the formation, from continuous geophysical logs. As the upper oceanic crust is a porous medium, many of the geophysical properties that are logged depend to varying degrees on porosity, e.g. sonic and seismic velocities, electrical conductivity, density. The porosity of the oceanic crust, however, occurs on several scales, ranging from grain-boundary and vesicular porosity seen in cores to large-scale fracture porosity that probably dominates the contribution to permeability but cannot be easily sampled with the drill. Thus, the log-derived porosity values cannot be calibrated against the core, and it is unclear which of the logs yields the most realistic estimates of in situ porosity.

As the electrical conductivity of the crustal pore fluids (which are very nearly seawater) is orders of magnitude greater than that of basalts, logs of electrical resistivity are quite sensitive to the porosity of the crust. Figure 3-2 shows electrical resistivities measured in Hole 504B, and apparent bulk porosities estimated by applying Archie's empirical relationship between resistivity and porosity. Among all the logs run in Hole 504B, the resistivity logs probably show the sharpest change across the transition from pillow lavas to sheeted dikes, with measured resistivities increasing by over an order of magnitude at about 900 mbsf, where greenschist-facies alteration minerals abruptly appear in the core. This is accompanied by a sharp reduction in estimated porosities, which approach 1% in the deepest dikes.

- 3.3 -
Figure 3-2. Geophysical and geochemical logs from ODP Leg 111, Hole 504B. The logs show porous and permeable pillow lavas (at top), grading into nonporous and impermeable sheeted dikes (at bottom). Total and fracture porosity were measured with a Dual-Laterolog electrical resistivity tool; permeability, with flow tests across packed-off intervals; magnetic inclination, from a 3-component, flux-gate magnetometer tool; and mineralogy, from elemental abundances measured by the geochemical logging tool. There is excellent agreement between core and geochemical logging results as can be seen from the blow-up at the right, where smectites (grey), laumontite (white), pyrite (yellow crystals)), and calcite (yellow) minerals can be seen within a mineralized breccia zone indicated on the geochemical log as spikes of chlorite, smectite and pyrite in a matrix of fresh basalt (plagioclase and clinopyroxene).
The contribution of fracture porosity to the total porosity was estimated by applying the same algorithm to resistivities measured with the Dual Laterolog, a medium-spaced log with shallow and deep scales of investigation that are respectively insensitive and sensitive to large fractures. As Figure 3-2 shows, the measured permeabilities correlate much better with the estimated fracture porosities, which are low throughout the lower pillow lavas and sheeted dikes, than with estimated total porosities, which are fairly high in the sealed pillow lavas of Layer 2B. The results of the permeability measurements and the geochemical logs suggest an alternate interpretation of the resistivity-derived apparent bulk porosity in Layer 2B (see below).

3. Magnetic structure of the crust at Hole 504B

Given its depth of penetration, Hole 504B provides key data on the properties of the magnetized layer that produces marine magnetic anomalies, which is often assumed to be on the order of 0.5-1 km thick. Several investigators have studied the magnetic properties of many relatively homogeneous, generally less-altered samples from Hole 504B. A synthesis of the results through Leg 83, emphasizes that the magnetic properties of the basalts are strongly controlled by post-emplacement alteration of the magnetic minerals. Therefore, the magnetic structure of the crust at Hole 504B should not be assumed to apply generally to oceanic crust, which is probably altered to different extents at other sites.

Hole 504B is located within a positive magnetic anomaly caused by reversely-magnetized crust formed about 5.9 Ma ago. As the site is located near the magnetic equator and the cores could not be oriented azimuthally, reversals were impossible to detect in the measurements on recovered samples, but were suggested by analyses of the horizontal components of the magnetic field logged downhole.

In pillow lavas, titanomagnetite formed at low temperature is the main magnetic mineral, and the average natural remanent magnetization is about 5 A/m. This is comparable to values from pillow lavas at other sites and slightly higher than the average values in most models of the marine magnetized layer. In the transition zone, primary titanomagnetite is strongly altered because of high-temperature hydrothermal circulation, and the mean natural remanent magnetization is less than 1 A/m; therefore, the transition zone probably does not contribute to the magnetic source layer. In the sheeted dikes, alteration is generally less extensive, magnetite is the main magnetic mineral, and the natural remanent magnetization is 1-2 A/m. Thus, the sheeted dikes are sufficiently magnetized to significantly contribute to the crustal magnetic field.

The average inclinations of the samples ranged from about -30° in the pillow lavas to about 8° in the dikes, leading to a proposal that the section penetrated by Hole 504B had been rotated about an axis parallel to the ridge axis, with the amount of rotation varying from about 20° in the pillow lavas to near 0° in the dikes (Becker, Sakai, et al., 1988). Such rotations due to extensional processes have been proposed to explain anomalous inclinations at other DSDP sites. However, if the crust at the site is indeed reversely magnetized, then it would have to have been rotated toward the ridge crest in order to produce the observed negative inclinations, contrary to most models for ridge crest processes (Becker, Sakai, et al., 1988).

The suggestion of a rotation of the upper section was strongly confirmed by a three-component magnetometer log conducted during Leg 111, which showed a change in the
logged inclinations at about 800 mbsf within the deeper pillow lava section, from about 15° in the pillow lavas to about 8° in the transition basalts and sheeted dikes below (Figure 3-2). This observation suggests that Hole 504B may intersect a tectonic feature - the relict trace of early dystric faulting within the rift valley - about 100-200 m shallower than the lithologic transition between pillow lavas and sheeted dikes. Such a fault trace may have been the permeable conduit for circulating hydrothermal fluids that strongly altered the magnetic minerals in the transition zone, and produced the heavily mineralized stockwork observed at the base of the pillow lavas.

4. Geochemical logging

During Leg 111, Hole 504B was logged with the geochemical logging tool. The variation in the log-determined geochemistry and mineralogy (Figure 3-2) is a response both to the original chemistry of the phryic and aphyric basalts and to the presence of alteration products such as clays, sulfides in the stockwork zone, and chlorite and actinolite in the dikes. The log results are consistent with the studies of recovered cores (Figure 3-2), but the logs clearly show that the secondary alteration products are tightly confined to fractures (the "spikes" of Figure 3-2) along contacts between relatively unaltered units of fairly homogeneous geochemistry. These contacts were poorly sampled in the recovered core, suggesting that the effects of alteration on the physical and chemical properties of the crust at Hole 504 are greater than was revealed in the core.

The confinement of alteration products to the discrete "breccia zones" confirms that the contacts between units were originally porous and permeable, but have been sealed by deposition of hydrothermal alteration products. The logged abundances of "breccia zones" or alteration products correlate with the apparent bulk or total porosities calculated from measured resistivities, in contrast to the lack of correlation between measured permeabilities and the resistivity-derived porosities (Figures 3-2). This suggests that some of the calculated apparent porosity may represent original porosity that has been filled with electrically conductive alteration products, particularly in the lower pillow alteration zone (Figure 3-3) within Layer 2B. Laboratory and log-derived measurements of Cation Exchange Capacity (CEC) of the clays in Hole 504B verify that the apparent porosity calculated from resistivities in the sealed pillow lavas of Layer 2B is too high. Better correlation exists between measured permeabilities and the true, clay-corrected in situ porosity than was originally thought.

5. Sonic and seismic structure of the crust

The short-wavelength sonic logs showed that the basement penetrated by Hole 504B can be divided into Layers 2A, 2B, and 2C on the basis of gradients in sonic velocity (Figure 3-4); the average sonic velocities in these layers are consistent with typical seismic layer velocities of the crust. The sonic velocity structure in Hole 504B is largely controlled by porosity; Layer 2B has apparently grown upward with time as pore spaces in Layer 2A have been filled with alteration products. Also, the sonic velocities of relatively unporous, homogeneous basalt samples from the dikes of Layer 2C are about 10% higher than similar fresh samples of pillow basalts from Layer 2B.
Figure 3-3. Detailed description of porosity structure off the upper oceanic crust at Hole 504B. Left, resistivity from shallow (LLS) and deep (LLD) penetrating Laterolog electrical resistivity log. The total porosity and fracture porosity are then derived from these curves. However, the total porosity also contains a signal that is from clays, not porosity. The breccia zones indicated by the geochemical log's mineralogy inversion (center) must be corrected for Cation Exchange Capacity (CEC) before reliable total porosity can be determined (right). The porosities measured on core samples agree much better to this curve.
Figure 3-4. Sonic velocities measured by a multichannel sonic log (center), determine the fine-scale features of the crust at Hole 504B. The model at right produces a structural interpretation (left) that agrees with the geophysical and geochemical logs, core results, vertical seismic profile (VSP) of figure 3-5, and the surface seismic profile of figure 3-6.
The velocity-depth function at Site 504 at wavelengths relevant to those used in seismic reflection profiling was measured with a vertical seismic profile (VSP) conducted during Leg 111. VSP interval velocities are generally consistent with the division of the section into Layers 2A, 2B, and 2C based on the sonic logs. More important, the VSP shows several prominent reflectors, some of which can be correlated with lithologic boundaries seen in the recovered core (Figure 3-5), allowing the hole to be fixed in the seismic section (Figure 3-6), and providing essential ground-truth for the interpretation of the regional seismic survey.

Even more exciting for future drilling prospects, there are two prominent reflectors below the present total depth of the hole (E and X on Figure 3-5), which may correspond respectively to the top of Layer 3 and to strong dipping reflectors within Layer 3. The depths to these reflectors are about 150 and 900 m below the present depth of the hole. Thus, it appears that the transition between Layers 2C and 3, presumably the transition between sheeted dikes and gabbros, which has never before been sampled in situ, is in reach of the next drilling leg to Hole 504B.

The longer-wavelength oblique seismic experiments detected a strong, ubiquitous refractions between Layer 2B and 2C about 1 km into basement, but did not detect the thin Layer 2A seen in the sonic logs and VSP. Significant anisotropy was detected in the upper crust immediately surrounding the hole, with velocities lower in the direction of spreading, consistent with a preferential orientation of fractures (sealed and/or unsealed) parallel to the axis of spreading. Strong lateral gradients in velocities, and presumably porosities, are found at scales of 1 km or more, and this variability may be related to the subdued hydrothermal circulation that was mapped by the surface heat flow survey.

Geochemical Fluxes in the Oceanic Crust (from Anderson et al., 1989)

The fluxes of elements into and out of the oceanic crust affect geological processes in a wide variety of locales. The entire volume of the oceans is thought to circulate through the ridge axes in approximately 7 Ma. Chemical exchange with basalt not only significantly alters the crust, but buffers the composition of the oceans. One-half of all the elemental species making up the stable composition of the oceans comes from this hydrothermal exchange, making this source as important to the chemistry of the ocean as river-input. Helium-3 and methane gasses which escape with the hydrothermal fluids provide geochemical tracers which can be used to map the deep circulation patterns of the oceans. 350 °C, superheated hydrothermal fluids exit the ridge axis at "black smokers", providing a view of active metallogenesis, as metal-laden sulfides are deposited directly onto the seafloor. Far off onto the flanks of mid-ocean ridges, cold-water circulation continues to exchange a chemical mass flux between the oceans and the crust. The chemical exchange with sea water produces clays and greenschist metamorphic alteration of the oceanic crust which, when subducted, releases a mass flux into the deep mantle producing volcanism above subducting plates, such as at island arcs.

Yet, we have little quantitative information about the geochemical mass balance between the oceanic crust and the oceans. The black smokers were not discovered until 1977. Mass fluxes out of the black smokers of the East Pacific Rise, Juan de Fuca Ridge, one locale on the Mid-Atlantic Ridge, one place in the Mariana back-arc basin, and the sediment-filled
Figure 3-5. Vertical Seismic Profile at Hole 5048. The many internal reflectors can be directly correlated with the structure from logs and core (right). Layered reflectors are also detected below total depth of the well (left).
Figure 3-6. Surface seismic reflection profiles from the area around Hole 504B. Stacked (above) and migrated (below) sections both show the layered nature of the oceanic crust.
Gulf of California have been reasonably well-documented. But not 1% of the ridge axis has been explored to date, let alone sampled. Only a primitive idea of the mass flux on the ridge flanks is available from two exhalation sites, the Galapagos and Mariana mounds. Chemical anomalies in sediment pore fluid show Mg, Ca, and Cl anomalies that indicate their source to be fluids altered by basalt-sea water exchange, but little time-dependent information is available from these data. Ophiolites offer an integrated view of the sum of all hydrothermal processes that have previously affected that sea floor, unfortunately including an overprinting of alteration accompanying emplacement onto land.

Additional information about the variability and evolution of the geochemical mass flux between the oceanic crust and sea-water can be gained from measurements made inside the oceanic crust. Hole 504B is the deepest penetration yet into the oceanic crust, and as such, it is the first reference section of oceanic lithosphere for comparison to geochemical mass balance models based upon laboratory experiments, surface sampling, and ophiolite models. However, the core recovery in Hole 504B was less than 20% of the drilled section. Geochemical logs of Hole 504B allow us to quantitatively determine the integrated, geochemical mass exchange that has occurred between the oceanic crust and sea-water over the 5.9 Ma history of the rock column (including that missed by the core).

There is widespread evidence at Hole 504B for extensive hydrothermal alteration of basalts from at least three different fluids. At the ridge axis, a high temperature, "black smoker-type" fluid interaction with cold, downward flowing sea-water resulted in the deposition of the "stockwork" mineralization zone found in the transition between pillow basalts and dikes. A subsequent low temperature ridge flank event deposited zeolites and clays throughout the pillow basalts, and particularly in Layer 2A. Metamorphism to a greenschist facies mineral suite has subsequently occurred in the transition zone and dikes.

Of importance is the total cation exchange between basalt and sea-water that occurred during these three alteration events. The geochemical logs allow us to characterize the changes in elemental abundances between the freshest and deepest dikes basalts and the shallower, more heavily altered rocks.

The geochemical log-derived, dry weight percent oxide variations of major elements over the depth interval of Hole 504B can be estimated by smoothing the geochemical, log-derived elemental abundances, then normalizing each to the composition of the freshest basalt present in the dikes at the very bottom of the hole (Figure 3-7). Significant horizontal fluxes may enter or exit the column, and as such would be seen as abrupt changes in the gradients of elemental fluxes. The assumption of a beginning composition for fresh basalt becomes critical, therefore, because a change in compositional abundances of fresh basalt with depth would introduce large errors into the vertical flux calculation. Fortunately, the composition of fresh basalt within Hole 504B remains remarkably constant (with the exception of a few thin flows of Fe-Ti enriched basalts).

To quantify the geochemical mass flux in Hole 504B, we must calculate the total mass of each element that has been moved by estimating the integrated change in composition of each element from the fresh basalt composition (Figure 3-8). There is little Al change throughout the well, but Si, Ca, Mg and Fe all show significant mass fluxes. Ti concentration appears to accompany that of Fe, as might be expected from laboratory experiments of basalt-sea water interaction. Si increases from the bottom of the hole to 4300 m, then decreases to the surface. Quartz precipitation upon cooling of an upward
Figure 3-7. Smoothed major element oxide concentrations from geochemical logs at Hole 504B, normalized to the mean composition of the freshest basalt found in the dikes at the bottom of the hole. Shading is enrichment, white is depletion relative to the freshest basalt standard (vertical lines).
Figure 3-8. Total geochemical mass flux in Hole 504B calculated by integrating geochemical logging curves of figure 3-7 from bottom to top of the well. These fluxes are the predicted total elemental exchanges that have occurred to date over the 5.9 Ma "lifetime" of this ocean crust.
moving hydrothermal fluid would account for such an increase in Si content. Abundant quartz was found filling fractures in this section of the hole.

Mg increase and Ca decrease is caused by exchange of cations during reaction of hot sea water and basalt. The recovered clays, chlorite, other alteration products, and pore fluids from the borehole prove that such reactions have occurred in Hole 504B. The integrated geochemical mass flux (F) quantifies the elemental fluxes involved in these reactions throughout the hole to the present day. In quantitative terms, 76.5 gm of Si, and 164.3 gm of Mg per square cm have been added to the oceanic crust of Hole 504B over a column the height of Hole 504B. Correspondingly, 178.6 gm of Ca and 211.6 gm of Fe have been lost to the oceans from the same volume.

The mass fluxes, F, as percentages of the total mass of each element available in the freshest dike basalt, F, are shown in Figure 3-9. The geochemical mass flux analysis suggests that Al has not moved substantially Si appears large in relative terms, but not in absolute terms because of the large number of Si cations available in basaltic rocks. K, as well as Ti, fluxes become important when viewed in percentage terms. It appears that almost 10 percent of the K is missing from Layer 2C, whereas almost 20% more K than that in fresh basalt resides in Layer 2A. Addition of K from both Layers 2B and 2C and cold sea water is therefore required in Layer 2A. Ti appears to have been lost during low temperature alteration - a surprise.

Thus, the chemical exchange between the oceans and the crust could be quantified if enough geochemical logs are obtained through a diverse suite of crustal drillholes. This is a long-term, thematic goal of the ODP Lithosphere Panel.

Gabbros of the Oceanic Crust (from Goldberg, 1988; Robinson et al., 1989)

Our knowledge of the composition and structure of the oceanic crust was increased significantly by logs from Hole 735, drilled on ODP Leg 118 into the Atlantis Fracture Zone on the Southwest Indian Ridge (Figure 3-10). While most of the hole penetrated relatively fresh gabbro for the first time in ODP, the geophysical logs clearly indicate a very high density zone filled with high neutron capture-cross-section elements (explained presently) located about 250m into the section (Figure 3-10). Photoelectric effect (Pe) and capture cross section (Σ) respond to the matrix mineralogy and to the presence of high neutron absorbers respectively. The geochemical logs show that elements responsible for the Pe and Σ anomalies are Fe and Ti (Figure 3-11). The cores from this interval also show enriched Fe and Ti, but the geochemical logs detail the variation, or layered structure of the Fe and Ti-rich zone much more completely (Figure 3-11). Depletion of Si, Al, and Ca accompanies the enrichment of Ti and Fe in this mafic intrusion zone.

The geochemical logs give an even more dramatic view of the processes that accompanied intrusion of this Fe-Ti-rich zone within the axial magma chamber that eventually froze to form this segment of crustal layer 3 (Figure 3-12). Below the Fe-Ti rich zone is a high gadolinium, high Thorium interval that likely represents a pathway for very high temperature fluids. Borehole packer tests and temperature log anomalies support this conclusion. Th is mobile only at 400 °C and higher. The heavy rare earth element Gd is not
Figure 3-9. The ratio of the total mass flux (figure 3-8) to the total mass of each cation available in the fresh basalt at Hole 504B gives a clear idea of the relative exchange that has occurred between basalt and sea water over the "lifetime" of the crust. Note the major exchange of potassium that has occurred both between the dikes (depletion) and the pillows (more enrichment from sea water than that delivered from below by hydrothermal fluids). The loss of Ti was unexpected. The exchanges of the other cations are predicted by laboratory experiments.
Figure 3-10. Geophysical logs from ODP Leg 118, Hole 735 drilled into gabbros of the Atlantis Fracture Zone. The density, photoelectric capture spectrum, and total capture cross-section (sigma) logs show clear indications of a titanium-rich fault zone or intrusion midway into the well.
Figure 3-11. Geochemical log-derived elemental concentrations calibrate well with laboratory analyses of core sample chemistry. The Ti-rich zone is defined more clearly by the logs than by the core analyses. Interlayering has produced the variability seen in the core results.
Figure 3-12. Details of the geochemical logs in the Ti-rich zone show that a thorium and gadolinium enriched interval forms the lower boundary of the Ti and Fe enriched interval. Pyrite mineralization within fractures are identified by sulfur spikes. The Borehole Televiewer ultrasonic image of one of these fractures is shown in Figure 3-13.
supposed to be mobile at all, indicating that this interval may contain a trondhjemite, or very late stage fractionate. Abundant Si supports this conclusion.

The sulfur curve locates pyrite rich veins that appear as distinct fractures on the ultrasonic borehole televiewer image of the wellbore (compare Figures 3-12 and 3-13). The geophysical and geochemical logs can not only locate fractures, but determine the chemistry of any fracture-filling alteration products.

Hot Spot Volcanic Cycles (from Pierce, Weissel et al., 1989)

Geochemical logs allow us to characterize variations in hot spot volcanics, as well as estimate their compositions. Consider the Hole 715 drilled during ODP Leg 115 on the Chagos-Laccadive Ridge, an island trail from the Mauritius hot spot that connects northward to the Deccan Traps of India (Figure 1-3). The basaltic basement of the Chagos-Laccadive Ridge is layered between what appears to be normal Mid-Ocean Ridge Basalt (MORB) and a Fe-Ti rich basalt that is not as heavily fractionated as the Leg 118 Fe-rich gabbros (Figure 3-14). The Gd curve clearly distinguishes the Rare Earth enriched hot spot Fe-Ti basalts from the depleted MORBs.

The sequence of eruptive activity for a hot spot is unknown because few drillholes such as Hole 715 exist. Do hot spots deliver a constant magma flux to the surface, or are we seeing magma blobs that periodically produce hot spot volcanism? An alternative way to determine the eruptive history of a hot spot is to record the variations in the abundance of volcanic ash on the sea floor surrounding a hot spot. ODP Legs 119 and 120 drilled several holes near the Kerguelen hot spot in the southeastern Indian Ocean (Figure 1-3). The volcanic platforms of Kerguelen, Broken Ridge and the Ninety-East Ridge were built up from Cretaceous time by volcanic activity of the hot spot.

The cyclicity of that eruptive history is shown by examining the volcanic ash layers from Sites 747, south of the hot spot, and 754 to the east (Figure 3-15). Core recovery in Hole 754 was too sparse to delineate any periodicity at all (Figure 3-16), except that there was a steady decrease in the total amount of ash as the site moved north away from the hot spot during the Tertiary. In contrast, the geochemical logs determine at least five major zones of abundant ash content, separated by quiescent zones (Figure 3-17).

A more precise tag between the volcanic ash cycles and Kerguelen comes from the Th/U ratio of the ashes. Basaltic sources typically have Th/U ratios of 4 to 6 whereas pelagic sediments have ratios of 1 or lower (Figure 3-18). The variation of the Th/U ratio logged at Sites 747 and 752 measured by the geochemical log shows a cyclical eruption history that can be dated using sedimentation rates determined from the cores (Figure 3-19). The cyclicity south of Kerguelen found in sediments deposited 70-90 ma has a periodicity of about every 2 Ma, whereas the period of volcanic ash occurrences in Hole 752B is shorter, at about every 640 Ka. The explanation for the discrepancy in period between the two wells may come from the position of each hole relative to the direction of prevailing winds then (Figure 3-15). Because Hole 752B was directly down wind from the hot spot, it received ashes from most eruptions. However, Hole 747A which is to the south of the hot spot, may have received only ashes from the largest eruptions.

The logging program thus provides evidence of temporal variations in hot spot volcanism that are only possible from continuous data. For example, magnetic
Figure 3-13. Amplitude and travel time images from the ultrasonic Borehole Televiewer display the fracture filled with pyrite that caused the spike of Sulfur in the geochemical log (figure 3-12). The images are of the cylindrical hole "unwrapped", with North at the left and right edges and the degrees displayed along the horizontal axes.
Figure 3-14. Mineralogy model of Hole 715 derived from elemental abundances measured by the geochemical logging tool. U, Th and Gd abundances in ppm are displayed at left. The reef from 7890 to 8150 feet depth is predominantly carbonate. The Sulfur content is associated with seladonite. The basalts of the Chagos-Laccadive Ridge basement are an alternating sequence of depleted MORBs and HREE enriched, Fe-Ti rich hot spot plume basalts.
Figure 3-15. A reconstruction of Broken Ridge back into place in the Kerguelen Plateau in Cretaceous time places the site of Hole 752 downwind from the likely prevailing paleowind direction then. Hole 747 was orthogonal to the wind direction, so presumably, a great eruption of the hot spot would be required to deliver volcanic ashes to this site. The spreading directions of old and new Southeast Indian Ridge spreading centers are also shown. The Ninetyeast Ridge is a hot spot trail away from Kerguelen.
Figure 3-16. The change over time of the amount of volcanic ash in Hole 754 estimated from recovered core. The general decrease in younger sediments is from the northward drift of Broken Ridge away from the Kerguelen hot spot after rifting by the Southeast Indian Ridge.
Figure 3-17. Mineralogy model of Hole 754 derived from elemental abundances measured by the geochemical logs. Note the cyclic nature of the variation in abundance of volcanic clays, compared to that observed in core (figure 3-16).
Figure 3-18. The Th/U ratio of basalts, andesites, and even high silica rhyolites averages 4:1, whereas that of pelagic sediments is < 1:1. The x's show that even leached volcanic ashes from the moats of volcanic islands like Hawaii maintain this high Th/U ratio.
Figure 3.19. K, Th, U and Th/U variations with depth recorded in Holes 752 and 747 by the geochemical logs. The volcanic ash units are distinguished by their high Th/U ratio as expected (figure 3.18). Note that whereas the K is enriched near the K-T boundary, the Th/U is not unusually high compared to other eruptive cycles. The high K is from the deposition of deep-sea clays when carbonate sedimentation was interrupted by the extinction event. The cyclical eruptive history of the Kerguelen hot spot appears to be independent of the extinction event. The shorter period of eruptions at Hole 752 versus that at Hole 747 is thought to be because of the more favorable placement of the former downwind from the hot spot. Only the largest eruptions deposited extensive ashes to the south.
susceptibility measured on cores also distinguishes ash flows because of their higher susceptibility, but the core record is not complete enough to define the pattern of cyclicity with anything like the accuracy of the log data (Figure 3-20).

State-of-Stress in the Lithosphere (from Pierce, Weissel et al., 1988)

Basement logs record another unique piece of geophysical data that is one of the main focal points of the COSOD II report: the state of tectonic stress in the oceanic lithosphere. Worldwide, the forces that drive plate tectonics work in a very systematic way (Figure 3-21). Where they have been mapped well, such as on the North American continent, the maximum compressive stresses are regionally consistent; in this case, generally northeast-southwest oriented. Before we can determine the forces responsible for such uniform stresses, we must map stress directions throughout several plates. However, plates are under the ocean, so the ODP must have some mechanism for mapping the distribution of tectonic stresses within and across plates, or we will never fully understand the driving mechanism for plate tectonics; or its corollary, how these forces interact across plate boundaries.

The determination of stress orientation in a borehole depends upon our ability to image the borehole wall, because basement rock fails under differential stresses that are relieved when the hole is drilled (Figure 3-22). Such borehole "breakouts" determine the direction of least compressive stress, which is perpendicular to the compressive stress direction.

Site 758 (ODP Leg 121), on the northern Ninety-East Ridge in the Indian Ocean (Figure 1-3) provides an excellent example of the usefulness of the measurement of borehole breakouts for the testing of tectonic models that predict the magnitudes and directions of the forces that push and pull plates across the earth's surface. The prediction of stress orientation in the vicinity of Site 758 from one such model is for compression in the NNW-SSE direction (Figure 3-23). Breakouts imaged in the basalt of Site 758 by the borehole televiwer show minimum compression in the east-west direction, an observation that verifies the prediction of the model that maximum horizontal compressive stress should be oriented N - S (Figure 3-24).

Summary

The study of the chemical and physical variations associated with construction and alteration of the oceanic lithosphere is not possible without logs and other in situ downhole experiments carried out in the ocean crust. In the future, long-term observatories will be established to continuously monitor active processes in the crust. We will probably look back at the expensive drillship trips back to such Holes as 504B, 395A and 418A as only the crude beginnings of our exploration effort to establish laboratories of the ocean floor. The technological advances necessary to construct such permanent observatories are in place. Only the will to proceed remains to be found. COSOD II clearly demonstrates that the future is fast approaching for direct, long-term observation of the oceanic crust.
Figure 3-20. The cyclical nature of volcanic ash deposition in Hole 752 is also indicated by the magnetic susceptibility measurements made on core, but gaps in the recovery cause several ash layers to be missed completely. Compare the continuous record from the Th/U log to the discontinuous susceptibility measurements. A borehole magnetic susceptibility log would make an excellent tool for the recording of volcanic ash sequences.
Figure 3-21. The world stress map contains estimates of the direction of maximum compressional stress within the plates derived from earthquake focal mechanisms, borehole breakouts, hydraulic fracture measurements, and contemporary surface folding. Huge gaps exist in Asia and on all oceanic plates.
Figure 3-22. Borehole breakouts are failures of the wall rock from wellbore caused by the local concentration of hoop stresses driven by tectonic stresses. Breakouts are found perpendicular to induced hydraulic fractures, as seen in this image of both in the Cajon Pass well, because the breakouts are oriented in the direction of minimum horizontal compressive stress, and hydraulic fractures propagate in the direction of maximum compressive stress.
Figure 3-23. A model for the driving forces responsible for the northward migration of the Indian Plate predicts maximum horizontal compressive stresses west of Indonesia to be oriented NNW-SSE. Hole 758 is located in sea floor predicted to have the largest differential horizontal stresses in the Indian Plate, and so should be an excellent place to look for breakouts to test the predictions of the driving-force model.
Figure 3-24. Borehole televiwer records from basement in Hole 758 locate breakouts on the east and west walls of the wellbore, indicating the maximum horizontal compressive stress direction to be N-S. The non-cylindrical image of the borehole is from eccentrcialization of the tool, which can be easily corrected for by forcing the image to become a cylinder. This correction will not affect the orientation of the breakouts in the general direction predicted by the driving-force model.
Chapter 4: Global Environmental Changes

A major new understanding of global climatic oscillations responding to the earth's own orbital perturbations provides the theoretical foundation that allows us to project present day phenomena into the geological past. Below, we begin with an understanding of how Milankovitch climate cycles produce geological change. Wireline logs that continuously record the sea floor's reaction to orbital cycles provide the pathway to discovery of past climates. From Milankovitch, we progress to glaciation, sea level change, and the extinction of the dinosaurs. Not only will we find climatic information in logs, but we will discover that an understanding of the geological mechanism responsible for cycles allows us to derive information about the age of rock from logs. Once we have understood the cause-and-effect between orbital perturbations and sediments, we can count cycles to refine sedimentation rates, place cores in their proper stratigraphic place, and ultimately, derive a climatic cycle-stratigraphy. The "Vail" coastal onlap curves are likely to be looked on in the future as our first attempt at such an understanding of the effect of climate on the stratigraphic record.

Milankovitch Climate Cycles and Wireline Logs (from Jarrard and Arthur, 1989)

Changes in the earth's orbital parameters are now recognized as an important cause of cyclical variations in global and regional climate. The periods of eccentricity (95,000-123,000 and 413,000 years), obliquity (41,000 years), and precession (19,000-23,000 years) have been observed in a variety of sedimentary sequences. These "Milankovitch periods" most often have been detected in Pleistocene deep sea sediments because of the available combination of both very strong glacial/interglacial climatic fluctuations and high-resolution dating of cores. The climatic effect of these cycles is not limited to the Pleistocene; they have been detected in Cretaceous chalk/shale sequences and Triassic lacustrine sediments as well (Arthur et al., 1984; Fischer, 1986; Fischer and Schwarzacher, 1984; and Olsen, 1986).

Chemical "tracers" such as variations in calcium carbonate concentration and oxygen isotopes, which are indicators of paleoproductivity, paleotemperature, and ice volume, are the parameters most frequently used for the study of Milankovitch cycles in pelagic deep sea sediments. More generally, the sedimentary response to the Milankovitch forcing function should vary regionally, depending on the type of paleoclimatic signal impressed on the sediments. Aridity/humidity cycles, for example, may cause detectable fluctuations in clay mineralogy or abundance in one region, while cycles of upwelling or surface temperature change may cause fluctuations in the biogenous component to be the dominant sedimentary response in another region. Thus, a comprehensive analysis of Milankovitch cycles in any sedimentary column requires determination throughout the sequence of the mineralogical abundances, and either porosity or grain size (Table 4-1).
Table 4-1. The sequence of cause-and-effect between Milankovitch orbital parameter changes and log responses. Changes in eccentricity, obliquity, and precession cause changes in the amount of the Sun's energy to hit the planet. This, in turn, causes cycles in aridity/humidity, wind and ocean current patterns, and sea-surface temperatures. These changes cause cycles of clay type and abundance, grain size, mineralogy, and composition and abundance of organisms that die to form deep sea sediments. The logs respond differently to several of these changes producing a complex interaction of geophysical and geochemical responses to climate change.
Wireline logs as well as core data can be used to detect periodic changes in mineralogy or porosity associated with orbital changes. Both physical properties (e.g., velocity, porosity, resistivity) and major element geochemistry can be used to detect such changes. Furthermore, continuous measurements are made every 15 cm down the borehole and most logging tools have a vertical resolution of about 50 cm so that no gaps exist in the recorded interval.

For detection of Milankovitch frequencies, wireline logs have three principal advantages over core analyses. First, the wide variety of geochemical and physical properties measured at each depth interval makes it likely that almost any significant periodic change in mineralogy or porosity will be detectable. Second, logging is much faster than laboratory analyses of a comparable number of discrete core samples. Third, the continuous logging measurements are independent of core recovery. The change from using a hydraulic piston corer to using either an extended core barrel or rotary corer results in a decrease in average ODP core recovery from 99% in the upper 150 m of the sediment column to 50-60% below 200 m. Also, this uneven core recovery includes both disturbed and undisturbed sediments with substantial uncertainty existing in the original depths of the undisturbed material.

For detection of Milankovitch frequencies, wireline logs share some of the same limitations as cores and have two unique, potential disadvantages. Both cores and logs require very good age control for accurate conversion from frequencies-in-depth to frequencies-in-time. They also both suffer from a limit due to spatial resolution. This is much more pronounced for logs, however, and temporal cycles which, for a given sedimentation rate, produce spatial cycles below the resolution limit of the tool will not be detected. Cycles in either cores or logs can sometimes be caused by local sedimentary processes rather than by regional climatic change. An example is turbidites, with a spatial-frequency that depends on source supply and source distance, and with a temporal-frequency that bears only a very indirect relation to climate. Additionally, logs obtained on ODP conceivably could contain a frequency that is an artifact of ship heave, in spite of the use of a wireline heave compensator. (In practice, logs obtained at different times show a close character match, indicating that residual ship heave is minor). Finally, the conversion from log response to mineralogy is not unique and requires some knowledge from cores of what minerals are present.

1. An example of Milankovitch climate cycles: ODP Site 645

ODP Site 645 was drilled in the west-central Baffin Bay, between Greenland and Canada during Leg 105. A 1147 m thick sequence of silty clays and clayey silts that were deposited during the last 24 m.y. make up the sedimentary section in this well. The sedimentary intervals corresponding to 1.3-1.7 and 2.1-3.3 Ma were logged with sonic, resistivity, and gamma ray tools. The strong similarity in character between sonic and resistivity logs (Figure 4-1) indicates that velocity variations are controlled by porosity variations. A strong cyclicity in the velocity log is present throughout the logged interval. The cycles lack the saw-tooth pattern characteristic of turbidites (gradually upward decreasing velocity and resistivity followed by abrupt, sharp rises). This observation confirms the core analysis that few turbidites are present. Possibly because porosity variations in cores are difficult to recognize visually, the cycles recognized from the logs
Logs can be used to determine variations in geological response to climate cycles over time.

Figure 4-1. The Fourier transformation from logs versus depth or calibrated to time produces amplitude spectra that have power peaks at periods of Milankovitch orbital variations. In these cases from Holes 646 and 645, porosity changes from bottom current changes correlate with the long wavelength periods of the Milankovitch climate cycles. The logs do not resolve the finer scale variations at these sedimentation rates. Each log has a distinctive resolution, with the Formation Microscanner dipmeter able to decipher mm changes, and the dual laterolog electrical resistivity tool only m changes, as the two extremes.
were not detected by shipboard core descriptions. However, an approximately 1-2 meter cyclicity in color banding was noted.

The logged interval is almost barren of microfossils, but the combination of sparse micropaleontological control and detailed magnetic reversal stratigraphy allows for rather good age control for this interval. Using the derived age/depth curve, the logs were converted from depth to age (Figure 4-1).

Fourier transformation to amplitude spectra permit a detailed examination of the frequency content of the logs. The spectra for five age windows of the sonic and resistivity logs from Site 645 are shown in Figure 4-1. Note that the natural logarithm of resistivity is used rather than raw resistivity because resistivity is logarithmically related to porosity. It is apparent that the same general frequencies are present in all age windows, although the relative magnitudes change through time. For example, from 2.1 to 2.5 Ma the dominant period of resistivity variations appears to be about 100,000 years (eccentricity), whereas from 2.65 to 3.3 Ma a much higher frequency of about 20,000 years (precession) is apparent. Peaks are evident at the 41,000 year obliquity period and 19,000-23,000 year precession period with gradual trends of increasing precession energy and decreasing obliquity energy with increasing age. Slight errors in the assumption of constant sedimentation rate are suggested by small systematic shifts of all observed peaks with respect to predicted peaks within a spectrum. For the 2.8-3.1 Ma interval, observed peaks are centered about 10% left of predicted peaks, suggesting that the sedimentation rate is about 150 m/m.y. rather than 135 m/m.y. A similar shift to the right in the interval 2.1-2.3 Ma suggests a sedimentation rate of about 120 m/m.y. In the interval 2.8-3.1 Ma, the portion of the amplitude spectrum tentatively correlated with precession may permit the resolution of both the 19,000 and 23,000 year precession periods. Thus, the logs can be used to refine the age-dating available from the core. But what is it the climate change that produces the cyclical porosity variation?

Fluctuations in bottom current activity are probably responsible for the cyclical variations in sonic and resistivity log responses at Site 645. These two porosity-sensitive logs are correlated with gamma-ray fluctuations in that increasing clay content is associated with higher sonic traveltime (lower velocity) and lower resistivity. During periods of decreased contour current intensity, more fine-grained clay minerals were deposited at this site. The geological reasons for the changes with time in predominant orbital control of sedimentation among eccentricity, obliquity, and precession are not so apparent! Yet we must understand cause and effect in the past if we are to predict such in the future.

2. A further example: ODP Site 646

ODP Site 646 from Leg 105 is located in the Labrador Sea on the Eirik Ridge about 300 km southwest of the southern tip of Greenland. A 767 m interval of visually monotonous silty clays and clayey silts was penetrated. The sediments represent approximately the last 8.5 Ma with an average sedimentation rate of about 90 m/m.y. On seismic sections, the Eirik Ridge is interpreted to be formed of drift deposits, with local sediment accumulation rates affected by bottom current activity. The onset of ice rafting at Site 646 occurs at 236 m, or about 2.5 Ma, based on the first occurrence of significant quantities of dropstones in the cores.
The entire drilled interval (0-750 m) was logged with the neutron, spectral gamma ray, and gamma spectroscopy tools. The openhole interval below pipe (206-737 m) was also logged with the sonic, gamma ray, and resistivity tools. A porosity log was calculated from resistivity using Archie's equation (Figure 4-1). This rescaling of the log does not affect visible cyclicity or amplitude spectra. As at Site 645, the sonic and transformed resistivity logs show very similar small-scale character because both logs are primarily controlled by porosity. The sudden porosity increase at 340 mbsf is caused by the first occurrence of siliceous microfossils and is accompanied by a change in mineralogy from 65% clay minerals and 20% quartz, to 45% clay and 45% quartz.

In the upper interval of Site 646, a strong amplitude peak occurs at a frequency of 9-11 cycles/78m, with a much smaller peak at 19-20 cycles/78m. Assuming a sedimentation rate of 95 m/m.y., the major peak has a temporal period of 85-100,000 years (eccentricity) and the secondary peak has a period of 38,000-45,000 years (obliquity). The amplitude spectrum in the lower interval is similar in character but shifted by approximately a factor of two in frequency, as expected for a constant temporal frequency but 50% reduction of the calculated sedimentation rate from core data. Again, the dominant period is about 100,000 years, but here the 41,000-year period is evident only on the sonic spectrum.

The simplest explanation of the velocity and porosity amplitude spectra of Figure 4-1 is that the patterns result from orbital variations with Milankovitch periods modulated by the vertical resolutions of the various logging tools. The sampling interval for all logs is 15 cm, but the vertical resolution is very different, 0.6 m for the sonic tool and about 1 m for the resistivity tool. These resolutions correspond to minimum temporal resolutions of 12,000 and 20,000 years at the 95 m/m.y. sedimentation rate in the upper interval, and 30,000 and 50,000 years for the lower sedimentation rate in the lower interval of Site 646. The 100,000 year eccentricity cycle should be readily resolvable in both intervals if present in the sediments; this temporal period is the strongest period in each interval. The 41,000 year obliquity period should be readily detectable in the upper interval, but in the lower interval it should be barely detectable on the sonic and probably undetectable on the resistivity-porosity logs. This is exactly the pattern seen in the amplitude spectra. The 19,000-23,000 year precession period, if present, should be detectable only by the sonic in the upper interval. It is not seen by either log from either interval. Peaks on amplitude spectra are increasingly smeared at higher frequencies by slight sedimentation rate variations.

The logging data suggest that fluctuations in clay content cause the cyclical porosity variations in the logged interval of both sites 645 and 646. The simplest explanation for this condition is that porosity fluctuations are caused by changes in strength of bottom currents. During times of weaker currents fine-grained clay minerals and nannoplankton can accumulate, and relatively small amounts of coarser-grained quartz and feldspar are carried to the site; consequently porosity is high. During times of stronger currents, the current intensity retards deposition of clay and nannoplankton; relatively more quartz and feldspar are deposited. However, the log data cannot determine whether the stronger currents cause an absolute increase in the accumulation rate of the coarser-grained minerals. The ultimate causes of the sedimentological cycles are that bottom currents change as climatic warming and cooling occurs at the surface of the oceans. Upwelling zones move in latitude and bottom currents change correspondingly.
Milankovitch Climate Cycles in Geochemical Logs from the South Atlantic
(from Mwenifumbo et al., 1988)

Geochemical logs provide a direct measurement of the changes in mineralogy accompanying the earth's response to Milankovitch climate cycles. On ODP Leg 114, Hole 704 was drilled into the Meteor Rise in the southern Atlantic Ocean (Figure 4-2). Calcium and silica measurements from the geochemical logging tool reflect changes in carbonate versus siliceous sedimentation as diatom content in the sediments varied with upwelling. Hotter climates pushed the upwelling zone to the south, while colder climates moved the diatom source to the north. The cyclical variation in calcium content is clearly out-of-phase with both silica and hydrogen, which are in phase (Figure 4-2), indicating that diatom-rich sediments are characterized by higher porosity than diatom-poor sediments.

Amplitude spectra for a moving depth window of 100 m, stepped every 50 m, show predominant energies at 3 and 5 m wavelengths (Figure 4-3). At the appropriate sedimentation rates determined from core, these cycles are at 44,000 years (obliquity) and 77,000 years (eccentricity). The suspected eccentricity period is less than the observed 95,000-110,000 year range for eccentricity, possibly indicating that the sedimentation rate determined from sporadic core recovery is too high by about 10%.

Climatic Cycles Back into the Past - A 31 Ma Example from the Weddell Sea (from Golovchenko et al., 1990)

The great promise of data from wireline logs for the determination of past climate change comes from their ability to produce continuous data regardless of the age of the sediment drilled through. In ODP holes core recovery drops dramatically with both age and depth.

On ODP Leg 113, Hole 693 was drilled into 31 Ma sediments on the Antarctic continental margin (Figure 4-4). Amplitude spectra of gamma ray, resistivity and sonic logs suggest a change in orbital drives when compared with predominant peaks in recent sediments (previous examples). The 41,000 year obliquity peak is much more prominent than the eccentricity peak at 95,000 years; this is a reversal from that in more recent sediments. Although a much more complete study of such differences is obviously required, the logging data clearly contain a vast wealth of information related to possible temporal and regional changes in the relative importance of orbital variations through geologic time.

Glaciation and its Effects on Wireline Logs (from Ollier et al., 1988)

Perhaps the most dramatic effect of global climate change in the recent geological past has been the rapid expansion and retreat of the great ice sheets. The timing and earliest onset of glaciation in the southern hemisphere was a major thematic goal of ODP Legs 113,
Climate changes produce cyclic alternation of Calcium and Silica-rich layers

LEG 114 : Site 704
Meteor Rise

Figure 4-2. Geochemical logs measure variations in Ca and Si that are out of phase because the Milankovitch climatic cycles have produced a latitudinal movement of the upwelling current that resided above this site in the recent past. Diatoms rich in Si were deposited when the upwelling current was above the site, and Ca shelled foraminifera were abundant when the upwelling zone moved away from the site. The porosity of the sediment, (seen from the abundance of H), is high when the diatomaceous Si-rich sediments were deposited, and low when the carbonate predominated.
Climate changes produce cyclic alteration of Calcium and Silica-rich layers

LEG 114 : Site 704
Meteor Rise

Figure 4-3. A 100 m wide moving amplitude spectrum was calculated at 2.4 m intervals of the Ca curve from figure 4-2. The predominant wavelengths of high Ca-content are at 3 and 5 m. Dating of recovered core place these periods at 44,000 and 77,000 years. The likelihood that these cycles are caused by Milankovitch climate cycles allows us to determine that the core-derived sedimentation rates are somewhat low, by about 10%. The fine scale variation in sedimentation rate can be seen from the variation in period of the predominant power peaks over this 50 m interval. The geochemical logs are being used to AGE-DATE the sediments for the first time.
Climatic cycles identified from logs

LEG 113 : Site 693
Weddell Sea

Figure 4-4. Logs provide a continuous record of sediment variations in a well. As long as unconformities are not crossed, it should be possible to map the relative interactions of the three Milankovitch orbital drives with the climate of the Earth long into its geological past. In amplitude spectra from 100 to 250 m into Hole 693 in the Weddell Sea, we can see that the sedimentary response to obliquity produces a steadily decreasing change in clay-content (gamma-ray log), and porosity (resistivity log), whereas the eccentricity change produced a steady increase in response of clay-content and porosity. We must understand why such changes occur in the response of the climate to external drives before we can have complete confidence in our predictive abilities to deal with man-made perturbations.
119 and 120. The effects of glacial advance and retreat can be readily seen from logs in Holes 739 and 742, drilled in Prydz Bay, Antarctica, during Leg 119. Here, a steeply dipping set of seismic reflectors has been truncated by advancing ice, forming an angular unconformity.

Geophysical logs show a sequence of high porosity, low porosity, high porosity layers, within the dipping reflectors which are present beneath about 175 mbsf in both wells (Figure 4-5). The occurrence of low porosities (<10%) within 100 m of the sea floor is an indicator of overcompacted sediments. For example, the North Sea is floored by such low porosity sediments as a result of erosion by ice. The sequence of tilting, ice erosion and retreat, deposition of unit 2, ice advance, and finally, ice retreat is indicated by the logs.

The hydraulics of this loading event are interesting, because though unit 2 is severely overcompacted in both wells, the dipping reflector unit 3 is not. The compaction of one layer sitting on top of an uncompacted layer requires that part of the weight of the overburden be supportable by fluid pressures in the uncompacted interval. Very low permeability is therefore required to prevent the squeezing out of the pore fluids in the dipping reflectors. In turn, high permeabilities must have allowed the pore fluids from unit 2 to be squeezed horizontally away from the ice load (Figure 4-5).

Sea Level Changes

Variations in sea level in the geological past have been inferred from transgressions and regressions recorded in sediments deposited on continental margins (Figure 4-6). These sea level changes are attributable to a variety of mechanisms including climatic changes or volume changes of the ocean basins caused by worldwide acceleration or deceleration of mid-ocean ridge spreading rates. The variation in sea level produces noticeable logging responses regardless of the driving force involved.

Consider for example the sea level record from an Eocene carbonate reef drilled at Hole 715 on the Chagos-Laccadive Ridge of the Indian Ocean (Figure 1-3) during ODP Leg 115. Geochemical logs show the reef to be composed of over 80% carbonate, but variations in sulfur composition also reflect changes in depositional environment as the reef grew (Figure 4-7). These changes affected the abundances of evaporites in the reef although none of the 5% of the section that was successfully cored were sulfates. The changes may be related to changes in eustatic sea level. These appear on the geochemical logs as sulfur-rich zones (Figure 4-7).

Amplitude spectra of the sulfur curve shows strong energy peaks at 25- and 50-foot wavelengths (Figure 4-8), whereas the Vail eustatic curve (Figure 4-6) shows low stands in the Eocene at 36, 40, 42, 49, and 54 Ma. A reef does not have a traditional "sedimentation rate" to convert from depth to age, but if the rock corresponding to the peaks in the sulfur curve could not be dated, the sulfur log might be used to identify lowstand ages for the reef (once again assuming that the evaporite abundances were being controlled by sea level related factors).

A more straightforward sea level-geochemical log correlation was found at Site 761, drilled into the Exmouth Plateau off western Australia on Leg 122 (Figure 1-3). Two clear low stands below the Cretaceous-Tertiary boundary were identified from lithological
Figure 4-5. Ice encroachment, loading and melt-back produce major changes in sediment properties of the sea floor. In Hole 739, drilled during Leg 119 in Prydz Bay of Antarctica, high porosity sediments (low resistivity) are found both above and below a unit of very low porosity (high resistivity). The stratigraphic progression is believed to be tilting of Unit 3, truncation by an advancing ice sheet, deposition of Unit 2 during melt-back, then loading of Unit 2 by new ice. Unit 2 compacted as pore waters were squeezed out horizontally from of the advancing ice. Unit 3, however, did not compact because the pore waters could not escape down dip along the dipping reflectors. Unit 1 was finally deposited passively as the ice melted-back again. A similar compaction history is found in nearby Hole 742.
Figure 4-6. Eustatic sea level changes derived from sequence stratigraphic interpretations of seismic reflection profiles produce high- and low-stand deposits, that if identified in logging data, can locate the well in time.
Figure 4-7. Changes in sulfur content in Hole 715 are attributed to environmental variations changing the abundance of evaporites. These may be due to changes in eustatic sea level.
Figure 4.8. The amplitude spectrum of the sulfur concentration from the geochemical log in Hole 715 (figure 4-7) shows periods of the sulfur peaks to be 25 and 50 ft. If this periodicity is due to sea level changes, then it can be used to tie into the eustatic sea level sequence curve (Figure 4-6).
changes observed in the geochemical logs (Figure 4-9). The Si-content of the sediment increases whereas the Ca-content falls as sea level drops. Al increases somewhat with Si indicating that clay-content is also increasing. The low-stands are marked by interbedded chalks and mudstones whereas the high-stands are represented by limestones. The depositional environment changes from shallow marine to deep-water carbonate platform then, as the margin continues to subside in the Tertiary, to deep marine. Not only can sea level changes be determined, but stratigraphic sequences from log patterns can be identified. Determination of such a sequence stratigraphy from logs is a far cry from a simple determination of impedance contrasts used to generate synthetic seismograms for correlation with surface seismic surveys. We are now able to see real cause and effect in the interaction of sea level change with marine sediments.

The Cretaceous-Tertiary Boundary

So far during the Ocean Drilling Program, logging data have been obtained across the extinction boundary between the Cretaceous and Tertiary (K-T) at 6 wells in the south Atlantic and eastern Indian Oceans. Beginning with the well we have just discussed, Site 761, we find the K-T boundary to be marked by abrupt changes in gamma ray, resistivity and velocity (Figure 4-10) as well as high clay content (Figure 4-9).

Hole 762, also drilled on the Exmouth Plateau (Leg 122, Figure 1-3), also records an increase in clay content across the K-T boundary as well as an even stronger velocity contrast (Figure 4-11). Here, the clays continue to a substantial depth above the boundary, where low velocities are no longer correlated with low resistivities.

The high gamma ray counts recorded above the K-T boundary may be from volcanic ashes from the Kerguelen hot spot, which was just to the south at this time (see below). However, low resistivity and velocity indicate high porosity for this interval. It is concluded that the increased clay content is from non-deposition of carbonates rather than from a dramatic increase in deposition from either a worldwide volcanic eruption event or from increased dust from a meteorite impact, the two most popular theories for the extinction of the dinosaurs.

Volcanic ashes can be identified on the logs by studying the Th/U ratios. As discussed in chapter 3, hot spot volcanics have Th/U ratios ranging from 4 to 6, whereas pelagic sediments have Th/U ratios < 1. The Th/U ratios of K-T boundary ashes from Sites 747 (Leg 120), and 752 (Leg 121), show not only that similar ashes are found both above and below the K-T boundary, but also that the occurrence of the ash deposits is related to hot spot activity rather than to an extinction event (Figure 4-12). Furthermore, the volcanic ash layers from the two sites have a trace element signature very similar to that of the volcanic rocks of the Kerguelen hot spot.

The K-T boundary is more than an extinction event, as was observed at Site 750, drilled into the central Kerguelen Plateau during Leg 120 (Figure 1-3). The boundary is a hydraulic discontinuity at this well, separating high permeability nanofossil chalks from only slightly less porous, but clearly less permeable chalks above. This conclusion is derived from an “invasion” profile of the well (Figure 4-13) showing that high resistivity, fresh water muds have significantly invaded the formation below the K-T boundary, but not above. The higher resistivity drilling mud raises the reading on the shallow resistivity
LEG 122 HOLE 761
SEDIMENTOLOGY INTERPRETATION
FROM GEOCHEMICAL LOGS

Figure 4-9. Geochemical logs from Hole 761 on the Exmouth Plateau off western Australia show an increase in Si-content as sea level low stands deliver more sandy sediments. The clay content of the sediments increases also, as can be seen from the increased Al-content. The Vail systems tracts, lithologies, and depositional environments can be identified solely from the elemental variations in the logs. The K-T boundary is recorded at 165 m depth as a decrease in carbonate-content.
Figure 4-10. The K-T boundary (figure 4-9) is seen at 170 m in Hole 761 geophysical logs as a high resistivity, high velocity, highly radioactive zone of low porosity.
Figure 4-11. The K-T boundary in Hole 762 on the Exmouth Plateau is a much sharper contrast of Gamma-ray energy, resistivity and velocity than in Hole 761.
LEG 121 HOLE 752B BROKEN RIDGE

LEG 120 HOLE 747C KERGUELEN

Figure 4-12. The K-T boundary was logged in both Holes 747 and 752 from the Kerguelen Plateau and Broken Ridge. Note the different character of the Th and K curves between the two wells. Hole 752 has a sharp K anomaly from clay deposition right at the boundary, whereas Hole 747 shows a built-up in clay deposition somewhat before the extinction event. Th-content in Hole 752 drops above the boundary, but increases in Hole 747. Therefore, local depositional variations seem as important as the extinction event.
Figure 4-13. The K-T boundary in Hole 750 south of Kerguelen is a major hydrological transition from permeable sediments below to impermeable sediments above, as can be seen from the invasion of the formation below the K-T boundary by fresh drilling fluids. The higher resistivity of the shallow sensing SFLU electrical resistivity curve is a further corroboration that fresh, higher resistivity drilling fluids have invaded the formation close to the borehole, but not far away (because the ILD and ILM deep penetrating resistivity curves still report the low resistivities of the saline formation fluids.)
Figure 4-14. Geochemical logs from Hole 700 on the Georgia Rise of the south Atlantic record the K-T boundary at 330 m depth. Here, there is no clay deposition at the event boundary, as can be seen from the lack of an anomaly in U, Th, K or Al curves. There is generally more clay present in the Cretaceous section than in the Tertiary sediments, however. The rapid increase in Ca above the K-T boundary shows how rapidly this nutrient-rich are returned to carbonate productivity after the extinction event.
curve but does not affect the deep resistivity log. The correspondence between the onset of invasion and the depth of the K-T boundary is striking.

Another K-T boundary was sampled at Site 700, drilled during Leg 114 in the southern Atlantic Ocean (Figure 1-2). The logs show no "ash flow event" at the K-T boundary similar to those observed near the Kerguelen hot spot. Clay content does steadily increase below the Cretaceous boundary, however, as can be seen from increased Al, Si, S, Th and Fe contents and decreased Ca-content in the geochemical logs (Figure 4-14). These clays are also from a potassium-rich source, the same as at the K-T boundary in the eastern Indian Ocean, but there is no "event" at the boundary. In contrast, the Ca content reaches its highest value 5 m above the extinction boundary, demonstrating the speed with which the prolific circum-Antarctic surface waters re-established productivity levels after the extinction event.

Summary

It is conceivable that someday we will be able to directly measure such chemical variations attributable to major climatic changes as iridium, oxygen isotopes, and carbon 14 with logging tools. Cryogenic germanium crystal detectors, focused neutron accelerators, and 4096-channel spectral analyzers are already under development. Many of the geochemical analysis techniques being developed by NASA for space may eventually find their way into the borehole. In any event, the future appears bright for the detection of climate changes with logs.
Chapter 5: Formation and Deformation Processes at Rifted and Compressional Continental Margins

Continental margins are of fundamental scientific importance because they provide a window into past earth history. They contain the vast thicknesses of sediments that record paleoenvironment, continental erosion, flexure of the lithosphere, and thermal evolution of the basins. These sediments are encapsulated in a time-ordered sequence that provides the basic evidence for basin evolution. Evidence of rifting is preserved in margin sediments that describe how vast landmasses are torn apart as plate tectonic processes carry the continents chaotically about the earth's surface. The collision of plates produces accretion along the margins of continents that preserve ancient ocean basins and slices of old oceanic crust. Sedimentary basins formed at continental margins are of immense economic importance because they provide most of the world's hydrocarbons. It is in these basins that organic debris is collected, buried and cooked to produce oil and gas. Almost all of the evaporite deposits, potash, phosphate, lithium, and cadmium in the world are deposited here. Hot fluids moving through continental margins produce large and economically important "hydrothermal" concentrations of manganese, cobalt, zinc, iron, lead, copper, sulfur, lithium, uranium, silver, and gold.

Drillholes into rifted and compressional margin sediments provide a direct view into the processes that have shaped the geological history of our planet. Wireline logging measurements are often the only continuous data recorded in these wells, and as such, they provide the framework for the interpretation of observations made on core.

The Oman Rifted Margin and Wireline Logs
(from Prell, Niitsuma et al., 1989)

The rifting of the Oman Margin was accomplished by a combination of mega-shearing associated with strike-slip motion between the Arabian and Indian Plates, and more classically rifted, pull-apart, listrically faulted, and tilted basement blocks (Figure 5-1). A set of holes was drilled during ODP Leg 117 across the rifted margin to study the interaction of a widespread oxygen minimum zone in the ocean waters associated with summer monsoonal upwelling and the subsidence and depositional processes of basin formation.

The anoxic bottom waters along the margin cause the organic content of the sediments to be extremely high, and the processes of burial of carbon-rich sediments are obviously relevant to the eventual maturation of these sediments into hydrocarbon-bearing source rocks in a future basin. The geophysical logs at Hole 723 (Figure 5-1) show strong correlation with the uranium variation determined from the geochemical logs (Figure 5-2). Velocity, resistivity, density and porosity reflect the character of the uranium variation downhole. These correlations indicate that a component high in uranium causes high porosity, with associated effects on other physical properties of the sediment. Clay minerals contain some uranium and cause high porosity. First, high porosities are found in
Figure 5-1. Structure of the Oman rifted margin with locations of Holes 723 and 728.
Physical properties are controlled by a component rich in Uranium

LEG 117: Site 723
Oman Margin

Figure 5-2. Uranium-content from geochemical logs in Hole 723 correlates with major changes in resistivity, photoelectric cross section, and density from geophysical logs, especially in 100-150 m depth interval.
the enriched zones, and clays are usually associated with low porosities. Uranium, however, does not correlate with either thorium or potassium content in the well, as would be the case if uranium-rich component were clays.

Both the total uranium and organic matter contents in the hole are an order-of-magnitude higher than in most deep-sea sediments. Organic matter is known to be often enriched in uranium, because uranium is precipitated from seawater at organic-controlled redox fronts. There is a general correspondence between uranium content and organic carbon abundance observed in the cores of both Holes 723 and 728 (Figure 5-3). Further, organic matter increases porosity, accounting for the strong correlation between uranium and porosity-sensitive logs. Therefore, the organic content of the wells can be determined from the uranium logs.

The anoxic bottom waters are not the only chemical anomaly found in the area. The surprising discovery of dolomite stringers within 200 m of the sea floor indicates active diagenesis is occurring in Hole 723 (Figure 5-4). The geochemical logs identify a freshening of the pore fluids in the diagenetic interval of the well, a point that was verified by chemical analyses on recovered pore waters. The geochemical logs (Figure 5-5) show excellent correlation between Mg and Ca, indicating that diagenesis is proceeding throughout the low chlorinity interval, not just in the dolomitized stringers themselves. Is the influx of fresher waters from land causing the dolomitization and the lowered chlorinity content? A regional "groundwater survey" using geochemical logs in shallow boreholes would answer this question.

The Exmouth Plateau and Wireline Logs
(from Haq, Von Rad et al., 1990)

ODP Leg 122 drilled several holes on the Exmouth Plateau off western Australia (Figure 1-3), a rifted margin of similar structure to that shown in Figure 5-1. Holes 759 and 760 are in a position seaward of that occupied by Hole 728 on the Oman Margin (Figure 5-6). Both wells show excellent examples of shoaling upward sequences caused by small-scale sea level variations superimposed upon a general subsidence of the basement block. The sediments of Hole 759 change from deltaic deposits of siltstones at 300 m depth to a deepening carbonate platform in which the characteristic sawtooth ramping of the gamma ray curve is caused by coarsening of grain sizes within each sea level cycle (Figure 5-7). In Hole 760, the sawtooth pattern deposits are found in non-marine claystones, silts and sandstones (Figure 5-8). The finer grained claystones contain abundant thorium whereas the coarser sandstones have low thorium content. Notice that the compaction of these intervals did not proceed uniformly, with two undercompacted sequences resisting porosity loss.

Subsidence can also be observed in Hole 762, drilled on the southern Exmouth Plateau. The geophysical logs show the general subsidence as a dramatic decrease in gamma ray counts and an increase in sonic velocity. The resistivity shows that compaction is again not uniform, with an overcompacted interval just above the transition from Barrow Delta sediments to nanofossil chalks (Figure 5-9).

The geochemical logs add another piece to the subsidence story. The transition from deltaic clays and silts to pelagic chalk is marked by an increase in Si content and a minimum
Uranium log tracks organic Carbon from core

LEG 117: Sites 723 & 728
Oman Margin

Figure 5-3. The Uranium-content also correlates with organic carbon variations measured on core from Holes 723 (left) and 728 (right). U₂O₃ is complexing with organic molecules.
Thin dolomite stringers occur in low-salinity pore fluid region and produce enormous spikes

LEG 117: Site 723
Oman Margin

Figure 5-4. At Hole 723, dolomite stringers are seen as very high velocity and resistivity spikes formed by diagenesis in the interval of the well with relatively fresh pore fluids, as recorded by not only the CV/H ratio from the geochemical logs but also from laboratory measurements of pore fluids recovered by a downhole sampler.
LEG 117 HOKE 723 GEOCHEMICAL LOGS

DRY WEIGHT % OXIDES

Figure 5-5. The geochemical logs show that throughout the fresh pore water interval of Hole 723, there is a positive correlation between Ca and Mg. An inverse correlation between these cations and Si indicates that interlayers are forming between dolomitic carbonate and silica-rich sediments. Diagenetic reactions from Ca-carbonates to Mg-carbonates are beginning throughout the interval, not just in the well-developed dolomitic stringers of figure 5-4.
Figure 5-6. Seismic profile across tilted block at the base of the Exmouth Plateau off western Australia, with locations of ODP Leg 122 wells shown. This block is in a similar structural position to that below Hole 729 of the Oman margin (figure 5-2).
Figure 5-7. Subsidence produced a transition from deltaic deposition on the tilted block to coarsening upward sequences within the newly forming carbonate platform of figure 5-6. The gamma-ray log shows these sequences particularly well because of the increased radioactivity if the finer grained component of each sequence. Resistivity and velocity show little change because to porosities within each sequence change little.
Figure 5-8. On top of the tilted block (figure 5-6), the geophysical logs show an even more abrupt transition from shallow water deposition of non-marine clays, silts, and sandstones to deep water carbonates of the platform. In this well, the coarsening-upward sequences are found in the shallow water deposits rather than in the platform carbonates.
Figure 5-9. The contrast in information delivered by the geophysical versus the geochemical logs is shown in Hole 762 on the Exmouth Plateau. The radioactivity, resistivity, and velocity logs show dramatic changes in depositional environment from silts and clays of the Barrow delta, through a transgressive siltstone sequence, to pelagic nannofossil chalks. The large decrease in velocity at the bottom of the hole is an artifact due to sonic tool problems. The geochemical logs do not show much chemical change as the plateau subsides, except that the sands of the transgressive sequence stand out as a high Si zone. The clays stay about the same composition throughout because the Si/Al ratio remains constant. However, the geochemical logs show in great detail how the nannofossil oozes contain finely interlayered clay units (the high frequency signal in the Si, Ca and Al curves). These climatically driven variations are not recorded by the geophysical logs because they do not produce large changes in physical properties of the sediments.
in carbonate deposition (Figure 5-9). The high frequency signal in both Si and Ca logs is from interlayering of clays throughout the well, as can be seen from the Si/Al ratio (a low Si/Al ratio is found in clays). However, the overall deposition of clays does not change much throughout the well because the average ratio remains relatively constant. Thus, the clay deposition rate remains constant as the Si content drops by half. The coarse sands are no longer being deposited as the sea floor is subsiding.

The South Orkney Rifted Margin

The sedimentary wedges built onto tilted basement blocks during rifting become excellent traps for hydrocarbons in the later history of a basin. Hole 696, drilled on ODP Leg 113, penetrated the top of such a wedge near the South Orkney Islands (Figure 1-2). Buildups of natural gas in the subsurface often are associated with "bright spots" in surface seismic profiles. High amplitudes from such a bright spot, followed by strong energy attenuation below, were interpreted from a seismic profile near Hole 696. This was a strong indication that gas might be encountered in the well (Figure 5-10). The hole was drilled only to the top of the bright spot for safety reasons, but the geophysical logs demonstrate that gases were indeed encountered. Consider the anomalous behavior of the logs from 580 to 600 mbsf. The caliper shows tight hole, but the velocity and resistivity indicate very high porosities. The deep penetrating resistivity measurement is actually much lower than the shallow resistivity curve, indicating further that the porosities increase away from the hole. There is no question but that this is an overpressured zone, indicating that an abundant gas reservoir probably exists below the well.

Compressional Continental Margins: the Peru-Chile and Barbados Trenches

The ODP logging experience in compressional continental margins is not as extensive as that on rifted margins, partly because of the more difficult drilling and logging conditions associated with accretion. However, several important results come from holes logged during Leg 112 on the Peru margin (Figure 1-1).

Hole 679 penetrated 300 m into the fore-arc basin 150 km west of the Peruvian coast (Figure 5-11). Resistivity and density logs show a normal decrease in porosity associated with compaction, but the salinity curve derived from the Cl/H ratio measured by the geochemical logs indicates freshening of the pore fluids below a diagenetic permeable layer which causes a prominent seismic reflector that can be traced to shore. The logs show no correlation between dolomitization and salinity, as was observed in the Oman Margin holes (compare Figures 5-3, 5-4, and 5-11). Instead, the fresher pore waters appear to be from an aquifer being fed by ground waters from land. Conclusive proof of such a hypothesis would again require an extensive set of geochemical logs in shallow boreholes in the region. Such mapping of regional ground water chemistry is routinely done on land, although pore fluid samples are usually used instead of log data.

Evidence of the accretion process itself is seen in logs run in the toe of the subduction zone during the same leg (Figure 5-12). Hole 685 penetrated a seismic reflector from one of the decollement surfaces caused by the underthrusting of young sediments scraped off
Figure 5-10. Anomalous behavior of log-responses frequently yield valuable information, such as in Hole 696 off the South Orkney Islands. The bright spot above diffuse reflectors indicates the possible existence of a natural gas reservoir in this tilted block. The first reflector was penetrated, then drilling was suspended because of safety considerations. The geophysical logs indicate that was a good decision. The caliper indicates closure of the well at 590 m depth, yet the velocity and shallow penetrating resistivity are extremely low indicating very high porosities. The further fact that the deep resistivity shows lower porosity supports a conclusion that this zone is gas-prone. The high porosities but tight hole indicate that gas is flowing toward the well.
Salinity Inversion in the continental shelf off Peru

LEG 112 : Site 679
Peru Trench

Figure 5-11. In the fore-arc of the Peru Trench, geophysical logs in Hole 679 identified a major seismic impedance boundary that forms a prominent reflector throughout the area. The geochemical logs show that the pore waters below the reflector are fresher than those above. The Cl/H ratio is used to determine chlorinity and infer salinity. The likely source of the fresh waters is an aquifer being fed from land 100 km to the east.
Logs show porosity inversion as a result of accretion across decollement.

Figure 5-12. At the toe of the accretionary prism of the Peru Trench, logs from Hole 685 define the impedance contrast that is responsible for the seismic reflector identified as a decollement surface between accreting sedimentary wedges. The impedance contrast is from a low porosity, high density, clay rich zone (high Al) bounded top and bottom by low clay (low Al) sediments.
the oceanic Nazca Plate onto the South American Plate’s accretionary prism. Velocity, resistivity and density logs identify the reflector as a overcompacted sediment that appears to form a hydrological cap over overpressured sediments that are below the reflector (Figure 5-12). However, the aluminum-content log shows that there is less clay associated with the overpressured sediments, which suggests that they may be higher in porosity rather than severely undercompacted. Thus, the combination of geophysical and geochemical logging gives a much more complete picture of the geology of this wellbore than does either alone.

On ODP Leg 110, a decollement reflector was also penetrated at Site 672, in the deformation front of the Barbados Trench. Here, the density also increases at the reflector depth. Slowness (1/velocity) determined from the multichannel sonic tool also delineates this impedance boundary that becomes the predominant reflector interpreted as the decollement surface (Figure 5-13). Fluids seem to be traveling along this surface, judging from pore fluid chemistry of samples recovered from this zone, whereas the reflector in the Peru accretionary prism seems to be the seal of an overpressured zone that extends for 30 m below the reflector (contrast Figures 5-12 and 5-13).

Depositional Processes in Sedimentary Fans

The major sedimentary basins of the world were constructed where large rivers build deltas and deep sea fans across continental margins. Logs provide detail necessary to decipher the stratigraphy of such fan deposits. The Indus and Bengal Fans, two of the largest active fans on the planet, were drilled during ODP Legs 116 and 117. ODP Leg 117 penetrated the distal end of the Indus Fan at Hole 720 (Figure 1-3). The depositional history of the sediments in Hole 720 was found to be dominated by alternating cycles of pelagic sedimentation, and of turbidites and coarse-grained channel flows from the Indus River to the north. The geochemical logs clearly show the pelagic cycles as low thorium-content sediments, and the Indus River deposits as thorium-rich rocks originating from the erosion of the Himalayas (Figure 5-14). Using impedance logs from the geophysical logging results to tie the thorium log to the surface seismic profile, the depositional signature of the seismic sequences in the vicinity of the hole were determined (Figure 5-14). Such detail could not be reconstructed from the cores, unless core recovery was 100% and considerable amount of time was spent analyzing core plugs. Comparison of logs data to cores indicates that core recovery was 80% in the pelagic sediments but only 10% in the turbidites.

At the distal end of the gigantic Bengal Fan, two tectonic processes are intermixed. Mid-plate compression has produced buckling and thrust faulting in the center of the Indian Plate, probably driven by forces from the collision of the Indian and Asian Plates forming the Himalayas. At the same time, the Bengal Fan has built out to the mid-plate deformation zone. Heat flow measurements across the deformation zone show heat being redistributed through fluid convection in the sediments and/or basement. Is the fluid flow driven by compression or by de-watering from the load of the Bengal Fan sediments?

Partly to answer this question, Hole 719 was drilled on the northern flank of one of these mid-plate thrust faults during ODP Leg 116 (Figure 5-15). Geophysical and geochemical logs in Hole 719 show porosity variations related to differential compaction.
Figure 5-13. The decollement surface was drilled and logged in the toe of the Barbados Trench at Hole 672. Here, multichannel sonic logs show a velocity boundary (decreased slowness) that was also found to be a density contrast from core measurements. Pore fluid chemistry indicated that fluids were flowing along this impedance boundary.
Figure 5-14. The origins of seismic sequences can be described by geochemical logs such as the Th curve recorded in the Indus Fan Hole 720 southwest of India. Here, low Th zones are pelagic deposits from the south, whereas high Th intervals are turbidites and abandoned fan channels from the Indus Cone. The direction of deposition can be inferred from the combination of geochemical logging and seismic reflection profiling (arrows).
Figure 5-15. During Leg 116, the extremities of the Bengal Fan were drilled in the mid-plate deformation zone south of India. The collision of the Indian and Asian Plates to form the Himalayas is thought to have caused compressive buckling of the plate in this area, as can be seen from the thrust faulting in the seismic profile. The heat flow in the area indicates fluids are flowing toward the thrust faults along several seismic horizons. Is the fluid flow from compaction in the Bengal Fan, or from hydrothermal circulation in the basement?
The Ca, Si and Al contents of the more compacted silts (Figure 5-16) show them to be lower in carbonate content than the more pelagic, high porosity, carbonate rich units. The silts are composed of a largely continental assemblage of feldspars, quartz and exotic "Himalayan" minerals rather than pelagic clays, as can be seen from the lack of correlation between Si, Al, K and Th in the well. De-watering of these Bengal Fan sediments provides a hydrological source for at least part, if not all, of the hydrothermal fluids observed to be convecting in the mid-plate deformation zone.

Summary

While we are admittedly just beginning to understand fluid flow processes in rifted and accreted continental margins, it is obvious that geophysical and geochemical logging delivers the essential data required to fully understand these phenomena. Neither cores nor surface seismic profiles preserve the in situ information and continuous records required to determine dynamic processes.
Figure 5-16. The logs from Hole 719 indicate that differential compaction is occurring between silts and clays of the Bengal Fan. High porosity units are sandwiched between lower porosity units (e.g., unit 3 between units 2 and 4). The geochemical logs show that the Si-rich sediments are not pelagic clays (with association of Si and Al, but not with K and Th), but Bengal Fan sediments composed of feldspars, quartz and other erosional products from the Himalayas. These silicates are more compacted than the carbonates (the Ca-rich units).
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OCEAN DRILLING PROGRAM

Wireline Logging Manual
Volume 6

Scientific Applications of Wireline Logs
(1985-1986)

Borehole Research Group
Lamont-Doherty Geological Observatory
Columbia University
Palisades, New York 10964

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Chapter 1

Introduction to Scientific Well Logging

The JOIDES Resolution sails the world's oceans, drilling and logging holes in the sea floor, often in waters deeper than 5 km. Geophysical and geochemical measurements made by lowering into each borehole highly sophisticated sensors attached to an electrically-conducting wireline are important to understanding the geology at each Ocean Drilling Program (ODP) site. Because logging tools and interpretation techniques were developed largely for use by the oil industry, they are designed to detect the composition and quantity of pore fluid (oil, gas, and water) present in a formation. ODP uses these high-technology tools for a different mission: to determine the character of a formation as well as the composition of the pore fluid. The main goal of the ODP Wireline Logging Program, operated by the Borehole Research Group at Lamont-Doherty Geological Observatory, is to develop new log interpretation techniques and so to demonstrate to the scientific community the versatility and power of logs as scientific tools. Below we reconsider logs by moving away from the traditional porosity-velocity-resistivity approach of the oil industry to one defined in marine geological terms. Consequently, we will discuss the different applications of logging not, for example, in terms of lithology, synthetic seismogram generation techniques, or porosities, but rather in terms of a plate-tectonic framework.

ODP has pursued the investigatory course set up by the International Phase of Ocean Drilling (IPOD), which divided the study of the oceans according to the theory of plate tectonics. The study of the ocean crust focuses on the physical and chemical processes which form and then age the oceanic lithosphere. The study of passive and active margins explores the tectonic processes of subduction, rifting, sedimentary basin formation, and continent/ocean boundary interactions. Research in the field of paleoclimate and sedimentary process postulates how the Earth itself has evolved through geological time.

These themes, as they have been expanded and modified by ODP, determine the major drilling and logging targets of the JOIDES Resolution. Below we present examples of how wireline logs are used to investigate geological processes beneath the sea floor. The examples are meant only to be illustrative, not exhaustive. In order to provide the most relevant demonstrations of the uses of ODP's wireline logging, we have tried to use ODP and DSDP case studies whenever possible. The data are derived from ODP and DSDP cruises up until Leg 111, which was completed in September, 1986, and are used here for educational purposes only.

Scientific Well Logging Techniques

Volume 3 of this Manual describes in detail the logging tools operated by the Ocean Drilling Program as well as their primary applications. As of September, 1986, three basic
measurements were made in boreholes by wireline logs: acoustic, electrical, and nuclear.

The resistivity tool, which measures the electrical resistivity of the formation, allows us to estimate the porosity of rock by recording variations in current intensity that depend on the type of fluid present in the pores and on the degree of interconnection of the pore space itself. The sonic tool excites small "micro-earthquakes" at kilohertz frequencies and, after the sound energy has passed through the rock, it records the "seismograms" at multiply-spaced receivers. Each sonic "firing" is like a small-scale refraction experiment conducted vertically over a few meters of the borehole. Analyses using many of the same techniques that are used in surface multichannel seismic reflection processing yield the elastic property information of the rock. Not only compressional and shear waves, but also Stoneley surface waves and normal mode coda are analyzed for velocity, spectral amplitude, and frequency changes, and coherency. The parameters change with lithology, degree of fracturing, alteration, diagenesis, permeability, and porosity. Ultrasonic imaging delivers a reflected image of the borehole wall as well as a precise, 360 degree caliper of borehole size changes. The logs, therefore, can detect and map borehole breakouts, which are caused by stress-induced, wellbore spalling. These logs are the only available so far that deliver information about the state of stress in the lithosphere.

Nuclear tools produce the most sophisticated downhole measurements. Not only do they measure the naturally radioactive components of rock, and so determine quantitative uranium, thorium and potassium contents, but also they bombard the formation with neutrons and gamma rays shot from chemical sources. The returned gamma rays can be read to infer porosity, density, and lithology. The newly-designed Geochemical tool string activates aluminum and manganese directly with a californium source, pulses neutrons into the formation with a "minitron", and counts the returned "neutron activation" spectrum with a 256-channel, downhole analyzer. Each 0.15 meters of the logged interval can yield contents of iron, aluminum, calcium, silicon, hydrogen, chlorine, titanium, gadolinium, potassium, and sulfur. Thus major- and selected minor-element chemistry is measured downhole. Though not as accurate in absolute terms as laboratory measurements made on core, the chemical logs detect relative changes occurring down the wellbore with accuracy and repeatability. With the measurements taken from the nuclear logging suite, lithologies can be inverted to their normative mineralogy so that alteration zones and formation boundaries become clearly defined.

Below we will see how to use the combination of these physical and chemical logging measurements to determine paleoclimate changes, volcanic cycles of island arcs, subsidence changes related to the rifting of continents, basalt stratigraphies and alteration histories, stratigraphic ties to multichannel seismic profiles, excess pore pressures within accretionary wedges, compaction and thermal histories of sedimentary basins, and the stress fields which drive plate tectonics.

The logging techniques are presented within the geological context of oceanic lithosphere, axial spreading and alteration, ocean/crust chemical interchange, stratigraphy, sedimentation, subduction, continental rifting, formation of sedimentary basins, plate-driving forces, and - because understanding ocean processes ultimately will lead to understanding continents - continental formation and deformation.
Chapter 2

Uses of the ODP Logging Suite

The three types of logging tools used on the JOIDES Resolution - acoustic, electrical and nuclear - can be combined to form a logging string customized to deliver the maximum information about any particular geological problem. The question targeted by the drilling expedition will determine the configuration of the string. It is in the combination of different types of measurements of geological parameters that logging finds its greatest interpretive power.

Before we see how to construct and interpret a logging suite, however, we should address a fundamental question. Why log? Doesn't ODP's continuous-coring program provide enough information to answer all geological questions about a particular site? The question and the logic behind it are not universal. For the oil industry, of course, they are turned around. Why core, when logging delivers all of the necessary geological information about a well? The industry sees continuous coring as wasteful and logging, which was designed expressly for finding hydrocarbons, as cost-effective. Marine geologists, on the other hand, can use cores to answer their most pressing questions about the lithology and the structure of a formation, but see pore fluid composition as of secondary interest. For the geologist the importance of logging lies in the inefficiency of coring.

Even if continuous coring resulted in continuous core recovery, which is not the case at the present time, logs measure physical and chemical properties for a considerable distance away from the wellbore itself, and at in situ temperature and pressure. When considering that the average core recovery rate is 50% in sediments and even less in hard rocks, the importance of logging as a continuous measurement becomes obvious. The recovered core must be placed in its proper lithostratigraphic position within the well. Important boundaries, time series variations, and entire units can be missed completely if logs are not available to provide context and to fill in the gaps. Both cores and logs are strengthened as interpretative tools by the use of the other when analyzing a well.

Log Applications

The geological uses of logging tools focus around determining 5 major characteristics of a well:

1. Stratigraphy, both seismic and structural
2. Lithology
3. Porosity and permeability
4. Rheological properties, such as elastic constants
5. Geochemistry and mineralogy.

Each logging string gathers information about one or more of the characteristics listed above (see Volume 3). The Dual Laterolog, for example, is an electrical tool which focuses a strong current horizontally into the rock surrounding a hole. It delivers very good porosity information, is an excellent bed-boundary detector, but is inadequate as a detector of impedance contrasts used to recognize seismic reflection horizons. The acoustic tool, on the other hand, detects impedance boundaries well, but yields only fair information about mineralogy changes in a well. Gamma ray spectroscopy, a nuclear tool, detects mineralogy changes very effectively. Again, it is the combination of these various tools which gives logging its strength as an interpreter of geology.

Relationships Between Logs

Consider a standard example of an excellent logging suite obtained during ODP Leg 103, which took place off the west coast of Spain.

The Galicia Margin is an old, passive, continental margin. Nonetheless, buried beneath the surface is geological evidence of the rifting between North America and Europe 160 million years ago. By drilling a transect of holes across the deepest part of this margin, ODP obtained the syn-rift and post-rift sedimentary records of the event (Figure 2-1). The standard Schlumberger logging suite from Site 639 (Figure 2-2) consisted of gamma ray, caliper, bulk density, photoelectric effect, sonic velocity, induction electrical resistivity, and natural spectral gamma ray.

The most obvious features seen in these logs are the one- to five-meter-thick levels characterized by high density (2.7 g/cm³), high sonic velocity (>6 km/sec), and high electrical resistivity (2000 Ωm). Despite the presence of these indicators, this rock was not determined to be igneous when the low photoelectric-effect value and the low potassium, uranium, and thorium contents were considered as well.

How did we determine the composition not only of these hard rock stringers, but also of the slow-velocity, high-porosity rock in between?

The lithological response to variations in bulk density and porosity was known for sedimentary basin rocks drilled by the oil industry (Figure 2-3). Yet the porosities of our hard rock stringers fell at the far left and bottom of the cross-plot of Figure 2-3, while those of the soft, slow sediments fell at the top right. Consider the sonic velocity-porosity relationship (Figure 2-4). Data from soft, marine sediments fell considerably off the standard "Wyllie relation," which is a linear interdependence between velocity and porosity. Our porosities for the sediment were often so large (>50%) that the matrix interconnectedness was poor. Thus we had the nonlinear behavior, which made determination of lithology by the conventional methods developed by the oil industry impossible.

Other lithologies, however, could be identified simply by looking at variations in velocity, density, and porosity logs. On board the ship it was possible to produce the lithology plot of Figure 2-5 by classifying the log responses of the formation into eight clusters. These clusters could then be identified by their best-fit positions within an M-N plot (Figure 2-6), where travel time divided by density was plotted against neutron
Figure 2-1. Ocean Drilling Program Leg 103 drillholes into the Galicia margin, offshore Spain (location above). Sedimentary structure (below) includes syn-rift and post-rift sediments deposited after the Galicia margin spread away from the east coast of North America.
Figure 2-2. Schlumberger logs from ODP Site 639, Leg 103 (Figure 2-1). Shaded areas are dolomite occurrences. On left is core recovery.
Figure 2-3. Porosity and lithology determination from formation density log and compensated neutron log (courtesy of Schlumberger). Mineral locations also indicated.
Figure 2-4. Porosity versus sonic travel time crossplot showing the change between very high porosity sediments (Raymer Transform blown-up to right) and sedimentary rocks.
Figure 2-5. Terralog cluster analysis of sonic (center), resistivity, neutron porosity and density logs from Hole 638C, Leg 103 (Figure 2-1). Lithologic column to right: percentages to left.
This crossplot may be used to help identify mineral mixtures from Sonic, Density, and Neutron logs. (The Neutron log used in the above chart is the CNL.*) Except in gas-bearing formations, M and N are practically independent of porosity. They are defined as:

\[ M = \frac{t_2 - t_1}{P_r - P_i} \times 0.01 \text{ (English)} \]
\[ M = \frac{t_2 - t_1}{P_r - P_i} \times 0.003 \text{ (Metric)} \]
\[ N = \frac{(\phi_i) - \phi_u}{P_r - P_i} \text{ (Either)} \]

Points for binary mixtures plot along a line connecting the two mineral points. Ternary mixtures plot within the triangle defined by the three constituent minerals. The effect of gas, shaliness, secondary porosity, etc., is to shift data points in the directions shown by the arrows.

The dolomite lines are divided as to porosity as follows:
1) \( \phi = 5.5 \) to 30 p.u.
2) \( \phi = 1.5 \) to 5.5 p.u. and \( \phi > 30 \) p.u.
3) \( \phi = 0 \) to 1.5 p.u.

Figure 2-6. M-N crossplot (see legend) of sonic, neutron and density log results with mineral locations shown (courtesy of Schlumberger).
Figure 2-7. Effect of misidentified depths results in apparent scatter (top), which disappears when the true depths are established (bottom).
<table>
<thead>
<tr>
<th>Table 2-1. Types of Editing Required</th>
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- **Mechanical Errors in Logs**
  - Depth Shifting
  - Log Calibration
  - Instrument/Electronic Noise (e.g., Cycle Skips)
  - Hole Washout
  - Hydrocarbon Effects (Invaded Zone)

- **Interpretive**
  - Check Shot or VSP Calibration
  - Depth Trend Relationships
  - Interlog Relationships (Crosstabs)
porosity divided by density. Quartz, calcite, and clays were correctly identified, and the high-density spikes were identified as dolomite. There was, however, no anhydrite in the cores from 639.

We turned to the core to verify the composition predicted by the logs. Even though recovery was poor in the more cemented intervals, a few pieces of dolomite were brought to the surface during coring. To assist in the log interpretation, physical properties derived from core analyses located dolomite on the M-N diagram. The logs in turn provided information about thickness and frequency of dolomite layers in the hole.

Log Corrections

Comparisons between logs must depend upon careful editing of common, misleading, data acquisition errors. These are usually of two types: mechanical errors occurring during recording, and interpretive errors, which are correctable by calibration and deskewing (Table 2-1). Depth-shifting is usually required because the wireline cable stretches between different lowerings of the tool string into the hole. Depth is often considered the most important datum recorded in logging; even so, it is not recorded downhole, but instead at the surface with mechanical wheel-counters.

Depth-shifting to calibration points, such as total depth or a casing shoe, can clear up considerable noise in a log (Figure 2-7). This can improve interpretation, as shown in the sandstone-limestone-shale lithology model of Figure 2-8. Here clusters of log responses are assigned either a sandstone, dolomite, or shale designation for a plot, such as that in Figure 2-5. After depth-shifting and editing, however, limestone, not dolomite, is seen to be the third lithologic component in the well.

Another technique useful for log comparison is the generation of "pseudo-logs". Consider the relationship between velocity and resistivity, Wyllie's and Archie's laws can be used to construct a pseudo-sonic log from the resistivity log alone (Table 2-2). If we are in a lithology foreign to these two logs, the pseudo-sonic and sonic logs will have little resemblance. But if we are in familiar sedimentary environments, they will correlate nicely (Figure 2-9). In some cases, in fact, the pseudo-log agrees better with the high-resolution, full-waveform sonic log than does the standard sonic log (Figure 2-10). Such techniques are useful for identifying not only bad or noisy data, but unusual log responses as well, as is typical in formations drilled by ODP.

Seismic-Core Ties Via Log-Generated Synthetic Seismograms

A seismic reflection survey is the main geophysical information used to decide not only where but also why to drill a particular hole. An important objective of logging is then to identify which rocks are responsible for seismic reflections coming from the sub-seafloor. The logs contribute to the interpretation of seismic reflection profiles through lithology and porosity determinations at exact depths in the well, as opposed to the time-depth relationship of the reflection profile. The generation of impedance logs from velocity and density logs allows for the calculation of synthetic seismograms which tie specific reflectors to exact depth intervals in the well (Table 2-3).
Figure 2-8. Use of M-N plot to determine lithologies. Logging data are assumed to be composed of combination of only these three lithologies at each depth point.
TABLE 2-2. PSEUDOSONIC LOGS

\[ \Delta T = \Delta T_{MA} + (\Delta T_F - \Delta T_{MA}) \times \sqrt{\frac{A \times R_{MF}}{R_{X0}}} \]

\[ \Delta T = A + B \times \sqrt{\frac{R_{MF}}{R_{X0}}} \]

\[ \Delta T = A + B \times \sqrt{\frac{1}{R_T}} \]

\[ S_{W}^{N} = \frac{A}{M} \left( \frac{R_{MF}}{R_{X0}} \right) \]

\[ S_{W}^{N} = \frac{A}{M} \left( \frac{R_{W}}{R_{T}} \right) \]
Figure 2-9. Pseudosonic log from resistivity log as in Table 2.2 compared to measured sonic travel times. Discrepancies are often locations of anomalous pore fluids (oil or gas) and/or pore pressures.
Figure 2-10. Pseudosonic log from resistivities as in Table 2-2 (center) is often closer to that measured by multichannel sonic log (right) than is simple sonic travel time log (left).
Table 2-3: **SEISMIC LITHOLOGY**

- **CORE DESCRIPTION**
  - X-RAY DIFFRACTION
  - PHYSICAL PROPERTIES

- **OTHER LOGS**

- **CROSS-SECTION OF LITHOLOGY & POROSITY**

- **LITHOLOGY & POROSITY AT SITE**

- **REGIONAL SEISMIC LINES**

- **SEISMIC AT SITE**

- **EMPIRICAL & THEORETICAL RELATIONS**
  - MATRIX VALUES

- **SONIC & DENSITY LOGS**

- **SYNTHETIC SEISMOGRAM**
Laboratory density and velocity measurements can be used to generate an impedance log, but even if recovery is high, the core values are often biased to too high values in igneous rocks and too low values in soft sediments. The igneous core samples selected for shipboard measurements are often the least affected by alteration, and therefore show the fastest velocity and highest density encountered in the well; the soft sediments, on the other hand, have been disturbed and mixed by the coring process, which causes unrealistically low velocities and densities. Logs circumvent these problems by measuring the impedance parameters at in situ pressure and temperature conditions (Figure 2-11).

The dolomite stringers encountered at Sites 638 and 639 of Leg 103 produce excellent impedance contrasts. They are clearly density and velocity boundaries; the question is whether they are too thin to produce reflections of seismic energy of 10 to 100 m wavelengths. The synthetic seismogram generated from the logs at Site 638 shows that the accumulation of dolomite interbeds is indeed thick enough to produce the reflectors mapped across the toe of the Goban Spur (Figure 2-12).

The geological question of the relation between these dolomites and syn-rift sediments is not answered either by the seismic section or by the logs. That interpretation is left to the scientists of Leg 103. Nonetheless, it is evident that the reflectors resulted from a secondary process which occurred after rifting was complete.

Multichannel Sonic Logging

We referred above to the enhanced resolution which can be attained from recording multiple sonic waveforms at progressively greater distances from the source. The Borehole Research Group Multichannel Sonic Tool brings the powerful seismic processing techniques developed for surface reflection surveying to logging data analysis.

Each 'chirp' of the sonic source becomes a mini-refraction experiment, because the sound energy moves radially outward from the tool, which is centralized in the well. At the rock interface, the sonic energy enters and travels down the wall of rock, appears again in the drilling fluid, and is received by the 12-transducer array located 1 to 3 m below the source (Figure 2-13).

The waveforms recorded with the Multichannel Sonic Tool resemble small microearthquake seismograms and can be analyzed as such. The compressional, shear, and surface wave coda separate into individual energy packets as the energy moves across the receiver array (Figure 2-13). The velocities of the coda packets are precisely measured by a seismic technique called "semblance". With semblance analysis, a series of increasing velocity increments are used to find the maximum statistical coherence of the multiple receivers, which gives a precise determination of velocity (Figure 2-14). The semblance coherence statistics are a good measure of the degree of energy loss across the array as well (Figure 2-15), and they correlate with the occurrence of open fractures encountered in the wellbore (Figure 2-15). The traditional full waveform display of a single receiver also allows for the qualitative identification of such energy loss (right in Figure 2-16), but the semblance statistic quantifies this energy loss for each separate coda (center of Figure 2-16, compared to the Borehole Televiewer ultrasonic image of the fracture at the left). This semblance statistic correlates well with fracture maps of the wellbore from Borehole Televiewer imaging (compare also the right with the center of Figure 2-13).
Figure 2-11. Compressional velocities and densities from logs compared to laboratory measurements on core (dots) from DSDP Site 613, Leg 95. Five meter average of log results is also displayed.
Figure 2-12. Synthetic seismogram generated from sonic velocity and density logs (ODP Leg 103) provides absolute depth tie to surface multichannel seismic reflection record. The reflectors at 6350 and 6500 msec travel time below the surface are encountered in the well at 185 and 298 m bbf. This identification allows for the correlation of reflector depths for considerable distances away from the wellsite.
MULTICHANNEL SONIC WAVEFORMS

Figure 2-13. Multichannel sonic logging tool contains 12 receivers spaced at 25 cm beginning 1 m below a 10-40 kHz source (left). The waveforms recorded from each 'chirp' of the source provide moveout velocities of compressional, shear and Stoneley energy (left). In addition, coherence statistics can be used to identify open fractures from energy loss within each waveform coda (center, compared to Borehole Televiewer image). The well can then be described in terms of 'semblance coherence', which correlates well with fracture locations determined from the BHTV (right).
Figure 2-14. Semblance analysis provides accurate velocity determinations by identifying the velocity of maximum coherence energy (right) within the twelve receiver waveforms for each source firing. The semblance coherence statistic is as useful as velocity itself (left) for geological interpretation.
Figure 2-15. Borehole Televiewer images (left) and multichannel sonic waveforms (right) make a powerful combination for the location and identification of open fracture systems within a well, such as at 78 m into the Palisades Sill, New York. The apparent lag of the sonic waveforms to deeper depth is caused by the zero reference depth of the tool being taken at the source 1 m above the receiver 12 waveform position (right).
Figure 2-16. Timing of minitron neutron bursts from the Schlumberger neutron activation logging tool (GST). $10^8$ neutrons are burst into the formation each 100 microseconds by a 60,000 volt charge released into a Tritium tube (top). The resulting gamma ray emission spectrum of the formation is recorded by a 256 channel photomultiplier. Elemental abundances can then be determined (courtesy of Schlumberger).
Nuclear Logging

In recent years, the traditional sonic, electrical, and nuclear logging tools have been enhanced in their geological interpretative capabilities by the introduction of multiple detectors and sonic/ultrasonic combinations. In the newly designed Induced Gamma Ray Spectrometry Tool a 'minitron' tube of tritium is pulsed once every 100 microseconds by 65,000 to 100,000 volts. The resulting burst of 10 neutrons from the tool produces gamma rays which impact a NaI crystal. The crystal then emits photoelectric energy. A downhole, 256-channel spectral analyzer transmits the gamma ray count rate from each separate energy window back to the surface (Figure 2-16). Hydrogen, chlorine, silicon, calcium, iron, titanium, gadolinium, and sulfur yields are extracted from their respective peak energy channels.

The Lithodensity Tool carries a cesium source in a pad pressed against the wellbore. Gamma rays emitted by the source are either Compton-scattered or photoelectrically absorbed by the electrons in the formation. The amount of gamma ray energy returning to a NaI-counting crystal is therefore inversely proportional to the electronic density of the formation, which is a function of its bulk density.

The Photoelectric Factor (PEF), on the other hand, is a measure of the capture cross-section of an element. By grouping into windows low energy (PEF) and higher energy (density) gamma ray regions of the total gamma ray spectrum, the PEF can be separated from the density measurement. The photoelectric absorption index of elements and minerals can be measured in the laboratory; the total PEF of a formation is the sum of the components. If we determine the major elemental concentrations of the rock-fluid system by neutron activation for all of the major elements, the PEF can then be used to calculate the abundance of the missing residual element. Si, Al, Fe, Ca, Ti, K, Gd, Cl, and H are measured by the geochemical tool. Of the major elements in basalt, only Mg and Na are not measured. Most Na encountered in the borehole is associated with Cl in the fluid (both borehole and formation fluid). The difference between the recorded PEF and that derived from the sum of the abundances of the other major elements (Table 2-4), results in an estimate of the weight percent of Mg and Na in the rock.

The addition of Mg and Na provides a virtually complete and continuous chemical determination of the major oxides composing the vertical section of the wellbore. In turn, this allows for the characterization not only of the structural and lithological units encountered in the hole, but also of the normative mineralogical constituents of the formation.

Both oxides and mineral estimates can be compared with x-ray defraction and fluorescence results from core analyses (Figure 2-17).

In the future there will be available an even more sophisticated geochemical tool that utilizes a cryogenic germanium crystal to obtain better spectral resolution than the existing NaI crystal (Figure 2-18). Such elements as Ni, Co, V, Sc, and Cr will eventually be measured by nuclear logs.

One practical use of this combination of neutron porosity and geochemical tools is that they can be recorded through the steel drill pipe when hole conditions are too degraded to allow open-hole logging. On Leg 101 in the Providence Channel of the Bahamas platform,
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Figure 2.17. From the abundances of elements (right), and mineral normative compositions (left), a factor analysis plot determines the relative abundances of minerals within the elemental yields (left, bottom). The result is a normative mineralogy log showing kaolinite, illite, feldspar, and quartz variations from Al, K and Fe elemental logs (center). (courtesy of Schlumberger)
COMPARISON OF NGT AND ERT ACTIVATION SPECTRA

ZONE1 AT BLANCO

Figure 2-18. The spectrum measured by the NaI crystal currently in use is smooth and relatively insensitive compared to the new cryogenic Ge-crystal tool now under development by Schlumberger (the ERT, enhanced resolution tool).
the drill string became stuck while the geochemical tool was being run. The main objective of the drilling was to determine the nature of the seismic reflectors, but this could not be accomplished solely by drilling, as the core recovery was only 7%. Instead, pseudo-density and pseudo-sonic velocities were estimated from the elemental variations measured by geochemical logging through the pipe. A pseudo-impedance log then produced a synthetic seismogram from the geochemical data. Prominent reflectors were indeed identified (Figure 2-19), but the geochemical log showed that the most prominent reflector ("A" in the Figure) at the bottom of the hole was caused by a "peg-leg" multiple (energy bouncing back and forth between the sea floor and a reflector higher up in the section). The real lithological reflector ("B") was smaller than this peg-leg multiple and was caused by porosity and chert content changes within the massive limestone of the platform top.
Figure 2-19. The neutron activation log was used on ODP Leg 101 to measure the elemental yields behind a stuck drillpipe at Site 626. The resulting pseudodensity and velocity logs made from these elemental yields produced an impedance log (right), and a synthetic seismogram (left, center) which identifies the rock layers responsible for the major seismic reflector in the well (left, and right center).
Chapter 3

Origin and Evolution of the Oceanic Crust

The current Ocean Drilling Program (ODP), as the successor to the Deep Sea Drilling Project (DSDP), focuses on geological objectives outlined by COSOD (Conference on Scientific Ocean Drilling). The main mission of ODP is to bring new technologies to bear on the following, broadly-defined geological problems:

1. Origin and evolution of the oceanic crust
2. Tectonic evolution of continental margins
3. Origin and evolution of marine sedimentary sequences

In the next Chapters, we will consider how logging data can contribute to scientific insights into each of these problems. First, we begin with the most exotic logging application: determination of ocean crustal properties. Even though logging tools and techniques were designed for use in sedimentary basins and not in basalts, the utility of logging measurements in this igneous environment is perhaps the easiest to illustrate. Though porosities are generally lower than any encountered in basins, the rock itself has such a strong lithological signal compared to the pore fluid that log response is easy to quantify.

Consider the basic stratigraphy of the ocean crust. It has long been assumed that seismic layering detects the presence of pillow basalts lying over dikes, which are over the gabbros of frozen magma chambers, which is over Moho and the mantle. Yet the geophysical measurements of the exact causes of those acoustic contrasts had not been fully understood until logs were run in layers 2A, 2B, and 2C of the oceanic crust. This is as far as the drill bit has penetrated the oceanic crust to this time.

Logs in Igneous Basement of Continents

On land the drill bit has penetrated geophysical basement reflectors, and logs have recorded their impedance contrasts. In fact, some of the most famous dry holes in the oil industry history have recorded long logging sections through igneous basement. The geological causes of the supposedly sedimentary seismic reflectors proved to be as variable as the general geological contrasts encountered on continents. Two of these wells serve to illustrate the importance of logging in the determination of igneous lithostratigraphy.

The Anschutz, Arizona State #1 was a 16,000-foot well which entered granites of the Arizona "overthrust" (Figure 3-1) at 700 feet beneath the surface and never exited into the
Figure 3-1. Arizona seismic cross section. Upper panel is uninterpreted "raw data". Lower panel is Anschutz interpretation. Numbers at margins of sections represent time in seconds. Anschutz-Texoma drill site has been projected on to the section. Seismic data courtesy of Pacific West Exploration Company, Denver, Colorado.
underlying sediments thought to be responsible for layered seismic reflectors evident beneath the overthrust (Figure 3-1). Sonic velocity, density, and gamma ray logs identified faults, mafic intrusives within the granite, and lithologic units discriminated by potassium content changes within the granite (Figure 3-2). Impedance contrasts from these changes explained two prominent deep reflectors crossed by the drill bit ("A" and "B" of Figure 3-2). These large overthrusts of granite over granite, however, could not explain the fine layering thought to represent sedimentary bedding in the seismic section. A dipmeter log, in which four orthogonal micro-resistivity electrode pads are pressed against the borehole wall, helped to explain this finer scale layering. The dipmeter precisely determines down to centimeter scales strike and dip of electrically contrasting units. A spectral analysis of the Anschutz well dip changes versus depth shows coherent cycles spaced every 200-300 feet varying between high- and low-dipping units (Figure 3-3). A synthetic seismogram, made with the assumption that dip changes produce reflection coefficient changes, predicts that much of the fine layering is caused by this coherent cyclicity of dip in the well (Figure 3-2). The geological cause of the dip changes must be related to mica or to other mineral elongation which is tilted by multiple, small thrust faults throughout the granitic section.

The Nellie #1 well in Pecos County, Texas, is another deep well that was drilled through igneous rock. The gabbros of an ancient magma chamber underlie the failed rift of the West Texas Permian Basin. Logs of compressional and shear sonic velocity and density and of photoelectric effect in the gabbros delineate impedance contrasts, which can account for the major reflections (A through F) seen by seismic reflection profiles near the well site (Figure 3-4). A geochemical log can be constructed from the mineralogical clustering of these log response parameters (Figure 3-4). Thus, in order to account for the reflection boundaries seen from the surface, gabbro, high Fe chlorite, and plagioclase variations down the hole are predicted.

The Seismic Stratigraphy of the Oceanic Crust

Logs are particularly useful for the identification of seismic boundaries because, unlike cores, they provide a continuous record. Impedance boundaries are made from vertically-stratified variations in the elastic properties of the rock.

The ocean crust is seismically layered. Take, for example, Hole 504B, which was drilled into 6-million-year-old crust on the south flank of the Costa Rica Rift in the eastern equatorial Pacific (Figure 3-5). This hole is both the deepest hole ever drilled in oceanic crust and that with the most complete suite of logging data. Sonic velocities through the pillows, breccias, and dikes of layers 2A, 2B, and 2C show a rather gentle change in slope from top to bottom of Hole 504B (Figure 3-5). The surface multichannel seismic section, in contrast, not only shows strong reflectors at the Moho and at layer 2-3 boundaries, but also shows dipping reflectors within layer 2 (Figure 3-6).

The Borehole Televiewer shows abrupt slope changes in most of the physical parameters at the layer 2B-2C, pillow-basalt-to-dike boundary. An impedance log from sonic and density logs shows several gentle increases in impedance within the dikes, with lower impedance "layers" found within layer 2B. These unit boundaries produce larger reflectors within layer 2B than do either the 2B-2C boundary (which is a broad slope
Figure 3-2. Synthetic seismograms generated from impedance contrasts measured by the traditional velocity and density logging data (right), and that predicted from dip changes measured by the dipmeter (left), compared to the surface seismic reflection profile across the Anschutz wellsits (center). The dipmeter impedance contrast produces more high frequency reflectors than the traditional display, as observed in the seismic profile.
Figure 3-3. Dipmeter and velocity logs (left) which were used to calculate pseudo impedance log and synthetic seismogram of Figure 3-2 at Anschutz well. Power spectrum from Fourier transform of dipmeter log shows predominant energy at 250 to 325 feet wavelengths, which produce excellent reflectors from seismic sources.
Figure 3-4. Mineralogy logs can be generated from the 'clustering' of velocity, photoelectric factor, and density log data about three endmember compositions: gabbro, chlorite, and plagioclase. A matrix inversion can be used to solve for the abundance of each lithology if the average velocity, PEF, and density of each can be specified. Here, basement well Nellie #1 in Pecos County, Texas yields logs that can be converted to a pseudo-impedance log (left) and a synthetic seismogram that predicts the reflectors A-F are caused by lithology changes indicated.
Figure 3-5. Downhole sonic velocities in the upper 1 km of basement in DSDP Hole 504B. On left is a schematic section indicating dominant lithologic units with depth. In the center are 10-m running averages of the downhole P and S velocities. On the right is a simplified velocity model where the sediment column is divided into three layers and the basement is divided into 100 10-m thick layers.
Figure 3-6. Seismic reflection profile across Hole 504B (figure 3-5).
change occurring over 100 m) or the interior of layer 2C itself (the upper section of which is predicted to be acoustically transparent; Figure 3-7).

Another form of oceanic crustal layering occurs at rifted margins where the first ocean crust is formed against stretched continental crust. The Voring Plateau was drilled on Leg 104 in an attempt to determine the cause of the prominent, seaward-dipping reflectors indicated by seismic reflection profiles across this rifted margin (Figure 3-8).

The wireline logs run in the hole showed strong physical property contrasts, with solid basaltic units of variable thicknesses separated by volcaniclastic sedimentary rock (Figure 3-9). The core alternated between basalts and volcaniclastic erosional debris from a shallow and quickly infilling ocean basin similar to that forming currently in the Red Sea. A detailed look at the logs shows that the contrasting responses to the hard basalt and to the soft volcaniclastic debris produce a cyclical impedance pattern (Figure 3-9).

A synthetic seismogram made from the impedance log (velocity times density) shows that prominent reflectors are predicted from the thickest flow basalt units (Figure 3-8). If the basaltic flows are too thin, the wavelength of seismic energy is too large to be reflected off these surfaces. The impedance match of seismic wavelength to basaltic flow thickness determines which reflectors appear on seismic across the region.

Logging in Old Oceanic Crust

Moving seaward from the earliest oceanic crust generated during rifting, Leg 102 conducted a full suite of logs at DSDP Hole 418A, drilled to a depth of 868 mbsf (324 m of sediments and 544 m of basalts) into 110-million-year-old Atlantic crust south of Bermuda. Differences in gamma ray activity allow one to separate the basement interval into three zones (Figure 3-10): an upper 64 m-thick unit (massive + slightly altered pillow basalts) showing low gamma ray values and high velocities, an intermediate 126 m-thick unit (highly altered pillow basalts and breccia) characterized by high gamma ray counts and lower velocities, and a lower unit, 274 m-thick (slightly altered pillows and massive basalts) which displays low gamma ray values and high velocities. Although velocities within the intermediate altered zone are lower than in the remainder of the hole (4.5 km/s versus 5.3 km/s), nowhere in Hole 418A are they as low as those that characterize the seismic Layer 2A. Here, alteration products such as smectite, calcite, and k-feldspar have almost completely filled the pore space, thus raising the in-situ velocities and eliminating Layer 2A as part of the crustal aging process. This hypothesis has been tested using the gamma ray curve as an indicator of alteration. In fact, because a good correlation is observed between the alteration profile obtained from cores and the gamma ray curve (Figure 3-11), this has been used to estimate the amount of smectite within the rocks and to correct the porosity measurements (Figure 3-12). The volume of smectite estimated should reflect the amount of smectite added to the crust by interaction with seawater since the basalts were emplaced at the Mid-Atlantic Ridge. Removal of smectite would leave the basalts in their original state. An upper and lower bound on the original porosity and velocity of the basement (Figure 3-13) are obtained assuming that (a) smectite replaced only part of the original porosity and (b) the original basalt matrix was also partly replaced by smectite (Figure 3-14). In the upper and lower units the reconstructed velocity is almost
Figure 3-7. Geophysical logs from Hole 504B, including fracture density and reflectivity from Borehole Televiwer imagery, clay content from nuclear, and porosity from long-spaced electrical resistivity, show gradient changes from Layer 2A downward into Layers 2B and 2C. Impedance from velocity and density produce synthetic seismogram (left) which shows strong reflector within Layer 2B, and relatively few reflectors of low amplitude within the top of the dikes of Layer 2C.
NORWAY, VORING PLATEAU
ODP SITE 642

Figure 3-8. Composite of location, seismic reflection profile, synthetic seismogram, impedance log, lithological column, and velocity-density logs of ODP Leg 104 Site 642. Major reflectors are caused by thick flow units within thinner, more interlayered units.
Figure 3-9. Geophysical logs from Site 642 (Figure 3-8). Flow basalts are characterized by high velocity, density, and resistivity values interbedded with highly radiogenic volcaniclastic levels.
Figure 3-10. Logs from ODP Leg 102, a re-entry of DSDP Hole 418A in 110 My old oceanic crust at the southern end of the Bermuda Rise. Lithologic column from cores (left) and logs (right). Note the magnetic reversal recorded with the 3-axis magnetometer.
Figure 3-11. Hole 418A, Leg 102 potassium content and total gamma ray counts plotted next to K₂O weight percent from analysis of cores. Also shown is a qualitative alteration index based on visual inspection of cores and core recovery percentages.
Figure 3-12. Summary of physical properties of basaltic rocks computed from logs at Hole 418A. Smectite volume calculation from gamma ray; total porosity from density-neutron combination after calibration and correction for smectite content; primary porosity computed from sonic log. Curves are smoothed by using a 31-point running average (5 m depth interval). PB = pillow basalt; MB = massive basalt; B = breccia.
Figure 3-13. Upper and lower bound on the original porosity and velocity of the basement at Hole 418A. The reduced velocities in 388-514 mbsf interval are consistent with seismic Layer 2A velocities previously calculated.
Figure 3-14. Model proposed to reconstruct the original porosity of the basement at Hole 418A. Replacement of the pore space by smectite (above) and replacement of the pore space plus basaltic matrix by smectite (below). $\phi =$ present porosity; $\rho_g =$ grain density of basalt; $\rho_{sme} =$ grain density of smectite.
unchanged; in the altered zone, however, the reduced velocities are in accordance with those of seismic Layer 2A.

The lower zone corresponds to the upper part of seismic Layer 2B. It does not show such extreme alteration infilling because it is composed of more tightly structured pillows and by massive units; also, there might have been a much lower initial permeability within this interval.

Permeability is measured by seating a packer across an interval of hole and pumping a small "slug" of pressure into the rock. The packer prevents the flow from returning to the sea floor around the outside of the drillpipe and forces fluid into the formation instead. The formation response to this pulse of pressure then determines its permeability. (See Appendix 1 for a description of the permeability measurement technique by Keir Becker, U. Miami).

Two other logs provided unique information at Hole 418A. The United States Geological Survey ran a magnetic susceptibility tool and the Federal Republic of Germany measured the 3 components of the earth's magnetic field with a magnetometer logging tool. Just above the layer 2A/2B boundary, a magnetic reversal was crossed, with basalts above being negatively magnetized and those below positively magnetized. Magnetic susceptibilities also change at this boundary, but they increase again 100 meters deeper in the section (Figure 3-10). This magnetic boundary is 10 to 20 m shallower than the gamma ray count change marking the layer 2A/2B boundary.

Another useful comparison between logs comes from the velocity structure of the crust measured by the two-source/two-receiver Schlumberger sonic tool (sonic velocity column in Figure 3-10) against compressional and shear velocities determined by the 12-channel sonic tool (Figure 3-10, next column to the right). Even though the general structure is similar, the multichannel sonic tool is less noisy, and bed boundaries are more precisely determined.

Intermediate-Age Oceanic Crust

Site 556 drilled in 37-million-year-old basalt to the west of the Mid-Atlantic Ridge, a DSDP hole in intermediate-age crust, yielded significant logging results (Figure 3-15). Compressional and shear velocities were measured by the Schlumberger two-channel tool, and Poisson's Ratio, combined with density, neutron porosity, and resistivity measurements, were used to identify five major lithological units (Figure 3-16): pillow basalts, massive flow units, basaltic breccia, gabbro breccia, serpentinized gabbro.

Since the latter two are thought to constitute the rock of the lower crustal layer 3, an examination of the log response within these lithologies was made. An M-N crossplot (see Chapter 2) clearly identifies clusters around which the log responses of the different units concentrate (Figure 3-17). The percentage of hydrous minerals in each lithology can then be determined from the apparent porosity differences between the sonic, nuclear, and electrical logs. As shown in Figure 3-18, the serpentinites are easily identifiable from the volume of hydrous alteration minerals. The gabbro, however, appears fresh and relatively unaltered. The serpentinites may have come close to the surface as the top and bottom of either a gabbroic intrusive sill or as a slice caught up in movement along a fault. In any event, the compressional and shear sonic energy spectra show a clear correlation with the
Figure 3-15. Location map for DSDP Hole 556 drilled at 38° 56.38' north latitude and 34° 41.12' west longitude in 3672 m water depth. Total depth drilled was 639 m, 461.5 m into calcareous sediments and 177.5 m into basalt and gabbro.
Figure 3-16. Composite logs run at Hole 556 by Schlumberger Well Services, Center: porosity (caliper hole size minus bit size), gamma-ray density, and resistivity (electrical resistivity). Right: gamma-ray density, and resistivity (electrical resistivity) were generally placed by the core recovery technicians. Lithologic boundaries were then determined from the changes in the porosity-log. Log-depths were then corrected for hole size, temperature, and pressure. Porosities are not corrected for bound water. Left: compressional and shear-wave velocity with Poisson's ratio as bold line on far left.

LITHOLOGY

PB - Pillow Basalt
MB - Massive Basalt
BB - Basalt Breccia
GB - Gabbro Breccia
SG - Serpentine Gabbro
Figure 3-17. Lithologies are identifiable on an M-N crossplot in Hole 556. S1, S2, and S3 are different sedimentary units. The igneous lithology locations other than those from Hole 556 are from oil-bearing formations in Argentina.
Figure 3-18. Clay-content log for Hole 556. Free water porosities for this hole are probably low, but the ratio is correct. Alteration has bound more water in hydroxyl minerals than is free in pore spaces in this hole. Fully 60% of the minerals in the serpentinite zones are hydrated. Clay-content log shown at right against volumes of clay on left.
degree of alteration in the deeper section of the hole (Figure 3-19). As the energy was preferentially lost in the serpentinizite alteration zones, it suggested that the origin of gabbro in the shallow oceanic crust may have been faulting. In fact, fractures are a very efficient conduit for energy transmittal away from the borehole (attenuation).

Young Oceanic Crust

Hole 504B penetrates over 1.5 km of 6-million-year-old oceanic crust in the eastern Pacific (Figure 3-5). Here the logging suite reveals three distinct layers: an upper, 150-m section of very low seismic velocity and resistivity, a middle layer of increased velocity and slightly higher resistivity, and a deep zone of high velocity and resistivity (Figure 3-7). The upper unit, even in this young crust, is highly altered, as can be seen from the neutron-density log porosity contrast. The density log sees a bulk rock density which is only lowered slightly by alteration products (the density of hydrous minerals is about 15% less dense than fresh basalts), whereas the neutron porosity reads quite high because of the abundant hydrogen present in both the pore space and the crack-filling hydrous minerals (Figure 3-18).

The most interesting section of this hole, however, is at the pillow basalt/dike transition boundary (layer 2B/2C). A massive sulfide mineralization stockwork was discovered here (Figure 3-20). This zone appears as the largest hydrous mineral content zone in the hole. Hot, upwelling, mineralized, hydrothermal fluids mixed with cold sea water at this depth in the crust to cause the deposition of this stockwork zone.

The degree of alteration in the hole also affects the sonic waveforms (Figure 3-21). Alteration content and attenuation of the sonic waveforms correlate qualitatively. Quantitative estimates of the amount of energy loss due to alteration zones of either open or filled fractures can be determined from spectral analyses of the sonic waveforms. There is over a 0.75 correlation coefficient between zones of low P and S sonic energy (measured in dB from the power spectra of the different waveform coda) and open fracture zones imaged by the ultrasonic Borehole Televiewer (Figure 3-22). Stoneley surface wave energy, and very high frequency normal modal energy and frequency changes also correlate with zones of fracturing seen by the BHTV. Energy loss and frequency shifts are likely from acoustic attenuation, or energy loss away from the borehole wall through open interconnected fractures. An as yet unsolved problem is the quantitative interrelation between acoustic attenuation and hydraulic permeability.

One of the interesting results from logging in Hole 504B was the detection of cyclicity down the wellbore. These cycles affect all the logs, including velocity, resistivity and the degree of fracturing, as recorded by the BHTV (Figure 3-23). Core recovery was <15% in the basaltic section of this hole, so the cores were not of much help in determining the cause of the cyclicity. The core did show high potassium contents in the layer 2A and upper 2B pillows, and high Fe, low Al, and low Ca in the stockwork and just below. But no cyclicity with a wavelength of 50 meters or so was detected in the chemistry from the cores.
Figure 3-19. The P energy, S energy, and alteration logs from Hole 556 were detrended, normalized, and bandpass filtered to pass only wavelengths of 20-100 ft. Note particularly strong correlation between P and S energy (arrows).
Figure 3-20. Average values in Hole 504B for NPHI (porosity calculated from the neutron log), DPHI (density calculated from the gamma-ray density log), MSI (minimum shale index from a dual-water CYBERLOOK program), NDI (hydroxyl-mineral content calculation from the differencing scheme), and core alteration. The last histogram was determined from least altered (0) to most altered (1), using visual descriptions from barrel sheets.
Figure 3-21. The raw sonic waveforms from the first receiver located 8 ft. above the source are correlated with the hydroxyl content log NDI. Blackness in the last curve is the percentage of matrix material, horizontal bars are every 10% of alteration products present (e.g., at 4100 m depth, 30% altered clays and zeolites, and 70% unaltered basalt are present in the rock).
Figure 3-22. Phase difference of TV (BHTV fractures plus voids) and P and S energy in Hole 504B. Positive correlation is between high energy and zones of low fracture level.
Figure 3-23. Band-passed velocity (solid), resistivity (dashed), and borehole televiewer fractures (dotted) logs from Hole 504B.
Nuclear Logging

Resistivity-acoustic-nuclear logs were recorded during Leg 83 through the pillow lavas of layers 2A and 2B and in the uppermost section of layer 2C dikes. In addition, during Leg 111, a geochemical logging string measured elemental abundances in the hole, allowing for the detection of cyclicity in aluminum content (Figure 3-24). The Al abundance changes appear gradual within units of a few meters thickness, whereas abrupt shifts occur between units (e.g., between 4500 m and 4700 m). The variation in Al content can be directly attributed to the plagioclase variations in the different basalt units encountered in the hole. High Al plagioclase-olivine and plagioclase-olivine-clinopyroxene phryic basalt units alternate with low Al olivine phryic basalts to cause the cyclicity (Figure 3-22). Mg/Ca versus Al/Fe has been shown to be an excellent differentiator of mid-ocean ridge basaltic magma evolution, with olivine fractionation distinctly higher in Mg/Ca than the high Al/Fe plagioclase trend (Figure 3-25). The Hole 504B bulk chemical composition shows that, although there are both phryic and aphyric units intermixed within each layer, there is a distinct trend toward the intersection of phryic and aphyric compositions toward the bottom of the hole. The dikes are the lowest Mg/Ca and Al/Fe rocks in the hole.

The Mg abundance calculated from the photoelectric effect in Hole 504B further shows characteristic "spikes" of high Mg systematically recorded throughout the section (Figure 3-24). These spikes generally correspond to the boundaries of Al units, and likely indicate the presence of Mg-clay bearing breccia zones. In addition, there is a general decrease in Mg content with depth in the well (Figure 3-24). This result contrasts with core analyses, which indicate a slight increase in Mg with depth. Cores probably represent the least-altered basalt present in the formation, while logs respond to the bulk composition of the rock.

Normative Mineralogy Log

The variation in Si, Al, Fe, Mg, and Ca recorded by the nuclear logs can be used to calculate normative mineralogy changes within Hole 504B. The distribution of minerals falls within a five-cornered solid with a major element at each point called a tri-dipyramid (a tridip diagram) (Figure 3-26). With five elements, six minerals can be calculated using matrix inversion techniques. The elemental composition of each mineral is specified from microprobe analyses of core (Table 3-1). These minerals fall within specific clusters of four-corner plots made from projected compositions for each face of the solid (Figure 3-26).

The log of mineral abundances shows two major mineralogical suites within the hole (Figure 3-27). Plagioclase + clinopyroxene + olivine forms the bulk of the formation (this is the basalt itself). A second component divides the basalt into specific units, and appears as large spikes of Mg, Ca, and Si-rich Amphibole (Actinolite in the dike section); Al, Fe, and Mg-rich Chlorite (in the dikes); Fe, Mg, and Si-rich Smectite clays (Figure 3-28).
Figure 3-24. Elemental abundances and ratios from Nuclear logs over Hole 504B basement section.
Figure 3-25. Mg versus Al and Mg/Ca versus Al/Fe cross plot for Hole 504B. Data from lower dikes. Trends and medians shown for other layers to show how composition changes up the hole. Olivine phytic and plagioclase phytic MORB basalt trends shown.
Figure 3-26. Three faces (below) of five-pointed tri-dipyramid solid (top) with mineral "cluster" locations indicated within elemental yields.
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<td>0.08</td>
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<td>0.53</td>
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<td>0.016</td>
<td>0.13</td>
<td>0.10</td>
<td>0.002</td>
</tr>
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<td>0.15</td>
<td>1</td>
<td>26.5</td>
</tr>
<tr>
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<td>10.2</td>
<td>19</td>
<td>0.01</td>
<td>0.025</td>
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<tr>
<td>Al/Fe</td>
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<td>10.2</td>
<td>19</td>
<td>0.01</td>
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Table 3-1
Figure 3-27. Normative mineral log from Hole 504B nuclear log elemental abundances and matrix inversion of normative mineral compositions shown in Table 3-1. Dark shading is abundance of actinolite and its low-temperature clay equivalent.
Summary of Logging Results at Hole 504B

The mineralogical variations in Hole 504B allow us fully to describe the geochemistry of the section through which we drilled, in spite of less than 20% core recovery. We find it remarkably homogeneous, with largely unaltered basalts separated into distinct units by breccia zones, both within the pillows and within the dikes (Figure 3-28). Basaltic chemical changes are predominantly plagioclase-olivine primary magma variations which show up as alternating zones of high plagioclase, low clinopyroxene phric basalts and high olivine, low plagioclase aphyric basalts (Figure 3-28).

In addition, the extensive volume of alteration minerals in the pillow layers 2A and 2B results in higher Mg and Fe and lower Ca content than in the dikes (Figure 3-28). This suggests that the degree of alteration is decreasing into the dikes, just as might be expected from the permeability and porosity variations which showed the dikes to be much tighter, lower porosity rock than the pillows (Figure 3-29). Fe and Ca are differently affected by alteration, with much more Ca leaving the basalt into hydrothermal fluids than Fe, which is more readily redeposited from the fluid into clays, chlorite, and other alteration products. Since the neutron activation log sees bulk chemistry, the chlorite or clay-rich breccia zones, including those at unit boundaries, are recorded as high Fe/Ca and Mg/Ca ratio areas (Figure 3-28). The increase in Fe/Ca spikes below the stockwork suggests that the alteration in the dike section is predominantly chlorite, just as was indicated by the laboratory x-ray diffraction analyses of mineralogical changes in the hole.

It is clear that the nuclear logs are sensitive to the chemical evolution of this young oceanic crust. A reasonable scenario for the evolutionary history of that crust might be as follows: Variable Al content eruption events alternated during original deposition of the 504B crust at the Costa Rica Rift ridge axis. The logs and core suggested that plagioclase changes caused these primary Al content variations. Subsequently, interaction with hot sea water began as the crust spread and aged away from the ridge crest. High temperature alteration appears to have been present throughout the dikes, but low temperature alteration trends are present within the log responses in the pillow section (the smectite to chlorite-rich clay transition. The cause of the cyclicity in geophysical and geochemical logs is the basaltic unit variation in plagioclase content of eruptive flows, pillows, and dikes, each of which is separated by distinct breccia zones.

Basalt-Sea Water Interaction

The information contained in the nuclear logs relates to bulk chemical changes occurring at the time of emplacement of the basalt from the magma chamber (plagioclase concentration changes) and to subsequent hydrothermal pore fluid-rock interactions. Expected changes are K and Mg into the rock in exchange for Ca, Fe, and Si out of the rock at low temperatures. Ca mostly exits the system in the pore fluid; whereas Fe, Mg, and Si are redeposited in vein-filling minerals. This is particularly evident in the distinct Fe/Ca and Mg/Ca spikes seen at Al unit boundary fracture zones in both wells (Figure 3-28).
Figure 3-28. Alteration state in Hole 504B shown from breccia curve (Act+Smec), plagioclase, clinopyroxene, Mg, Al, smectite, chlorite, Mg/Ca, and Fe/Ca abundances derived from Nuclear Logs.
Figure 3-29. CDP Leg 111 geophysical experiments in Hole 504B. Left to right: bulk permeability measured by the packer experiment, fracture and total porosities determined from electrical resistivities, normative mineralogies and relative Mgo and Al2O3 contents determined from spectral analysis of neutron activation logs, and magnetic inclination. Normative mineralogies were determined by recalculating elemental contents of Si, Al, Fe, Mg, and Ca into the normative components actinolite (ACT), chlorite (CHL), plagioclase (PLAG), clinopyroxene (CPX), olivine and smectite, assuming typical local compositions for the normative minerals. Normative plot units indicate the fraction (1 signifies 100 normative weight percent) of the rock formed by each normative component. Relative contents of Mgo (MG) and Al2O3 (AL) were shown as counts, where 1 signifies the maximum observed. Average amount of Mgo is 7 weight percent, and of Al2O3 is 22 weight percent. ST denotes the 10 m thick stockwork-like unit.
The relative chemical exchange budget can be calculated from the bulk rock elemental abundance changes. The estimated weight percent exchanges between sea water and basalt in Hole 504B are less than 0.01% K, but more Mg (1.8%), entering the rock, and 2.2% Ca, 4% Fe, and 1.9% Si exiting the system. These fluxes compare favorably with the ridge axis exchange fluxes measured from hydrothermal waters currently being exhumed by the newly forming oceanic crust (Table 3-2). Ca, Fe, and Si are all greater in the hot spring fluids than bottom sea water, with most of the Fe forming pyrite and other sulfide mineralization on and below the sea floor (the stockwork).

In conclusion, the Nuclear Logs are a powerful geochemical tool, which, combined with the full suite of geophysical logging tools, will add to the scientific insights possible from future drilling into oceanic crust.
Table 3-2. The fluxes of dissolved chemical species into and out of the ridge axes.

<table>
<thead>
<tr>
<th>Species</th>
<th>Ridge flux mol/a</th>
<th>River flux mol/a</th>
<th>Ridge/River</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>$1.25 \times 10^{12}$</td>
<td>$1.9 \times 10^{12}$</td>
<td>0.66</td>
</tr>
<tr>
<td>Mg</td>
<td>$-7.7 \times 10^{12}$</td>
<td>$5.3 \times 10^{12}$</td>
<td>-1.4</td>
</tr>
<tr>
<td>Ca</td>
<td>$2.4 \times 10^{12}$</td>
<td>$12 \times 10^{12}$</td>
<td>0.4-0.2</td>
</tr>
<tr>
<td>Mn</td>
<td>$6.18 \times 10^{11}$</td>
<td>$4 \times 10^{9}$</td>
<td>15-45</td>
</tr>
<tr>
<td>Si</td>
<td>$3.1 \times 10^{12}$</td>
<td>$6.4 \times 10^{12}$</td>
<td>0.48</td>
</tr>
</tbody>
</table>
Chapter 4

Stratigraphy and Sedimentation

The two major physical determinations made from logging data are lithology and porosity. These, in turn, carry information about the stratigraphic sequence penetrated by the drill bit and the sedimentology surrounding the drillhole. In order to make general geological conclusions from logs, they must be tied to core results and to seismic information.

Sonic waveform analyses, electrical resistivities, natural gamma ray counts, neutron porosity and bulk density logs combine to provide sedimentological, as well as physical property information about the rock. Consider DSDP Site 613 in the Baltimore Canyon area offshore New Jersey. Here, the density and the compressional velocity logs show an interesting inversion between 2600 m to 2775 m below rig floor (100 to 325 m below sea floor) (Figure 4-1). Below 2775 m there is the typical increase in both velocity and density with depth. Laboratory measurements on recovered core (small dots of Figure 4-1) are consistently lower than the log values, as can be expected in soft, surface sediments with 50-70% porosities. In fact, this velocity and density inversion might not be believed without corroboration from the logs.

The very low velocities and densities are accompanied, surprisingly, by very high sonic amplitudes (Figure 4-2). A Hilbert transform breaks the incoming sonic waveform into complex and real components, which permits displays of changes in instantaneous amplitude and frequency as different waveform energy packets arrive at the receiver. This seismic technique is particularly useful for differentiating coda within the waveform. The Hilbert-transformed amplitude envelope clearly shows the unusual characteristic of the faster velocity section below 2775 m being also of lower amplitude than the slower formation above (Figure 4-3). Such an amplitude-velocity anomaly is caused by diagenesis at this well site. The slower, lighter sediments above the diagenesis boundary must be rigid enough to pass energy efficiently, though slowly. Below, the energy must pass quickly, but be attenuated severely by the sediments. Electron microscopy analyses of the core show the diagenetic origin of this particular anomaly. Above the boundary, forams and radiolarias form a "hollow sand" matrix with high porosity, low density, and a rigid, "slow but loud" latticework. The spaces within the forams and radiolarias are all filled with pore water. At 325 m below the sea floor (2775 mbrf), the pressure and temperature increases enough so that the silica dissolves from the rad shells and reforms within the foramin shells. Suddenly, there is a high density, high velocity matrix, but the new latticework is not nearly so well interconnected. Energy loss increases even though the sonic velocity also increases.

We can observe this decrease in rigidity directly from further analysis of the Hilbert-transformed sonic waveforms. Ordinarily, the shear wave is not recognizable in soft sediments because if it is excited at all, it travels at slower velocities than the direct water wave moving down the wellbore from source to receiver. Since the water wave is of large
Figure 4-1. Velocity and bulk density from logs, DSDP Leg 95, Site 613. Dots are measurements made on recovered core. Bars are five meter averages of log data.
Figure 4-2. Sonic waveform log of DSDP, Leg 95 Site 612. There is no recognizable S-wave between the first-arriving compressional wave and the highest amplitude Stoneley wave from the near 8’ receiver.
Figure 4-3. Hilbert transform of sonic log waveform, DSDP Leg 95 Site 612 yields envelope of instantaneous amplitude spectrum. Note that though velocity increases at 2750 m depth (arrival time decreases) and amplitude decreases for the receiver 12' from the source.
amplitude, the shear wave arrival is masked. There are surface normal modes, called pseudo-Rayleigh waves, which are induced in boreholes through soft sediment and travel at about 95% of the velocity of the shear wave. Their frequency, and that of the shear wave itself, are higher than that of the water wave. A Hilbert-transformed instantaneous frequency analysis of the sonic waveforms across this diagenesis boundary shows a clear shear or pseudo-Rayleigh wave arriving at 1800 to 2000 microseconds travel time, from which Poisson's Ratio can be estimated (Figure 4-4). The high Poisson's Ratio above versus below the diagenesis boundary (slower P wave but same S wave velocity above) verifies the conclusion that the lattice work is less rigid after dissolution than before.

An inverted depth-porosity sequence is also found at Site 647 in the Labrador Sea, drilled on ODP Leg 105. Here porosities detected by the resistivity log increase to >80% 125 m below the sea floor (Figure 4-5). Porosities appear to be 60% both above and below this 125-m-thick interval. The core results showing the same porosities might not be believed without independent corroboration from the logs. A lowered natural gamma ray output of the sediments suggests lower clay content. The high porosities are from a diatomaceous ooze layer, which supports extremely high porosities within its shell structure.

At Leg 105 Site 646, again in the Labrador Sea, we see a clear lower boundary to the high porosity diatom layer at 335 mbsf (Figure 4-6). Notice, however, that the Th/K ratio is higher in the diatom layer than below. We suspect, therefore, a change in clay type across the transition from high Th to low Th clay. Rather than crossing a diagenesis boundary at 335 m, which would not affect the Th/K ratio, we conclude that the zone of upwelling nutrients responsible for the abundance of diatoms moved away from the well site at the age of the transition sediments. Such a change in oceanographic currents carries climate information, as we will see when we return to this site in the stratigraphy section of this chapter.

Diagenetic information of another kind is found in the sedimentary column at Hole 504B in the eastern Pacific. In order to drill a deep basalt hole, casing was set before logging the sediment section. At Hole 501, a few hundred meters to the west, the youngest occurrence of chert in the oceans was found during DSDP Leg 68. The extent of the chert layering was hinted at by the Borehole Televiwer imagery, which suggested that the apparently thick chert layer was instead composed of numerous thin chert stringers. The thickest chert layer imaged was only 3 m thick (Figure 4-7). The hydrology of the basement at Hole 504B depends on the extent to which the ocean crust's hydrothermal convection system is sealed off from the ocean by an impermeable sedimentary cap. Obviously, a continuous chert layer is an excellent hydraulic seal. The geophysical measurements in Hole 504B suggest that drilling penetrated just such a cap, with the basement convection system isolated from the ocean so that large underpressures below the hydrostatic built up beneath the chert. Consequently, ocean bottom water began flowing into the basalt once the chert lid was penetrated.

On ODP Leg 111 geochemical logs were recorded through the cased-off sediments at Hole 504B. While there was a clear signal of high sulfur content from the gypsum in the casing cement, numerous thin chert layers high in Si were recorded within 100 m of basement (Figure 4-8). The thickest was 2 m, and the most numerous zone was 50-75 m above basement. The similarity between chert layering at holes 501 and 504B suggests at
Figure 4-4. Instantaneous frequency from Hilbert transform of sonic waveforms (near receiver), DSDP Leg 95 Site 612. Note S-wave identifiable from departure of frequency packet at 1900 microseconds arrival time (2725 m) from the trend of the P-wave energy.
Figure 4.5. Gamma ray, porosity from electrical resistivity and sonic travel time from logs, ODP Leg 105 Site 647, Labrador Sea. Pluses are porosity measurements from core. Note porosity and travel time inversion at 125 mbsf.
Figure 4-6. Gamma ray, Thorium, Potassium (K), sonic travel time and porosity from resistivity log, ODP Leg 105, Site 646.
Figure 4-7. Borehole televiewer imagery at DSDP Site 501. The horizontal axis represents the televiewer sweep azimuth around the borehole; horizontal exaggeration is 3:1. Strongly reflective of the borehole is shown in white; weak reflectivity is shown in black.
Figure 4-8. Neutron activation log of sedimentary section of Hole 504B, ODP Leg 111, done through casing. Chert stringers are indicated by abundant silicon zones (black bars). The clay-rich zone is shown by the high level of potassium at 3570 to 3642 m.
least local continuity of the chert beds and large underpressures within the crust which were probably supported by this relatively impermeable cap.

Logs and Stratigraphy

The stratigraphic sequence penetrated by the drill bit is both the most frequent drilling target (usually based upon seismic reflection interpretations), and the hardest to decipher purely from cores. Consider, for example, the Baffin Bay Site 645 of Leg 105. Somewhere between 3.1 and 3.3 seconds of two-way travel time on the seismic reflection profile across the drill site is the onset of ice rafting, which marks the last retreat of an ice cover on the Northern Baffin Bay (A-B of Figure 4-9). This major reflector is a marker horizon for the whole area. The drilling mission was to determine the exact stratigraphic sequence accompanying the proposed onset event.

Two attempts were made to core through the suspected reflector event with little to no core recovery. Where is the onset, and why was the recovery so poor? The suspicion onboard the JOIDES Resolution was that the interval was sand-rich and that the sand was washing out.

The gamma ray log indicated that the interval was generally clay-rich, with perhaps two thin sand units, which were indicated by low gamma ray values at 360 mbsf and 390 mbsf (Figure 4-9). The resistivity and velocity logs suggest, however, that a major impedance boundary is located at the deeper sand-rich interval. This is the onset reflector for ice rafting. X-ray diffraction data on recovered core, representing a substantial effort to obtain clay mineral contents (right in Figure 4-9), does not recognize this boundary, but erroneously puts it at either 350 m or 430 m depth. Contrast these spot readings with the continuous log results. The core and log results are each mutually supporting. It is the combination of core and log data which gives the true stratigraphic sequence at Site 645.

The sonic and density logs produce an impedance contrast which can be used to generate a synthetic seismogram explaining remarkably well the observed reflection profile (Figure 4-9).

One has to be extremely careful about inferring seismic reflectors from core changes, because nearly all seismic reflectors are interference patterns. The thickness of a given impedance contrast versus the particular wavelength of seismic energy can have as much to do with the strength of a reflector as with its stratigraphic contrast. An high-frequency water gun can see a different set of reflectors from those produced by a low frequency air gun.

There are two additional logs which are useful when deciphering the correlation between the velocity-density impedance log and the seismic reflection record. The Multichannel Sonic Tool (MCS) gives highly accurate interval velocities, and the Well Seismic Tool (WST), a downhole hydrophone, receives low frequency seismic energy from the surface and transmits the signal up a logging cable. The latter can also record reflections from below total depth in the well, and so is extremely useful for identifying how much more drilling is required to reach a particular reflection horizon beneath the bit.
Figure 4-9. Top, seismic reflection profile across ODP Leg 105 Site 645. Bottom, seismic reflection section A-B (see above), compared to impedance log and synthetic seismogram (center) from velocity and density logs. Clay mineral content from natural gamma ray log compared to core measurements (dots) and core recovery (right). The major reflector seen on the seismic section can be clearly identified in the logs as a high gamma ray, clay-rich zone at 370-380 mbsf. Core from that reflector horizon can then be identified.
Stratigraphic Cycles and Milankovitch Climate Changes

Causes of long-term changes in ocean circulation and how they relate to climate and earth orbital parameter changes are first-order problems to be addressed by ODP. How the circulation pattern of the oceans changes with time in response to orbital changes will allow us to carry back in time the climatic history of the planet. Deep-sea sediments record these changes within their stratigraphic record, and logs form an important methodology for detecting these changes. The problem requires a continuous stratigraphic record of the well in order to track movements of upwelling zones, boundary currents and cold versus warm water cells. Cores have time gaps caused by imperfect recovery. Even hydraulic piston coring, which returns >95% of the cored interval, requires costly and time consuming double, and sometimes triple, overlap because the critical boundary is invariably in the missing section. Logging, however, returns a continuous set of measurements every 15 cm with standard logs, and every 2.5 mm with ultra-high resolution electrical resistivity imaging.

The response of glaciers to climate change has led to identification of cold and warm water cycles in oxygen 18 isotopic variability in deep-sea sediments, which have major correlation peaks every 19, 24, 43, and 106 thousand years (Figure 4-10). Earth orbital parameter variations are thought to drive these climatic cycles (collectively known as Milankovitch cycles; Figure 4-10). Eccentricity changes at 95 thousand years, obliquity at 41 thousand, and precession changes at 19 and 23 thousand year intervals were recognized by Milankovitch in the 1940's. These changes are thought to drive the climatic history of the earth. Verification of these cycles back in time is a major mission of stratigraphic work carried out on the JOIDES Resolution.

A mission of drilling in the Labrador Sea on Leg 105 was to track the movement of an upwelling zone across the drill site from the Paleocene to the lower Pliocene. Logs run in the hole recorded cycles which are clearly correlatable with the main Milankovitch climatic cycles (Figure 4-11). At Site 646, the diatoms above the major sedimentation boundary at 335 m record a change in porosity caused by fluctuations in the latitude of the center of the upwelling zone across the well site prior to 2.8 million years ago. This change produces variability of over 15% in porosity, an easily detectable change in resistivity and sonic logs run in the hole. The extremely high sedimentation rate of 100 m/my makes the wavelength of each cycle easily detectable within the resolution powers of the logging tools to periods of 41,000 years. The log cycles versus depth must be converted to cycles versus time by age-dating the core and, subsequently, determining the sedimentation rate.

The sensitivity of the standard logs to porosity cycles can be seen by examining the porosity changes encountered below the diatom rich layer, where the sedimentation rate falls to 52 m/my. The cycles versus depth are condensed (Figure 4-11), and the sonic log detects the 41,000 year period, but the resistivity tool does not. The vertical resolution of the sonic tool is about half a meter, whereas the resistivity tool averages values over about one meter surrounding the logging tool.

Ordinarily, the usefulness of logging tools to detect Milankovitch climate cycles is reduced in low sedimentation regions because of the lack of vertical resolution that we mentioned above, but the recent move toward high resolution logging tools has quickly
Figure 4-10. Top: Power spectrum of the climatic changes from $\Delta^{18}$ changes plotted against the frequency of occurrence. Peaks in power at 106,000, 43,000 and 24,000 years mean that glacial events are likely to occur with this cyclicity. Milankovitch calculated cyclicity of the Earth's orbital changes that match the periodicity of glaciers over the last few hundred thousand years. There is a delay between changes in the orbit and the onset of glaciation that would be expected.
Figure 4-11. Porosity from electrical resistivity log, ODP Leg 105 Site 646 (left). Power spectrum from Fourier transform of porosity log above 340 m shows major energy peaks at 95,000 and 41,000 year periods (right, top). Sedimentation rates are from core paleontology. Spectra of porosity and velocity logs below 340 m show peak energy at 410,000 and 95,000 year periods (porosity log) and 95,000 and 41,000 years (sonic spectrum dotted). Sedimentation rate changes from 100 m/ma (top) to 52 m/my below 340 m. The periods of dominant log energy are similar to cycle periods from Milankovitch climate changes.
improved the situation. For example, Site 646 was the first for which the geochemical tool was available for routine ODP use. The calcium/silicon compositional variation curve from this nuclear log has a resolution of 1.5 cm, so both the 19,000- and 23,000-year cycles were recognizable within the spectra of the calcium and silicon abundance logs (Figure 4-12).

The utility of such time series logging extends beyond climate-cycle identification. If a clear Milankovitch cyclicity can be established, then the cycles can be counted with depth to give the logs an ability which they never had: age dating. We can assume, for example, that each major peak encountered down the well at Site 646 is an added 95,000 years of stratigraphic time-progression.

The New Formation Microscanner

One new tool, for which ODP has a great need, is the Formation Microscanner (FMS) from Schlumberger. Because its diameter, however, is too large to be lowered through the drill pipe, efforts are underway to modify it. (Note: the redesigned Formation Microscanner has been routinely used in ODP boreholes starting with Leg 126).

The FMS is a four-arm dipmeter, with 16 high-resolution electrodes on each pad (Figure 4-13). These buttons measure the changes in formation electrical resistivity to such fine resolution that an electrical image of the rock encountered by the pad can be produced (Figure 4-14). Fractures, dipping beds and major porosity changes are detectable with the ample resolution of this tool, which makes it a powerful dipmeter as well as a potential age-dating log for the future. For example, consider drilling into a delta to find patterns of deposition. Two other cycles are superimposed upon those induced by the river: climate and the closely related fluctuations in sea level. Ultra-high resolution logs might allow one to identify and filter out the climate and sea level peaks from the spectrum of the log, leaving a clearly attributable signal of the past movements of the delta.

Additionally, the combination of FMS and neutron-activation logging will allow for the identification of chemical changes seen in the layering. Figure 4-15 shows a set of beds dipping 45 degrees to the north-northeast (tadpole plot at left) cut by a vertical, healed fracture (image at center). The beds are identified as being composed of alternating layers of Ca rich calcilutite and Si rich calcisiltite from the neutron activation log.

Major stratigraphic and sedimentological missions of ODP not only benefit from logging, but probably could not be accomplished without logging. Logs provide the essential addition to core of a continuous time series measurement of the geology of the borehole wall. Together, continuous core and continuous logs give the best possible methodology for solving the remaining geological problems to be addressed by ODP.
Figure 4-12. Neutron activation log measures sedimentary parameters with greater resolution than resistivity or sonic logs. Power spectrum of calcium/silicon elemental abundance ratio, ODP Site 646, shows prominent energy peaks at 19,000 and 23,000 years as well as 41,000 and 95,000 years. Again these are periods of Milankovitch climate cycles.
Figure 4-13. Tool configuration of Schlumberger's advanced formation microscanner (courtesy of Schlumberger).
Figure 4-14. Resistivity changes are measured over such short spacing (0.15 cm) that images can be reconstructed of the electrical resistivity of the wellbore wall.
Figure 4.15 Dip, resistivity traces, formation microscanner images and core for comparison of imaging ability of Formation Microscanner (courtesy of Schlumberger).
Chapter 5

Logging in Subduction Zones

The continental margins of the Earth are formed by three tectonic processes related to the present and past movements of the plates: 1) shear motion such as that occurring along the west coast of California associated with slip along the San Andreas Fault, 2) passive subsidence since initial rifting of a continent such as that occurring along the east coast of the United States, and 3) accretion from subduction of one plate beneath another such as the volcanicity and associated tectonics of the northwestern United States. Logs add important information about the geological processes prevalent in each of these environments. Because much of the destructive earthquake activity and volcanicity is associated with subduction tectonics, we will examine the usefulness of logging in such areas first.

One major objective of ODP is to study the accretionary processes that add sea floor sediments and crustal rocks to the edges of continents at subduction zones (Figure 5-1). Previous DSDP results from offshore Japan and Guatemala show that both erosion of continent and accretion to continent can occur at subduction zones. The pressure, flow and composition of pore fluids provides one important control for these processes, and logs are extremely useful for the quantitative study of such fluid-rock interactions (such as overpressure).

Consider the Guatemala Trench drilled on DSDP Leg 84. One of the few complete suites of Schlumberger geophysical logs recorded during DSDP was run in Site 570 in the forearc region of the subduction zone (Figure 5-2). Evidence of overpressure was found in both cores and logs. Clathrates, or frozen methane hydrates were cored from a 10 m thick interval about 250 m below the sea floor, and the logs recorded low gamma ray, very high electrical resistivity, fast velocities and very low densities in this interval (Figure 5-3). These hydrates are in an otherwise uniform lithology of grayish green to olive mudstones. The frozen hydrates are at the appropriate thermodynamic conditions for their formation: cold temperature, but high pressure, and are a common and unremarkable occurrence in accretionary prisms.

Of particular interest is the zone from below the hydrates to basement. The standard log response in a well is decreasing porosity with increasing depth from the sonic, resistivity and density logs. This normal compaction process is evident in the logs above the clathrate zone (Figure 5-4). Below the clathrate, however, the relationship between porosities determined from the three different logs is reversed. Low density-determined porosities correlate with high resistivity-derived and sonic-derived porosities. Such log responses characterize unconsolidated zones in sedimentary basins and indicate the presence of overpressure. The clathrates appear to be an impermeable cap trapping excess pore pressures which in turn appear to extend downward even into the serpentinite basement rocks at Site 570 (Figure 5-5).
Figure 5-1. The structure of all subduction zones is generally the same, with an accretionary wedge of sediment from the ocean basin being offscraped onto the landward plate. A forearc basin forms when sediments from the volcanic island arc are ponded between the accretionary wedge and the arc. Decollement faults are found within the accretionary wedge (heavy black lines).
Figure 5-2. Sketch map of the Middle America Trench. DSDP Leg 84 rectangle shows the location of the Guatemala transect drillholes, and the smaller square represents Site 565 off Costa Rica.
Figure 5.3. Caliper, gamma ray, laterolog electrical resistivity, sonic velocity and density from logs of DSDP Site 570, Leg 84, offshore Guatemala. Clathrate zone of frozen gas hydrates at 1965 m on logs (above) is seen in core (below).
Figure 5.4. Cross-plots of porosities calculated from density and resistivity logs (top), DSDP Site 570. Excess pore pressures trapped beneath the gas hydrate cap produce high density-derived porosities and low resistivity-derived porosities. Crossplot of porosities derived from density and sonic logs, DSDP Leg 84, Site 570 (below). Excess pore pressures beneath clathrate cap cause high apparent density-derived porosities and low sonic-derived porosities.
Figure 5-5. Left, sonic, resistivity, density and neutron porosities from Site 570. DSPHI and RPHI are density-sonic porosity and density-resistivity porosity differences. LLD and LLS are deep and shallow Laterolog resistivities, and the difference is shown as DELTAR. CEDA is compressional energy difference between waveforms 1 (CEW1) and 2 (CEW2). PPRA is averaged compressional spectrum center frequency.
Density-derived porosity is calculated from bulk rock densities, and excess pore pressures lower the whole rock density. That is, overpressures lower the bulk density and therefore raise the porosities calculated from the density log. In contrast, resistivities and velocities are significantly raised by excess methane hydrate present in an overpressure zone, and porosities so calculated are very low. The differences between sonic-derived versus density-derived porosities and resistivity-derived versus density-derived porosities are excellent indicators of overpressures from methane hydrates (Figures 5-5 and 5-6).

The degree of overpressure appears to drop exponentially beneath the clathrate cap (Figure 5-5). This is an indication that overpressures are trapped beneath the clathrate cap. Also, there is a marked difference between shallow and deep Laterolog resistivities, which indicates that the pore pressure near the borehole is less than that far from the borehole. That is, there is pressure release into the borehole. The overpressure itself cannot be very large, however, because the lithostatic pressure from 250 m of sediments with 55% porosities is only 7 bars above hydrostatic pressure. If in situ excess pore pressure were to exceed this value, hydraulic fracturing of the overlying cap rock would be likely.

Another indicator of overpressure is the attenuation effect of excess pore pressures on the transmissivity of sonic energy. The spectral analysis of compressional sonic waveforms shows an energy drop and center frequency increase in the higher pore pressure section of the well (Figure 5-5). The increased attenuation is likely caused by the decrease in contact-point rigidity of the matrix caused by the increased pore pressures. A crossplot of center frequency versus density shows an increase in frequency abruptly at the clathrate boundary, then a gradual decrease in center frequency with continued depth as the excess pore pressures decrease back to normal (Figure 5-6). This phenomenon is caused by the 'filter-characteristics' of the overpressured zone. Higher frequency energy is preferentially passed as low frequency energy is lost in the larger volume of pore spaces separating the rock matrix.

The processes which deform sediments from the subducting plate during subduction-related accretion are driven by excess pore pressures. That is, mobility of thrust sheets depends upon reduced shear strength from increased pore pressures. The source of the water is the compaction process itself, and that force is from plate convergence (Figure 5-7). The example above, though for a specialized segment of the overpressure problem, demonstrates the utility of logs for quantitative descriptions of pore pressures encountered during drilling.

Volcanic Processes at Subduction Zones

At subduction zones, cold lithosphere is underthrust back into the hot mantle, cooling it somewhat. Yet this mechanism produces most of the volcanoes active on the Earth's surface. Further, most of the violent eruptions in human history have come from volcanoes positioned above subducting lithosphere. Both the violence, and more fundamentally, generation of the magmas are thought to be related to volatiles released during dehydration of the oceanic crust at considerable depths beneath volcanic arcs during subduction (Figure 5-8).

This volcanic process is still poorly understood, however. For example, we know little about the mechanism or the timing of the magma ascent above slabs. Logging delivers
Figure 5-6. Compressional wave center-frequency crossplotted versus density from logs of Site 570. 1 is above the clathrate, 2 is the clathrate zone, 3 is from overpressured zone just beneath gas hydrate, and 4 is in basement.
Figure 5-7. Subduction scrapes off soft sediments into an accretionary wedge of inverted stratigraphy. The sediments nearest the surface are often the oldest, with new sediments from the plate being added to the bottom of the pile. The wedge must grow greater than 30 km thick before its height overcomes its increased weight and the prism breaks the surface and becomes land.
Figure 5-8. The detailed structure of a subduction complex.
useful information about the timing and composition of volcanic eruptions from long ago in geological history. Interestingly, this information is often recorded not in lava flows, but in ash layers and volcaniclastic sediments deposited long distances from the volcanic source.

ODP Leg 107 Site 651 drilled in the Tyrrhenian Sea between Italy and Sardinia in the Mediterranean Sea (Figure 5-9). The Tyrrhenian Sea is a back-arc basin formed very recently by sea floor spreading behind the northwest dipping subduction zone beneath the boot of Italy. As such, its geometry is similar to other back arc basins such as the eastern Caribbean, Scotia Sea, and Banda Sea (Figure 5-10). Active volcanoes surround the basin on three sides.

One mission of the drilling was to determine the relative importance of volcanic sediment versus pelagic carbonate deposition in the newly opened basin. Core recovery averaged about 40%, and most was a carbonate rich, fine grained mudstone. Few volcanic sediments were recovered.

The logs run in the hole indicate instead that the predominant sediment at the site is not carbonate, but volcaniclastic rich in potassium, uranium and thorium (Figure 5-10). Velocity, density, neutron porosity and electrical resistivity log responses were used to perform an analysis of the lithology of the well. The results suggest four major layers of extensive volcaniclastics were deposited within the upper 300 m of sediments at Site 651 (Figure 5-11). Carbonate variations in the core results do not clearly define these layers, but in retrospect, support the log interpretation.

There appear to be four separate eruption-frequency peaks: near 140 m, 180 m, 250 m, and 290 mbsf (Figure 5-11). Sediment ages from paleontological analysis of recovered core from near these ash-rich intervals date them crudely at 180,000, 330,000, 500,000, and about 700,000 years before present. The logs are recording evidence of massive eruption events on the continents surrounding the Tyrrhenian Sea. The thick layers of ash concentrated at these four depths require multiple eruptions from multiple volcanoes to produce the thicknesses observed.

We have little other geological evidence of such long-term periodicity of volcanic eruptions in arc volcanoes above subduction zones. How the cycles relate to the subduction process and its accompanying supply of volatiles into the mantle remains unknown. The logs do, however, carry further evidence about the place of origin of the ash. Uranium/thorium levels in volcanic provinces surrounding the Tyrrhenian Sea show two provinces (Figure 5-12). The high U to Th ratio of the volcaniclastics indicate that they originated from the northern Roman Province to the north of the drill site, rather than from the Province to the southeast. The logs even contain data pertaining to the prevalent wind and ocean circulation patterns over southern Italy over the past one million years: from the north rather than the south.

Logs have only recently begun to be applied to subduction zone problems, but their ability to deliver a continuous measure of physical and chemical parameter variations with depth promises to add considerably to our understanding of forearc, arc and back-arc processes. We have a particular need for data on the timing and variability of subduction zone events such as, for example, the beginning and subsequent cessation in back-arc spreading.
Figure 5-9. Location map of holes drilled in the Tyrrhenian Sea during ODP Leg 107.
Figure 5-10. Structure of the Tyrrhenian Sea (top left) is similar to other back-arc basins such as the Carribean (bottom left), Scotia Sea (top right), and Banda Sea (bottom right).
Figure 5-11. Logs from Leg 107, Site 651. Carbonate content from limited core recovery (center) cannot discriminate volcaniclastic cycles determined from logs (right).
Figure 5-12. Possible volcanic sources for volcaniclastic ash layers deposited in Tyrrhenian Sea.
Chapter 6

Rifting and Subsidence of Continental Margins

The early rifting history of continental margins remains one of the outstanding problems of the Earth Sciences. Such events are important not only because they are the mechanism by which new oceans are formed and continents are torn apart, but because the heat and desiccation which accompany rifting produce the hydrocarbon maturation and eventual structural traps (salt domes) for many of the world's oil and gas deposits.

Ocean drilling is the only way to study this process in detail because the predominant forces involved come from great depth and a continuous depth section of the well is recorded. Below, we discuss the methodology to use geophysical and geochemical logs both in newly rifted and old, well developed sedimentary basins. In the latter case, the determination of the relative importance of the major forces driving subsidence of a basin are emphasized.

The Rifting Event

The predominant forces involved in the rifting of continents are extensional. Continents are pulled apart by deeper seated processes acting on entire plates. The evidence for this is the prevalence of normal faulting, and the thinning of the continental crust which comes from stretching. This stretching event brings the asthenosphere closer to the surface, until eventually, no continental crust remains. A new ocean basin then begins to form with sea floor spreading producing normal oceanic crust and mantle.

The stretching process is recorded in the sediments deposited in the graben formed by brittle failure caused by stretching (Figure 6-1). The rift zone topography very much approximates that of a mid-ocean ridge rift valley.

It is these syn-rift sediments, rather than the post-rift sediment which yield most geological information about the stretching process. ODP Leg 107 drilled Site 652 into the pre-, syn-, and post-rift sediments of a tilted block of the lower continental margin of eastern Sardinia (Tyrrhenian Sea; Figure 5-9). The sequence logged through the upper Miocene (Messinian) consists of thin alternations of gypsum- and carbonate-bearing sandy silts or sands, and less calcareous clays and muds. These are separated from a similar sequence, richer in gypsum and anhydrite, by a polygenic pebble horizon, about 15 m-thick. The entire sedimentary sequence is barren, and likely deposited in a shallow lacustrine environment during the early stages of rifting.

Neutron activation logging through the Messinian section of the well from 200 to 350 mbsf recorded Fe, Ca, Si, H, and Cl variations through the hole. Ratios of these curves (Figure 6-2) were calculated for a better identification of the lithologic changes. High Fe and Si layers (corresponding to high IIR and LIR) can be observed within the dominant
Figure 6-1. Left: Syn-rift sediments are deposited into a new forming basin, which is caused by the stretching of continental crust. Right: Post-rift sediments are deposited into the new ocean basin, as extension by sea-floor spreading takes over after continental stretching is complete.
Figure 6-2. Neutron activation log from Site 652, Leg 107. IIR (iron indicator) = Fe/Si+Ca; PIR (porosity indicator) = H/C1; LIR (lithology indicator) = Si/Si+Ca; GIR (gypsum indicator) = S/Ca+S1. Clay-rich levels, interpreted as cycles, are marked by black bars.
high Ca (low IIR and LIR) carbonate section. These layers have been interpreted as clay-rich levels. Since during the Messinian the Mediterranean desiccated and evidence of fluctuations of the sea level due to evaporation or influx of water from the Gibraltar Strait are frequently recorded in the sedimentary sequences, the deposition of these clay-rich layers might have been climatically controlled. As alternative, they might represent occasional deeper water erosional infilling from the surrounding continent which rapidly fills the newly forming basin whenever it suddenly deepens from rift related subsidence. On the other hand, the coarser grained carbonatic sediments deposited when the basin remained passive for long periods of time.

This observation can be directly tied to stretching models of continental rifting, since these models predict exponential subsidence accompanying the rifting and stretching process. The logs add to the models in that the clay layers are possibly infilling events caused by rapid subsidence, or "jerks downward". The carbonatic deposition occurs when subsidence is passive, and slow enough to allow uniform carbonate sedimentation. This active downthrow is likely accomplished along basin boundary faults. The fact that the depth interval between turbidite events is decreasing uphole suggests that stretching is slowly progressing from long-spaced jerks to shorter, more frequent jerks culminating in steady-state spreading or that the sedimentation rate has decreased upward in the section. The observed periodicity in subsidence and sedimentation is consistent with stretching models, but adds detail to the models not seen in either seismic reflection profiles from the area, or in the core from the well.

Backstripping and the Subsidence History of Rifted Margins

The vertical movements detected in the rifting stage by the logs from the Tyrhenian Sea continue to a lesser extent throughout the evolution of a continental margin. It is this subsidence which drives the formation of sedimentary basins, since the accumulation of sediment itself requires only proximity to an erosional source (continents) and a depression in which to accumulate (the newly deepening basin). Although the load of a massive sedimentary pile drives the basin to sink further, it is the tectonic subsidence which provides the continued downward force responsible for the primary accumulation of the sedimentary section.

The force driving tectonic subsidence is thermal contraction from cooling of the lithosphere after the heating event which results in rifting. The development of models to describe the history of this heating and subsequent cooling event is an area of intense research at the moment. Complexities such as multiple heating pulses and complicated subsidence histories must be delineated before the origin and causes of continental rifting can be understood. The North Sea, for example, is a basin which underwent multiple heating events. The hydrocarbon accumulations associated with North Sea traps, and other tectonically subsiding basins of the world, owe their thermal maturation to these heating events.

The prediction of where new accumulations of hydrocarbons might be found depends upon an understanding of the thermal history of a rifted continental margin. Consider the east coast of the United States. There are large hydrocarbon traps to be found within the more than 10 km of sediments in this basin which resulted from the cooling and subsidence
of continental margin crust rifted from Africa in the Jurassic. Was there enough heating from initial rifting to mature hydrocarbons to fill these traps?

In fact, there are three inter-related forces which result in subsidence of an old margin such as that offshore New Jersey: thermal cooling, thinning of the crust itself so that the cooled crust returns to a lower base level than it started, and loading from the sediments which fill any depression in the surface of the Earth (Figure 6-3). Maturation depends only on the first of these forces, thermal heating and cooling.

The eastern U.S. coast consists of many structures which would ordinarily provide traps for hydrocarbons. A prominent reef accompanied by diapirs exists on the edge of the margin (Figure 6-4). These are two of the most prolific trapping mechanisms known. The question is whether the margin was stretched sufficiently to heat the sediments to maturation. In order to answer this question, the amount of stretching and thermal subsidence must be measured in logs from wells.

Logs provide the crucial information to "backstrip" a margin. Backstripping removes sedimentary load-induced subsidence in order to reveal the true heat signature from tectonic stretching, thinning, and cooling.

The COST B-2 and B-3 wells were drilled offshore New Jersey not to find oil, but by the U.S.G.S. as a 'stratigraphic test'. The logs from those wells contribute compaction and porosity information necessary to calculate the subsidence caused by the weight of sediments. The difference between this subsidence and the total thickness of the well is the tectonic subsidence, after minor fluctuations in sea level are accounted for (Figure 6-5). The tectonic subsidence can then be compared to rifting models to predict the degree of stretching responsible for the additional subsidence observed beyond that accounted for by backstripping. The steeper this change in depth with time, the more severe the stretching. The degree of stretching and thinning is represented by the 'Beta' value of a margin. Beta values of 3 to 4 for offshore New Jersey indicate two to three hundred percent stretching of the crust during rifting (Figure 6-6). That is, the resultant thinned continental crust beneath the margin sediments is one half to one third its original thickness. This amount of heating would produce hydrocarbons, but in 80 to 120 million year old sediments now buried 5 to 10 km beneath the surface. Whether these hydrocarbons have migrated upsection to suitable, and economically developable, traps is still in question.

Subsidence of the Straits of Florida

To further illustrate the insights gained from logs in such environments, consider the tectonic problem of the subsidence history of the Bahama platform studied during ODP Leg 101. There are two conflicting hypotheses about the origin of the Bahamas platform: either grabens, rifting and differential subsidence related to the initial rifting away from Africa has produced the present topographic relief of the platform, or passive carbonate bank progradation and differential growth of the reef has produced that relief. Obviously, the hot tectonic source of the former would mature hydrocarbons more efficiently than the cold biological source of the latter.

Site 626 was drilled 450 m into the deep water sediments of the Straits of Florida, an area never drilled before, but where more subsidence should have occurred if rifting produced the topography of the Bahamas Bank. An 18,000 foot oil company well exists in
Figure 6-3. Three principle modes of lithospheric subsidence are thermal cooling, thinning, and emplacement of a load.
Figure 6-4. The corresponding rifted margin of North America has over 10 km of sediment under the continental margin. The outward growing reef at the continent-ocean boundary also tells a tale of the changes in the edge of the continent with time.
Figure 6-5. Total subsidence at two deep wells drilled off the east coast of the United States. The total subsidence is made up of three principal components, sedimentary load-induced (stippled), thermal or tectonic cooled (hatched), and minor sea-level changes (vertical hatching). Tectonic subsidence, which is called "backstripping", is obtained by removing the sedimentary load-induced component and sea-level changes from the total subsidence.
Figure 6-6. The amount of stretching during initial continental rifting controls the amount of heat in a basin during its cooling process. Here, backstripping was used to identify 200 to 300 percent (beta = 3 to 4) stretching offshore New Jersey.
shallow water on the western edge of the Bahamas bank (the Great Isaac well), and there are several wells available on the east coast of Florida with which to compare subsidence histories with those from the Straits of Florida (Figure 6-7). Either the Bank and Straits wells subsided at the same tectonic rate and biological progradation was the dominant force which generated the topography of the western Bahamas Platform, or the Straits shows evidence of much greater thermal subsidence because they are above the old stretched crust of a rifted graben.

Neutron porosity logs from the two different wells show the same general compaction relation (Figure 6-8) of decreasing porosity with increasing depth. This porosity versus depth relation must be combined with accurate biostratigraphic ages in order to establish accurate sedimentation rates. Cores are of course the best way to determine this, although the Great Isaac well has no core (cuttings were used). Third, sea level changes must be known. Since the wells are so close to each other, sea level changes should affect each in the same way, and so sea level changes were neglected.

The sedimentation rate and compaction histories of Site 626, the Great Isaac well and two on the east coast of Florida, the Palm Beach and Key Largo wells, show that Great Isaac is subsiding at a much greater rate than the others (Figure 6-9). Sedimentation rates have not yet been backstripped from these wells, so the differential subsidence could be from a much greater sediment load at Great Isaac instead of from thermal subsidence.

These backstripping calculations still leave Great Isaac subsiding at twice the rate of the other wells (Figure 6-10). This is suspicious because the other side of the bank (Florida) is subsiding the least, as if a thermal rifting event were off to the east of Great Isaac instead of in the Straits (the only deep water, graben-like structure in the immediate area).

An additional complexity can account for further 'subsidence' of Great Isaac sediments. The Bahamas Bank has prograded across the location of this well but not the others (Figure 6-11). Thus the sedimentation rate has greatly increased as the water became shallower at Great Isaac. The added subsidence observed in the Great Isaac well is not from thermal subsidence but from growth of the reef complex from east toward the west.

The tectonic subsidence corrected for both backstripping and progradation shows that Site 626 has indeed subsided more than the Bahamas and Florida wells, but the amount of additional subsidence is only 200 m or so (Figure 6-12). The origin of this differential subsidence rate could simply be from the fact that the crust beneath the Straits is older, and therefore has subsided by an added 200 m, to that beneath the Bahamas Bank and Florida. No dramatic evidence for stretching beneath Site 626 versus Great Isaac and the Florida wells is evident. Therefore, thermal rifting is not suspected as the mechanism driving subsidence in this area.

Although the well logs enter only one segment of the backstripping equation, they are an essential determinant of the compaction history of the sediment column. As such, they contribute equally to a better understanding of the subsidence history of sedimentary basins.
Figure 6-8. Porosities from neutron logs, ODP Leg 101 Site 626 (dotted) and the Great Isaac oil well (solid).
Figure 6-9. Subsidence curves for Site 626 and the Great Isaac, Palm Beach, and Key Largo wells. The indication of two ages in the Great Isaac well at the same depth represents uncertainty in the Miocene section of the well.
Figure 6-10. Backstripped wells from the Straits of Florida, corrected for compaction, and non-tectonic subsidence.
Figure 6-11. Progradation history of the Bahamas bank between the Great Isaac well and the Site 626 wells.
Figure 6-12. Subsidence history of the Straits of Florida wells backstripped, then corrected for progradation. The resultant subsidence curves are from tectonic processes such as thermal cooling.
Chapter 7

Logs From Transform Fault Plate Boundaries

Other tectonic environments to be drilled in ODP include shear zones such as transform fault plate boundaries, fracture zones, and backarc basins. The problems to be addressed by logging in such regimes are somewhat different from those within stable plate interiors and at ridges and subduction zones. Structural relationships are both more complex and more crucial to the deciphering of the tectonic processes active in shear zones. The major logging tool from the oil industry used to determine structural information in situ, the dipmeter, is presently unavailable to ODP because the drill pipe is too small for the tool. A modified version is in the planning stages, so a discussion of how to do science with the dipmeter is relevant to ODP scientists. (NOTE: Dipmeter and Formation Microscanner have been routinely run in ODP boreholes since Leg 126). Also, the Borehole Televiewer (BHTV) provides formation dip whenever the layers produce strong acoustic reflectivity contrasts (about 50% of the time).

The determination of strike and dip of layers is the most fundamental measurement made by a structural geologist. Such data are particularly useful in zones of complex tectonic deformation such as at shear boundaries. Here, plate tectonics does not work completely and precisely. Overthrusting, onlap and offscraping all occur as the broad forces pushing and pulling plates are complicated by the detailed three dimensional topography of plate edges. Strike and dip variations measured within wells add a third dimension to surface mapping.

The primary tool for measurement of strike and dip is the electrical resistivity difference recorded by four orthogonal pads squeezed against the wellbore wall (Figure 7-1). The orientation relative to magnetic north is recorded at the same time so that electrical conductivity contrasts around the well can be oriented. The exact geological cause of the conductivity contrasts is not of so much interest as the depth in the well at which high or low resistivity layers are detected by each of the four pads. Strikes and dips of these layers are then determined.

The Borehole Televiewer images the borehole, so if hardness or lithology contrasts result in differing reflection coefficients for different layers, it too can image dip and determine strike (Figure 7-2). Because the BHTV is a 360 degree rotating transducer oriented to north by a fluxgate magnetometer, it is much more accurate at determining dip. Its vertical resolution is about 1.27 cm, whereas the dipmeter resolution is about 1 cm.

The Dipmeter and Faulting Along The San Andreas Fault

As an example of the utility of dipmeter logging along transform fault boundaries and with the hope that this service will soon be available to ODP, consider the results from the
Figure 7-1. The different measurements of the 4-arm dipmeter (courtesy of Schlumberger).
Figure 7-2. Televiwer for ultrasonic borehole imaging, used to measure the state of stress deep in the crust. By imaging the borehole wall with ultrasound signal, it is possible to "see" where the rock has broken away because of the same stress that drives the plates across the surface of the Earth. The orientations of these "breakouts" indicate the direction the maximum push is coming from, and helps to establish which forces are driving the plates.
site of the United States' continental scientific drill hole at Cajon Pass, California. Here, the Transverse Range mountains and the San Andreas Fault meet (Figure 7-3). The result is a dogleg in the fault, and severe tectonic disruption of the strike-slip forces active along the fault. Major secondary faults branch off the San Andreas to the south (the San Jacinto Fault) and to the east (the Squaw Peak Fault; Figure 7-4). Arkoma Oil and Gas Co. drilled a 2 km well within 4 km of the San Andreas fault hoping to find oil trapped in sediments squeezed by the conflicting tectonic forces. Instead, they encountered granite at 750 m depth, and did not come out of basement to total depth.

A dipmeter log was run in the hole to attempt to determine why the sedimentary section is so thin. The dipmeter shows uniform, steeply dipping beds over the upper 375 m which are Punchbowl terrigenous sandstones dipping 50-70 degrees to the northeast (Figure 7-5). At 375 m, a drastic unconformity is crossed, with beds beneath dipping less than 10 degrees. The interval between 300 and 375 m consists of a series of shallow to steep shear zones characteristic of drag along the topside of a major thrust fault. One other major fault is seen in the dipmeter log at 300 m, with shallow to steep dips all facing to the northwest rather than to the northeast. There are also three minor faults at 190, 215, and 270 m, each with horizontal dips.

Steep structural dips can be removed from a dipmeter log to reveal the depositional dips masked by the deformation. Gentle 10 to 20 degree folding to the south is also recorded in the log data, but is partially obscured by the steep structural dip. The usefulness of the dipmeter log becomes apparent when these structural constraints are applied to a geological model of deformation along the San Andreas fault in the vicinity of Cajon Pass.

There are two sedimentological formations evident from the well cuttings and the regional geology surrounding the well: the Punchbowl above and the contemporaneous Crowder terrestrial sands below the unconformity. Prior to 10 million years ago, deposition of these two units occurred from stream beds feeding into two adjacent basins. The San Andreas fault did not yet exist in Southern California because the Farallon Plate had not been fully subducted beneath the Sierra Nevada subduction complex (Figure 7-6).

The subduction of the Farallon spreading center 10 million years ago placed North American Plate in contact with Pacific Plate (Figure 7-6). The resultant motion was strike-slip, with the Pacific Plate moving to the northwest along the newly formed San Andreas Fault. The wellsite at Cajon Pass however was thrust from the southwest to the northeast by the dogleg in the San Andreas. The steep dips encountered in the well above 375 m resulted when the Punchbowl was forced on end as it was thrust across the top of the Crowder (Figure 7-7).

The dipmeter then records 20 degree folding to the southwest in this entire sedimentary section. The northwest striking fault is likely a normal fault which was the last structural overprint of the existing wellsite geology. Present day extension was preceded by initial thrusting and considerable strike-slip movement since other pieces of the Punchbowl-Crowder system are found 150 km to the northwest on the Pacific side of the San Andreas fault.

This example from Cajon Pass demonstrates how important oriented structural information is from a well. Logs are the only sure way to obtain such data in a continuous fashion.
Figure 7-3. Physiographic map of California and Nevada. The San Andreas Fault is the linear, northwest-southeast striking feature separating the great valley of central California from the coast. The Sierra Nevada mountains separate the rest of California from the stark Basin and Range of eastern California and all of Nevada. The Cajon Pass scientific well is at the intersection of the San Andreas Fault and the east-west trending Transverse Range in southern California.
Figure 7-4. Detailed geological maps of the area surrounding the Cajon Pass continental scientific drillhole.
Figure 7-5. **Left:** Dip angle and azimuth from dipmeter data in the Arkoma Federal 1-26 well (correlation length 1.2m, step distance 0.6m, and search angle 30°). **Right:** Resistivity data recorded with a spherically focused sensor in the Arkoma hole.
Figure 7-6. From bottom to top, the Farallon plate is being progressively shortened by subduction (railroad track symbols) under California. The Sierra Nevada mountains were formed at the start of this subduction. Gradually, the East Pacific Rise was subducted as entire pieces of the Farallon plate disappeared. When the ridge axis was subducted, the plate boundary motions along the California coast switched from the North America-Farallon pole to the North America-Pacific pole of rotation and the San Andreas Fault (horizontal arrows) was born.
Figure 7-7. Schematic of tectonic model which can explain the dipmeter structural information at Cajon Pass. Upper left, Punchbowl and Crowder terrestrial sandstones deposited in adjoining basins 10 million years ago. Upper right, Punchbowl was overthrust from the SW over Crowder. Middle right, a steeply dipping thrust fault cut through the thrust plane. Middle left, erosion exposed the thrust plane and thrust fault. Lower left, entire section was folded 20 degrees to the NE. Lower right, normal fault cut the section, and then further erosion truncated the folded section, exposing the thrust plane and thrust fault.
Chapter 8

Borehole Shape and The Stresses That Drive Plate Motions

Perhaps the most important unanswered question concerning plate tectonics is: "What forces drive the plates and determine their relative and absolute motions?"

As a result of these unknown driving forces, the stress regime internal to each plate and at its boundaries is only partially understood. At ocean ridge crests, hot molten material rises topographically above the existing cold lithosphere, and a "downhill" gravitational force pushes laterally from the ridge crest. In addition, the gravitational force of a cold lithospheric slab subducting in oceanic trenches pulls the plate laterally. The former creates compressional stresses and the latter tensional stresses in each plate (Figure 8-1). The resultant force in each plate then contributes to the forces at its boundaries, and the relative motion of the two plates determines the type of interaction at their boundary. For example, cold lithospheric plates moving laterally against one another create transverse boundary forces and ultimately transverse faults, such as the San Andreas or mid-ocean transforms. Alternatively, when two plates are pulling or being pulled apart, a spreading center forms where molten material wells up into the expanding fissure and creates new lithosphere. If instead, two plates are converging, one usually subducts beneath the other into the mantle. The interaction at plate boundaries is thereby the result of intraplate stresses, and vice-versa. As such, the driving force for plate tectonics remains an enigma because the initiation of the process is still unknown.

The absolute motions of lithospheric plates relative to a fixed mantle can yield insight into the relative orientation and magnitude of these intraplate and boundary stresses. In Figure 8-2, the Pacific plate, for example, is moving in a northerly direction relative to North America, but in a northwesterly direction relative to the mantle. Fixed mantle plumes, such as that forming the Hawaiian-Emperor seamount chain, can be used to determine the relative motion of the lithospheric plates as they leave a traceable geologic record. At the 40 million-year-old Coco seamount, a rapid change in plate motion occurred leaving a bend in the seamount chain, and the tectonic stresses that gave rise to this relic remain a puzzle to geoscientists.

To determine the tectonic driving forces, a knowledge of intraplate stresses and the resultant plate motions is clearly required. Fortunately, the determination of the orientation and magnitude of intraplate forces is now retrievable from direct geophysical measurements. Earthquake focal mechanisms, hydraulic fracturing and well logging in boreholes can all provide information relevant to this question. However, earthquakes do not occur in geographically widespread areas and the resultant intraplate stresses cannot be fully resolved. Hydraulic fracturing is an alternative method commonly used for stress determination which creates a rupture inside a borehole parallel to the maximum horizontal stress direction. With this technique, the hydraulic pressure in a packed-off interval of the borehole is increased until the rock breaks at a level related to the magnitude of the
Figure 8-1. Longitudinal rolls in the mantle are caused by plate drag. Other plate forces are thought to arise from gravitation pull from the slab (A) and push from the elevated ridge axis (B).
Figure 8-2. Relative (top) and absolute (bottom) plate motions. Arrows are vectors with velocity represented by the length of each arrow.
maximum horizontal stress. Measurements can also be obtained as a function of depth using borehole techniques.

The intraplate stresses in the continental United States have been routinely updated on maps produced by M.D. Zoback and M.L. Zoback using [primarily] earthquake and hydrofracture data (Figure 8-3). They observed that the United States central craton is generally under northeast-southwest compressional stress, whereas the western basin and range province is under northwest-southeast tensional stress.

The Borehole Televiewer as a Stress Determinant

The orientation and magnitude of intraplate forces is also directly measurable by determination of breakouts of the borehole wall. Breakouts form as drilling of the borehole places the wallrock into local tension and the regional stresses concentrate around the new opening. Borehole wall failure, or breakout, occurs when these stresses exceed the shear strength of the wallrock.

Well logging, in particular using the acoustic borehole televiewer, can provide a high-resolution geometric scan of the shape of the borehole to identify breakouts (see Ch. 1, BHTV). The orientation of a drilling-induced breakout is perpendicular to the direction of maximum compressional stress, whereas a hydraulic fracture is parallel to this direction.

Consider the state of stress in southeastern New York state in the Kent Cliffs #1 borehole. This mid-craton site is remote from active North American plate margins and ideal for an intraplate stress study. Both hydraulic fracture stress measurements and a borehole televiewer survey were made at the same time. As shown in Figure 8-4a, a wellbore breakout and a hydraulic fracturing occur between 2835 and 2845 ft. The hydraulic fracture is observed as a thin, dark sinusoid intersecting the borehole at 2839 ft and exiting at 2843 ft with a northeast-southwest strike and southeast dip. Note that the hole is inclined 15 degrees from vertical, explaining why the vertical fracture appears as a steeply dipping feature. The breakouts observed in the televiewer image are shown as wide, stripped zones in the Figure oriented in the northwest and southeast quadrants. A televiewer-derived cross-section of the wellbore at line 2841' shows the depth of the breakouts into the borehole wall. Hence, in the Kent Cliffs borehole the direction of maximum horizontal compression is parallel to the northeast-southwest strike of the hydraulic fracture; the minimum horizontal compression is parallel to the northwest-southeast orientation the breakouts. These stresses may have been produced by compression from the mid-Atlantic Ridge far off to the Northeast.

State of Stress at Hole 504B

As 70% of the Earth's surface is covered by oceans, the use of ODP boreholes for the determination of intraplate stresses will greatly increase the map coverage of stress measurements. A borehole at Site 504B on the southern flank of the Costa Rica Rift is an ideal place to begin such intraplate stress investigations, because a "ridge-push" force from the north and a "trench-pull" force from the southeast may both affect the local stress
Figure 8-4. (a) Hydraulic fracture image returned to the surface from soft rubber impression packer (solid line), and borehole breakouts from BHTV images. The hydraulic fracture strikes in the maximum horizontal stress direction, and breakouts form along the minimum horizontal compression direction.
(b) Cross-section of the borehole at 2841 ft showing breakout azimuth (from televiewer data).
regime (Figure 8-5). The site is located in 6 million year old crust only 220 km distant from and one km deeper than the ridge crest. The Costa Rica Rift is also the easternmost spreading center segment before the Nazca-Cocos-American plate triple junction.

In Figure 8-6, the BHTV images in basaltic ocean crust at the site show that breakouts are oriented WNW-ESE. This orientation is maintained throughout the uppermost km of the ocean crust (Figure 8-7) and suggests that both compression (ridge-push) from the NNE ridge boundary and extension (trench-pull) from the ESE trench boundary affect the intraplate stress at this site.

Another Pacific drillhole shows breakouts in a 35 million-year-old mid-plate setting 1500 km west of the East Pacific Rise (Figure 8-8). In Figure 8-9, wellbore breakouts can be observed in BHTV images in Hole 597C in a NNE-SSW orientation. This orientation is not perpendicular to the East Pacific Rise, implying that ridge-push is not a dominant force far from spreading centers. Near this site, however, convective rolls in the mantle beneath the Pacific Plate have been imaged by satellite altimetry and are aligned in a west northwesterly direction, exactly perpendicular to these mantle rolls (Figure 8-10). The mid-plate stress regime may be controlled by these mantle rolls, or alternatively by an underplate frictional force (mantle drag).

Magnitude of Stress From Breakouts

The borehole televiewer data also provides information about the magnitude of local stresses. The predicted shape of a breakout as a function of differential horizontal stress is shown in Figure 8-11. Variability in real cross-sectional shapes can be averaged to compare with these theoretical predictions. As this theory suggests, increasing the differential horizontal stress widens and deepens the breakout while increasing the differential pressure between the formation and the borehole annulus decreases the stress required for breakout formation. Therefore, additional information on the in-situ pore pressure or the differential horizontal stresses is needed to estimate stress magnitudes from breakout shape.

In the Kent Cliffs #1 borehole, the breakout shape (Figure 8-4) can be interpreted to result from three different stress regimes based on the theory discussed above:

a) 100 bars differential horizontal stress with no differential pore pressure between the formation and the annulus

b) 75 bars differential horizontal stress with formation pore pressure less than the annulus pressure by about 25 bars

c) 125 bars differential horizontal stress with formation pore pressure greater than the annulus pressure by about 25 bars

The hydraulic fracture at this depth was created by a maximum horizontal stress of 200 bars and minimum horizontal stress of 86 bars. The differential stress (114 bars) implies a formation overpressure of 20 bars. As determined by the pumping history at this depth, large overpressures were maintained in the packed-off interval for 45 minutes and pressure diffusion into the formation could likely have produced the excess formation pressures. Since no breakouts existed before the hydraulic fracture was induced, the breakouts probably formed after the pressure in the annulus was bleed off, leaving a stress regime
Figure 8-5. Location map of Hole 504B, with ridge push force from the north and trench pull force from the east, southeast. Borehole breakout stress directions determined from BHTV imagery also shown.
Figure 8.6. Borehole breakouts imaged with a BHTV in Hole 504B at depths indicated.
Figure 8-7. Cumulative orientations of BHTV imagery, Hole 504B. Least compressive stress is horizontal and oriented 120 and 300 degrees.
Figure 8.8. Location map and earthquake focal mechanism solutions around DSDP Hole 597C. Age isochrons shown along with absolute plate motion of the Pacific Plate (bold arrows). Maximum and minimum horizontal stress directions determined from BHTV imagery of breakouts also shown.
Figure 8-9. Cumulative orientations (left) from borehole breakouts imaged with BHTV (right).
Figure 8-10. The horizontal rolls under the Pacific plate can be observed from the small difference in the Earth's gravity pull between upwelling (highs) and downwelling (lows) limbs of the rolls. This image comes from satellite measurements of gravity. The Pacific Plate is moving to the Northwest. The fracture zones are east-southeast scars in the plate.
Figure 8-11. Borehole breakouts predicted for stress differences indicated (in bars). (a) no differential pressure between borehole and formation. (b) formation pore pressure greater than borehole pressure (mud weight). (c) borehole pressure greater than formation pore pressure. For case (c) the heavy mud weights prevent breakouts and stabilize the hole during drilling.
similar to (c) predicted above. Despite the complexity of this example, it is clear that the BHTV delivers a unique set of information to determine in-situ stress regimes in the crust.

Conclusions

In this volume, we have given examples of geophysical and geochemical log analysis to help understand puzzles in the geological sciences. There is extensive work published on the use of logs in sedimentary basins which is partially reproduced by a U.S.G.S bibliography in Appendix II. The topics covered include facies analysis, depositional environments, abnormal pressure detection, and geothermal well logging. The exciting new developments in scientific well logging in the ODP will consistently deliver new scientific answers leg after leg.
APPENDIX I

A GUIDE TO ODP TOOLS
FOR DOWNHOLE MEASUREMENTS

Keir Becker
Rosenstiel School of Marine and Atmospheric Science
University of Miami
4600 Rickenbacker Causeway
Miami, Florida 33149

OCEAN DRILLING PROGRAM

TEXAS A&M UNIVERSITY

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ODP Downhole Tools

page 1

I. INTRODUCTION

A. Purposes of this manual

Logging and downhole measurements have been emphasized in the Ocean Drilling Program (ODP) as important scientific tools that provide key data to significantly augment and complement the results of coring. Because of the strong commitment to downhole measurements for ODP, a very advanced suite of logs and downhole experiments is presently available or under development for routine ODP use. However, it is sometimes difficult for the uninitiated shipboard scientist to understand the limitations and operational requirements of the many available tools, and to plan and then successfully implement a specific downhole experiment on a given leg or series of legs.

The primary purpose of this manual is, therefore, to provide some guidance for scientists interested in those downhole tools that ODP routinely provides, by describing several key aspects regarding these tools: requirements for advance planning, procedures for shipboard operations, and basic methods for data interpretation. For many of the ODP downhole tools, fully-detailed operating instructions written by the tool designers or manufacturers are available at ODP and on board JOIDES Resolution, and will only be briefly summarized here, emphasizing those factors that are important in planning and then conducting the measurements.

The purpose of this manual is quite similar to that of the ODP Logging Manual, which describes the logging tools and scientific logging services provided by the Borehole Research Group (BRG) at Lamont-Doherty Geological Observatory (LDGO). (Copies of the ODP Logging Manual are available from BRG, and Worthington et al. (1987) have written a brief, useful summary of the ODP logging facilities.) In this manual, 'ODP' will be used to refer to the ODP Science Operator at TAMU, and 'LDGO' will refer to the ODP Logging Contractor. ODP and LDGO divide responsibilities for downhole tools as follows: LDGO is responsible for providing logs measured with tools run on the seven-conductor logging cable (or 'wireline'), whereas ODP is responsible for those tools used with the drill string and/or the non-conducting coring line (or 'sand line').

Most of this manual consists of chapters describing the following types of measurements that can be routinely made with tools provided by ODP: (1) borehole- or pore-fluid sampling, possibly with in situ pressure measurements, (2) temperature measurements in sediment or in open borehole, (3) permeability measurements using drillstring packers, and (4) orientation of advanced hydraulic piston corer (APC) cores. Many other types of measurements are possible, and several new tools are being developed by investigators cooperating with ODP. The final chapter of this manual describes some of the new tools now under development, and specifies the conditions that must be satisfied before ODP will assume responsibility for routinely providing these measurements.

The remainder of this introductory chapter summarizes the information that is essential to assure that the routine measurements provided by ODP can actually be made in a manner that satisfies scientific goals:
(1) requirements for advance planning for measurements using ODP tools, 
(2) an overview of the tools routinely available from ODP, and (3) the 
compatibility of these tools with the various ODP coring and engineering 
systems.

B. Advance planning requirements for routine ODP tools

To ensure successful use of specific ODP downhole tools on a particular 
leg, it is advisable to start planning at least one year pre-cruise, and it 
is essential to keep two organizations fully informed: ODP itself, and the 
JOIDES panel structure via the Downhole Measurements Panel (DMP).

ODP is charged with implementing the scientific planning approved by 
the JOIDES Planning Committee (POCM), which acts with the advice of the 
JOIDES panels, including DMP. About one year pre-cruise, DMP considers the 
proposed programs for logging and downhole measurements for each site of 
each leg, and passes its advice to POCM, to ODP, and to LDGO. In its 
deliberations, DMP reviews measurements included within normal drilling 
proposals and separate proposals for special experiments. During the first 
two operating years of ODP, DMP has generally endorsed full programs of 
logging and downhole measurements at most sites, and POCM has often 
accepted this advice unless ship time is very limited.

Thus, ‘normal’ programs for use of ODP tools are usually approved for 
all sites by DMP and POCM. However, details of implementing these programs 
are often not considered by these committees, but instead are left to the 
co-chief scientists to specify at the planning meeting that normally occurs 
about 4 months pre-cruise at ODP. To ensure that ODP is fully equipped and 
staffed to support a program of routine downhole measurements on a given 
leg, it is essential that the co-chief scientists develop a comprehensive 
plan for these measurements well before this pre-cruise meeting.

For extraordinary programs of downhole measurements with ODP tools -- 
e.g., special ‘holes’ devoted to pore-water sampling and temperature 
measurements, or extensive programs of packer measurements -- JOIDES 
approval is required well before the pre-cruise meeting to guarantee the 
necessary ship time and extra effort by ODP. Such approval can be obtained 
by including the plans for special downhole measurements in the original 
drilling proposals considered by the JOIDES panels, or by submitting 
special proposals to JOIDES for consideration by DMP and POCM.

C. Overview of downhole measurements provided by ODP

ODP provides the tools and technical support to allow downhole sampling 
of fluids (in addition to pore fluids recovered in cores) and the 
measurement of several basic physical parameters: temperature, pore 
pressure, permeability, and APC-core orientation. With the exception of 
APC-core orientation, several different tools are available to measure 
these parameters in different situations, such as while coring sediments, 
between cores at the bottom of the hole, or in open hole. The ODP tools 
are not used with the logging cable, but instead are deployed using the 
drillstring and/or coring line in several possible modes, for example: (a) 
lowered on the coring line to either seat in the bit or run beyond the bit 
in open hole, (b) lowered to the bit as part of the APC coring assembly, or
(c) built into the drill string. There are many options for using these tools, and the focus of this section and the next is to outline these options, leaving other details for subsequent chapters.

ODP will generally staff each leg with at least one marine technician trained in the use of these tools, with the exception of the drill-string packers, which may require a special tools engineer in addition to a packer scientist. The marine technician is responsible for preparing and deploying the tools, and for the initial transfer of raw data to the shipboard computer and standard processing for archival at ODP. The shipboard scientists are then responsible for further processing and data interpretation. Some of the computer programs available aboard ship for this processing are discussed in later chapters.

Fluid sampling and in situ pressure measurements

Two probe-type tools are routinely available for sampling fluids ahead of the bit in sediments soft enough for the probes to penetrate. These tools are officially termed ODP WSTP samplers because they are capable of measuring temperature or pressure in addition to taking a water sample. However, they are sometimes referred to as the old Barnes/Uyeda probe (inherited from DSDP) and the new Barnes sampler, after the original proponents, Drs. R. Barnes and S. Uyeda.

The WSTP samplers are run on the coring line between cores and require 2-3 hours in addition to coring time to collect samples. The probe lands in the bit so that it extends up to 1 m into the sediment ahead of the bit; thus, the sediment to be cored next is disturbed. The WSTP samplers collect small fluid samples (30-70 ml primary samples) through an orifice in a probe that may also be instrumented with a thermistor or one or two pressure transducer(s). If the pressure data on penetration are of sufficiently good quality, they can sometimes be interpreted to estimate in situ pore pressure and possibly permeability.

In sediments that are too lithified for the WSTP probes to penetrate, a probeless pore-water sampler can be used in conjunction with the rotatable drill-string packer. This ‘probeless PWS’ consists of a WSTP sampler without the probe (i.e., without temperature or pressure sensors), so nothing extends beyond the bit, and several sealed core barrels used as a ‘vacuum’ source to draw a large volume of fluid through a small sample chamber. This tool is meant to be used with the rotatable drill-string packer to seal the annulus so that pore fluids are sampled, not drilling fluids. Use of the packer requires considerable time and effort, as outlined below.

In open hole, the WSTP samplers can also be used to sample borehole fluids up to 1 m below the bit. Also, larger volume samples (0.5 liter) can be taken with tools made by Kuster Co. that are run on the coring line to a distance below the bit deemed safe by the Operations Superintendent. (In addition, Schlumberger tools for sampling open hole fluids may be available through LIDO.)
Temperature measurements

Two types of tools are routinely available for measuring temperatures in sediment and in open hole: the WSTP tools mentioned above, and miniature recorders used within special APC cutting shoes. These tools are normally used separately to obtain single measurements of temperature at discrete depths during a sequence of coring a hole through sediments. Or, they can be configured together for simultaneous use without coring. Either tool or the combination can be washed and pushed through soft sediments or run into open hole to measure temperatures at multiple depths during a single lowering.

The APC temperature recorders were originally developed by Dr. R. Von Herzen during DSDP; ODP is purchasing a newly designed version from Bowmar-White Co. This device monitors the temperature of a single sensor within the APC cutting shoe; on penetration, the corer must be held in the sediment for 5-10 minutes to obtain enough data to allow extrapolation to in situ temperature. It is typically run every 2-4 cores in an APC hole, but can be used only to depths where the force required for pullout is within safe limits, usually about 100-200 meters below seafloor (mbsf).

The WSTP tools can generally be used to greater depths, but require 2-3 hours for runs on the coring line between cores. These tools continuously sample the resistances of single thermistors mounted in cylindrical probes that are lowered into the bit and then pushed into the sediments. Thus, these tools can be used only in sediments soft enough to be safely penetrated, typically to a few hundred mbsf. The probe must be held in place for 5-10 minutes to obtain enough data to allow extrapolation to in situ temperature.

Permeability measurements using packers

A packer produces a hydraulic seal in a borehole, allowing the hydrologic properties of the formation to be tested by applying differential fluid pressures to the isolated section. Three packers are available in ODP: (1) a drill-string straddle packer presently supported by an NSF grant to the University of Miami, (2) a rotatable drill-string packer operated by ODP, and (3) a wireline packer operated as a logging tool by LIDO. All of these packers are manufactured by TAM International, and use inflatable rubber/steel elements to seal the borehole.

Of these packers, only the drill-string straddle packer has been used successfully and proven for routine use. With sufficient advance notice, this packer is generally available for ODP, but it can be used only as part of a non-coring bottom-hole assembly (BHA) in reentry holes that penetrate reasonably stable formations. Permeability measurements in holes that penetrate unstable formations or in single-bit holes require the ODP rotatable drill-string packer, which is designed to allow rotation, circulation, and, ideally, very limited coring without inflating the packers.

Any use of these packers will require considerable preparation and significant amounts of ship time. To date, skillful SEDOO core technicians have undertaken the responsibility of preparing drill-string packers for deployment. The procedures for formation testing with drill-string packers
are quite complicated, and require participation of a shipboard packer scientist, possibly with the help of an ODP special tools engineer.

The prime data in formation testing are fluid pressures measured with recorders that are run into the isolated zone when the packer is inflated. Both drill-string packers utilize mechanical Kuster pressure recorders attached to 'go-devils' that are dropped down the drill-string into the packers and enable the mechanisms for inflating the packers. The Kuster pressure records are scratched (quite accurately) onto special charts, which should be read with a Kuster microscope. In the future, electronic pressure recorders may also be available, instead of or in addition to the reliable Kuster recorders.

Formation testing procedures at each setting depth typically run 4-8 hours, including the time required to drop and retrieve the go-devils. For permeability measurements using the straddle packer after coring a reentry hole, up to one day's time will be required for a pipe trip to build the packer into a logging BHA. In some cases this will not actually cost extra time, as the packer is compatible with logging and it may be possible to accomplish a full program of logging and packer measurements during the single pipe trip required to deploy a logging BHA in a reentry hole.

The LDDO wireline packer is designed primarily for measuring in situ pore pressure and sampling formation fluids from a narrow straddled zone, but it may allow permeability measurements at low test pressures. The probeless PWS mentioned above was designed (but has not yet been used) for sampling fluids from formations isolated by the rotatable packer, and other sampling go-devils for the drill-string packers may be developed soon (Chapter VI).

Orientation of APC cores

The azimuth and deviation from vertical of (non-rotary) cores taken with the advanced hydraulic piston corer (APC) can be measured routinely using an Eastman-Christensen magnetic 'multishot' camera. This device records photographs of a magnetic compass and pendulum taken at pre-selected intervals. It is installed in a non-magnetic sinker-bar/pressure-case that connects the coring line to the APC barrel, and must be used with a special non-magnetic drill collar in the BHA.

Thus, the decision to obtain oriented piston cores at a given site must be made before the BHA is made up and pipe run into the hole. An extra 5-10 minutes per oriented core is required for handling the multishot assembly. Oriented cores can be obtained only to depths that are safe to core with the APC, typically on the order of 100-200 m/feet, depending on the force required for pullout.

D. Compatibility of ODP tools with ODP operations and engineering systems

ODP is a very advanced and specialized drilling program, and has developed a wide range of engineering and coring systems for use in various operational situations. The ODP tools for downhole measurements are not always compatible with certain engineering and coring systems, and care must be taken to verify that measurements can actually be made as planned.
Table I-1 summarizes the situations in which ODP downhole tools are normally used; these normal methods are discussed in the following chapters. There are many other operational configurations that are not listed in Table I-1 in which it may still be possible to make these kinds of measurements. The full range of possibilities is considered in Table I-2, which summarizes the compatibility of the ODP downhole tools with the various ODP engineering and coring systems.

The ODP downhole tools, coring systems, and engineering systems will be modified as necessary for enhanced performance, and the information presented in Tables I-1 and I-2 and in this manual may be subject to change. The information presented in this version is current as of the end of Leg 118 in December 1987. For further information, clarification, or updates regarding the compatibility of possible configurations, please contact Mr. Dan Reudelhuber, Senior Drilling Engineer at ODP, or the ODP Supervisor of Drilling Operations, or the ODP Supervisor of Development Engineering.
Table I-1. 'Normal' configurations for routine deployment of ODP tools for downhole measurements. 'Time required' is time needed in addition to planned coring operations.

<table>
<thead>
<tr>
<th>Type of Measurement</th>
<th>Tool Used</th>
<th>Method of Deployment</th>
<th>Time Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore water sampling:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unlihified sediments</td>
<td>WSTP</td>
<td>Lowered on coring line into bit between cores</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Semi-lithified sediments</td>
<td>Probeless FWS</td>
<td>Lowered on coring line into bit, with rotatable packer inflated</td>
<td>4-6 hours</td>
</tr>
<tr>
<td>Borehole water sampling</td>
<td>WSTP</td>
<td>Lowered on coring line into clean-out bit in open hole</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>(in open reentry hole)</td>
<td>Kuster sampler</td>
<td>Lowered on coring line through bit into open hole</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Pore pressure:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediments</td>
<td>WSTP</td>
<td>Lowered on coring line into bit between cores</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Hard formation</td>
<td>Kuster pressure gauge</td>
<td>In go-devil freefallen to inflate drill-string packer</td>
<td>3-4 hours</td>
</tr>
<tr>
<td>Temperature:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediments</td>
<td>APC T tool</td>
<td>(1) In APC while coring</td>
<td>10-15 minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2) Lowered on coring line into bit without coring</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Borehole (in open reentry hole)</td>
<td>WSTP</td>
<td>Lowered on coring line into bit without coring</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Orientation of APC core</td>
<td>APC T tool</td>
<td>Lowered on coring line into bit</td>
<td>2-3 hours</td>
</tr>
<tr>
<td></td>
<td>WSTP</td>
<td>Lowered on coring line into bit</td>
<td>2-3 hours</td>
</tr>
<tr>
<td></td>
<td>Multishot camera</td>
<td>In sinker bar while APC coring</td>
<td>5-10 minutes</td>
</tr>
<tr>
<td>Permeability:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Soft sediments)</td>
<td>maybe WSTP</td>
<td>Lowered on coring line into bit between cores</td>
<td>2-3 hours</td>
</tr>
<tr>
<td>Semi-lithified sediment</td>
<td>Rotatable packer</td>
<td>In BHA; activated by freefallen go-devil</td>
<td>4-8 hours*</td>
</tr>
<tr>
<td>Hard rock</td>
<td>Straddle packer</td>
<td>In BHA; activated by freefallen go-devil</td>
<td>4-8 hours*</td>
</tr>
</tbody>
</table>

* - use of either drill-string packer may also require up to a day for a pipe trip to install the packer in the BHA.
Table I-2. Compatibility of ODF downhole tools among themselves and with principal ODF operations and coring systems.

<table>
<thead>
<tr>
<th>Downhole Tools</th>
<th>WSTP (a) in sediment</th>
<th>Probesless PGS</th>
<th>Kuster Water Sampler</th>
<th>APC T (a) coring sediment</th>
<th>APC (b) in sed. w/o coring</th>
<th>APC (c) open reentry hole</th>
<th>Straddle Packer</th>
<th>Rotatable Packer</th>
<th>Kuster Pressure Gauge</th>
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<tbody>
<tr>
<td>WSTP (b) open reentry hole</td>
<td>-</td>
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<tr>
<td>Probesless PGS</td>
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<td>Kuster Water Sampler</td>
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<td>APC T (a) coring sediment</td>
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<td>(b) in sed. w/o coring</td>
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<td>(c) open reentry hole</td>
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<td>APC Orientation</td>
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<tr>
<td>Straddle Packer</td>
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<td>Rotatable Packer</td>
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<tr>
<td>Kuster Pressure Gauge</td>
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<th>Rig Floor Systems</th>
<th>Coring Line</th>
<th>Drill-string Bower Comp.</th>
<th>Wireline Logging</th>
<th>Side-Entry Sub</th>
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<th>Single-Bit Hole</th>
<th>Cased Reentry Hole</th>
<th>Preeval Reentry Cone</th>
<th>Drill-in Casing</th>
<th>Hard-Rock Guide Base</th>
<th>Unsupported Hard-Rock Spud-in</th>
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<tr>
<th>Coring Systems</th>
<th>BCB (Rotary Core Barrel)</th>
<th>APC (Advanced Piston Corer)</th>
<th>BCB (Extended Core Barrel)</th>
<th>NCB (Navisdrill Core Barrel)</th>
<th>BCB (Positive Displacement Motor)</th>
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<th>Bit Release and Float Valves</th>
<th>Mechanical Bit Release</th>
<th>Hydraulic Bit Release</th>
<th>Passive (Baker) Float Valve</th>
<th>Lockable Float Valve</th>
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</tbody>
</table>

**Key:**
- **R** Required for operation of tool listed at top of column.
- **!** Can be activated simultaneously, during a single trip of the coring line.
- **?** Can be run separately during the same pipe trip, in the proper sequence.
- **X** Not incompatible, but operationally undesirable or questionable.
- **!** Incompatible during a single pipe trip - can be run in the same hole only during separate pipe trips into a reentry hole.
- **!** Not applicable - by definition the possibility should not arise.
II. IN SITU FLUID SAMPLING AND PORE PRESSURE MEASUREMENTS

A. Introduction

Tools to sample fluids in situ were built early during DSDP and have continued to evolve during ODP. Barnes (1979) pioneered this effort and has developed two generations of tools designed to sample sedimentary pore fluids through a probe that extends about 1 m ahead of the bit. The first generation tool was modified during DSDP to allow measurements of temperature (Yokota et al., 1980; Uyeda and Horal, 1982) or pore pressure (von Huene, 1985). These capabilities have been integrated into the redesigned second-generation tool (Barnes, 1988), and these tools are now officially termed the ODP WSTP tools (water sampler, temperature, pressure tools). The use of the WSTP tools to measure temperature is discussed in Chapter III.

Barnes' (1979) goals were to sample sedimentary pore fluids in situ, in order to (1) complement and calibrate the chemical analyses of pore fluids squeezed from cores, and (2) provide undisturbed samples for determination of in situ concentrations of dissolved gases. The tools developed for these purposes have also proven useful in sampling borehole fluids that have partially re-equilibrated with pore fluids in reentered basement holes, such as Holes 395A, 418A, and 504B. However, the borehole fluids that the WSTP tools sample in the vicinity of the bit are often displaced and/or contaminated by the massive drill string. When it is essential to avoid the effect of the drill string on borehole fluids in a reentry hole, ODP now operates Kuster water samplers that can be run on the coring line through the bit to sample fluids from open, undisturbed hole.

The WSTP and Kuster tools can all be described as 'passive' samplers (Mottl et al., 1983, 1985), in that the fluids sampled are those that are in the immediate vicinity of the sampler, whether in sediments penetrated by a probe or in open hole. In some situations it may be more desirable to actively draw a sample from the formation, such as in semi-lithified or lithified sediments that cannot be penetrated by the WSTP probe, or in open basement holes where the borehole fluids have not equilibrated with pore fluids. In such cases, it may be possible to use either the LDCD wireline packer, or a 'probeless PWS' (a WSTP with the TP-probe removed) in conjunction with a drill-string packer to seal the annulus and prevent sampling of borehole fluids. Such 'active' methods involving wireline or drill-string packers would require several hours per sample and have not been attempted as of Leg 118, but they are feasible.

B. Pore fluid sampling with the WSTP tools

Barnes (1979) described the first generation WSTP sampler, which was modified several times during DSDP, and was often called the 'Barnes sampler' or the 'Barnes-Uyeda probe.' Barnes (in press) describes the redesigned WSTP tool for ODP (Figure II-1), and the excellent results obtained with the prototype during Leg 110. The WSTP tools are self-contained, battery-powered tools adapted to an inner core barrel assembly that is deployed in the RHA. The sample chamber and electronics (timer and temperature pressure data recorder) are contained within the inner core barrel; only a strong probe that contains the sampler filter and temperature or pressure sensors protrudes below the bit.
Figure II-1. Block diagram (not to scale) of the WSTP tool. (1) pressure case relief valve, (2) upper pressure case bulkhead, (3) sample chamber pressure relief valve, (4) sample overflow chamber, (5) sample coil, (6) sample coil pressure relief check valve, (7) sampling control valve, (8) D.C. gear motor, (9) timer-controller, (10) inner case assembly, (11) data recorder or other electronics package, (12) pressure case, (13) nickel-cadmium battery pack, (14) pressure transducers, (15) lower pressure case bulkhead, (16) pressure transducer inlet filter, (17) 0.8 mm bore fluid inlet tubing, (18) drill bit; (19) filter element, (20) thermistor probe. SW#1 = motor shut-off and reversing switch, SW#2 = manual motor switch. Solid heavy lines are fluid pathways.
Barnes has written a very detailed shipboard operating manual for the new generation of WSTP tools, copies of which are available from ODP. Table II-1 shows Barnes' table of contents, indicating the range of subjects and instructions covered in detail in the manual. Table II-2 repeats the specifications for the WSTP tools, as given by Barnes. Appendix A includes a copy of the form that is completed by the scientist or downhole tools technician who oversees deployment of the WSTP tools. The following overview of the methods to deploy the WSTP tool for sampling pore fluids from sediments is excerpted from section III-B of Barnes' manual ('The Downhole Run').

Downhole conditions vary and the procedures used to ensure a useful sample will have to vary accordingly. However, fill at the bottom of a hole is a normal occurrence, so the procedure should be designed to remove as much fill as possible and permit the probe to penetrate undisturbed sediment at the hole bottom. Several deployment methods have been devised for the WSTP tool: (1) latched-in operation, (2) free fall, (3) collet system, and (4) rotatable packer. Other deployment methods are under consideration, but the necessary special hardware has not been developed at this time.

(1) Latched-in operation can be used during any drilling mode, but it is the only normal deployment method available during rotary coring.... The sampler is lowered on the coring line and latched into the BHA like a regular core barrel. Only the filter probe extends below the drill bit. The usual procedure would be to keep the fill washed out of the hole by pumping as the tool descends. The bit should be raised several feet above hole bottom long enough to latch the sampler into place, and then lowered while still pumping until the bit reaches the hole bottom or the desired weight on bit is attained [to allow heave compensation and maintain probe positioning], whichever comes first. Then the circulation pumps should be shut down.

The probe should be lowered into the bottom about 3 minutes before the delay time ends and raised about 3-1/2 minutes after the sample time ends.... The sampler must be left in the mud long enough for the valve to close, in addition to a timer safety margin.

(2) Free fall deployment was first tried on Leg 112. It can be used during APC/XCB [extended core barrel] mode. The sampler... is connected to two inner core barrels, one standard 15' and one short 12'.... With this assembly the whole WSTP tool can drop below the drill bit.

The hole is washed to the bottom and the drill bit is then raised several feet off the hole bottom. The sampler–core barrel assembly is pumped down the drill pipe and the filter probe penetrates the formation below the drill bit using the kinetic energy of the fast free fall. The drill bit can move up and down without disturbing the filter because the inner and outer barrels are not latched together.... In addition, the drill bit is raised
Table II-1. Table of Contents of R. Barnes' manual for the operation of the WSP tool.

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   A. Preparing Sampler for Downhole Use
      Flushing Sampler
      Sample Coils
   B. The Downhole Run
   C. Recovery of Sampler and Sample Handling
   D. At the End of a Cruise

IV. Checklists: Short Form
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V. Detailed Notes
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   C. Pressure Adjustments And Check Valves
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VI. Electrical Specifications and Schematics
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   B. Batteries and Battery Charging

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   B. DSDP Timer, Handwired
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   A. Pore Pressure/Heat Flow Recorder
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IX. List of Engineering Drawings
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   B. ODP Drawings

X. Commercial Parts List

XI. Data Sheets, Engineering Drawings

XII. Sampler Photographs
Table II-2. General specifications: ODP wireline water sampler, 
    temperature, pressure tool.

OPERATING PRESSURE: Design = 10,000 psi minimum (6.8x10^7 Pa),
collapse/burst = 20,000 psi minimum (13.8x10^7 Pa).

OPERATING TEMPERATURE: Currently to 75°C, with new electronics to 125°C, 
    high temperature version (planned) to 250°C minimum.

pH, SALINITY: Compatible with 15-3PH, 304 and 316 stainless steel, 
    and 4130 alloy.

NUMBER OF SAMPLES PER RUN: One.

OPERATING DEPTH: 10,000 m (max) at 0-30°C using backup rings, 6500 m 
    (max) to upper temperature limits.

SAMPLE VOLUME: A) High quality sample suitable for chemistry and gas 
    concentration, up to approximately 70 mL.
    B) Overflow sample mixed with approximately 75 mL 
    distilled water and 1 mL drill water, up to 1200 mL.
    C) With extra Lynes Sample Barrels (Packer 
    Configuration), approximately 60 L.

All of these sample volumes available simultaneously.

TEMPERATURE: +0.05°C precision.

FLUID PRESSURE: 0-10,000 psi, 2 channels; 
    1 channel—Formation Fluid Pressure, 
    1 channel—Drill Hole Pressure.

Temperature and pressure data recorded digitally in 64K byte RAM memory.

OPERATING TIME: A) Delay to sample: 0-13.2 hr (normal range 0-6.6 hr). 
    B) Sample time: 0-13.2 hr (normal range 0-49.5 min). 
    C) Accuracy: ±0.4% (0-50°C).

TYPE OF SAMPLING: High quality suitable for quantitative gas 
    concentration analysis, and chemistry compatible 
    with stainless steel container. Low contamination by 
    borehole fluid during soft sediment sampling.

LIMITATION: Formation fluid cannot be filtered from low water 
    content, low permeability sediments. However, 
    temperature and formation fluid pressures can be 
    measured to strength limits of probe.
off the hole bottom, which may be important for accurate formation fluid pressure measurements. This deployment method should not be used if lithified layers might be encountered, because the penetration of the probe is not controlled. In soft sediments, the probe may penetrate several meters into the next core section.

(3) As an alternative to the free fall method, ODP is developing ... the collet delivery system. This system has been tested, but it is still under engineering development as of Leg 117. The idea is to provide a controlled penetration as in the latched-in method, a limited range of decoupling between the BHA and the sampler as in the free fall method, and in addition a mechanism to allow the probe to retract inside the drill bit if hard sediment is encountered that could otherwise bend the filter probe. [As this method is developed, more details will become available from the ODP engineers.]

(4) A special sealed probe system [probeless FMS] has been developed to use the WSTP tool with the rotatable packer.... This system has not yet been used and has been taken back to shore.... Anticipated usage of this system is low [until the rotatable packer is successfully field-tested -- see section E of this chapter, and Chapter IV].

Note that these methods as described by Barnes are the best methods to use when the primary purpose of the tool lowering is to obtain a water sample. However, when it is equally important to measure in situ temperature, it may be necessary to modify these methods as described in Chapter III. For example, while only one water sample can be taken during a single deployment, it is possible also to make several measurements of temperature at different depths during the same deployment, but it is critical to carefully plan the sequence so that the probe is at the desired depth at the proper time for sampling fluids.

Note also that the success of the WSTP tool in capturing pore fluids as opposed to drilling fluids depends both on penetrating the sediment and on holding the probe stable during the sampling period. With the standard, ‘latched-in’ method of deployment, maintaining probe position is best accomplished using the drill-string heave compensator, which requires placing about 5000 lb weight on the bit. Thus it is difficult to sample pore fluids from very shallow sediments, which are generally not competent enough to support this weight. In deeper, more lithified sediments, greater amounts of weight may be required for penetration, and the act of penetration may open fractures in the formation, allowing drilling fluids to contaminate the sample. In practice, the WSTP samplers have been effective at depths of about 50 to a few hundred mbsf, depending on the properties of the sediment.

C. Pore pressure measurements with the WSTP tools

Pore pressure is a crucial parameter that reflects and influences hydrogeologic and tectonic processes, but it is difficult to measure in situ because the emplacement of a measuring tool often disturbs the formation and fluid pressures in the vicinity of the tool. The WSTP probes
have been instrumented with pressure transducers to determine pore pressures, but the results have been difficult to interpret in any quantitative sense. Ideally, pore pressure and possibly even permeability could be determined either from the decay of a pressure pulse on instantaneous insertion of a probe or from the rebound of pressures after a period of fluid sampling through the probe (Figure II-2).

The DSDP WSTP tool was first instrumented with a pressure transducer in an attempt to measure excess pore pressures in sediments cored during Leg 84 (von Huene, 1985). The redesigned WSTP tool can be equipped with two pressure transducers, one for reference hydrostatic pressure, the other to measure sediment pore pressure around the probe (Barnes, 1988). While these transducers have worked well, the data have justified only qualitative interpretation because of possible physical disturbances during emplacement in the sediment. In fact, Barnes (1988) found the pressure data more useful as diagnostic of downhole events during the sampling process (Figure II-3).

Note that the WSTP was configured to allow concurrent measurements of temperature and pressure, as illustrated in Figure II-3, only during Legs 110-112. However, in its present configuration, the WSTP will support the measurement of temperature or pressure, but not both at the same time, in addition to water sampling. In the future it is possible that the WSTP probe could be redesigned to once again allow concurrent temperature and pressure measurements.

The disturbances that may affect pore pressure measurements include (1) movement of the probe during the measurement, disrupting the seal between the probe and surrounding sediments and allowing contamination by borehole fluids at hydrostatic pressure, and (2) compression of the formation and pore fluids from above by the weight put on the bit in attempting to hold the probe stationary. Any concurrent temperature measurements and water samples will of course also be sensitive to probe movements, but will not be affected as much as pressure measurements by weight placed on the bit and transmitted to the formation.

If the WSTP is deployed using the normal 'latched-in' method described above, the only way to keep the probe stable in the formation is to use the heave compensator, which requires that a minimum amount of weight (at least 5000 lb) be put on the bit. Thus it may be impossible to avoid the effect of this weight on measured pressures, unless a different method of deployment is used. For example, the collet delivery system that is presently being developed would allow some decoupling between the bit and the probe, and might lessen the effect of any bit weight on the pressure measurements.

Note that, when the new WSTP is used for sampling and temperature or pressure measurements during a single run, it may use much of its battery power before the run is over. While the recorder is presently being modified to reduce the battery drain, it is prudent to check at the pre-cruise meeting that an adequate supply of the rechargeable batteries will be on board JOIDES Resolution for legs with heavy planned usage of the WSTP tools.
Figure II-2. Generalized record of pressures measured with the WSTP tool. Annotated to show functioning of probe during a set of measurements. From von Huene (1985).
Figure II-3. Actual records of pressures and temperatures measured with the WSTP tool during ODP Leg 110. Note that as presently configured,
D. Borehole fluid sampling with WSTP and Kuster tools

In addition to sampling pore fluids from penetrated sediments, the WSTP tools can also be used to sample borehole fluids, as can larger volume fluid samplers made by Kuster Company of Long Beach, California. The WSTP tools are described in the previous section: Figure II-4 shows the Kuster sampler, and Table II-3 gives its operating specifications. ODP purchased three of the 500-ml Kuster samplers for Leg 111, and now maintains them for use as needed. Kuster provided relatively brief operating instructions, which are available from ODP and are summarized in the following paragraph.

The Kuster sampler is a relatively simple tool consisting of a sample bottle with an inlet valve, two non-return valves, a locking device, and a mechanical clock. In operation, the clock is wound and the tool is lowered into open hole on the coring line. When the clock reaches the programmed sampling time (60 or 150 minutes after being wound), it releases the locking mechanism, thereby allowing the inlet valve to open and the sample chamber to fill. When the fluid pressure inside the chamber plus the spring pressure of the non-return valve reaches in situ fluid pressure, the non-return valves close and seal the sample chamber. Once the sample has been taken, the sampler should not be lowered any deeper into the hole, as increasing the external pressure will re-open the valves and allow the sample to be contaminated.

When the tool is retrieved to the surface, the pressurized sample must be released using a special extractor body, to which a system of high-pressure valves and hoses is attached. There is no 'standard' valve/hose system available, and a custom system may need to be constructed for each leg, depending on such factors as anticipated sample pressures, requirements to preserve dissolved gases, etc. It is the responsibility of the co-chief scientists, in consultation with participating fluid chemists, to specify any special requirements for such a sample extraction system at the pre-cruise meeting.

Operational considerations for sampling borehole fluids

Immediately after drilling a hole, the borehole fluids are composed primarily of the surface seawater used to flush cuttings during drilling. Thus it is normally of interest to sample borehole fluids only if considerable time has elapsed since the hole was drilled, so that the fluids have partially re-equilibrated with in situ pore fluids -- a situation that occurs only when a reentry hole is revisited. If borehole fluids are to be sampled (and temperatures measured) when a re-equilibrated borehole is reentered, it is essential that this be done before any significant disturbance to the borehole fluids occurs, as might be produced in reaming the hole, circulating to condition for logging, or even running a sinker bar on the coring line to verify that the hole is open.

The WSTP and Kuster tools are deployed on the coring line in different ways, which will affect the choice of a sampler in a given situation. To sample borehole fluids, the WSTP is lowered (but not latched) into the bit, so that the probe collects fluids from within 1 m of the bit, which may have been somewhat disturbed, displaced, or contaminated by the massive steel drill-string. On the other hand, the Kuster samplers are lowered
Figure II-4. Schematic of the Kuster water sampler.
Table II-3. Specifications, Kuster water sampler.

**SAMPLER PART NO. 11500**

**SPECIFICATIONS**

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<td>Operating depth, water</td>
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</tr>
<tr>
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<tr>
<td>Material</td>
<td>Stainless steel, copper-nickel alloy, copper, nitrile neoprene</td>
</tr>
<tr>
<td>Clocks</td>
<td>60 or 150 minutes, programmable</td>
</tr>
</tbody>
</table>

**Sampler**

- 250 cm³ Operation above 200°C P/N 11500
- 250 cm³ P/N 11500-1
- 500 cm³ P/N 11501
- 500 cm³ Operation above 200°C P/N 11501-3
- 1000 cm³ P/N 11501-1
- 1000 cm³ Operation above 200°C P/N 11501-2

**NOTE:**

1. For operation above 200°C use hi-temp O-rings.
2. For continued operation above 260°C use perfluoroelastomer O-rings.
through the bit into open hole, ideally far enough away from the drill string to sample undisturbed fluids.

The Kuster sampler might therefore seem to be a better choice to obtain undisturbed fluids, but the WSTP tool may be required if there are any doubts about whether the hole is free and clear of any bridges or obstructions. If there is any chance of obstructions, it is safer to reenter the hole with a clean-out bit and run the drill string to the bottom of the hole, rotating and circulating where necessary to clean the hole. As the bit is worked down the hole during such a clean-out process, it is possible to pause at nearly any depth in the hole, to lower the WSTP tool into the bit and sample borehole fluids just ahead of the bit, which may be affected to some degree by any required rotation and/or circulation.

There will probably be concerns about hole conditions in reentering holes into sedimentary formations, holes into rubbly basement, and basement holes in which the sediments are not completely cased off. Such concerns should be carefully considered by the co-chief scientists and ODP engineers at the pre-cruise meeting, where the decision should be made as to what apparatus is to be run first into a reentered hole. These concerns will be relatively minor in reentering a properly cased basement hole with a good drilling history and no indications of hole stability problems.

Two examples may be helpful:

(1) Leg 103 reentered Hole 41B in 1985, about 8 years after it was drilled with little difficulty during Legs 51 and 52. However, as the lower 200 m of sediment had never been cased, and a logging tool was feared to have been lost in the hole during Leg 52, the initial reentry was made with a clean-out bit, which was run to hole bottom, encountering bridges but no logging tool. During two pauses in this clean-out pipe trip, the WSTP tool was lowered into the bit to sample borehole fluids and measure borehole temperatures, with fair results (Salisbury, Scott, et al., 1986).

(2) When Legs 70, 83, and 92 revisited Hole 504B, the initial reentries were made with a clean-out bit, and the WSTP tool was deployed several times during the clean-out pipe trips. As no obstructions were encountered, no rotation or circulation was required, and the fluid samples and temperature measurements were generally good (Mottl et al., 1983, 1985; Gieskes et al., 1986; Becker et al., 1983a, 1983b, 1985). When Leg 111 reentered Hole 504B, no hole problems were expected, and the initial reentry was made with a light-weight French temperature logging tool, which was run to within 55 m of hole bottom, followed by several runs of Kuster water samplers and a Schlumberger water sampler. The temperature data were excellent but the water samplers were plagued by tool failures unrelated to hole conditions (Becker, Sakai, et al., 1988).

E. Active fluid sampling utilizing packers

When a packer is used to seal a borehole, the fluids in the sealed section are isolated from further contamination and mixing with seawater. If a sufficient volume of fluids can be pumped from a zone sealed by a
packer, pore fluids will be drawn into the borehole, and a borehole fluid sample may then contain a significant component of pore fluids. Several devices have been proposed to sample pore fluids in such an 'active' manner in conjunction with packers, but none of these has been tested or proven as of the end of Leg 118. In the future, the following tools may be available for active sampling using packers: the LDCO wireline packer, the ODP 'probeless PWS,' and a sampling go-devil for the drill-string straddle packer that is presently being developed and is briefly described in Chapter VI.

The wireline packer is configured like a logging tool, and is intended to be run on the logging line into open hole, to sample fluids from isolated zones of the formation. It consists of a short straddle packer, 1-4 sample bottle(s), downhole pumps and valves to inflate the packers or pump fluids from the formation to the sample bottles, and electronic sensors to monitor key properties of the fluids to be sampled, such as pressure, temperature, pH, Eh, and concentrations of certain ions. With real-time surface readout of these fluid properties, the operator will be able to assess whether the fluids being pumped past the sensors contain true formation fluids, and to fill the sample bottle(s) when the fluids are worth sampling for detailed analyses. The wireline packer is presently being constructed by TAN International, the manufacturer of the ODP drill-string packers, and is scheduled for testing during Leg 124E. Further information is available from the LDCO Borehole Research Group.

The 'probeless PWS' (pore water sampler) comprises a WSTP tool modified to be used in conjunction with the inflated ODP rotatable drill-string packer, which is described in Chapter IV. The WSTP tool is modified by replacing the probe containing its temperature and pressure sensors with a short filter assembly, so that no part of the probeless PWS extends beyond the bit (Figure II-5). In addition, a large (up to 60 l), divided, evacuated core barrel is attached, with the intent of drawing a large volume of fluids from the isolated section of the borehole. The last 0.1-1.2 l of fluid drawn into the sampler is captured separately, in the normal WSTP sample coils and chambers. If a sufficiently small section of permeable formation is isolated by the packer, then the fluids sampled later should contain a greater component of pore fluids. It should then be possible to estimate the composition of in situ pore fluids by extrapolating along a mixing line determined by the successive sample aliquots.

As noted above, the rotatable packer has not been used successfully yet, and the probeless PWS has therefore never been tested. Development of this mode of sampling has been suspended until the rotatable packer is proven, but it may also be feasible with the reliable drill-string straddle packer. Note that any procedures and equipment developed to sample fluids in conjunction with drill-string packers must be consistent with procedures for using the packers, which are described in more detail in Chapter IV.

In particular, it may not be possible to lower a sampler into a drill-string packer after it has been inflated, for the following reason: Once the packer is inflated, the drill-string heave compensator must be engaged to avoid dislodging the packer; as the packer will hold the bottom of the drill string in place, the heave compensation will result in relative movement between the top of the pipe and the rig floor. It would
Figure II-5. Schematic of sealing probe assembly for use with the ODP drill-in packer. Packer element is located on the outer core barrel above the section shown in the figure. The lower bulkhead of the WSTP tool is attached to the probe about 25cm above the landing sub. The arrows show flow of water through the probe from the filter to the water sampler inlet port. (1) standard ODP landing sub, (2) support bearing, (3) probe to outer core barrel seal, (4) special sealing sub-assembly, (5) probe tip assembly, (6) filter element, (7) drill bit.
then be very difficult, dangerous, and probably contrary to SEDCO safety policies to attempt to 'stab' a sampling tool into the moving top of the pipe. (It might be possible to hold the top of the pipe stationary at the rig floor if bumper subs have been included in the BHA, but bumper subs may seriously compromise the packer operations.) Therefore, any sampler must be lowered into the packer before the packer is inflated, and the sampler must then also functionally substitute for the go-devil that would normally be used to enable packer inflation. (See Chapter IV.)
III. TEMPERATURE MEASUREMENTS

A. Introduction

The geothermal gradient is a fundamental property of the crust that influences and reflects the effects of tectonic, hydrologic, and geochemical processes, and accordingly temperature was among the first downhole properties to be measured during DSDP. In fact, Von Herzen and Maxwell (1964) actually measured sediment temperatures during drilling at the preliminary Mohole site, and a strong effort was made to measure downhole temperatures from the beginning of DSDP. Erickson et al. (1975) and Hyndman et al. (1987) reviewed the downhole temperature measurements made during DSDP and the techniques for determining in situ temperatures from the measured values.

Several methods are presently available in ODP to measure downhole temperatures, including two tools operated by ODP to measure sediment temperatures — the WSTP and the APC temperature (T) recorders — and logging tools operated by LOGO and some independent investigators to measure temperatures in open boreholes. The use of the ODP WSTP and APC T tools in their primary mode, measuring sediment temperatures during the process of coring a hole, will be described in detail in this chapter. In addition, the use of these tools to obtain profiles of borehole temperatures in open hole or of sediment temperatures in an uncored 'hole' will be discussed.

While the WSTP and APC T recorders can both be used to measure sediment temperatures, they differ in their application in three key ways: (1) The WSTP is used to measure temperatures between coring periods, and thus requires 1-3 hours for each measurement, whereas the APC T tool is used during the process of cutting a hydraulic piston core, and only requires 10-15 minutes of additional time. (2) During a measurement, the WSTP tool is pushed into uncored sediments and will disturb the section to be cored next, whereas the APC T tool should not affect the quality of the next core. (3) The WSTP can be used to depths at which the sediments can be safely penetrated with the probe, typically several hundred mbsf. In contrast, the APC T tool can be used only to depths at which the force required on pullout is within safe limits, typically to about 100 mbsf. Neither the WSTP nor the APC T tool is effective at very shallow depths, where the sediments are not competent enough to hold the probe stable.

Temperatures measured in the probes downhole do not often reach full equilibrium with in situ values, and must usually be corrected for two major effects, the thermal disturbance to the borehole and surrounding formation by drilling and circulation (e.g., Bullard, 1947; Jaeger, 1961), and the transient approach of probe temperature to sediment temperature (Bullard, 1954), typically due to the decay of frictional heating of the probe on penetration into the sediments. The former will be mentioned only briefly, as it usually affects open-hole temperature logs measured shortly after drilling, which are not normally attempted using the ODP tools. The gradual approach of probe temperatures to in situ values is clearly seen in data measured in sediments with the WSTP or APC T tool, and the methods and shipboard computer programs required to extrapolate the measured temperatures to in situ values will be briefly summarized.
B. Temperature measurements with the WSTP tools

Most of the tools used to measure temperatures during the early stages of DSDP (Figure III-1; see Erickson et al., 1975) were similar in concept to the present WSTP tool, which also incorporates the capability to sample pore fluids and to measure pressure instead of temperature (Chapter II; Barnes, 1988). Yokota et al. (1980) and Uyeda and Horai (1982) described the temperature recorder for the first WSTP tool, which they developed before Leg 60. This tool was known during DSDP as the Barnes-Uyeda probe or Tokyo T-probe and is still used extensively on JOIDES Resolution. There are two versions of the temperature recorder for the present WSTP tool, redesigned by R. Current, C. Current, and D. Cash at ODP.

Tool specifications

The temperature-measuring systems of the two generations of WSTP tools are similar in concept, but differ primarily in their electronic capabilities. The WSTP tools employ battery-powered recorders with electronic memories to monitor the resistance of a single thermistor in a probe that protrudes about 1 m ahead of the bit (Figure III-1). The first-generation WSTP tool is limited to storing only 128 values of thermistor resistance, and can be programmed to read these values at 1- or 2-minute intervals during stations that last about two or four hours, respectively. The first version of the second-generation WSTP recorder can sample 16,000 values from three channels (temperature plus two pressure transducers) at an interval of up to about 5 seconds. This recorder has occasionally failed under tough deployment conditions, and a simpler, more reliable recorder is also available. This new version can record only one data channel (i.e., temperature but not pressure), and can store up to 2048 values sampled at a programmable interval.

The single thermistor is encased in a steel probe with an outer diameter of 1.25 cm, with a slight taper on the new version (Figure III-2). Therefore the probe has a time constant in sediments on the order of 2-3 minutes, and it must be held in position for about 10 minutes to obtain enough data to reliably extrapolate to in situ sediment temperature.

Preparation and deployment

The WSTP tool will be programmed and prepared for deployment by the ODP downhole tools technician(s), who will need to know the parameters to be measured (temperature or pressure and/or fluid sample) and the depth of measurement several hours in advance. It is advisable to check the thermistor calibration and electronic circuits by verifying the ice-point reading occasionally and by substituting a decade box for the thermistor before and after sites. A fully charged battery should be used, particularly if extensive instrument testing is conducted immediately before deployment and/or a long station is planned with all three measurement capabilities.

As described in Barnes’ operating manual and excerpted in Chapter II, the WSTP can be used in several deployment modes. Barnes’ instructions are directed toward obtaining the best water sample, and will generally apply to measuring temperature. However, if the primary objective of lowering
Figure III-1. Diagram of the type of sediment temperature probe used for the majority of the Deep Sea Drilling Project heat flow measurements (after Exickson et al., 1975). From Hyndman et al. (1987).
Figure III-2. Detail of the thermistor probe and pore fluid filter assembly for the ODP WSTP tool.
the WSTP is to obtain the best temperature data, slightly different procedures might be followed, as will be discussed here.

The standard method is described by Barnes as ‘latched-in operation’ (see Chapter II) and requires about 1-3 hours between cores (depending primarily on water depth) to measure temperatures at a chosen depth. Normally, the tool is lowered on the coring line and latched into the bit held just above the measurement depth. As the tool is lowered to the bit, a 5- to 10-minute pause to check recorder performance should be made at the mud line, where the temperatures inside the pipe should be close to (but possibly slightly higher than) the stable bottom water temperature. Once the tool is latched into the bit, the pipe is then lowered, pushing the probe to the measurement depth in sediments ahead of the hole that ideally are undisturbed by previous drilling. If pore fluid sampling is the primary goal, Barnes recommends pumping as the tool is lowered to wash fill from the bottom of the hole; if a good temperature measurement is the primary goal, it may be better to minimize pumping and avoid disturbing temperatures at the measurement depth.

At the measurement depth, the probe is held stationary using the heave compensator, as follows: As the probe is pushed into the sediments, a small amount of weight can be transferred from the derrick to the bit, by adjusting the amount of weight that is compensated. The heave compensator will be effective at maintaining the position of the bit and probe only when the amount of weight that will be held by the bit is greater than the sensitivity of the heave compensator, about 5000 lb. Thus, the measurement should be taken at the depth where sufficient weight can be maintained to hold the probe stationary, which will not necessarily correspond precisely to a pre-selected depth. In particular, it is very difficult to measure temperatures in very shallow sediments, which are not competent enough to support the minimum weight required for heave compensation.

Maintaining the probe stationary for about 10 minutes is the primary consideration in obtaining good temperature data with the WSTP. The weight required to penetrate the sediments and to hold the probe in place will depend on the strength of the sediments, and will generally increase deeper in the section. If too little weight is applied, the probe may be allowed to move, degrading the data through two possible factors, additional frictional heating on probe movement and leakage of borehole fluids around the probe. On the other hand, if too much weight is placed on the bit, the probe may be slowly pushed ever deeper, resulting in continuous frictional heating, and the formation may even be fractured, allowing borehole fluids to leak around the probe and affect the measurement. For temperature measurements, it may be better to apply slightly too much weight, unless it is also critical to obtain good pore pressure data that would be degraded by compression of the sediments.

Data retrieval and processing

The ODP downhole tools technician is responsible for dumping the raw thermistor resistance data to the shipboard VAX, for converting these data to temperatures, and for producing a standard plot of measured temperatures versus time using the ‘PicSure’ graphics program on the VAX (e.g., Figure II-3). This is accomplished in the technicians’ 'DOWNHOLE' account on the
VAX, from which the scientist may obtain copies of the data files and standard data reduction programs. The data files are archived as prime data at ODP, but require further processing to determine in situ temperature, which is the responsibility of the scientist.

The scientist should be concerned with at least two stages of processing: first, possibly correcting the raw data according to the results of calibrations before or after the station or at mud line during the station; and second, extrapolating the corrected temperatures to the in situ value. A rigorous theory describes the approach of a cylindrical probe to in situ temperature after penetration (Bullard, 1954; Jaeger, 1966), and the in situ temperature should be determined by fitting the measured values to Bullard’s (1954) F-function (tabulated by Lister, 1979; see also Hyndman et al., 1979). At present no official ODP programs are installed on the shipboard VAX to accomplish this, but various programs have been left by shipboard scientists, and Lister’s (1979) table is available in the shipboard collection of reprints (see Appendix B).

C. APC temperature tools

With the advent of the hydraulic piston corer during the late stages of DSDP, Dr. R. Von Herzen developed a miniature recorder designed to fit in the cutting shoe and measure sediment temperatures as a core was taken (Figure III-3; Horai and Von Herzen, 1985; Koehler and Von Herzen, 1986). The last of these tools is still in use on JOIDES Resolution, but has a limited useful life remaining. ODP has had a redesigned version on order from Bowmar-White Co., to be delivered in 1988. The Von Herzen and Bowmar-White tools are similar in function and are collectively termed APC T tools (advanced hydraulic piston corer temperature tools).

As noted above, the major advantage of the APC tool over the WSTP is that the APC tool is used to measure temperatures as a piston core is taken, with very little time required in addition to that needed to take the core. On the other hand, use of the APC tool is limited to depths at which the force required on pullout is within safe limits, roughly the upper 100 m. This depth limit is somewhat less than the limit for simple APC coring, because the sediments will ‘grip’ the corer more tightly during a 10-minute station to measure temperatures than during a 1-minute penetration to cut a core.

Tool specifications

The APC T tool consists of a programmable miniature recorder about 12 cm long and a small battery pack, both of which fit into cavities in the APC cutting shoe (Figure III-3). Originally, separate cavities were cut for the recorder and battery pack, but the newest design features a semi-annular cavity with a removable carrier for the recorder and battery pack. The Von Herzen version can be programmed to record up to 1300 values of the resistance of a calibrated thermistor, sampled at a selectable interval of 0.1 second to as much as 100 minutes. The Bowmar-White version uses a calibrated platinum resistance device, and can be programmed to record up to 3000 values of the raw temperature values, sampled at an interval of 0.1 second to 24 hours. The tools and programming instructions are more fully described in two users’ manuals, one by Koehler and Von Herzen (1986) and one in preparation for the Bowmar-White tool.
Figure III-3. Diagram of the hydraulic piston corer temperature measurements system embedded in the core shoe (after Horai and Von Herzen, 1985). From Hyndman et al. (1987).
The single sensor of the APC tool is positioned close to the tip and edge of the cutting shoe (Figure III-3), which is represented as a perfectly conducting annular cylinder in processing the measured temperatures (Horai and Von Herzen, 1985; Horai, unpublished ms.). The wall thickness of this annular cylinder is about 1.5 cm, giving it an effective time constant of roughly 2-3 minutes in sediments. Thus the APC must be held in place for about 10 minutes to record enough data to reliably extrapolate to in situ sediment temperature.

Preparation and deployment

The APC T tool is normally used on selected cores in a sequence of APC cores in the upper 100-200 m of sediments, and the allowable depths of measurement are determined by the lengths of the cored intervals, usually 9.5 m. The selection of temperature stations and preparation of the recorder must be carefully coordinated to avoid disrupting the coring routine, which can be surprisingly rapid-fire at a typical APC hole. The scientist must consult in advance with the ODP lab officer and downhole tools technician, to specify the cores on which temperature is to be measured and the recorder programs to be used. In recent usage, the Von Herzen recorder has typically been programmed to record thermistor resistance every 10 or 15 seconds during a station 2 or 3 hours long.

The downhole tools technician will prepare the recorder and cutting shoe, and deliver the assembly to the rig floor at the appropriate time. Until the Bowmar-White tool is produced in quantity, it will probably not be possible to measure temperatures more frequently than every third core, because of the time required to dump previous data, replace batteries, reprogram the recorder, replace it in the cutting shoe, and redress the shoe.

If the APC T tool and cutting shoe are ready at the appropriate time, the station will proceed like a normal piston core, with one obvious exception: After the corer is hydraulically fired into the sediment, it must be held in position for about 10 minutes to record enough data to allow in situ temperature to be determined. The corer is then retrieved in normal fashion; when it is brought on deck, the cutting shoe is broken off and given to the downhole tools technician before the core is removed from the core barrel.

Data retrieval and processing

As with the WSTF tool, the downhole tools technician is responsible for dumping the raw data to the shipboard VAX, for converting these data to temperatures (if necessary), and for producing a standard plot of temperatures versus time. This will be accomplished in the technicians' 'DOWNHOLE' account on the VAX, from which the scientist may copy the data files and data reduction programs. As presently written, the programs and command files pertain to temperatures obtained by converting resistances of the thermistor in the Von Herzen tool, and they will require some revision to accommodate the Bowmar-White tool. The data files and standard plots are archived as prime data at ODP, but require further processing to determine in situ temperature, which is the responsibility of the scientist.
To determine the best estimate of true sediment temperature, the measured temperatures must be fit to the function that describes the approach of the APC cutting shoe to in situ temperature after penetration. This function was formulated by Horai (unpublished ms.) and the data reduction procedure is summarized by Horai and Von Herzen (1985). Copies of these papers are available in the shipboard reprint collection (see Appendix B). The procedure for data reduction is somewhat interactive and subjective, and must be conducted carefully, because (1) Horai’s formula probably does not apply at very short times after penetration, and (2) the thermal properties of the cutting shoe introduce an ambiguity in assigning an effective time origin in treating the data.

Horai’s programs were rewritten and thoroughly documented for ODP in 1987 by K. Becker, and are available on the shipboard VAX in the scientists’ ‘HEATFLOW’ directory. Copies of the programs and documentation are available from ODP. Figure III-4 shows an example of excellent data recorded with the Von Herzen tool during Leg II, and the fit of the data to the theoretical cooling curve, calculated with the revised programs presently available. When the Bowmar-White tool is put into service, these programs will require further revision, although the basic algorithms will remain effective.

D. Use of ODP tools for discrete temperature ‘logs’

The sections above have concerned the deployment of the ODP temperature recorders in their normal mode of obtaining single values of sediment temperature per tool lowering at discrete depths during the process of coring a sediment hole. It is also possible to use these tools to obtain readings of temperatures at multiple depths during a single lowering, either in open borehole or in sections of sediment that are not cored. For such stations, the procedures for tool preparation and data processing are basically the same as discussed above, although somewhat longer recording programs may be appropriate. Only the methods of deployment are different, as will be discussed here.

To obtain such discrete temperature ‘logs,’ either the APC T recorder or the WSTP can be used, although the APC tool is often preferable for reasons discussed below. During these stations, the tool is lowered to the bit, and the pipe is moved in stages so that the temperature sensor is held for about 10 minutes at each of the measurement depths. The tool can be lowered to the bit either on the coring line or by freefall, but if it is run on the coring line, the range of measurement depths is limited to about 20 m because it will not be possible to add or remove pipe over the coring line. Twenty meters corresponds to the approximate length of drill pipe that can be drawn up in the derrick before the station and then lowered into the hole with the coring line once the tool is run to the bit at the beginning of the station. Thus, deployment by freefall is necessary if it is desired to measure temperatures over a depth range that is greater than about 20 m. The APC T tool is more appropriate for freefall, because it will generally withstand the deceleration on landing much better than the WSTP tool.
LEG 111  CORE 677B-10  APC TEMPERATURES

TIME (minutes)

- MEASURED TEMPERATURES
- BEST-FIT THEORETICAL DECAY

FIRST 6 DATA POINTS IGNORED IN FIT
THERMAL CONDUCTIVITY = 1 W/M-K
EXTRAPOLATED TEMPERATURE = 20.452 °C

Figure III-4. Actual temperature data collected with the APC T recorder during Leg 111, with the best-fit model for the approach of the cutting shoe to in situ temperature.
Logging sediment temperatures without coring

If the temperature profile is to be measured in sediments, the recorder must be latched into the bit. The pipe is then pushed and washed through the sediments to just above each of the measurement depths; the pumps are then shut off and the tool is pushed into place and held stationary for about 10 minutes using the drill-string heave compensator as described in section B. It is preferable to use the APC T tool for this kind of station because less sediment must be displaced in penetrating with the annular APC cutting shoe than with the larger profile WSTP. In addition, the WSTP probe may bend if an obstruction is encountered, possibly preventing it from being withdrawn through the bit by normal means. As illustrated by the example in Figure III-5 (from Detrick, Honnorez, Bryan, Juteau, et al., 1988, at a low heat flow site), the resulting temperature record will clearly show the effects of fluid circulation and frictional heating as the probe is moved between measurement points, but good data can still be collected at the measurement depths if the probe can be held stationary.

Logging open-hole temperatures

Upon returning to a reentry hole in which the borehole fluids have reequilibrated with the geothermal gradient, it is usually critical to log borehole temperatures and sample fluids before any other operations disturb the borehole. Ideally, a continuous temperature log should be obtained using a lightweight tool on the logging cable, as was done when Leg II revisited Hole 504B (Becker, Sakai, et al., 1986). However, this will not be allowed if the hole is not expected to be completely free of bridges or obstructions. In that case, true logging will not be permitted until the hole has been cleaned out by running the pipe and bit to hole bottom, but this cleanout pipe trip will disturb the thermal equilibrium of the borehole fluids.

Nevertheless, a temperature log and fluid samples can still be obtained, by deploying an ODP temperature tool to the bit as this cleanout trip is made. During such an operation, the recorder probably should not be latched into the bit, so that it will be pushed back up inside the pipe if an obstruction should be encountered. To minimize disturbances to the borehole fluids, the pipe should be run very slowly and carefully into the hole, avoiding circulation and rotation unless absolutely necessary to clear an obstruction. Pauses can be made during this cleanout pipe trip at nearly any depth, to measure temperatures, sample fluids, or retrieve and re-deploy the tool. It is even possible to configure the WSTP and APC T tools together, and run them simultaneously to assure recovery of equilibrium temperature data in the event of a tool failure. Figure III-6 shows the data obtained with the APC T recorder during this kind of station when Leg 92 reentered Hole 504B (Leinen, Rea, et al., 1986); the WSTP tool was run simultaneously to sample fluids and record backup temperature data which are not shown.
Figure III-5. Temperatures measured with the APC recorder during Leg 109 in the uncored sediment.
Figure III-6. Temperatures measured with the Von Herzen APC T recorder during Leg 92 reentry of Hole 504B.
IV. DRILL-STRING PACKERS

A. Introduction: Packers

A packer can be defined simply as a device that produces a hydraulic seal in a borehole (Figure IV-1). If the integrity of this hydraulic seal is properly maintained, the hydrologic properties of the formation can be tested, by applying differential fluid pressures to the isolated section. Formation properties that can be measured using a packer include pore pressure, transmissivity, from which permeability can be derived, and (less accurately) storage coefficient, which is directly related to formation porosity. In addition, it may be possible to sample fluids from the section of borehole isolated by a packer; if the formation is permeable enough, the sample may contain a component of formation fluids.

A drill-string packer is designed to be part of the BHA; a wireline packer is a separate tool lowered on a conducting cable into open hole, like a logging tool. A drill-string packer or a wireline packer can be configured as a straddle packer, which incorporates two hydraulic seals and allows the zone between the seals to be tested or sampled. In contrast, a single-element packer isolates the zone between the packer seal and the bottom of the hole.

Three packers are presently available in ODP, all manufactured by TAM International of Houston, Texas:

1. A non-rotatable drill-string packer that can be configured as a single packer or a straddle packer, presently supported by an NSF grant to the University of Miami. This packer was used successfully during Legs 109, 111, and 118, and is available for use in reentry holes that penetrate stable formations.

2. A rotatable drill-string packer operated by ODP, intended for use in less stable formations, where a rotational capability may be required for safety reasons. This packer was tested during Leg 110, and the design was subsequently modified, but the redesigned version has not yet been used. It is sometimes called the 'TDP,' or TAM Drilling Packer.

3. A wireline packer operated by the Borehole Research Group at LIGO, intended primarily for fluid sampling, but also capable of limited formation testing. The wireline packer has not been used yet, but is scheduled for land tests in 1988 and full ODP testing during Leg 124E.

The use of the two drill-string packers will be fully discussed in this chapter. The use of the wireline packer will not be detailed here, as it is an LIGO logging tool and has not yet been proven for routine use.

B. ODP drill-string packers

Unless it is specially engineered, a drill-string packer should be kept in tension, like the drill pipe above the BHA, and should not be included as part of a coring, rotating BHA. Thus, formation testing with the non-rotatable drill-string packer will require separate pipe trips into
Figure IV-1. Sketches of TAM inflatable drill-string packers.
A. A single-element packer, which isolates the formation between the element and the bottom of the hole.
B. A straddle packer, which separately isolates the zone between the elements and the zone between the lower element and the bottom of the hole.
reentry holes that have already been cored. As described below, the packers are compatible with logging, and it may be possible to accomplish logging and packer measurements during a single pipe trip.

The special engineering required of the rotatable drill-string packer includes a strengthened internal mandrel to withstand both the torque and compressive loads of drilling, and a plumbing system that will permit cuttings to be circulated away without inadvertently inflating the packer elements. While the ODP rotatable packer was designed to be compatible with coring, during initial testing rotation has destroyed the packer elements. Thus this packer has not yet been proven for use in a ideal mode of coring ahead, pausing for measurements, coring ahead, etc. Instead, it should probably be used in a reentry/logging mode, in holes where there is any chance that the formation may collapse around the packer, necessitating a rotating capability to free the BHA (e.g., in sediments).

Packer elements

The packers used in ODP are inflatable packers, which seal the borehole using hybrid rubber/steel elements that are inflated with seawater pumped down the drill string from the rig floor. Each of these elements consists of an internal rubber bladder, which is bonded to an expandable steel strength member, which in turn is bonded to an outer rubber cover. The outer rubber and the steel serve to ‘grip’ and seal against the borehole wall; and to protect the inner bladder, which must remain unpunctured for the packer to remain inflated.

The proprietary TAM design uses a tight, ‘Chinese-finger’ weave of stainless steel wire rope as the element’s internal strength member (Figure IV-2). This has the advantage that good bonds can be maintained between the woven cable and both the inner and outer rubber during expansion and contraction of the element. However, this type of element may be weak at very high degrees of inflation, if the cables separate to the extent that the rubber in the gaps must bear too much of the inflation pressure.

The elements for the two TAM drill-string packers have the same external dimensions, threads, and seal surfaces, but different internal diameters. The internal mandrel of the rotatable packer is larger to withstand torque during rotation. Thus the element for the rotatable packer has a larger internal diameter, and it can be used on the non-rotatable (straddle) packer. However, the elements for the non-rotatable packer have too small an internal diameter to be used on the rotatable packer.

Inflation of packer elements using go-devils

The TAM packer elements can safely be inflated to as much as twice their uninflated diameters. However, a greater degree of inflation requires more time for full deflation, and produces a weaker hydraulic seal that can withstand a lesser range of test pressures (Figure IV-3). Thus, effective formation testing requires that the packer(s) be positioned in zones where the borehole is in good condition and in gauge, where the degree of packer inflation can be kept reasonable. Such zones are usually apparent in logs that should be run before packer tests are begun, such as caliper, borehole teviewer, resistivity, density, and sonic logs.
The outer packer sheath is made from a special oil-resistant nitrile rubber compound. The sheath can be built up to a larger diameter if desired, and special, high-temperature compounds are available.

Inflating fluid is contained between the packer inner tube and the packer mandrel. Inflating fluid can be whatever is in the work string: mud, completion fluid, oil, nitrogen, even air.

Standard seal length is 48 inches (packers smaller than 2½-inch OD have shorter seal elements).

Figure IV-2. Anatomy of the rubber elements used on the ODP drill-string packers manufactured by TAM International.
Figure IV-3. Capabilities of the standard TAM elements to withstand differential test pressures versus hole size.
After the drill-string packer is positioned in the desired zone, inflation of the element(s) is accomplished by pumping seawater from the ship down the pipe. Before pumping, the inflation mechanism is enabled by free-falling a retrievable go-devil, which keys into the packer plumbing system. (Note that inflation of the 1200 wireline packer is accomplished by an electrically powered downhole pump.) A properly seated go-devil may perform several functions, including (1) forming a hydraulic seal within the packer to direct the fluids pumped from the rig either into the elements for inflation or into the formation for testing, (2) carrying the pressure recorders that monitor the data needed to determine pore pressure and permeability, and (3) possibly carrying a sample chamber. Using go-devils that are retrievable with the coring line, multiple sets of the ODP drill-string packers can be made, as long as the elements hold pressure and seal the borehole.

Temperature limitations of the ODP drill-string packers

The temperatures to which the drill-string packers can be used are limited by the temperature ratings of the rubber compounds that compose the packer elements and inner seals. Standard nitrile o-rings and elements are rated to about 100°C. Commercially available o-rings made of special elastomers are effective to temperatures as high as 300°C. However, the combination of elasticity, strength, and resealability required of the rubber in the inflation elements is difficult to achieve at high temperatures. Packer elements made with high-temperature rubber compounds will probably be effective to 200-250°C, but only at limited test pressures and limited degrees of expansion (10-20%), and such elements may last only for single settings. During Leg 111, two special elements rated to 120°C were successfully used at temperatures of 120-145°C in Hole 504B, but lasted for only one setting each.

Compatibility of ODP drill-string packers with logging

All of the standard logging tools will pass through either drillstring packer, unless a packer go-devil is in place. Either packer can be built into a logging EHA, and packer measurements may not require a special pipe trip in addition to the trip necessary for logging. Packer measurements are usually run after the completion of wireline logging, because of the chances of a go-devil getting stuck in the pipe or of rubber from the packer elements stripping off in the hole. Also, the logs are usually important in locating formations in which to set the packer.

In some situations, it may be better for operational reasons to run a separate pipe trip for packer measurements. For example, the packer EHA may require more drill collars than an optimal logging EHA to balance the upward force on pressurizing the zone isolated below the packer. It may be necessary that most or all of the EHA be in the hole below seafloor during logging, and a heavier, longer packer EHA would limit the shallowest depth to which logs could be run. Thus, if it is essential to log the upper 50 m of a reentry hole, separate pipe trips might be required for logging and packer measurements.

Logging or experiments will generally not be permitted through an inflated packer, as this would involve unsafe procedures on the rig floor.
as follows: When the packer is inflated and gripping the borehole wall, the BHA is immobilized, and the drill string must be heave-compensated to avoid tearing the packer loose. With the drill string compensated, the upper end of the pipe will move relative to the heaving rig floor, and it would be very difficult and unsafe to attempt to ‘stab’ a long logging tool into the end of the pipe. In addition, the compensation of the wireline is not coordinated with the compensation of the drill string, and the risk of coiling or stretching the cable within the pipe might be unacceptable.

C. TAM straddle packer

The design of the TAM straddle packer is quite simple, as it has no rotational capability and is intended primarily for measurements in reentry holes that penetrate stable formations. By assembling it in the BHA with or without a few essential parts, this packer can be used in four resettable modes:

(1) as a single-element packer,
(2) as a double-element (double-seal) single packer,
(3) as a straddle packer,
(4) as a straddle packer allowing the option to separately test the straddled interval or the interval below the packer.

All of these configurations are fully compatible with logging, so that packer measurements will not necessarily require an exclusive pipe trip. (The minimum I.D. of this packer is 3.94" for a single packer configuration or 3.81" for a straddle packer configuration.)

When a straddle configuration is used, the straddle interval can be as small as 1 m, and can be changed by spacing 9-m sections of drill pipe between the elements. Hydraulic continuity is maintained between the elements by connecting them with 3/8"-diameter stainless steel tubing external to the spacing drill pipe. Thus, if either element or the tubing fails to hold pressure, neither element can be inflated. This is a good safety feature, in that once the packers are inflated, a hydraulic failure anywhere in the system will result in the deflation of both elements, not permitting an element to remain locked in an undeflatable position.

Depending respectively on whether a single or a straddle configuration is deployed, the first or both of two go-devils assembled from common parts will be used:

(1) a go-devil with 3.99"-diameter seals and stop rings, that seals above the single packer (or the upper straddle element) and keys into the sub-assembly that controls inflation and deflation of the single (or entire straddle) packer;

(2) a go-devil with 3.89"-diameter seals and stop rings that passes through the control sub and seals the drill pipe at the lower straddle packer, allowing the straddled interval to be tested.

Self-contained Kuster pressure recorders are attached to the upper go-devil to record pressures in the isolated section, whether it be between a single packer and the bottom of the hole or between the two inflated
elements of the straddle configuration. During operations with the straddle packer, a single pressure recorder can also be hung below the lower go-devil to test for leakage from the straddled interval. In the near future, self-contained electronic pressure recorders that function like the Kuster recorders may be available.

At present neither go-devil can sample formation fluids, but it would be feasible to develop this capability. In fact, J. Cann is presently developing an electronic sampler that functions like a go-devil in controlling packer inflation; this sampler is described briefly in Chapter VI. In addition, it might someday be feasible to configure modules of the LIDO wireline packer in a similar fashion as a sampling go-devil for the straddle packer.

Each go-devil must be retrieved with a standard overshot on the coring line. The use of the single packer configuration is straightforward, requiring just one freefall/retrieval round-trip of a single go-devil. Use of the straddle configuration requires a more complex and time-consuming sequence of go-devil operations: First, the upper go-devil must be dropped to allow inflation of both packers and possibly testing of the zone below the lower packer; second, to test the straddled interval the upper go-devil must be retrieved, the lower go-devil dropped into place, and the upper go-devil dropped a second time; and third, at the end of the experiment, two trips of the coring line are required to retrieve both go-devils.

Inflation of the TAM straddle packer utilizes the drill-string heave compensator, as follows: To enable inflation, the upper go-devil must seal properly in the packer control sub. This assembly incorporates one principal moving part that can shift vertically by about 20 cm, controlling whether or not the inflate/deflate port to the elements is open. This control tube is directly connected to the drill string, and its position is controlled from the rig floor using the sensitive drill-string heave compensator. When the drill string is freely suspended, both the flow paths into the elements and down the pipe/up the annulus are open, so that pressure in the elements must remain the same as in the borehole. Thus, the elements will remain uninflated until the upper go-devil is in place and the rig pumps are used to pressurize the elements. When the elements are fully inflated against the borehole wall, the heave compensator is adjusted to put some weight on the packer, shifting the control tube so that the inflate/deflate ports are closed and the packer elements are locked in the inflated position. Then, after the completion of formation testing, the packers can be deflated simply by pulling up on the drill string at the rig floor, opening the inflate/deflate port whether or not the go-devil is in place.

A shipboard manual contains full schematics and gives detailed instructions for:

1. assembling the non-rotatable drill-string packer as a single packer or as a straddle packer.
2. testing the assembled packer before deployment, and
3. deploying and operating the packer and go-devil(s).
been produced by the ODP engineers responsible for its development. The redesigned TAM rotatable packer has not yet been used, but is scheduled for testing during Leg 124E in early 1969. The ODP manual and this section may be revised after completion of these tests. In particular, after these tests it will be more apparent to what extent the rotatable packer will actually work in a rotating mode, and how well formation fluids can be sampled using the 'probeless PWS' with the packer, as is discussed briefly in Chapter II.

E. Formation testing using ODP drill-string packers

Using a packer, several hydrologic parameters of the formation can be determined in various types of tests that involve controlled pumping of seawater from the rig floor into the isolated interval. In all of these tests, the critical parameter that is actually measured and from which the formation properties are derived is fluid pressure in the isolated section of the borehole. During testing it is also important to measure fluid pressure at the rig floor pumps, as well as the volume and rate at which fluid is pumped into the isolated zone.

On JOIDES Resolution, two powerful pumps are available for inflating the packer and testing the formation: the 'cement' pump and the 'mud' pump. The mud pump is directly controlled at the rig floor by the driller and is more convenient, particularly for setting the packers. The cement pump is controlled below the rig floor and is thus much less convenient, but it may be more appropriate when accurately measured, smaller volumes of higher pressure fluid are required.

Downhole pressure recorders

Downhole pressures can be measured using several kinds of recorders. At present, ODP maintains three self-contained mechanical model K-3 recorders made by Kuster Co. (Figure IV-5, Table IV-1). These are calibrated for three different pressure ranges (0-9050, 0-11,900, and 0-15,275 psi), and can be set to record for 3, 6, or 12 hours. The pressure records are scratched quite accurately onto small coated brass charts. As only one size of chart is produced, some resolution is lost if a longer recording time is chosen; in recent practice, the recorders have been set for 3 or 6 hours. The charts must be read using a calipered, microscopic chart reader, one of which is kept at the University of Miami.

The Kuster K-3 recorders are housed in special carriers that attach to the go-devil that enables inflation of the packer. Normally, two K-3 recorders are attached to the go-devil to provide redundant data in case one recorder malfunctions. In the near future, self-contained electronic pressure recorders will be purchased through the University of Miami. Like the Kuster recorders, these electronic recorders will be housed in special carriers attached to the go-devil. Thus, the electronic recorders will be effectively interchangeable with the Kuster recorders, except that the electronic data will be accessible immediately after the go-devil is retrieved.
Figure IV-5. Schematic of the Kuster K-3 pressure recorder used to measure pressures in the intervals isolated with the ODP drill-string packers.
Table IV-1. Specifications, Kuster K-3 pressure gauge.

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th>K.2</th>
<th>K.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranges</td>
<td>1.000-16.000</td>
<td>1.000-20.000</td>
</tr>
<tr>
<td>Pressure Element</td>
<td>32°-700°F. (0°-370°C.)</td>
<td></td>
</tr>
<tr>
<td>Temperature Element</td>
<td>(Limit span to 200°F.)</td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>1&quot;</td>
<td>1½&quot;</td>
</tr>
<tr>
<td>Length, with filter</td>
<td>39.1&quot;</td>
<td>41.3&quot;</td>
</tr>
<tr>
<td>Length, with bellows</td>
<td>44.6&quot;</td>
<td>47.4&quot;</td>
</tr>
<tr>
<td>Length, with Temp. Element</td>
<td>51&quot;</td>
<td>53½&quot;</td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Gauge, pounds</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Temperature Gauge, pounds</td>
<td>6½</td>
<td>9½</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Recorder</td>
<td>¼ of 1% of range</td>
<td>¹⁄₄ of 1% of range</td>
</tr>
<tr>
<td>Temperature Recorder</td>
<td>± 2°</td>
<td>± 2°</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>.05%</td>
<td>.04%</td>
</tr>
<tr>
<td>Stylus Travel, inches</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Clock Ranges</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3, 6, or 12 hours</td>
<td>12, 24 or 48 hours</td>
<td></td>
</tr>
<tr>
<td>30, 60 or 120 hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead Screw Turns</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Chart Size</td>
<td>2½&quot; x 3½&quot;</td>
<td>2½&quot; x 4½&quot;</td>
</tr>
<tr>
<td>57.2 mm</td>
<td>66.7 mm</td>
<td></td>
</tr>
<tr>
<td>± 92 mm</td>
<td>± 124 mm</td>
<td></td>
</tr>
</tbody>
</table>
Pressures measured during formation testing

In testing the formation using a packer, it is important to carefully control the packer inflation pressure. This is defined as the pressure (relative to hydrostatic) at which fluid is pumped into the packer element(s) when it is inflated and is measured at the rig floor pumps during inflation. The inflation pressure must be carefully chosen, based on anticipated hole conditions and formation properties, and on the planned test pressures. Given good hole conditions, the elements should be inflated to about 500-1000 psi, or to roughly half the planned test pressures if higher pressures are planned. If the inflation pressure is improperly chosen (either too high or too low), a 'leaky' packer seal may result, which will certainly affect any measurements but will not necessarily be recognizable in the pressure data. In addition, care must be taken not to inflate the element(s) to a pressure high enough to actually fracture the formation and thereby invalidate any testing. This upper limit on inflation pressure will depend on the lithostatic pressure and strength of the formation.

It is critical to measure and distinguish three different pressure values in the isolated section of the borehole: hydrostatic pressure, in situ pore pressure, and test pressures. This necessity dictates the overall sequence in the testing procedure at each isolated zone:

1) Hydrostatic pressure must be measured first, before the packer is inflated, both to check the recorder calibrations and to provide a reference baseline to compare the measurements of in situ pore pressure and test pressures. The hydrostatic pressure baseline is usually obtained by waiting 10-20 minutes after the go-devil lands in the packer, before pressuring up to inflate the packer.

2) When the packer is inflated, fluid pressure in the isolated section of the borehole will slowly approach in situ pore pressure of the formation, which may differ from hydrostatic pressure. If it is critical to determine pore pressure, as much as 2-3 hours of passive recording may be required before active testing to provide sufficient pressure data to accurately extrapolate to in situ pressure.

3) In active testing, permeability can be estimated from the transient behavior of pressure in the borehole in response to controlled pumping from the rig floor through the go-devil and into the formation. Two principal kinds of tests have been used in previous DSDP/ODP permeability measurements, pulse or 'slug' tests and constant-rate injection tests, which are described in detail below.

Active formation testing

The permeability of a formation that is isolated by a packer can be determined by any number of methods. The simplest and most direct of these are pulse tests and constant-rate injection tests, both of which involve applying controlled fluid pressure to the isolated zone using the rig floor pumps. Figure IV-6 reproduces a Kuster pressure record from Leg 118 that illustrates both kinds of tests.
LEG 118  HOELE 735B
GO-DEVIL #2: PACKER SET AT 389, 299, AND 223 MBSF

KEY:
- a = go-devil lands, packer set at 389 mbsf
- b, c = pulse tests at 389 mbsf
- d, e = move packer to 299 mbsf
- f, g, h, i = pulse tests at 299 mbsf
- j = move packer to 223 mbsf
- k, l, m = pulse tests at 223 mbsf
- n = constant-rate injection test at 223 mbsf

Figure IV-6. Actual pressure data collected with the Kuster K-3 recorder during Leg 118 operations using the non-rotatable drill-string packer as a single packer, showing good examples of both pulse tests and constant-rate injection tests.
In a pulse test, the downhole recorders monitor the decay of a short, effectively instantaneous pressure pulse applied by the rig floor pumps. In a relatively impermeable formation, the decay of such a pulse will be long compared to the duration of the pulse, and the pressure data can be treated with the theory for an instantaneous pulse (Cooper et al., 1967; Papadopulos et al., 1973; Bredehoef and Papadopulos, 1960). The decay of an instantaneous pulse is described by a complicated integral involving two dimensionless parameters, which depend respectively on 'transmissivity' (a function of permeability) and 'storage coefficient' (a function of porosity). Fitting pulse test pressure data to this function generally resolves transmissivity much better than storage coefficient, yielding estimates of permeability but not necessarily of porosity.

In a relatively permeable formation, a pressure pulse will decay too rapidly to allow resolution of transmissivity, and constant-rate injection tests are appropriate. These involve pumping into the formation from the rig floor at a known constant rate, and monitoring the approach of the downhole pressure to a nearly steady-state value. The transmissivity and permeability can be estimated using the theory for a constant line-sink with a Darcy's law boundary condition (e.g., Matthews and Russell, 1967; Snow, 1968). In practice, it may take upwards of an hour of constant-rate injection for quasi-steady-state to be reached, and permeability is usually estimated from the results of several injection tests at different rates.

Formation tests, particularly pulse tests, may be more effective if the isolated formation is 'shut-in' downhole, i.e., if the fluids in the tested interval are kept isolated from the fluids in the borehole above the test interval. Downhole shut-in can be achieved using a one-way valve in the go-devil that will allow pumping into the isolated formation but will not allow pressure to transmit up the drill string once pumping is stopped. If the isolated zone is shut in, the downhole pressure data may provide more accurate estimates of formation properties, but the pressures measured at the rig floor will reveal nothing about the downhole testing. If the test interval is not shut in, downhole conditions can be monitored by measuring pressure and flow rate at the rig floor, but the downhole pressure data must be corrected for the properties of the entire pressurized column of fluid in the borehole, and larger errors are likely in calculating permeabilities. Downhole shut-in has not been attempted in ODP packer work to date, partly because of go-devil complications, but mostly because it has been deemed important to monitor downhole conditions and events in real time with the rig floor gauges and recorders.

In oceanic sediments and crust, the ranges of permeability over which pulse tests and constant-rate injection tests yield reasonable permeability estimates overlap, and it is often not possible to determine before testing which type of test will be more appropriate. As injection tests disturb the pressure field in the isolated formation to a greater degree than pulse tests, it is advisable to attempt pulse tests before injection tests. If several pulse and/or injection tests are to be attempted in a single formation, the pressurized system should not be allowed to 'flow back' between tests, and the pressure should be allowed to decay naturally as much as possible between tests. If the hole is kept 'shut in' (at the wellhead or downhole), the effects of the individual tests will be superimposed in a straightforward manner, and it will be possible to correct for the effects of previous tests.
The programs of testing will vary from hole to hole, depending on the formation permeability. Further guidance can be gleaned from several good examples: the work done during DSDP in Hole 395A by Hickman et al. (1984) and in Hole 504B by Anderson and Zoback (1982) and Anderson et al. (1985), and the measurements made during ODP Legs 109, 111, and 118 in Holes 395A, 504B, and 735B by Becker et al. (in preparation). (For the ODP work, see also relevant sections in Detrick, Hommerez, Bryan, Juteau, et al., 1988; Becker, Sakai, et al., 1988; and Robinson, Von Herzen, et al., in press.)
V. "MULTISHOT" CORE ORIENTATION TOOL

ODP operates an Eastman-Christensen magnetic multishot camera to measure orientation of non-rotary cores taken with the advanced hydraulic piston corer (APC). This tool provides a photographic record of a magnetic reference azimuth, the deviation of the core from vertical determined with a pendulum, and the magnetically determined azimuth of that deviation. The multishot continuously records images of its compass/pendulum 'angle unit' on 10-mm movie film at pre-selected intervals. As with other tools used with the APC, the use of the multishot tool is limited to depths at which the force required on pullout is within safe limits, typically 100-200 mbsf.

To fully utilize the magnetic orientation capabilities of the multishot tool, a special 30' non-magnetic drill collar must be included in the BHA just above the lowermost drill collar (also known as the outer core barrel). Therefore the decision to obtain oriented piston cores at a given site must be made before the BHA is made up and the pipe is run into the hole. The multishot camera is housed in a non-magnetic pressure case that is installed between two non-magnetic sinker bars in the assembly used to connect the coring line to the APC core barrel. When coring commences, handling the multishot will add 10-15 minutes per core to normal coring times.

The ODP downhole tools technician is responsible for all phases of operating the multishot tool, including tool preparation for each core, removing and developing the film after the run, interpreting the film record, and recording the relative azimuth angle, deviation from vertical, and direction of deviation on special envelopes in which the developed film is stored. The azimuth orientation angle is recorded as the clockwise angle (when looking down) between magnetic north and the double lines drawn on the core liner. The physical alignment between the double line on the core liner and the reference 'rubber' line that is superimposed over the compass image on the multishot pictures is accomplished using a series of mechanical devices built into the equipment. The total error in azimuth orientation reading introduced by these mechanical devices should not exceed 3°.

Even if the non-magnetic drill collar is not installed in the BHA, the multishot can be used to measure the deviation from vertical without any determination of orientation, also known as 'drift' of the hole. The multishot angle unit determines the verticality using a pendulum suspended over a bulls-eye. The amount of drift can be read from the developed film, although the azimuth of deviation from vertical is meaningless when the multishot tool is used in the presence of a magnetic drill collar.
VI. TOOLS DEVELOPED AND/OR OPERATED BY THIRD PARTIES

Many of the ODP tools described in this manual were first developed by independent scientists and then turned over to DSDP/ODP for routine use. Similarly, several advanced tools are presently under development by 'third-party' investigators, independently of but with the cooperation of ODP and/or LDOO, and may someday be available for routine ODP use. The scientists developing these tools are fully responsible for all aspects of their operation, until such time as the tools are proven for routine use and ODP or LDOO assumes responsibility for maintaining and deploying them.

The ODP policies for assisting in tool development and for assumption of responsibility for a proven tool are described in this chapter. In late 1987, POOM became concerned that certain future legs depend heavily on the development of particular tools and/or experiments, and instructed DMP to actively monitor the development of these tools. ODP had adopted procedures for dealing with 'third-party tools' in mid-1987, and DMP suggested a policy that was consistent with these guidelines, but that applied to both new downhole tools for ODP and new logging tools for LDOO. The essence of this policy is as follows (subject to revision by DMP and POOM):

DMP categorized two types of tools—instruments under development and established tools—and suggested procedures to be followed during development and during transfer of established tools to ODP (or LDOO). Even before DMP begins to monitor a tool under development, an investigator should contact ODP regarding preliminary ideas for a new tool. The primary initial contact is ODP's Manager of Development Engineering and Drilling Operations, who will advise the investigator on design feasibility and compatibility with existing ODP systems, and will refer the investigator to other key ODP personnel with relevant input.

A. Policies for tools under development

It is the responsibility of the investigator to obtain funding for the development of a new tool, and to obtain DMP endorsement and POOM approval of the ship time required to develop and deploy the tool. For DMP to monitor a tool under development or to consider endorsing deployment on JOIDES Resolution, the principal investigator should prepare a development plan, in consultation with ODP and DMP. This development plan should:

- justify the acceptability, desirability, and usefulness of the measurement,
- identify development milestones,
- make provision for land testing,
- satisfy safety considerations,
- specify shipboard requirements such as data processing, technical support, and special facilities, and
- confirm that the tool will be available for ODP use after development, with endorsement by the funding agency if title and responsibility for the tool are to be transferred to ODP.

If DMP endorses the proposed plan, DMP will review progress at regular intervals and will evaluate tool performance after each deployment. ODP will work closely with the principal investigator on the development of an approved tool. The ODP effort will be coordinated by an engineer in the
B. Policies for transfer of established tools to ODP

Once a third-party tool has been developed, tested, and successfully deployed from JOIDES Resolution, the investigator may either retain control of maintenance and future deployments of the tool, or transfer responsibility for routine maintenance and operations to ODP (or LDCO, if appropriate). If the investigator elects to retain control of the tool, he/she then assumes full responsibility for obtaining funding, DMP and POOM endorsement of all scheduled deployments, and invitations from ODP for the participation of necessary shipboard personnel. If the investigator wants ODP to assume responsibility for the tool, formal approval is required from ODP, DMP, and POOM. This approval will be based on the following criteria:

- The tool is in demand for use on future ODP cruises.
- The nature and quality of the data produced are a valuable addition to the ODP database.
- Deployment of the tool is safe and truly routine, i.e., the rig floor crew and marine technicians are fully trained in running the tool and recovering the data.
- ODP can afford to operate the tool, in terms of both funds required for supplies and maintenance, and time required of the technical staff.
- The independent investigator has provided ODP with (a) a full manual for operations and maintenance, including design drawings, (b) complete information regarding sources, costs, and time required to obtain replacement parts and supplies, and (c) full documentation of the processing that must be applied to the data and/or samples collected.
- Approval of the pertinent funding agencies.

If a third-party tool has been developed and tested, but has not yet met the above criteria for transfer of responsibility to ODP, then shipboard scientists or site proponents who wish to use the tool on a given leg must make arrangements with the third-party investigator. Such arrangements will require endorsement by DMP and POOM, and ODP must be kept fully informed because shipboard operations, time estimates, shipping requirements, etc., will be affected. In such a case, it should not be assumed that ODP will automatically provide the technical support and supplies for the third-party tool, and these responsibilities should be clarified at the pre-cruise meeting.

C. Third-party tools presently under development

Several new tools are presently under development by independent investigators, with varying degrees of documentation. When POOM formalizes (in mid-1988) the DMP criteria for tools under development, more uniform documentation will become available. If more information is desired than is provided in the following brief descriptions, the independent investigators should be contacted directly.
Geoprops probe (D. Karig and E. Taylor)

The Geoprops probe is essentially a miniature, instrumented straddle packer, to be deployed on the coring line into a 4"-diameter hole cored up to 4 m ahead of the bit with the Navi-Drill. The tool is to be equipped with sensors to measure temperature, pore pressure, and permeability, to sample pore fluids, and to map borehole breakouts. Efforts to develop this tool have been prompted by the difficulties experienced in attempting to measure important hydrogeologic parameters in unstable formations in subduction zone complexes, but the tool will be applicable in many other situations. A feasibility study was completed in early 1988, and a proposal was submitted to NSF for development of a tool in time for Leg 129 drilling in the Nankai Trough.

APC lateral stress tool (K. Moran, Canada)

The lateral stress tool (LAST-I) will include sensors to measure anisotropic horizontal stress, pore fluid pressure, and temperature in situ, in conjunction with the APC. The instrumentation will be incorporated into the present APC shoe, with a special, reverse cutting edge to minimize sediment disturbance on the outside of the shoe. The LAST-I is the first phase of a two-phase program to develop ODP instrumentation to measure in situ stress and deformational properties in sediments; in the second phase a self-boring pressuremeter will be developed. The LAST-I is scheduled for non-ODP sea trials in 1988, and is intended for ODP use during Leg 129 drilling in the Nankai Trough.

APC pore water sampler (R. Barnes)

In 1987, Dr. R. Barnes was developing a small-volume fluid sampler intended to be inserted in the cutting shoe of the APC and to sample pore fluids as an APC core is taken, similar in operation to the APC T tool. A prototype of this tool was not quite ready for testing scheduled for Leg 117, and further development has proceeded slowly since then.

Pressure core sampler (ODP)

ODP expects to complete development of a new pressure core sampler (PCS) in 1988 and test the unit during Leg 124 or 124E. This tool will be freefallen into position and hydraulically actuated to recover a pressurized sample. Figure VI-1 illustrates the conceptual design for the detachable pressurized sample chamber, which is rated for a 10,000-psi working pressure. The first version of the PCS will recover a pressurized sample 1-9/16" in diameter and 32" long, and will allow for subsampling of the gases and interstitial water before decompressing the sample. ODP will supply subsampling manifolds, designed to fulfill the requirements of the scientific community. Any input or inquiries for further information should be directed to T. Pettigrew, the ODP Development Engineer responsible for design and testing of the PCS.

Sampler go-devil for drill-string straddle packer (J. Cann, U.K.)

J. Cann is presently developing an electronic sampler that functions like a go-devil in controlling packer inflation, and incorporates
Figure VI-1. Conceptual schematic for the new ODP pressure core sampler.
electrodes for feedback regarding the *in situ* composition of pore fluids to be sampled. The sampler will probably include sensors to measure temperature, pressure, pH, eH, and concentrations of various ions. The problems discussed in Chapter IV regarding use of tools on the logging cable in an inflated packer will probably require that this tool be developed as a battery-powered, downhole-recording unit that does not allow real-time feedback to the rig floor as to sample composition. This tool is intended to be tested in 1969.
REFERENCES


ODP DOWNHOLE TOOL
DATA SHEET

Channel Measuring Filename

<table>
<thead>
<tr>
<th>Channel</th>
<th>Value</th>
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<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Recording interval________
HF & Pressure Delay Time________min
PW Delay Time________min
PW Sample Time________min
Water Depth________meters
Subbottom Depth________meters
Probe Depth________meters

Probe Length________cm
Thermistor #________
Recorder Package #________
Sea State________
Last Core #________
Overpull Pressure________ x 10^3 lbs

DELAY
00 Min 00 Sec

OPERATIONS

On Deck Turn-on Time
Start Down Pipe
Start Pumping
Stop Pumping
At Mudline
Start Down
Check for Latch-in
Lowering to Bottom
On Bottom
Heave Comp On
Heave Comp Off
Bit off Bottom
At Mudline
Start Up
On Deck
Instrument Off

REMARKS

Local Time________
Strokes/minute________
Stay________min
Stay________min
Stay________min
Stay________min

DISTANCE OF BIT OFF BOTTOM________m.
WEIGHT ON BIT________ x 10^3 lbs
Wt. on Bit: Steady?________
Variable?________
Increasing?________
Decreasing?________

Total water filtered________ml
Cu coil column________ml
Stainless coil volume________ml

Comments:

FM5000 These data are to be processed into a computerized data base along with existing standardized data from other legs and will be accessible to the scientific community at large. RECORD ALL MEASUREMENTS CAREFULLY, COMPLETELY, AND LEGIBLY.

REV. 9/86
## ODP Downhole Tool Data Sheet

<table>
<thead>
<tr>
<th>HF</th>
<th>PW</th>
<th>P</th>
<th>HPC/HF</th>
</tr>
</thead>
</table>

**Recording Interval**: 1 or 2 MIN

**Probe**: 

**Thermistor**: 

**HPC/HF Recorder #**: 

**Water Depth**: 

**Sea State**: 

**Lowering Type, Wireline**: Free Fall OR 

### Delay

<table>
<thead>
<tr>
<th>MIN</th>
<th>SEC</th>
<th>Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>On Deck Turn On Time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Start Down Pipe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Start Pumping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stop Pumping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At Mudline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Start Down</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check for Latch-in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lowering to Bottom</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On Bottom</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heave Comp On</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heave Comp Off</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bit Off Bottom</td>
</tr>
<tr>
<td></td>
<td></td>
<td>At Mudline</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Start Up</td>
</tr>
<tr>
<td></td>
<td></td>
<td>On Deck</td>
</tr>
</tbody>
</table>

### Remarks

**Local Time**: 

**Strokes/Min**: 

**Stay**: 0 MIN

**Stay**: 0 MIN

## WT on Bit

$\text{WT on Bit} \times 10^3 \text{ lbs}$

**Steady**: 

**Variable**: Increasing Decreasing
APPENDIX B. CONTENTS OF
"SELECTED REPRINTS FOR ODP DOWNHOLE MEASUREMENTS"
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A. Theory of heat conduction


B. Approach of a cylindrical probe to in situ temperature


C. Approach of the APC shoe to in situ temperature

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D. Thermal conductivity measurements


E. Borehole temperatures — theory


F. Borehole temperatures -- DSDP review and examples


G. Permeability measurements and hydrofracture — theory


H. Permeability measurements and hydrofracture -- DSDP examples


I. Large-scale resistivity experiment


OCEAN DRILLING PROGRAM

Wireline Logging Manual

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Bibliography of Well Log Applications
(Cumulative Edition)

Stephen Prensky
U.S Geological Survey
Denver, Colorado 80225

SEPTEMBER, 1990
Introduction

This edition of the the Bibliography of Well-Log Applications is a new cumulative version which combines the original bibliography by Prensky (1987) with the published annual updates (Prensky, 1987, 1988, 1989). The, as yet unpublished, update for 1989-90 is included as well. In addition, many papers have been re-grouped and several new topical areas added. The bibliography now has over 2,700 individual citations.

No attempt has been made either to cull older citations, which by now may have been superceded by newer papers, or to select the "best" papers on a particular topic. All papers that come to my attention which meet the criteria stated below, and which can be obtained by the USGS library, are included.

The purpose of this bibliography is to emphasize applications and various uses of well-log data. The following general criteria are applied to papers to determine whether they will be included: 1) the paper must be written in English, 2) It must be obtainable by a research library, 3) the majority of the paper should discuss a particular application of well-log data or have immediate impact on the use of such data. Consequently papers concerning theoretical or mathematical subjects (i.e., modelling), instrumentation design and development, and laboratory research, are generally excluded. For lack of space, abstracts are excluded (except for extended abstracts) and cross-indexing has been kept to a minimum. This edition is now available on diskette upon request to the author.
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Part A: BASIC WELL LOGGING

1. FUNDAMENTALS OF WELL LOGGING AND WELL-LOG INTERPRETATION

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XII. Conditions and Special Situations Affecting Tool Response


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XIII. Crossplot Techniques and Applications

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