THE ROLE OF DOWNHOLE MEASUREMENTS IN MARINE GEOLOGY AND GEOPHYSICS

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Abstract. During the last 25 years, downhole measurements have been increasingly used for scientific applications in marine geology and geophysics, particularly in deep-sea drilling operations. Used mostly by the oil industry to map promising formations for exploration and production of hydrocarbons, a variety of instruments have been developed that can be lowered down drill holes to extract information about the subsurface geology. In the last decade, advances in computers, software, and data transmission have greatly increased the amount and quality of data that such instruments can provide. Relatively new instruments that image the borehole wall with high resolution can reveal layers and faults that previously could be seen only in core sections. Downhole measurements play a crucial role in linking core data with regional geophysical surveys and in providing data where core sections could not be obtained. Examples of recent scientific applications and approaches are presented that address previous problems with data quality and changes in properties over time after a hole is drilled. The role of downhole measurements is discussed for two broad areas of research: the structure and composition of the Earth's crust, most of which is formed at mid-ocean ridges, and past changes in Earth's environment recorded in the deep-sea sediments overlying the crust. Finally, new emerging technologies and experiments that promise significant advantages over current methods for downhole measurements in marine geology and geophysics are discussed.

INTRODUCTION

The scientific use of downhole measurements in marine geology and geophysics has become increasingly important in recent years. The methods and tools are derived largely from those developed for oil and gas exploration and are applied to recent scientific problems in the Earth's oceans. The purpose of this review is twofold: first, to present applications of state-of-the-art downhole measurements in recent marine science problems, and second, to review both existing and new methodologies for downhole measurements with new scientific directions. During the last 25 years, the Deep-Sea Drilling Project (DSDP) and its successor since 1984, the Ocean Drilling Program (ODP), have been progressively expanding the role of downhole measurements. These programs have successfully fulfilled their scientific missions by drilling holes in nearly all the different geologic settings of the world's oceans. A total of 170 drilling expeditions, or "legs," around the world's oceans have been successfully completed at the time of this writing. More than 1000 drill holes have been cored, after which many have in turn been logged using downhole instruments. While downhole measurements were conducted in less than 14% of all marine holes drilled during the DSDP, they have been made in more than 56% of the holes drilled by ODP. This dramatic increase in ODP's use of logging is due to several causes, including permanent shipboard systems for routine operations, vast improvements in downhole instrumentation technology and drilling methods, and new measurements made on core samples that allow for one-to-one correlation with similar measurements made downhole.

There have been numerous published discussions of the scientific goals and overviews of DSDP and ODP that include elements of specific downhole measurement capabilities, their successes, and their failures. For general and historical background of the DSDP and ODP, the interested reader is referred to *Revelle* [1981] and the proceedings of the International Conference on Scientific Ocean Drilling (COSOD) in 1987 [*Joint Oceanographic Institutions for Deep Earth Sampling and Joint Oceanographic Institutions, Inc.*, 1987]. For more detailed information on specific drilling locations, the Initial Reports and Scientific Results of the ODP and DSDP offer summaries, and various monographs of the American Geophysical Union present synthesis articles for sites around the globe. For a more detailed discussion of particular downhole measurements, a number of smaller proceedings outline various specific applications [e.g., *Worthington et al.*, 1987; *Hyndman*, 1991; *Cullen*, 1994]. Reviews of current downhole technologies are also periodically published in industry journals [e.g., *Snyder and Fleming*, 1985; *Prensky*, 1994].

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Continental scientific drilling programs have also successfully used downhole measurements to achieve their objectives. Downhole experiments support and enhance core-related studies of the subsurface in almost every environment and in nearly every scientific discipline. During the last decade, several continental scientific drilling programs conducted by Germany, Japan, Sweden, the United States, Russia, and Ukraine have relied on the extensive use of downhole measurements [*Zoback et al.*, 1994]. Often the results of these efforts complement the goals of the ODP in advancing new scientific applications of downhole measurements, and together, these programs are moving researchers toward a global scientific investigation using downhole instruments to measure in situ properties of the Earth.

The scope of this review focuses on past, present, and future scientific applications that have used or will use "short-term" experiments, that is, measurements that themselves do not require instruments to be deployed for more than several hours or days in the subseafloor. Such measurements can be repeated over longer periods for time series studies. This class of downhole measurements is commonly referred to as "logging" and is distinct from the class of instruments deployed below the seafloor for long-term studies. The latter class may be referred to as in situ "observatories" and is discussed in less detail (the reader is referred to recent workshop reports by *Hyndman* [1991] and *Carson et al.* [1994] for an overview of and further references to a variety of downhole observatory applications in marine research). The reason for this distinction is methodological, not scientific, as both types of deployments are complementary. The short-term logging measurements that are primarily addressed include (1) measurements made in a borehole by instruments lowered on a wireline, (2) measurements made while drilling, and (3) measurements repeated over time. A short background is given first to define the current types and range of measurements that can be made by logging. Then a discussion of strategies for downhole measurements is presented, followed by a discussion of various scientific achievements of downhole measurements over the past several years. Within this last section, two broad disciplinary areas are discussed: the Earth's crust and Earth's environment. The applications of many different downhole measurements fall into these two categories, both of which contain several subdisciplines that illustrate the broad range of questions which can be addressed using downhole methods.

The scientific objectives for the future of marine scientific drilling have recently been outlined in the ODP Long Range Plan [*Joint Oceanographic Institutions, Inc.* (*JOI*), 1996]. This plan describes the directions for marine scientific drilling from now through 2008 and the new technologies that will be required to accomplish them. The plan relies heavily on downhole experiments to achieve its scientific objectives. It also maintains the historical premise that [*Worthington et al.*, 1987, p. 135] "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." Given these views of the future, the summary provided here of recent scientific applications and new methods for downhole measurements leads to the conclusion that downhole data are irreplaceable assets in marine geology and geophysics; planning and use of downhole experiments in the future should expand, both while drilling and in existing holes. The scientific legacy of new downhole data will undoubtedly continue to advance marine science in several disciplines.

BACKGROUND

During the previous decade, downhole measurements have become viewed as essential and complementary to measurements made on recovered core. They are critical for measurements, such as temperature, that must be made in situ. The scientific objectives at most study sites are addressed with a multidisciplinary strategy, integrating measurements made on core samples with those made downhole and placing both in the context of regional geophysical and seismic studies. *Worthington et al.* [1991] summarize this multiscale approach to drilling investigations and suggest that data integration will be the hallmark of the geosciences in the 1990s. Figure 1 shows their illustration of the range of experimental scales of investigation used today. The multiple scales of investigation used with seismic, downhole, and core data acquired in the same geological environment complement each other extremely well. Seismic sections are the basis for a regional description, downhole measurements are of an intermediate scale and give continuous information in the region surrounding the borehole, and core samples provide detailed information on physical properties and age. Downhole, core, and seismic data used jointly also contribute to the confidence in each individual data set. Unlike measurements on core samples, which are often disturbed during the process of recovery, downhole data provide a set of continuous logs of information and sample a larger volume of rock than core measurements. Because logs have much greater vertical resolution than surface data but little lateral resolution, the combination of the two defines subsurface geological structures far better than either data type can alone. The difference in the scale of physical phenomena affecting each type of measurement may be extreme. The scale ratio from core to log may be greater than 2×10^3; the ratio from log to seismic section may be 10^6 to 10^7 times larger. In most integrated scientific applications, therefore, downhole measurements provide three complementary advantages: (1) data are acquired under in situ

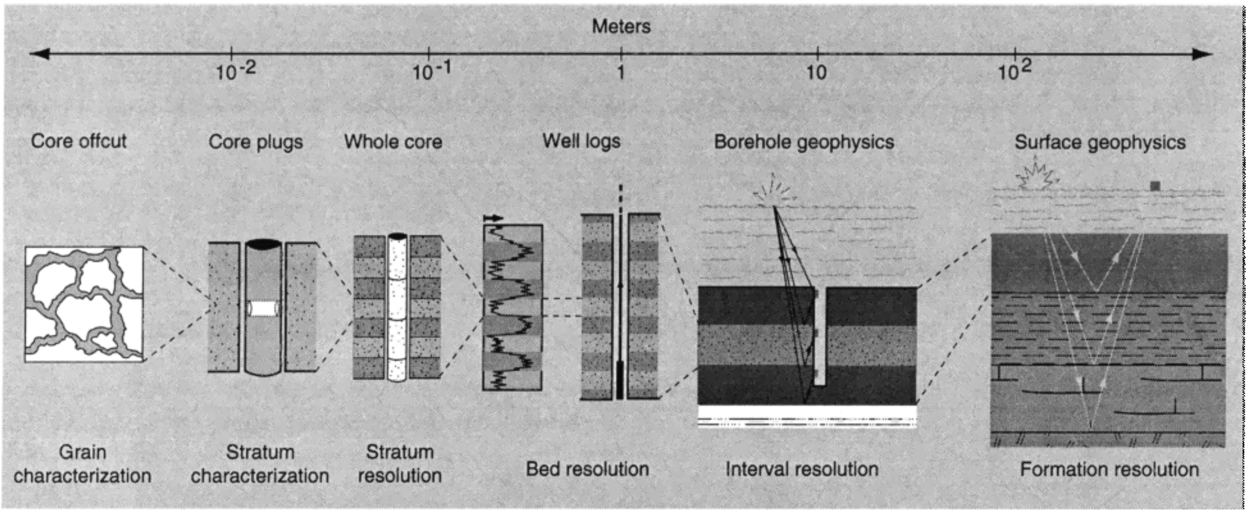

Figure 1. Schematic diagram illustrating the different scales of measurement in geophysics [after *Worthington et al.*, 1991]. The span of measurements from core samples to seismic surveying is greater than 10^4, complicating the interpretation of data from samples to regional geology without intermediate-scale logging and borehole measurements.

conditions, (2) data are acquired in continuous profiles measured throughout the interval with no missing sections, and (3) data are sampled at a larger scale, intermediate between core and seismic measurements.

In most drilling environments, continuous coring does not result in continuous core recovery. In fact, core recovery by techniques other than piston coring is less than 50% on average, and this proportion is often disturbed by the drilling process [*Hyndman*, 1991]. As a result, the true core depth becomes ambiguous. Drilling disturbances within a recovered section can be corrected, however, by correlation with continuous logs, so that preferential recovery of particular rock types can be documented. In Figure 2 a nonrepresentative section of interlayered basalt and sediment near the Juan de Fuca ridge in the northeastern Pacific would have been interpreted from the recovered core alone, but the continuous log profiles reveal layers of sediment between basalt that were not recovered through coring. Despite such successes, complete recovery of continuous log profiles is still not possible. With current wireline technology, the interval immediately below the seafloor is not logged because the drill pipe must be lowered 80–100 m to ensure hole stability in the softest sediments for logging to begin. To benefit from core-log correlation, the stratigraphic interpretation from logs is limited to below this depth and only where high-quality data are recorded.

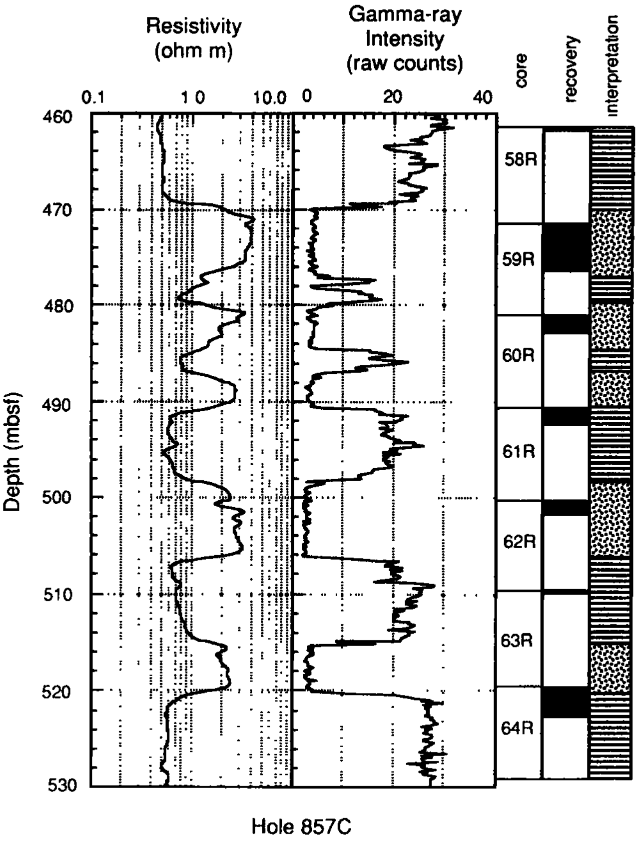

Figure 2. Logs of electrical resistivity and natural gamma radiation in a layered basalt-sediment sequence in ODP Hole 857C near the Juan de Fuca ridge in the north eastern Pacific [from *ODP Leg 139 Scientific Drilling Party*, 1992]. Core recovery (black zones) is partial and is arbitrarily set at the top of each core section, biasing any subsequent geologic interpretation. The complete interpretation (dotted zones are basalt) is based on the logs. Depth is in meters below sea floor (bsf).

Downhole Measurements: Logging

In 1927, C. and M. Schlumberger made the first well log near Paris. It was a simple electrical current experiment that used an electrode placed at a series of horizontal points on the ground to make measurements and detect variations in geological structure below the sur-

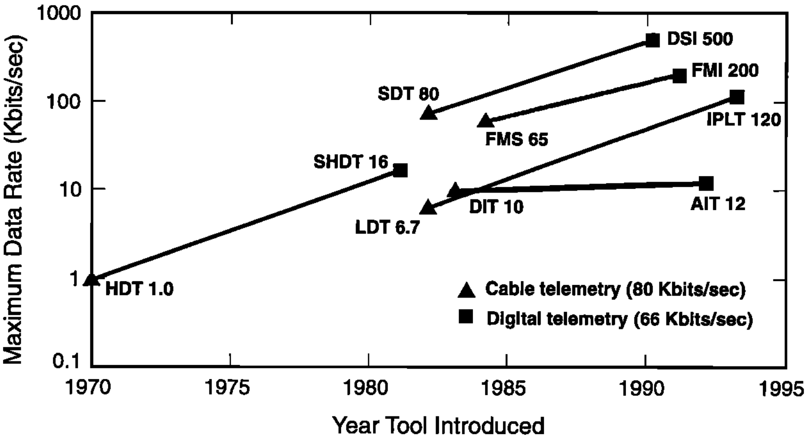

Figure 3. Telemetry rates for common wireline tools showing the steady increase in data rates over the past 25 years (after *Prensky* [1994]; data from Schlumberger). See Table 1 for list of abbreviations.

face. During the 1930s, they evolved this method into a simple tool consisting of an electrode and a current source that made continuous measurements of the subsurface resistivity with each lowering into a borehole. Depth was determined by measuring the length of the cable run into the hole, as it is today. The interpretation of these continuous logs for oil exploration helped to determine bed thicknesses, identify clay-rich and hydrocarbon-bearing zones, and provided a rough estimate of formation permeability, all qualities that could be correlated between holes. In the 1940s, *Archie* [1942] linked laboratory measurements of resistivity to the amount of water and hydrocarbon in pore space, which greatly improved log interpretation. In various modifications his empirical relationship is still used to calculate porosity and fluid saturation from resistivity logs. In the mid-1940s through the 1970s, rapid technological advances made it possible to estimate porosity using nuclear activation, gamma radiation, and acoustic techniques. The resolution of the logging measurements also improved with the development of sensors that extended close to the borehole wall. In the 1980s, continued advances in digital data acquisition and signal processing have made it possible to evaluate logging data as they are collected, so that decisions can be made on site to enhance data quality and interpretation. With these improvements, logging has become the standard for evaluating subsurface geology in the oil industry; it is now often the sole source of data used for geological interpretation because of the difficulty and expense of routine coring.

Over the past 10 years, researchers in academia and industry have steadily improved the accuracy and sophistication of geophysical and geochemical logging measurements. Most downhole experiments use technology developed by industry; a small, yet significant, number use technologies developed for scientific research. The recent history of advances in all of these technologies parallels advances in data transmission and computer capabilities, which have led to a remarkable increase in the quantity and speed of downhole data acquisition and processing [*Prensky*, 1994]. Figure 3 shows how increases in data transmission have accompanied the introduction of a number of commercial instruments over the past 10 years. Advances in acquiring scientific data for marine geology and geophysics have followed closely from these new technological developments.

Prensky [1994] provides an excellent summary of current downhole technologies; *Doveton* [1986], *Serra* [1987], *Ellis* [1987], and the *Borehole Research Group* [1990], among others, have summarized the principles of downhole measurements and the interpretation of logging data in scientific applications. The interested reader is referred to these publications for a more detailed discussion. The following summary of downhole logging measurements is included only to present a general overview of the methods used and the range of data and their measurement resolutions.

Typically, logs made downhole fall into three general categories: electrical, nuclear, and acoustic. In addition, borehole imaging, temperature, and various other in situ properties can be measured downhole using wireline logging tools. Although the accuracy, resolution, and applications differ for each type of measurement, together they provide a comprehensive data set that can be used as a proxy for the subsurface geology. Each type of measurement is discussed briefly below; a summary of the vertical resolutions of several common devices which range from a few millimeters to over a meter is presented in Figure 4 (see Table 1 for abbreviations). Most typical logging devices have a vertical resolution of at least 0.5 m, so that beds thinner than this are difficult to study [*Allen et al.*, 1988; *Tittman*, 1991].

To maximize the vertical resolution of logging data, it is important to minimize effects that may introduce additional uncertainties in the correlation between the recorded data and depth, such as motion due to ship heave. In 1988 a hydraulic heave compensator that moves the wireline opposite to heave motion while logging was first developed and used on the ODP drill ship. *Goldberg* [1990] measured the effectiveness of this wireline heave compensator by comparing measurements of the acceleration of a downhole tool with the displacement of the motion compensator on the ship. The measurements indicate that heave amplitudes reach about

2.5 m with vertical accelerations of up to 8% of G in seas with 3–4 m waves. As the ship's dominant period was about 8.5 s, the maximum downhole displacement and velocity due to heave were reduced to 1.5 m and 1.0 m/s, respectively, using the wireline compensator. Since typical logging speeds are 0.2 m/s or less, in high seas it is possible that a tool could move downward even when it is being pulled uphole on the wireline. Much of this motion is probably stopped by friction between the tool and the borehole wall; however, recent corrections in the control of the heave compensator further reduce the effects of heave by a factor of 2–3, eliminating the possibility that wireline motion could be reversed for most logging operations. As a result, downhole logs obtained at different times are consistent under most sea conditions, and the residual heave effects on vertical resolution are negligible for most downhole tools.

Electrical resistivity logging tools. Devices that gather data on a formation's electrical properties measure currents that propagate through the borehole and pore fluids in the surrounding rock and sediment layers. Water is a ubiquitous and conductive fluid underground; its electrical conductivity increases with the concentration of Na^+ and Cl^- ions and with temperature, which increases the mobility of the ions. Electrical resistivity measurements in a formation therefore allow one to estimate its porosity, fluid content, and often the degree of fracturing. Clays also contribute to the measured electrical conductivity because of the negative ions commonly associated with the molecular structure of various Al-bearing minerals found in many clays [*Ellis*, 1986]. Self-potential devices measure the electrical potential generated by ions flowing between the borehole and pore fluids. This measurement is related to clay content in a formation; it is high where resistivities are low. In most ocean drill holes, however, seawater fills both borehole and pore space, and the self-potential measurement is poor. Induction devices are used to measure lower (<100 ohm-m) resistivities; current-generating devices (laterologs) are used to measure higher resistivities (>100 ohm-m) that may occur in the calcareous and igneous rocks encountered in ocean drilling. Most measurements of electrical resistivity are made by induction tools, with vertical resolutions ranging between 0.5 m and 2.0 m. The varying spacing between electrodes on these tools measures resistivity at different depths in the borehole wall. If drilling fluids have invaded significantly into the formation, these measurements are not equal, and their difference allows one to make an estimate of formation permeability.

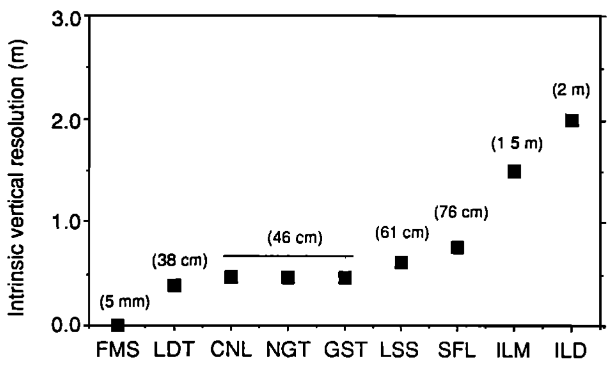

Figure 4. Intrinsic vertical resolution of various wireline tools representing the minimum depth interval for which a meaningful log measurement can be obtained (after *deMenocal et al.* [1992]; data from *Allen et al.* [1988]). See Table 1 for list of abbreviations.

TABLE 1. Abbreviations for Downhole Tools and Logs

Abbreviation	*Definition*
AIT*	Array Induction Imager Tool
BHTV	Borehole Televiewer
CNL*	Compensated Neutron Log
DIL*	Dual Induction Log
DSI*	Dipole Shear Sonic Imager
FMS*	Formation MicroScanner*
FMI*	Fullbore Formation MicroImager
GST*	Gamma Ray Spectroscopy Tool
HDT*	High Resolution Dipmeter Tool
ILD	Induction Log, Deep
ILM	Induction Log, Medium
IPLT*	Integrated Porosity Lithology Tool
LDT*	Litho-density* Tool
LSS*	Long Spacing Sonic Tool
MDT*	Modular Formation Dynamics Tester
NGT*	Natural Gamma Ray Tool
NMR	Nuclear Magnetic Resonance Tool
RAB*	Resistivity-At-Bit Tool
SDT*	Sonic Digital (Array-Sonic*) Tool
SFL*	Spherically Focussed Resistivity Tool
SHDT*	Stratigraphic Dual-Dipmeter* Tool

*Trademark of Schlumberger.

Acoustic logging tools. Acoustic tools record compressional, shear, and surface waves in the borehole environment, much like a seismic refraction experiment that operates in the kilohertz frequency range [e.g., *Paillet et al.*, 1992]. Energy generated by one or more sources in an acoustic instrument is transmitted into the borehole fluid and then propagates as refracted and surface waves at the borehole wall. Energy is received at one or more sensors on the logging tool at a transit time proportional to their distance from the source. Wave velocities can be determined by comparing arrival times of different waves. Using asymmetric acoustic sources in the borehole, acoustic tools can now be used to estimate shear wave velocities in most marine environments [e.g., *Zemanek et al.*, 1991]. Compressional and shear wave velocity measurements can be used together to compute the elastic properties of a formation, such as the Poisson's ratio, which depend on lithology and porosity. Wave amplitudes can be measured directly at each sensor or between sensors and primarily reflect the coupling of energy between the formation and the borehole. In fractured and heterogeneous formations the coupling of energy decreases, and wave amplitudes can be used to indicate fracturing and heterogeneity at the scale of centimeters to meters in the formation. Most acoustic logging tools measure compressional waves which penetrate 0.1–0.5 m into the borehole wall, with vertical resolutions of 0.5–1.5 m. Other instruments that clamp geophones downhole and record energy from seismic sources on the surface penetrate through hundreds of meters of the formation. Such vertical seismic profiles (VSPs) typically provide acoustic velocity and amplitude profiles with vertical resolution of 5.0–50 m.

Nuclear logging tools. This class of instruments measures naturally occurring radioisotopes and mineral constituents of the formation, as well as the fluid content in pore space. They are sophisticated devices that rely on statistical counting of subatomic particles and advanced computer analysis for interpretation. Three types of nuclear measurements are typically used in marine scientific applications: natural gamma ray activity, gamma ray scattering, and neutron scattering.

Gamma ray activity tools are perhaps the most common nuclear measurement instruments and detect the radioactive decay of natural isotopes of potassium, uranium, and thorium using a scintillation counter and a crystal detector. The response of the detector is a simple function of the concentration by weight of the radioisotopes and the formation density. The average depth of penetration of the measurement into the borehole wall is about 0.5 m, and vertical resolution is approximately 0.3 m [*Allen et al.*, 1988]. The natural gamma ray log usually responds to clay content in a formation, where naturally radioactive elements concentrate, or to alteration minerals that have these minerals present within oxides and other compounds. The concentration of the natural radioisotopes is therefore largely controlled by depositional environments and diagenesis.

Density tools use a gamma ray source, usually ^{137}Cs, to bombard the formation with gamma rays that are scattered through the rock and gradually lose energy. Sensors pressed against the borehole wall measure the energy flux of gamma rays returned to a scintillation counter and crystal detector which captures photons emitted by Compton scattering. The radiation returned is directly related to the electron density in the formation, which in turn is related to the bulk density of the rock [*Doveton*, 1986; *Ellis*, 1987]. The electron density is low for most pore-filling fluids and can therefore be used as an indicator of rock composition. The depth of investigation into the borehole wall of density tools depends on the density of the formation; greater density reduces the penetration of emitted gamma rays into the borehole wall. In porous and permeable formations, densities are typically measured to approximately 0.5 m into the borehole wall, and the vertical resolution of the measurement is approximately 0.4 m.

Neutron tools employ either a Am-Be radioisotope or an electrical generator source to bombard the formation with neutrons. After the neutrons collide with molecules of like mass in the formation, such as H, sufficient energy is transferred to slow the neutrons down enough to drop below 0.1 eV energy, constituting the epithermal-thermal neutron transition. Neutron responses are therefore strongly affected by the porosity and pore fluids in the formation and by minerals such as clay that have considerable water bound in their molecular structure [*Broglia and Ellis*, 1990]. Some neutron tools utilize a pulsed-neutron accelerator to bombard the nuclei of minerals in the formation. The spectrum of gamma ray energies emitted by these interactions is recorded using a crystal detector and provides a measure of the abundance of the major mineral-forming elements, such as Fe, Si, Ca, and Al [*Herron et al.*, 1993]. The elemental abundances may be used to estimate mineral concentration when core materials can be combined to provide sufficient calibration [*Kerr et al.*, 1992; *Myers*, 1992]. Nuclear magnetic resonance (NMR) tools measure the H present in the formation and pore fluid by inducing proton movement around a pulsed magnetic field [*Brown and Gamson*, 1960; *Jackson*, 1984]. The time decay of the resonance signal is also directly related to the pore size distribution and can be used to indicate formation permeability. Neutron measurements penetrate 0.5–1.0 m into the formation, and the vertical resolution of the measurement is approximately 0.4 m.

Borehole imaging tools. Imaging tools deliver high-resolution pictures of the wall of a borehole using precision measurements of either electrical conductivity, optical variation, or acoustic reflectivity. These three imaging techniques are complementary, since conductivity (electrical), color (optical), and reflectivity (acoustic) are controlled by different physical and chemical characteristics of the rock. The images are always oriented to a magnetic reference measured downhole. Electrical imaging provides approximately 5-mm resolution of the borehole wall by sensing contrasts between high- and low-conductivity features, such as water-filled fractures or fine-scale bedding variations [*Serra*, 1989]. Devices such as the Formation MicroScanner™ (FMS) and Full-bore Formation MicroImager™ (FMI) measure the borehole's surface conductivity on four pads pressed against the borehole wall with vertical resolution 10^2 times finer than most other downhole measurements (see Figure 4). Optical imaging also offers high vertical resolution but is limited to holes containing transparent borehole fluids. Ultrasonic imaging devices generate a complete 360° image of the reflectivity of the borehole wall, an advantage over the four-pad electrical method, with a vertical resolution of 2–3 cm. The dip, strike, width, and depth of geological features intersecting a borehole may be measured using any of these imaging devices [e.g., *Paillet et al.*, 1990; *Luthi and Souhaite*, 1990]. Images can be visually used to compare logs with cores for bedding orientation and to study fracturing, structure, and borehole shape.

Temperature tools. Temperature logging typically involves measuring a continuous profile of borehole fluid temperature as a proxy for the in situ formation temperature by reading resistance variations due to temperature-sensitive electrodes located in the borehole. Such measurements must be made after the fluid temperature has recovered from drilling-induced disturbance, or must be extrapolated between several intermediate times, to estimate undisturbed formation temperature. *Erickson et al.* [1975] describe a method to measure in situ temperature directly while coring that was used to compute heat flow through the ocean floor. These measurements were made using a self-recording temperature probe that protruded into thermally undisturbed soft sediment ahead of the core at selected depths. Although the technology has improved, modified versions of this approach still provide a reliable estimate of formation temperature and are superior to borehole fluid measurements. Self-recording temperature logging tools and versions of the coring temperature probe are used today in routine ODP operations.

Logging-while-drilling tools. Over the last 5–10 years, new technology has been developed to measure in situ properties in oil industry drill holes that are drilled horizontally where conventional logging with a flexible wireline is not feasible. This innovative technology is called "logging while drilling" (LWD) and uses sensors placed just above the drill bit, allowing measurements of porosity, resistivity, density, and natural gamma radiation, among other properties discussed below, to be made minutes after the drill bit cuts through the formation [e.g., *Allen et al.*, 1989; *Bonner et al.*, 1992; *Murphy*, 1993]. A schematic diagram of LWD instruments is shown in Figure 5. These sensors allow data to be recorded almost immediately after drilling, so that ephemeral in situ physical properties can be measured. The primary advantage of LWD over wireline logging in near-vertical oceanic holes is that data can be acquired without gaps below the seafloor, at the bottom of the drill hole, or through intervals that are difficult to drill and often deteriorate after drilling. However, differences in measurement technologies must be taken into consideration when directly comparing results from wireline and LWD tools [e.g., *Evans*, 1991].

Instruments for making measurements while drilling have recently been developed for investigating a variety of other formation properties. When acoustic velocities exceed approximately 2 km/s, they can be measured during drilling [e.g., *Aron et al.*, 1994]. A resistivity device can be used to generate high-resolution (approximately 5 cm), oriented images using sensor electrodes that rotate near the drilling bit and produce a full 360° scan in medium- to high-resistivity formations, as shown in Figure 6 [*Lovell et al.*, 1995]. The recorded images resemble FMI data with somewhat poorer resolution, but unlike the FMI, wall coverage is complete and data are recorded before hole conditions can severely deteriorate. Using these image data, three-dimensional stratigraphic and structural interpretation is possible with less than complete core recovery. Neither resistivity imaging nor sonic measurements made while drilling has been used yet in deep marine environments.

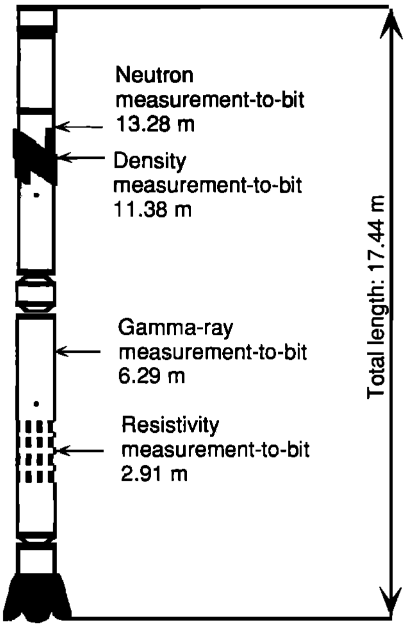

Figure 5. Schematic diagram of logging-while-drilling (LWD) tools located immediately above the drill bit that enable measurements within minutes after the hole is made [from *Shipley et al.*, 1995].

Downhole Measurements: Long-Term Observatories and Multiple Reentry Logging

In recent years, several independent approaches to long-term and multiple-reentry measurements in boreholes have been based on the emplacement of instruments after drilling is completed. Such experiments are designed to measure seismic, physical, and fluid properties, pore pressure, and chemistry in reoccupied marine boreholes that have recovered from drilling-induced disturbance over periods of months to years. Long-term borehole observations may be used to monitor many geologic processes, including tectonic movements, heat flow, hydrogeology, and earthquake activity.

One technology that has recently been developed allows for seafloor reentry of preexisting holes and their hydraulic sealing and instrumentation for long-term monitoring of in situ temperature and pressure. To do this, the exchange of seawater with formation fluids must be sealed off, the seafloor itself in the vicinity of the borehole must be impermeable relative to deeper layers, and time must elapse to allow the borehole pressure and temperature to return to their ambient conditions before drilling. Regions of permeable ocean crust overlain by marine sediments, buried faults, and deep deformation zones are good environments for such experiments. Fluid samplers and thermistor arrays can be emplaced in sealed boreholes to monitor pressure, temperature, and fluid changes under in situ conditions for up to 3 years after deployment using current data-recording capabili-

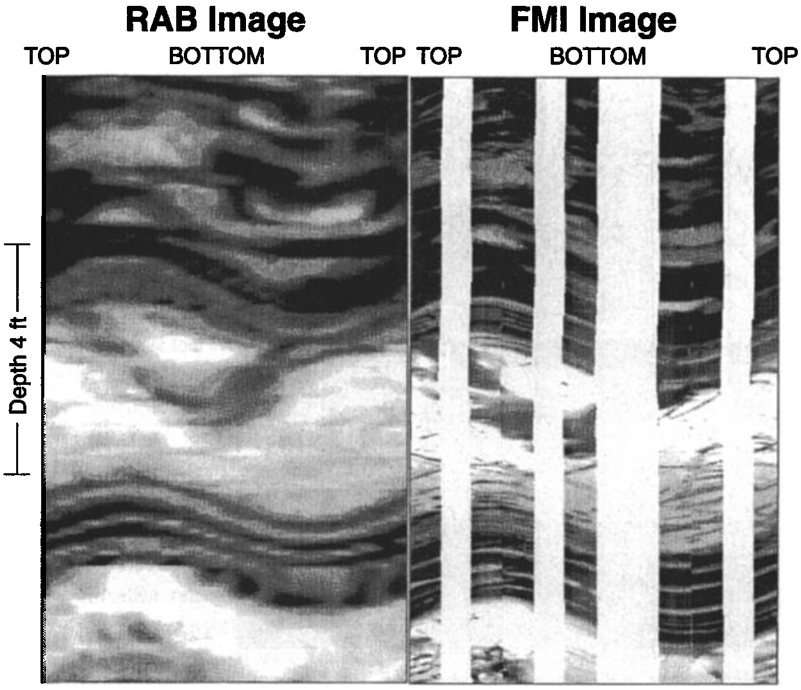

Figure 6. Comparison of (left) Resistivity-at-bit LWD tool and (right) FMI wireline tool electrical images of dense fracturing in marine sediments [after *Lovell et al.*, 1995]. Both images of the interior of the borehole wall are oriented to top at 0° magnetic declination. Although the LWD tool measures with >30 times poorer vertical resolution than the wireline tool, it offers the advantage of data coverage around the entire circumference of the borehole and measurements within minutes after the hole is made. See Table 1 for list of abbreviations.

ties [*Davis et al.*, 1992]. Since 1991, more than 10 instrumented and sealed borehole observatories have been established by ODP. The borehole seal and instrumentation package must be deployed using a drill ship; subsequently, an observatory may be serviced and data recovered by submersible or by remote-operation vehicles. *Davis and Becker* [1994] describe the preliminary results of recovered temperature data from the earliest borehole observatories, which indicate that high-temperature fluids may be expelled for long periods of time in the crust. Long-term fluid samplers emplaced in borehole observatories have not yet been recovered.

Downhole logs have been recorded by revisiting and reentering preexisting holes after drilling using standard oceanographic ships and submersible-assisted systems [*Langseth and Spiess*, 1987; *Gable and DIANAUT Shipboard Party*, 1992; *Spiess et al.*, 1992]. In these reentry experiments a remote deep-sea vehicle suspended various logging tools over preexisting holes and lowered them on a wireline. The DIANAUT program [*Gable and DIANAUT Shipboard Party*, 1992] used a submersible-assisted system to reenter three Atlantic holes. Wire line operations at these sites included temperature, caliper, and borehole televiewer logs; clamped borehole seismometers; and downhole fluid samplers [*Floury and Gable*, 1992; *Morin et al.*, 1992; *Gieskes and Magenheim*, 1992]. The postdrilling thermal equilibration of these holes was critical for accurate in situ temperature and fluid sampling; in addition, the negligible effects of heave for submersible-assisted reentry operations improved depth accuracy of the imaging and high-resolution logs. *Spiess et al.* [1992] and *Montagner et al.* [1994] described wireline reentry experiments for marine tests of low-frequency seismic noise as a step toward evaluating different approaches to acquiring broadband seismic data in the world's oceans. *Stephen et al.* [1994] indicated that seismic noise in the upper 100 m of sediments below the seafloor was reduced for a borehole geophone system deployed during a wireline reentry operation in the western Atlantic.

Most logging tools could be deployed by wireline reentry. Downhole tools that were omitted during drilling operations because of time or weather restrictions or tools that are too large to be lowered through the drill pipe could be used. Current ODP limitations restrict instruments to those that can be lowered through a 10-cm drill pipe, yet they must be able to make measurements in holes that are often as large as 30 cm in diameter. This gap seriously limits sensor design and restricts the use of many existing wireline devices. Borehole gravimeters that measure bulk density, resistivity imaging tools that extend for greater borehole coverage, nuclear magnetic resonance tools that estimate sediment permeability, and downhole samplers that extract pore fluids could be deployed by wireline reentry [e.g., *Schultz*, 1989; *Colley et al.*, 1992; *Black*, 1992; *Schlumberger Educational Services*, 1992; *Morriss et al.*, 1993]. In addition, holes drilled through unstable formations that must be cased to prevent collapse can be logged with certain tools by wireline reentry. Porosity and velocity have been measured successfully behind the casing using high-energy nuclear and low-frequency shear sonic tools that penetrate deeply into the borehole wall [e.g., *Moos et al.*, 1997]. When repeated logs are acquired by wireline reentry, whether to compensate for time, technical, or physical constraints during drilling operations, the data can also be used to study temporal changes in formation properties over periods of days to years.

Over time, the physical properties of formations penetrated by a borehole, as well as the borehole itself, change as stresses are applied and fluids flow through them. Such temporal changes can be measured only over an elapsed period of time. Downhole measurements made days to years after a borehole is drilled allow properties such as temperature and pore fluid composition to approach their condition prior to drilling. Repeated deployment of wireline logging tools provides logs that reflect temporal changes in the physical and borehole properties. An example of temperature logs repeated during four experimental episodes spanning 6.5 years is shown in Figure 7. These temperature logs were recorded in ODP Hole 504B in the eastern equatorial Pacific as drilling penetrated progressively deeper into the oceanic crust and illustrate the change in the movement of fluids in the ocean crust over time [*Langseth et al.*, 1983; *Gable et al.*, 1989]. *Alt et al.* [1993] estimate the equilibrium bottom hole temperature to be about 195°C at a depth of 2111 m below the seafloor. *Becker et al.* [1983], among others, describe a decrease, followed by an increase, in fluid flow within the upper 400 m of the borehole since it was drilled, as monitored by these successive temperature logs. The decrease in temperatures reflects the downhole flow of cold seawater through permeable cracks and faults in the oceanic crust, which results in chemical exchanges with the rock [*Alt et al.*, 1986]. Downhole temperature measurements made over time, as well as long-term measurements made in sealed boreholes, allow for study of the longevity and distribution of fluid circulation in the crust.

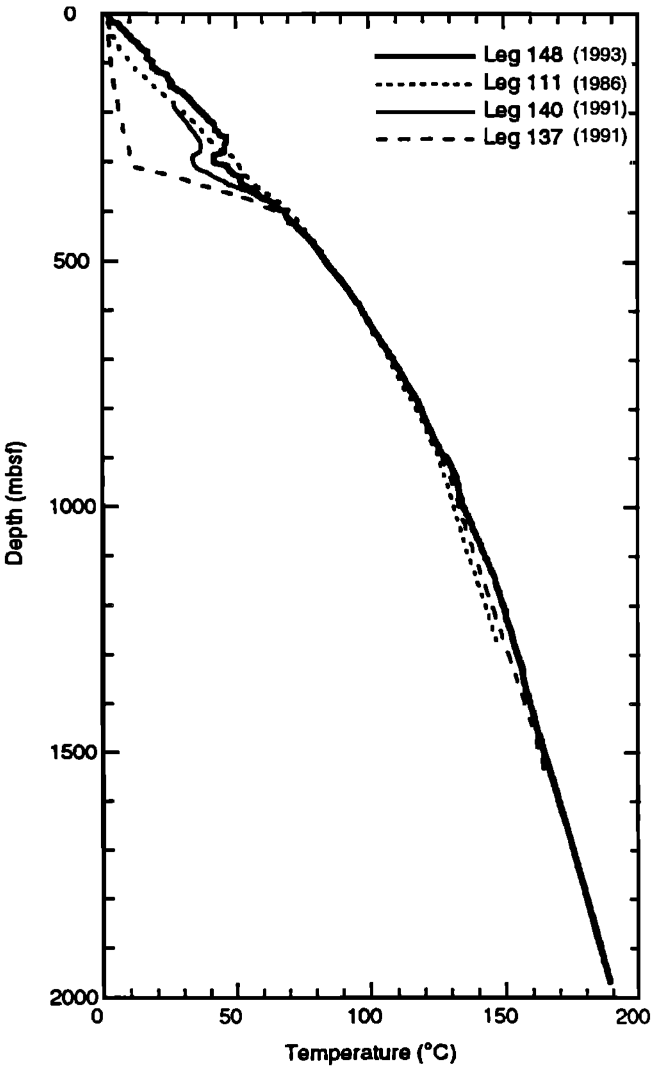

Figure 7. Temperature logs recorded in ODP Hole 504B successively during four expeditions over 6.5 years [after *Alt et al.*, 1993]. The variations in temperature over time illustrate the episodic downhole flow of cool ocean water into the uppermost 300–400 m of porous formations below the seafloor.

Experimental Strategy

The best designed downhole experiments take into account which instrument, or combination of instruments, will provide the highest-quality data needed to address a scientific objective. Drilling technology also dramatically affects the collection of high-quality downhole information. An appropriate strategy may include the drilling of dedicated holes for wireline logging, use of logging while drilling, wireline reentry logging, repeating logs over time, or interpretation of logs jointly with core analyses. Improved experimental strategies have contributed as much to the success of downhole measurements in marine geology and geophysics as the development of new instrument technology.

The lack of a riser and drilling mud cake in deep marine drilling operations makes the use of wireline logging technology more challenging than in continental or oil industry drilling, where risers are commonplace. A riser system circulates drilling fluid down the drill pipe, through the bit, and around the exterior of the drill pipe back to the platform. The drilling fluid, or "mud," usually contains dense and viscous compounds that clean the borehole, build up a mud cake to stabilize it for logging, and return rock cuttings to the surface for examination. Without a riser, fluid circulates down the drill pipe but is not returned to the surface, and the hole conditions are less stable. In addition, the diameter of the drill pipe is larger when a riser is used, allowing more width for downhole instruments. Nevertheless, engineering advances have improved hole conditions for downhole measurements in lieu of a riser. Among the most prominent, a drill pipe is lowered to clear borehole obstructions while a wireline tool is downhole. The drilling of dedicated holes without coring also improves hole conditions for downhole measurements. In the future, with the development of the planned deep-sea riser system and other engineering advances, drilling and hole conditions are expected to improve well beyond current capabilities and to continue to add to the scientific success of these experiments.

SCIENTIFIC APPLICATIONS

There are few areas of marine geology and geophysics that cannot benefit from logging and downhole measurements. Data are recorded in situ and usually in a continuous profile to the bottom of the borehole, providing researchers with an accurate proxy of the geology at various depths. Exploration of the structure, deformation, and stresses in the Earth's crust that are accessible by drilling has often been supplemented by downhole measurements and proven to be critical in understanding subsurface phenomena. The Earth's environment likewise has been investigated by scientific drilling and downhole measurements to discern details of the sediment record over time. In the following sections, recent research studies that highlight the application of downhole measurements to topics related to the Earth's environment and Earth's crust are discussed.

Paleoclimate

Because Earth's climate has large effects on the ocean's chemistry, circulation, and biological productivity, changes in the global environment leave a recognizable signature in the deep-sea sedimentary record. How the global climate system has changed and the causes of these changes therefore may be deduced from downhole data if these signatures can be measured. Short- and long-term changes in such variables as temperature, humidity, and wind patterns, the influx of energy from the Sun, sea level, water temperature, and oceanic upwelling can all affect the mineralogy, porosity, and grain size of sediment layers deposited on the seafloor. Most downhole log responses are affected by sediment porosity, which is closely related to the mineralogy and grain size, both of which can vary dramatically as ocean upwelling patterns and mean water temperature alter biologic productivity. The amount of clay incorporated in the sediment is also often determined by climate and will strongly affect the mineralogy and porosity. The natural gamma ray log is particularly sensitive to these variations in clay content. If the temporal changes can be adequately resolved, the geophysical and geochemical measurements taken downhole can serve as proxies for climate change in the sediment record. Using downhole logs in paleoclimate studies has the significant advantage of measuring several independent parameters that all reflect climatic changes throughout the stratigraphic sequence. In addition, the continuous and uniform sampling of downhole records allows for rigorous statistical analyses that are not possible using short or incomplete data from core sections.

Of the numerous interrelated factors driving climatic changes, few are generally accepted to be more important than the variation in Earth's tilt and orbital cycles around the Sun. *Milankovitch* [1941] was the first to recognize that periodicity in Earth's orbit and tilt alters the solar energy flux falling at any given latitude in cycles lasting thousands to hundreds of thousands of years [e.g., *Hays et al.*, 1976; *Shackelton et al.*, 1984]. Due to the gravitational pull of the Sun and Moon on the equatorial bulge of the Earth, our planet wobbles slightly as it spins, defining its precession. This wobble results in climate cycles that last 19,000–23,000 years. The Earth's tilt, or obliquity, varies with a period of 41,000 years, and its orbit varies from nearly circular to 95% eccentricity with periods of 95,000 and 413,000 years, affecting its distance from the Sun. These periodicities have been observed in a number of marine and terrestrial sedimentary environments. Pliocene and Pleistocene marine sediments have demonstrated the clearest correlation between sedimentary layers and Milankovitch periodicities because of the high recovery of material that can be accurately dated using marine core sections. Climate cycles are not limited to the younger sediments, however; coring in both Cretaceous and Triassic rocks shows evidence of Milankovitch cycles [*Arthur et al.*, 1984; *Fischer*, 1986; *Olsen*, 1986].

Milankovitch orbital variations may alter the depositional environment considerably. Spectral analysis of the continuous and regular sampling that log data provide can resolve Milankovitch periodicities and thus sedimentation rates for a known depth interval. In cores, sedimentation rates are typically determined by estimating the elapsed time between biostratigraphic, radioisotopic, or magnetostratigraphic markers that can be identified. This requires an absolute timescale, which can be supplied by correlating Milankovitch periodicities with the cores. Using the continuous logs to identify cycles, a timescale can be extended millions of years into the past with greater precision than can be achieved with the core-based methods alone. Log data may be used to illustrate major trends and rapid changes in the sedimentation rate by shifts in the wavelength of their variation with depth in areas with variable or discontinuous accumulation or poor age control from core data [*Molinie et al.*, 1990]. *Jarrard and Arthur* [1989] describe a method to determine sedimentation rates using log data that requires neither precise biostratigraphy nor an absolute timescale. They constrain the sedimentation rate to the Milankovitch orbital periods by computing spectra of log data and identifying peaks in the continuous spectra that have a constant spacing ratio between them. The use of spectra for interpreting precise sedimentation rates between time markers identified in cores has proven to be a powerful technique in paleoclimate studies.

In 1989, a site in the Sea of Japan was drilled through 2.8 m.y. of fine sediment layers to a depth of 459 m below the seafloor. *Ingle et al.* [1990] describe the recovered core as dark opal-rich layers with organic carbon interlayered with clay-rich sediments that are derived from aeolian dust blown from loess deposits in China. The layers alternate about every 4 m. Variation in natural gamma radioactivity versus age in this hole is shown in Figure 8, where the age-depth conversion has been computed from a sedimentation rate that was constrained by paleomagnetic reversals and biostratigraphy recorded from the core. Increases in gamma radiation reflect high clay content of the continental clay-rich layers, which have abundant K and Al. These cyclical signatures are apparent in other downhole data; the density and resistivity logs reflect the lower porosity of the continental clays. *DeMenocal et al.* [1992] compare the gamma ray log and a marine $\delta^{18}O$ record to illustrate the strong correlation with variations in northern hemisphere ice volume [e.g., *Raymo et al.*, 1989]. The concentration of $\delta^{18}O$ has often been used as a proxy for paleoclimatic changes in ice volume, temperature, and sea level because it has a lower concentration in fresh water from polar ice than in seawater. When polar temperatures decrease, ice volume increases and sea level drops; in warmer periods, ice volume decreases and sea level rises. The increased gamma radioactivity in the clays in the Sea of Japan is associated with long periods of drought when loess deposits erode and are transported eastward by prevailing winds. When the Asian climate warms, the major deposition in the Sea of Japan is much lower in radioactive K as well as Al, and the deposits are interpreted to be fluvial.

The most prominent periodicity of the climatic variation in the Sea of Japan is 41,000 years, corresponding with the predicted Milankovitch cycle caused by changes in Earth's tilt. Figure 9 illustrates how the downhole logs from the Sea of Japan can be used to determine characteristic periodicities for a time interval. Note that different instruments vary in their time resolution. All three resistivity logs show the characteristic 41,000-year periodicity, as well as variability at shorter periods, using two of the three different tools, the shallow resistivity log with 0.75-m resolution and the FMS log with 5-mm resolution (see Figure 4). *Worthington* [1990] described a relationship based on the Nyquist periodic sampling condition between the instrument resolution h (in meters), the sedimentation rate s (in meters per million years), and the cycle period τ (in millions of years) to be $h = s\tau/2$. For a given sedimentation rate, climate cycles below this resolution limit of the instrument will be aliased and appear at lower frequencies. The deep resistivity log has 2-m vertical resolution and requires a sedimentation rate of at least 20 m/m.y. to detect eccentricity cycles of 95,000–123,000 or 413,000 years and at least 100 m/m.y. to detect precession cycles of 19,000–23,000 years. With the FMS tool the minimum sedimentation rate required for detection of 19,000- to 23,000-year precession cycles is 22 m/m.y., which is commonly exceeded in many nonerosive marine environments. Using the FMS, cycles at even finer scales can be detected. For example, the 7-m interval of the FMS log in Figure 9 corresponds approximately with a 60,000-year interval shown in the deep and shallow resistivity logs and resolves cycles with suborbital periods as short as 6000 years. Peaks in the spectrum represent the 41,000-year cycles as well as the lower-magnitude peaks at suborbital periods of 6000, 8000, and 12,000 years [*deMenocal and King*, 1995]. The causes and consequences of suborbital periods in the range of 2000–10,000 years are not well understood, but they have been linked to cycles in ocean circulation, iceberg rafting in surface waters, and solar radiation [e.g., *Dansgaard et al.*, 1982; *Henrich*, 1989]. The ability to predict these short-period, non-Milankovitch events that cause abrupt changes in climate may benefit society significantly if potential hazards due to sea level rise, drought, or solar radiation can be prevented.

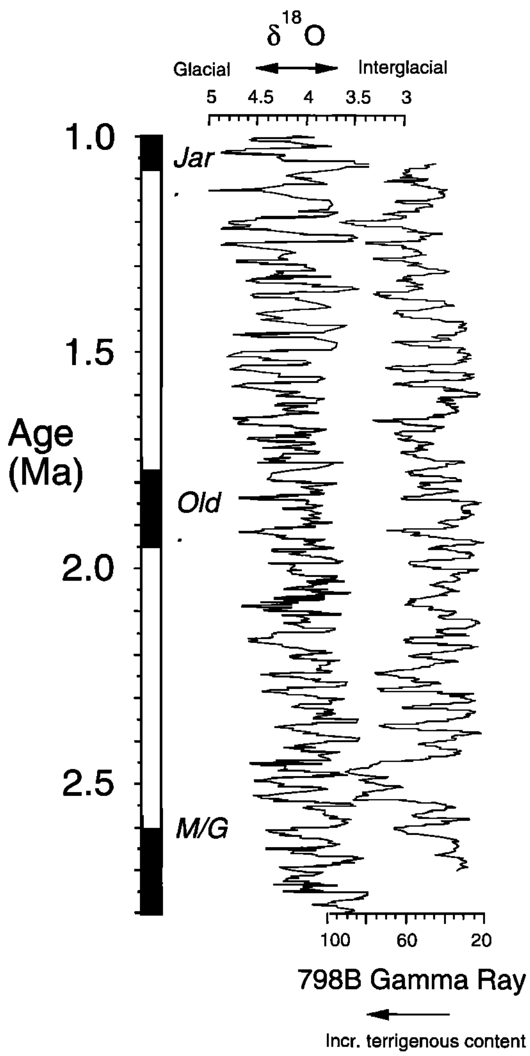

Figure 8. Correlation of the natural gamma radiation log in ODP Hole 798A in the Sea of Japan with the marine $\delta^{18}O$ record from the North Atlantic [from *deMenocal et al.*, 1992]. The depth scale of the log was converted to age using the paleomagnetic reversal sequence shown. The fine-scale correlation between the logs confirms that aridity during glacial periods cause terrigeneous deposits in the Sea of Japan.

In summary, the wide variety of properties measured using logs can detect periodic changes due to climate or other driving forces continuously and at extremely fine scale. Detection methods using downhole data are powerful, rapid, and complete compared with laboratory analyses on core samples and are independent of core recovery, which is rarely continuous in the deeper boreholes.

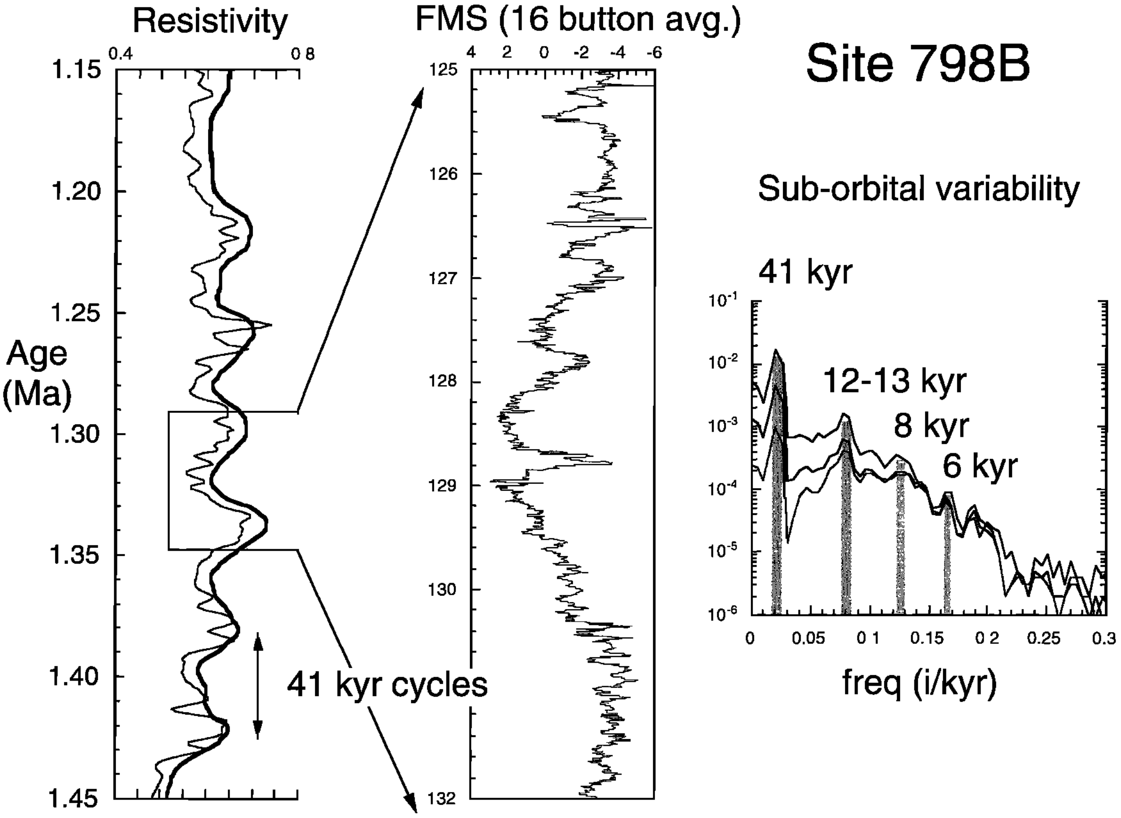

Figure 9. Comparison of data from three wireline resistivity tools: shallow and deep resistivity and the averaged FMS record that show cycles at a 41,000-year orbital period and below in the comparative power spectra [after *deMenocal and King*, 1995]. The resistivity logs have been converted to age, and the averaged FMS data are plotted on relative scale over a 7-m interval. The fine vertical resolution of the FMS data allows observation of periods as short as 6000 years.

Magnetostratigraphy

The ability to obtain direct and closely spaced measurements of absolute age has been a long-term goal of marine sediment coring. Usually, biostratigraphic or magnetostratigraphic time markers are identified in a core sample and their age is interpreted from the tie to a magnetic reversal timescale or biostratigraphic stage. From the accumulation of sediment between age markers, the sedimentation rate can be determined in recovered core sections where sedimentation has been uninterrupted. With the development of downhole instruments that can measure high-resolution magnetic field intensity, however, a direct and continuous in situ record of the marine magnetic reversal history may be effectively measured in a variety of sedimentary environments.

Precession magnetometers and induction susceptibility tools have been used in combination to determine the in situ magnetostratigraphy in weakly magnetized sediments [*Desvignes et al.*, 1992; *Etchecopar et al.*, 1993; *Pozzi et al.*, 1993]. These tools are used in combination in order to subtract the induced magnetization of the sediments from the total measured magnetic field and determine the polarity of the remanence. In recent studies in Pliocene sediments from the northern Pacific, remanent magnetostratigraphy has been measured downhole and correlated both with core measurements and with the geomagnetic polarity timescale over several hundred meters depth [*Thibal et al.*, 1995]. Figure 10 shows the downhole polarity sequence compared with the reversal time scale. Although the downhole record agrees with the polarity sequence derived from core data, it is more complete and allows for a confident comparison with a geomagnetic timescale. In addition, the continuous downhole geochronology provided an uninterrupted record of paleomagnetic intensity. *Thibal et al.* [1995] compared the continuous change in relative magnetic intensity over time at this high-latitude site with the results from low-latitude core measurements made by *Valet and Meynadier* [1993] and confirmed that magnetic intensity decreases sharply at the onset of a reversal, followed by an increase in field strength. Each period of constant polarity then decreases in intensity. This interpretation of the downhole data suggests that the duration of the Earth's polarity field is inversely proportional to the mean rate of decrease of magnetic intensity, that is, its length is determined by the intensity of the reversal.

In addition, downhole magnetic susceptibility logs have been correlated to core susceptibility measurements at several sites, providing excellent stratigraphic control [*Pariso and Johnson*, 1991; *Robinson*, 1992; *Du-*

buisson et al., 1995]. In recent drilling along the east flank of the Reykjanes Ridge in the North Atlantic, identifying changes in the Pliocene-Pleistocene climate was improved by a high-resolution correlation of core and log measurements of magnetic susceptibility [*Higgins et al.*, 1997]. In Figure 11, core and log magnetic susceptibility profiles at a site drilled through sediments accumulated over the past 3–3.5 m.y. at a high sedimentation rate (120–170 m/m.y.) were correlated peak by peak. The log data provide stronger susceptibility signals and more continuous records than core measurements, filling gaps limited by the core recovery in the deeper interval of the hole. Both data sets show Milankovitch periodicities extending to the bottom of the hole and can be used to improve biostratigraphic and magnetostratigraphic age dating determined from cores. The dating of sedimentary sequences using continuous magnetic logs or by correlation with Milankovitch cycles observed in other logs provides a critical link between depth and age in marine basins.

Methane Gas Hydrates

Downhole measurements in sedimentary basins reveal in situ properties that are hard to measure from core samples, such as high-pressure and gas-rich zones. Methane gas hydrates are formed from methane in the buried sediments on continental margins when the methane-water mixture freezes at cold temperatures and high pressures in a thermodynamic stability zone. Often sand, clay, and mixed sand-clay sequences contain pressurized, methane hydrates that can be detected by large seismic reflections that run parallel to and below the seafloor and usually indicate their spatial distribution [e.g., *Stoll*, 1971; *Kvenvolden*, 1993; *Wood et al.*, 1994]. Downhole logs have recorded data of the ephemeral properties of methane hydrates where they have been indicated on seismic surveys but have dissolved or been severely altered by attempts to drill and core them [*Collett*, 1993; *Prensky*, 1995]. The downhole velocity data have proven critical in quantifying the nature of this seismic reflection; velocity decreases owing to free gas below the hydrate layer and generates a large seismic reflection [*MacKay et al.*, 1994; *ODP Leg 164 Shipboard Scientific Party*, 1996]. Because the occurrence of methane hydrates and free gas may be predicted from seismic data and detailed downhole velocity data, more reliable estimates of the volume of gas and methane hydrate can be made to indicate the extent of this vast untapped natural resource.

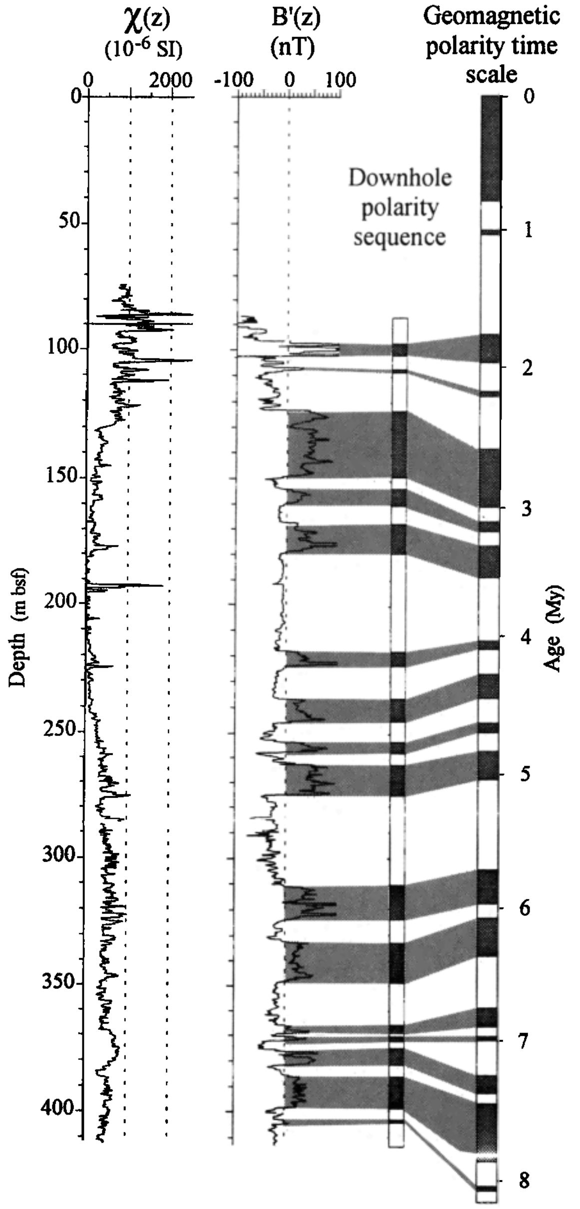

Figure 10. Comparison of downhole magnetic susceptibility $X(z)$ and remanent field $B'(z)$ results in ODP Hole 884E in the northern Pacific with the geomagnetic polarity timescale [from *Thibal et al.*, 1995]. The interpretation of the downhole polarity sequence from the logs enables sedimentation rate and magnetic reversal strength to be determined where core data are not available.

Ocean drilling has acquired logs in methane hydrate at several sites, most recently on the Blake Ridge off of the U.S. eastern seaboard. Other locations of marine hydrates that have been drilled include the Guatemala, Peru, and Cascadia coastal sediments [*Mathews and von Huene*, 1985; *Miller et al.*, 1991; *MacKay et al.*, 1994]. Because the porosity and permeability of sediments play a critical role in gas migration and stability of methane hydrates, in situ measurements of their physical properties are essential. On the Guatemala margin, evidence of high pressure was found in both recovered core and in logs of a 10-m-thick methane hydrate about 250 m below the seafloor [*Mathews and von Huene*, 1985]. The data indicated low gamma ray and density, high electrical resistivity and acoustic velocity, and generally consistent and uniform clay composition through the drilled interval. From these downhole measurements, *Mathews* [1986] assessed the concentration of methane hydrate. *Collett* [1993] applied a similar approach using downhole logs on the continental slope of Alaska. An increase in

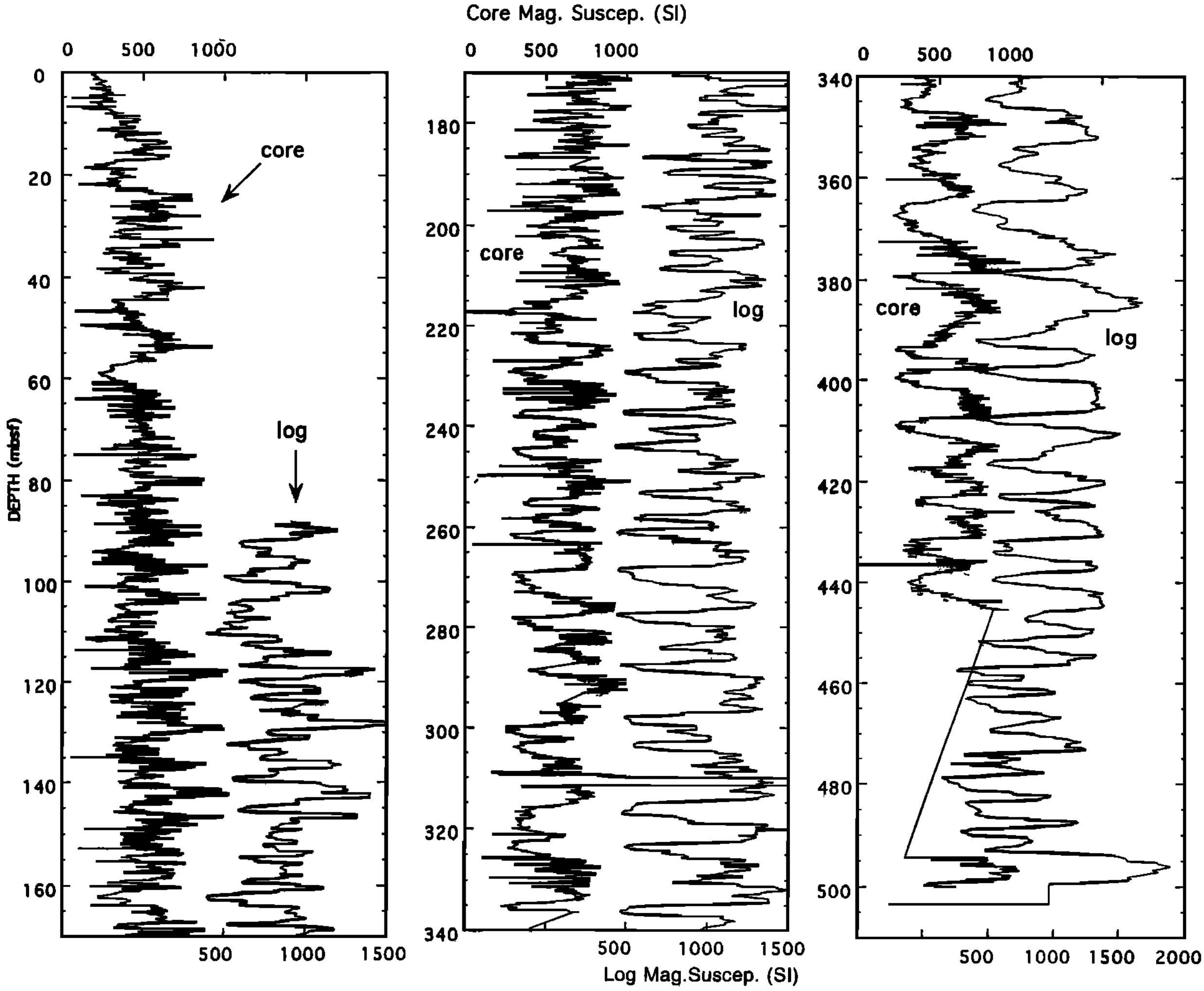

Figure 11. Comparison of downhole magnetic susceptibility log and shipboard measurements on core sections recovered from Hole 984D in the North Atlantic [after *Higgins et al.*, 1997]. The excellent correlation allows gaps in core data to be inferred from the log results to improve the age dating determined from cores.

electrical resistivity and acoustic velocity was associated with the hydrate occurrence because the frozen hydrate reduced porosity and stiffened the sediment beyond what might be expected from sediment compaction. On the Blake Ridge, recent logging reveals increases in velocity and resistivity with increasing hydrate occurrence to a depth where the hydrates become unstable; then decreases in velocity and resistivity below it are associated with the presence of free gas [*ODP Leg 164 Shipboard Scientific Party*, 1996]. The use of LWD technology would insure the measurement of in situ properties with a minimum of drilling and coring disturbance of methane hydrate and gas-bearing sediments.

Volcanics and the Cretaceous-Tertiary Boundary

Volcanic eruptions and the traces they leave in the marine sedimentary record are not well understood, but ash layers recovered in core sections or observed in downhole measurements provide distinct markers for the dating of large eruptions. In marine sediments, volcanic ash layers are often found with marine carbonates and nonvolcanic clays. Ashes are often observed in core samples and can be distinguished by their relatively high ratio of Th/U concentration [e.g., *Schlich et al.*, 1989]. When abrupt boundaries between carbonates, clay, or ash layers occur, downhole log images are particularly useful for identifying the location and attitude of these unconformities. Figure 12 shows a FMS resistivity log from the Sea of Japan that illustrates a 1-cm-thick, horizontal ash layer at 174.7 m depth within porous carbonate sediments that occurred during a short, nearby volcanic eruption at approximately 1.5 Ma. The high-resistivity (white) ash layer marks a definitive point that was used to shift the expansion-corrected core by +0.70 m to match the downhole log. Ash layer correlation from hole to hole is particularly informative where core recovery is low or when pulses of volcanic activity can be identified and dated. In the Mediterranean, for

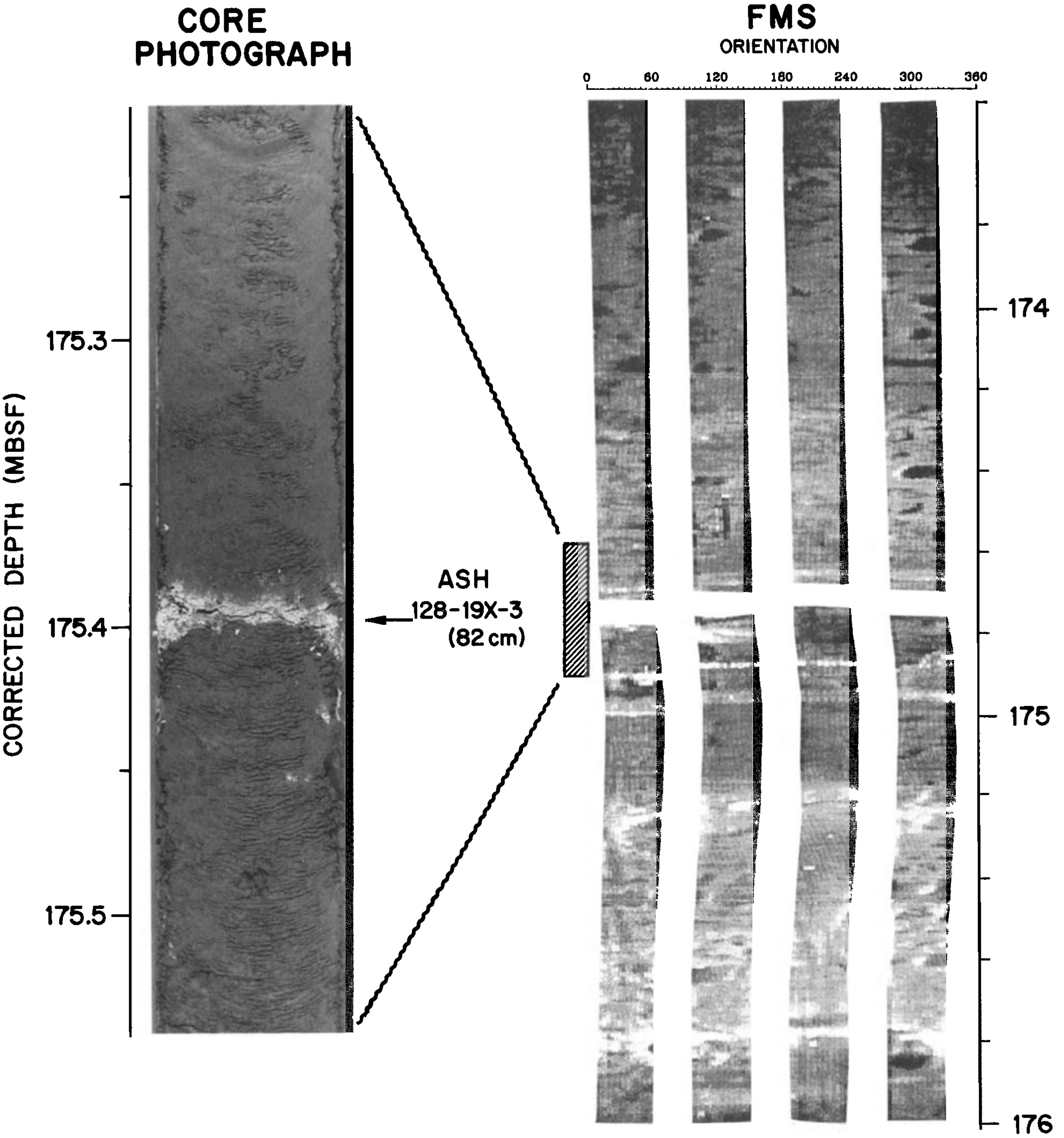

Figure 12. Example of the correlation between (left) a core photograph and (right) an FMS image of a 1-cm-thick ash layer in ODP Hole 798B in the Sea of Japan [from *deMenocal et al.*, 1992]. The FMS images of four orthogonal traces are oriented to north at 0° magnetic declination and represent the ash as a high-resistivity (white) flat layer at 174.7 m bsf. The expansion-corrected core depth was shifted by +0.70 m to match the downhole log.

example, downhole logs were used to determine zones of abundant ash separated by 150,000- to 200,000-year periods of marine deposition [*Kastens et al.*, 1987].

Using downhole logs, the boundary between the Cretaceous and Tertiary periods has been studied at eight sites, in the south Atlantic, Caribbean, and eastern Indian Oceans. At each site the extinction boundary was determined using biostratigraphic markers and lithologic changes observed from core sections. At most of these locations, however, incomplete core recovery has made the exact location and thickness of the boundary difficult to determine. Although the downhole signatures of the Cretaceous-Tertiary (K-T) boundary are not always distinctive, these data can be critical in determining the contact and thickness of sedimentary deposits near the K-T event. The boundary is often marked by abrupt

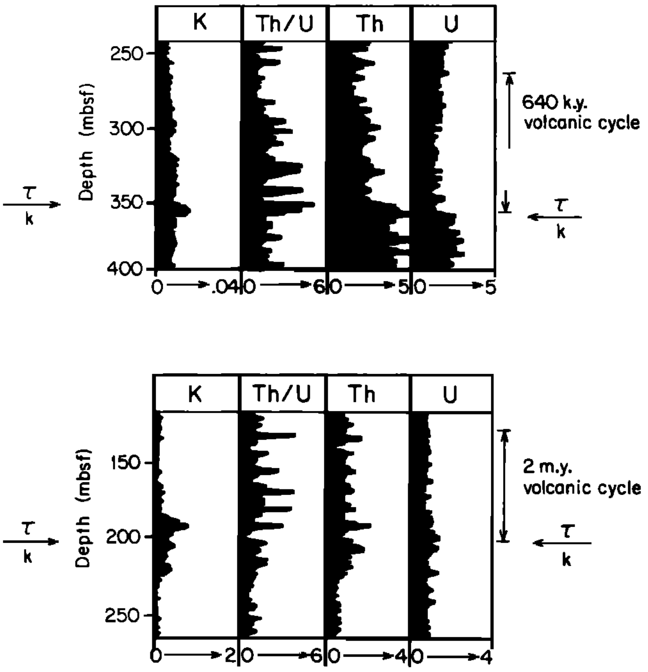

Figure 13. Variations of potassium, thorium, and uranium versus depth recorded in two ODP holes in the central Indian Ocean [from *Pratson et al.*, 1990]. Potassium is enriched at the Cretaceous/Tertiary (K-T) boundary due to nondeposition of carbonates, although the thorium/uranium ratio does not distinguish the volcanic cycles above or below this boundary.

increases in natural gamma radiation, indicating high concentrations of K-rich clay as well as volcanics with high Th/U ratios. Anomalies in resistivity and velocity logs are also often observed at the K-T boundary. In Figure 13 the K-T boundary at two sites on the Kerguelen Plateau in the Indian Ocean is illustrated by natural gamma ray logs as a thin zone enriched in K. At the K-T event, the nondeposition of carbonates causes clay to concentrate, but the clays are not distinctive in Th and U [*Pratson et al.*, 1992]. The Th/U ratio shows that volcanic ash layers are found both above and below the K-T boundary and are related to the same volcanic source, but they do not correlate with the extinction event.

At other Indian Ocean sites on the Exmouth Plateau, the K-T boundary is indicated by an increase in clay content as well as by decreases in velocity and resistivity [*Haq et al.*, 1990]. Resistivity logs on the Exmouth Plateau also indicated a reduction in permeability above the K-T boundary [*Borehole Research Group*, 1990]. In the southern Atlantic Ocean, however, drilling across the K-T boundary does not reveal volcanic ash layers like those observed on the Kerguelen Plateau but reveals an increase in K-rich clay below it [*Ciesielski et al.*, 1988]. Recently, downhole density, natural gamma ray, resistivity logs, and FMS images at two sites in the central Caribbean have detected the thickness of thin clay layers bounding the K-T extinction event observed in core sections (H. Sigurdsson, personal communication, 1996). The log data made it feasible to determine the thickness of the poorly consolidated boundary clay deposits, which were only partially recovered by coring. From the downhole data in these studies, it is clear that increased nondeposition of carbonate marked by K-rich clay deposits is typical across the K-T boundary. However, regional volcanism, rather than a distinctive worldwide event, may be superimposed on these downhole signatures.

Earth's Crustal Structure

Oceanic crust underlies 60% of the Earth's surface. It is formed at mid-ocean ridges by a complex combination of processes, including extrusion of lava, intrusion of basalt dikes, and underplating of magma, which plays an important role in the mass balance on Earth. As the crust ages over several hundred thousand to a few million years, it thickens from a few hundred meters at the ridge to several kilometers in the deep ocean. Models of the formation and layering of the oceanic crust have relied almost exclusively on the results of seismic refraction experiments [*Raitt*, 1963; *Talwani et al.*, 1971; *Houtz and Ewing*, 1976; *Ewing and Purdy*, 1982; *Vera et al.*, 1990]. If drilling through the sequence could be achieved, it could verify which model of the structure and evolution of the oceanic crust is correct. Unfortunately, penetrating deep enough to core crustal sections has proven to be a difficult task throughout the history of ocean drilling, and a complete crustal section has not been achieved to date. A variety of oceanic crustal environments have been drilled, however, from young midplate basalt to flood basalt provinces to highly deformed gabbro, but in many cases, hole instability has been the major reason for the somewhat limited recovery of core and downhole data [e.g., *Gillis et al.*, 1993; *Cannat et al.*, 1995]. One of the most successful DSDP/ODP efforts devoted four legs to drilling and logging at Sites 417 and 418 in Cretaceous age crust in the Atlantic [*Hyndman et al.*, 1984; *Salisbury et al.*, 1988]. These expeditions acquired a comprehensive suite of downhole measurements that significantly augmented the core-based lithology and understanding of the seismic and porosity structure of the upper oceanic crust. Few sites have been as successful, and only one hole has been drilled to a greater depth into the crust.

Drilled during seven DSDP and ODP expeditions to over 2.1 km below the seafloor, Hole 504B in the eastern equatorial Pacific is the world's deepest DSDP/ODP penetration in the oceans. Hole 504B has been the most intensely studied site using core and downhole data, yet it still penetrates through only 30% of the oceanic crust. Table 2 summarizes four drilling and logging expeditions in the eastern Pacific and other crustal site locations since 1993. It is clear that coring, and especially logging, in the ocean crust is not often as successful as it has been in Hole 504B. With typical core recovery well below 50%, the downhole log recordings of porosity, perme-

TABLE 2. Recent Drilling and Logging at Crustal Sites

	Holes Drilled	*Holes Logged*	*Total Depth Logged, m*	*Maximum Penetration, mbsf*	*Average Core Recovery, %*
North Atlantic	17	0	0.0	125.7	12.7
Mid-Atlantic	15	0	0.0	200.8	32.1
East Pacific	2	2	2078.8	2111.0	17.8
Central Pacific	13	1	84.0	154.5	22.5

ability, and velocity profiles have been essential for evaluating the layered stratigraphy of the oceanic crust and linking rock properties, such as porosity and permeability, to seismic data.

Porosity variation is often used to explain changes in both log and seismic velocities with depth in the crust [e.g., *Mathews et al.*, 1984; *Moos et al.*, 1986; *Detrick et al.*, 1994], although nearly all logs respond in different ways to porosity over different scales. Which type of log yields the best estimate of porosity in a particular environment is not clear, but resistivity measurements have been used most often. *Francis* [1981] used a large-scale experiment in sediments to measure resistivity over intervals of 10–50 m; in Hole 504B a similar method was used to measure resistivities in the ocean crust [*Becker*, 1985]. Both large-scale experiments generally agree with lateral resistivity logs. The porosity logs computed using *Archie*'s [1942] empirical relationship from resistivity data in the crust reflect pore spaces filled both with seawater and with residual alteration minerals that are deposited by hydrothermal fluids. To interpret these results, alteration effects in the apparent porosity estimated from downhole resistivity data must be accounted for and corrected [*Pezard*, 1990].

Hole 504B comprises over 1.7 km of pillow lava and sheeted dikes with permeability as low as 10 microdarcy and corrected porosity less than 0.5%, effectively sealing all but the uppermost 300–400 m of the hole to hydrothermal fluid flow [*Becker et al.*, 1989; *Alt et al.*, 1993]. Measured downhole permeabilities decrease with porosity and with depth and correspond to zones of distinctive crustal structure [*Anderson et al.*, 1982]. *Anderson et al.* [1982], *Becker et al.* [1989], and *Alt et al.* [1993] conclude that fracturing contributes most to the open porosity and permeability and extends only to a shallow depth in Hole 504B. *Pezard* [1990] has measured the amount of fracturing using the resistivity log and FMS imaging. *Little and Stephen* [1985], *Moos et al.* [1986, 1990], and *Wilkens et al.* [1991], among others, correlate the uppermost fractured and permeable layers in Hole 504B to changes in crustal structure that increase velocity with depth in the hole.

Numerous experiments verify a strong correlation of velocity with porosity in crustal rocks [e.g., *Fox et al.*, 1973; *Christensen and Salisbury*, 1975; *Wilkens et al.*, 1983; *Christensen et al.*, 1989]. Laboratory-derived velocities on ocean crustal samples, however, are difficult to correlate with seismic refraction velocities because of the presence of secondary voids, such as fractures, and alteration effects [e.g., *Purdy*, 1987; *von Herzen et al.*, 1992]. Sonic logs and borehole seismic experiments agree well with seismic refraction results because they span larger volumes that include the secondary voids and alteration effects. Figure 14 illustrates the downhole changes in velocity and resistivity (which is inversely related to porosity). *Detrick et al.* [1994] show a layered velocity model derived from seismic refraction data that indicates a gradational change in the velocity structure at approximately 1.2 km within the sheeted dikes in Hole 504B. In typical layered models of oceanic crust, however, this change has been associated with the boundary between sheeted dikes and gabbro; its location higher in the sequence may be due to an increase in fracturing and porosity at a shallower depth.

In addition to velocity, seismic attenuation can play a major role in understanding the alteration, fluid inclusion, texture, microstructure, and heterogeneity of the oceanic crust [*Jacobson and Lewis*, 1990; *Wepfer and Christensen*, 1990; *Jacobson*, 1992]. Figure 15 illustrates the magnitude of attenuation due to velocity heterogeneity measured using different downhole and core data; measurements at the scale of log data agree with direct attenuation estimates made using downhole seismic data [*Swift and Stephen*, 1992; *Goldberg and Yin*, 1994]. Using the velocity log in Hole 504B, *Goldberg and Sun* [1997] correlated porosity and velocity changes with seismic attenuation due to scattering from heterogeneity that is largely due to changes in crustal morphology. They found that seismic attenuation varies exponentially with porosity and therefore decreases as the structure of the ocean crust changes with depth. Downhole measurements of velocity, porosity, and attenuation are effective predictors of changes in structure, particularly in the absence of core in crustal drill holes, and are critical for comparison with seismic refraction data in the investigation of the layered structure of the Earth's crust.

Geochemistry of the Oceanic Crust

Fluid flow through permeable layers in the oceanic crust is important in controlling the chemistry of the rock as well as the seawater. Our knowledge of the composition and chemistry of the oceanic crust has been greatly enhanced by downhole measurements. In particular, nuclear logs which are sensitive to elemental chemistry of crustal materials can read changes in bulk chemical composition with depth [*Herron and Herron*, 1990;

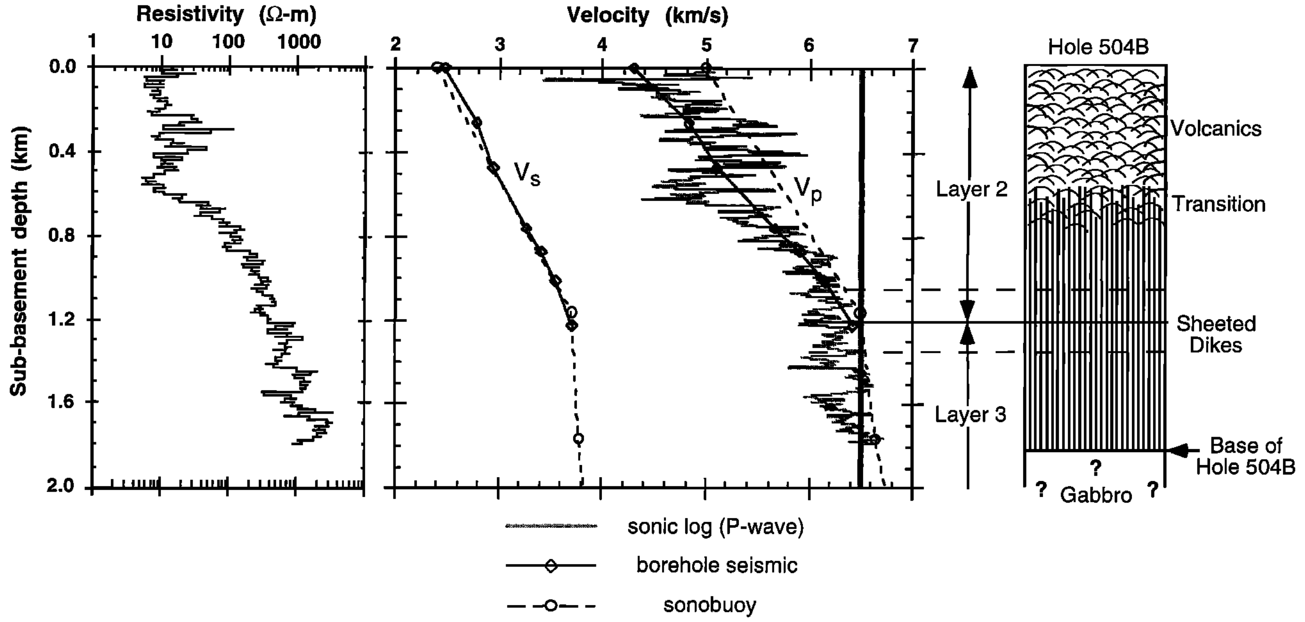

Figure 14. Summary of crustal velocity and resistivity logs in ODP Hole 504B in the eastern equatorial Pacific with the crustal velocity structure estimated from seismic surveys and lithostratigraphy inferred from core [from *Detrick et al.*, 1994]. The data indicate a change in vertical velocity gradient at approximately 1.2 km subbasement that is associated with a physical change within the sheeted dikes (layer 2–layer 3).

Herron et al., 1993]. *Thompson* [1973] describes the hydrothermal alteration that subsequently affects the fluid and rock chemistry and that may also be observed using information from geochemical logs [e.g., *Anderson et al.*, 1989, 1990]. In fresh basalt subjected to low-temperature alteration, K and Mg from seawater typically replace Ca, Fe, and Si [*Alt et al.*, 1986]. Using downhole nuclear logs in Hole 504B, *Anderson et al.* [1989] measured the bulk elemental abundance in basalt and computed the relative chemical change that the rocks had undergone. They then compared the results with fresh basalt from newly formed oceanic ridges and found from this comparison that Ti is absent and that K is enriched by 20% in the upper crust and depleted by 10% in the lower crust. Their findings suggest that hydrothermal fluids have mobilized the low-temperature alteration products Ti and K through confined high-porosity and permeable zones that later become sealed at shallow depths by mineral deposition along thin horizons.

In a similar example in the southwest Indian Ocean, downhole nuclear logs were acquired through 500 m of gabbro in a fracture zone [*Robinson et al.*, 1989]. This section of lower crustal material penetrated deformed and altered rocks that showed no evidence of the systematic layering expected from similar sections on land. Figure 16 shows highly enriched concentrations of Fe and Ti measured by the nuclear activation log in a 40- to 50-m-thick structure near 250 m depth. This enrichment

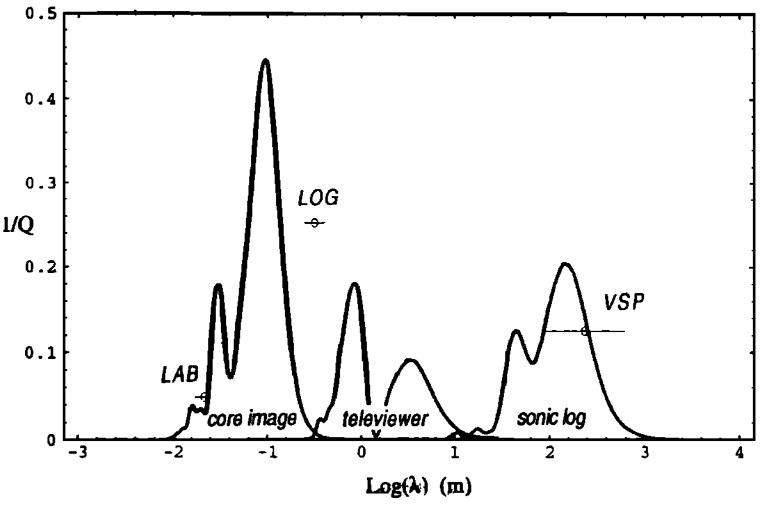

Figure 15. Comparison of computed attenuation spectra (curves) with average direct measurements from laboratory, sonic waveform, and VSP data (bars) from ODP Hole 735B in the southwest Indian Ocean [from *Goldberg and Yin*, 1994]. Major peaks in the computed spectra are attributed to formation heterogeneities that scatter acoustic energy.

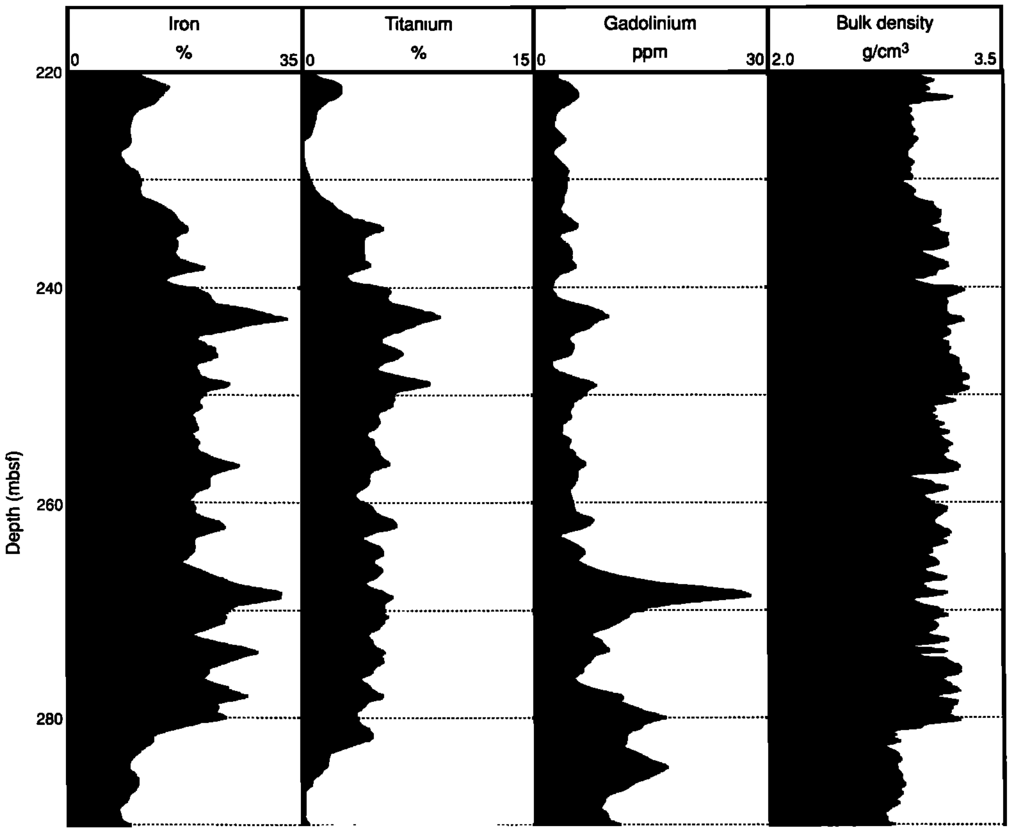

Figure 16. Nuclear log data from ODP Hole 735B in the southwest Indian Ocean illustrating the layered composition of gabbro and a thick titanium-rich (>5% weight percent) layer between 230 and 280 m bsf [after *Worthington et al.*, 1991].

is also responsible for other physical anomalies in this zone that are observed in downhole velocity, density (shown), and magnetic susceptibility profiles [*von Herzen et al.*, 1992; *Goldberg et al.*, 1992]. *Dick et al.* [1991] interpret the mineralization of this layer as the result of vertical faulting and extensive high-temperature alteration in the fracture zone. Downhole geochemical data are critical in determining bulk elemental composition and the chemistry of fracture-filling minerals in the crust, particularly since core recovery of fractured and altered crustal rocks is typically poor.

State of Stress

Stress plays a critical role in determining local fracturing, porosity, and tectonic processes in the Earth's crust. These properties of the crust depend on its strength in relation to the size of the tectonic forces acting upon it. The in situ stress is critical to understanding these tectonic processes. From cores, in situ stresses can be estimated using laboratory techniques to measure microfracture displacements or shear failure strength; however, for the measurement to be meaningful, the orientation of the stresses and the cores must be determined. Because of the typically sparse recovery of core material in the oceanic crust, core orientation is difficult and rare. Log data processed to generate borehole images may aid by orienting structures partially observed in core sections. One example of a borehole image through a basalt sequence in the Sea of Japan is shown in Figure 17. The FMS tool was passed two times over this interval with a rotation of approximately 45° between passes; this resulted in eight separate traces from the four orthogonal sensors on the tool. The layered structure of basalt pillows over this 2.5-m interval is apparent, as well as the electrically conductive (dark) fluid-filled contacts and fractures within them, which appear to consist of sequences of 20- to 30-cm-thick, west dipping lava flows. The orientation and dip of each flow can be determined in the FMS image from the amplitude and orientation of its sinusoidal shape [e.g., *Paillet et al.*, 1990]. Where continuous downhole images have been acquired, they have almost always aided significantly in differentiating lithologies and structural features, such as in these basalt flows, and have often enabled study of the state of stress by orientation of the recovered core.

Images that are recorded over the same depths in core and logs can be aligned using distinct features that are jointly tied to the downhole magnetic reference point. Using core and log data together in this manner, *MacLeod et al.* [1992, 1996] was able to orient the fractures in complex tectonic settings in the Pacific. In these studies, fractures identified in core and in FMS images

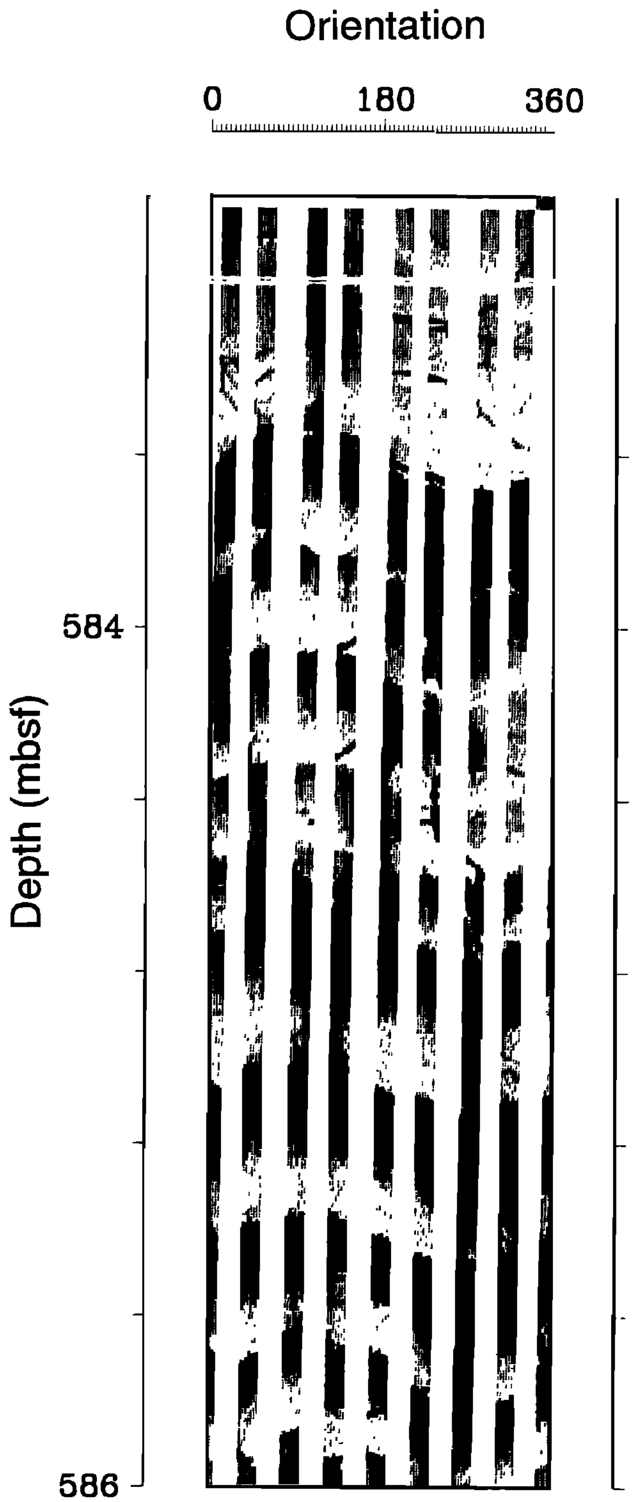

Figure 17. Example of an FMS image through a basalt sequence in ODP Hole 798B in the Sea of Japan. The FMS tool was run two times over this interval with a rotation of approximately 45° between passes, resulting in eight separate traces from the four orthogonal sensors. The layered structure of basalt pillows over this 3-m interval is apparent, as are the electrically conductive (dark) fluid-filled contacts and fractures within them, which appear to consist of a sequence of 20- to 30-cm-thick west dipping lava flows.

over the same interval of deformed and altered rock were statistically compiled, then compared and aligned to magnetic north. By their orientation, MacLeod concluded that the rocks reflected tectonic stresses and high-temperature deformation from early in the region's history. *Mathis et al.* [1995] also describe a precision visual method to align individual features in core and downhole images, rather than by a statistical compilation of the two data sets. This method may be used for detailed correlation and alignment with a magnetic reference as long as both the core and downhole images overlap.

Fracturing and borehole breakouts may be the direct result of stresses and can also indicate the regional stress fields [e.g., *Bell and Gough*, 1979; *Paillet et al.*, 1990; *Moos and Zoback*, 1990]. Breakouts form around a borehole when regional stresses cause shear failure and pieces of the wall fall out. Downhole imaging tools such as the acoustic televiewer or FMS can identify and orient borehole breakouts and fractures that may be used to infer regional stress fields [*Zemanek et al.*, 1970; *Plumb and Hickman*, 1985]. In Hole 504B, *Newmark et al.* [1984], *Zoback et al.* [1985], and *Morin et al.* [1990] measured breakout orientation and suggested that a strike-slip stress regime exists to 1.3 km depth below seafloor, a finding consistent with regional earthquake focal mechanisms. *Pezard et al.* [1997] have suggested a stress change in Hole 504B at this depth and strike-slip deformation below. In general, the stress regimes in the ocean crust are not completely understood; many factors affect the orientation and magnitude of stress-induced fractures, drilling-induced thermal fractures, and breakouts in a borehole. Direct downhole measurements that generate images provide the only means of observing these features.

An alternate, but untried, approach to estimating stress magnitude and direction in the ocean crust could use logging instruments that directly measure shear wave velocity and anisotropy [e.g., *Zemanek et al.*, 1991]. Both laboratory and downhole data indicate that velocity and amplitude changes occur in formations that are seismically anisotropic as a result of fracturing and stress fields not associated with disturbances in the immediate vicinity of a borehole [*Emersoy et al.*, 1994]. With this approach, the relationship between downhole velocity and the state of stress in the oceanic crust could also be investigated.

Passive Margins

Many of the large basins of the world's oceans are partially filled with sediments transported from land during the cyclical oscillations of global sea level. Major rivers build deltas and together with marine sediment sources can generate a complex stratigraphic history. Identifying boundaries between layers is critical because the accumulation of sediment records a history of the marine environment in the basin. Sedimentary layers within a basin are often interpreted from regional seismic surveys rather than by coring, but by accurately matching the seismic boundaries with the corresponding layers in the core, the exact depositional environment of each seismic layer can be determined. Downhole experiments can link these data by spanning the scale of centimeters in core samples to the scale of a few hundred or thousand meters typical of marine seismic surveys. Downhole measurements provide continuous records of sediment density, porosity, and acoustic velocity, parameters that can locate unconformities and identify stratigraphic boundaries in basins that fill episodically as sea level rises and falls. The stratigraphic sequence inferred from complete downhole profiles is therefore essential to "ground truth" the interpretation of seismic reflections. By combining density and acoustic velocity logs to produce a series of reflection coefficients versus depth, a synthetic seismogram can then be generated. The details for developing synthetic seismograms from log data are well described in basic geophysical texts [e.g., *Doveton*, 1986]. The direct correlation of a synthetic seismogram with a seismic trace enables location with pinpoint accuracy of the changes in physical properties at specific depths that may then be associated with a particular seismic reflection.

Tectonic extension on passive continental margins and in new ocean basins leads to subsidence. A critical element in deciphering the tectonic and subsidence history of a sedimentary basin is a reliable measurement of in situ porosity. As a basin fills through geologic time, porosity decreases as the sedimentary load increases. Accurate porosity data can reveal sediment layers that have been progressively compacted as the underlying basement has thinned, stretched, cooled, and subsided over time [e.g., *Watts and Steckler*, 1979]. Off the eastern U.S. coast, porosity logs from several holes indicated that lithology controls the compaction of sediments as well as their depth of burial, particularly when clay is present [*Goldberg et al.*, 1987; *Guerin and Goldberg*, 1996]. The estimation of porosity using downhole measurements remains one of the most important applications in deciphering the stratigraphic history of a basin for both oil exploration and academic research.

Early rifting and subsidence of the Mediterranean followed by multiple tectonic events has generated a complex stratigraphy through its history. Downhole geochemical measurements through Miocene carbonate sequences off the coast of Cyprus provided critical data for identifying early basin deposits that were not recovered during coring operations. Figure 18 shows a distinct 4-m-thick interval that has high S/Ca and low Cl/H ratios, identifying it primarily as a gypsum layer [*Emeis et al.*, 1996]. From its position in relation to the recovered core sections, this evaporite deposit corresponded to an age of approximately 6 Ma. Similar geochemical observations from cores played a large role in the discovery of the Messinian desiccation event, a period of global cooling and sea level lowering at 6–7 Ma when the Mediterranean dried up. *Emeis et al.* [1996] observe the Messinian desiccation event uniquely using the logging data at this site.

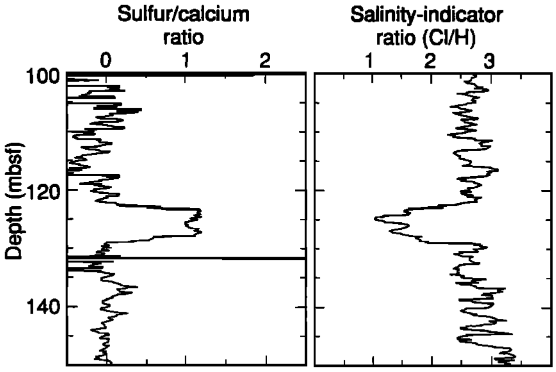

Figure 18. Example of a 4-m-thick layer with high sulfur/calcium and low chlorine/hydrogen ratios from the geochemical log, identifying it primarily as gypsum in ODP Hole 967C in the eastern Mediterranean Sea [from *Emeis et al.*, 1996]. The logs provided critical data in identifying this early basin deposit that was not recovered during coring operations.

Active Margins

Tectonic processes deform the Earth's crust, particularly along the margins of continental and oceanic plates, where massive shear zones or active subduction of one plate beneath another may occur. At convergent plate boundaries a wedge of deformed rocks known as an accretionary prism is scraped off the descending plate. In 1993 and 1994, drilling and logging results in the Cascadia and Barbados accretionary prisms produced new understanding of these active tectonic regimes, their physical properties, and the migration of pore fluids. Downhole data were used to address critical questions such as the physical properties at the plate boundary fault, its role as conduit for fluid movement, and the deformation of sediment accreted in the prism [e.g., *Hyndman et al.*, 1993; *Moore et al.*, 1995]. Log data are particularly useful in that they can quantify these properties in situ with minimal effects from coring. Data on such transient features as faults or high-pressure zones must be recorded immediately before they become altered by the sampling process.

Downhole data in ocean drill holes have been acquired using LWD in one region (two sites) on the Barbados accretionary prism in 1994. High-quality physical property measurements were made in this environment where wireline logging had previously been unsuccessful owing to poor hole conditions [*ODP Leg 156 Shipboard Science Party*, 1995]. Figure 19 illustrates a seismic depth transect across the interplate fault zone (high-amplitude reflectors at approximately 5.5 km depth) with two density profiles in superposition acquired using LWD. Porosity has been computed from the density log, and the details in one hole show that porosity and resistivity information vary inversely with depth (Figure 20). It is easy to identify two thin 0.5- to

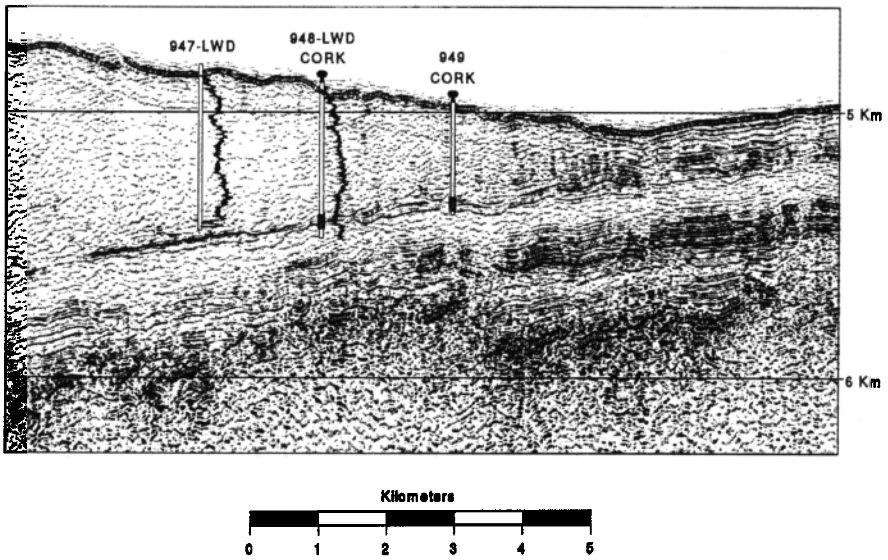

Figure 19. Seismic cross section and logging-while-drilling density logs in superposition at two sites on the Barbados accretionary prism [after *ODP Leg 156 Shipboard Science Party*, 1995]. The LWD tools in ODP Hole 948A were successful in penetrating the plate boundary fault that can be identified by the large reflection near the bottom of the holes where wireline tools had previously failed.

1.5-m zones of high porosity and low resistivity within the fault zone using the LWD data, which are too thin to be resolved seismically. *Moore et al.* [1995] suggest that these zones are tectonically significant because the pore pressure inferred from the porosity surpasses 90% of the overburden pressure, dilating and fracturing the formation. Their interpretation of the in situ porosity implies that a lateral influx of fluid occurs in the Barbados accretionary prism, causing large seismic reflection amplitudes and high-pressure zones that are localized by the fault structure. The ability to acquire and resolve in situ data of ephemeral properties, such as these thin high-porosity layers, is critical because they change immediately after the hole is drilled.

Using wireline logging technology, faults within an accretionary prism may be visualized and their properties measured when hole conditions permit logging. In the Pacific, near the New Hebrides islands, both downhole image logs from the borehole televiewer and FMS are able to resolve a thin, 80-cm-thick fault zone within the prism (dark zones), indicating a high water content over this interval (Figure 21). In other accretionary prisms on the Cascadia and Nankai margins, wireline porosity logs show similar zones of high water content associated with faulting, although sediment composition and the degree of cementation differ between these locations [*Hyndman et al.*, 1993; *Jarrard*, 1997]. It is clear that downhole measurements both using wireline and LWD technologies have identified porous fault zones within accretionary prisms, although LWD measurement of physical profiles are clearly more robust than standard wireline techniques.

The Future of Downhole Measurements

In the past, drilling legs that have been devoted to downhole experiments have been highly successful because of their uniquely focused objective. With ODP's future commitment to drilling deeper and performing more experiments in ocean boreholes, dedicated legs for downhole measurements and multiple expeditions to the same site will be essential. When operations occur over a long time at a particular site, rapid ship-to-shore data communication can be used to evaluate and control data acquisition and to provide scientific expertise beyond that available at sea. Improved communications will permit a continued increase in scientific observations using both short- and long-term downhole experiments

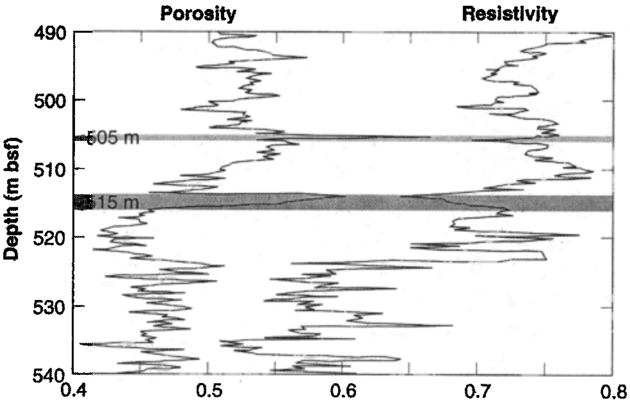

Figure 20. Details of porosity and resistivity logs through the plate boundary fault in ODP Hole 948A that indicate high porosity and low resistivity in 0.5- to 1.5-m zones that are too thin to be resolved seismically [from *Moore et al.*, 1995].

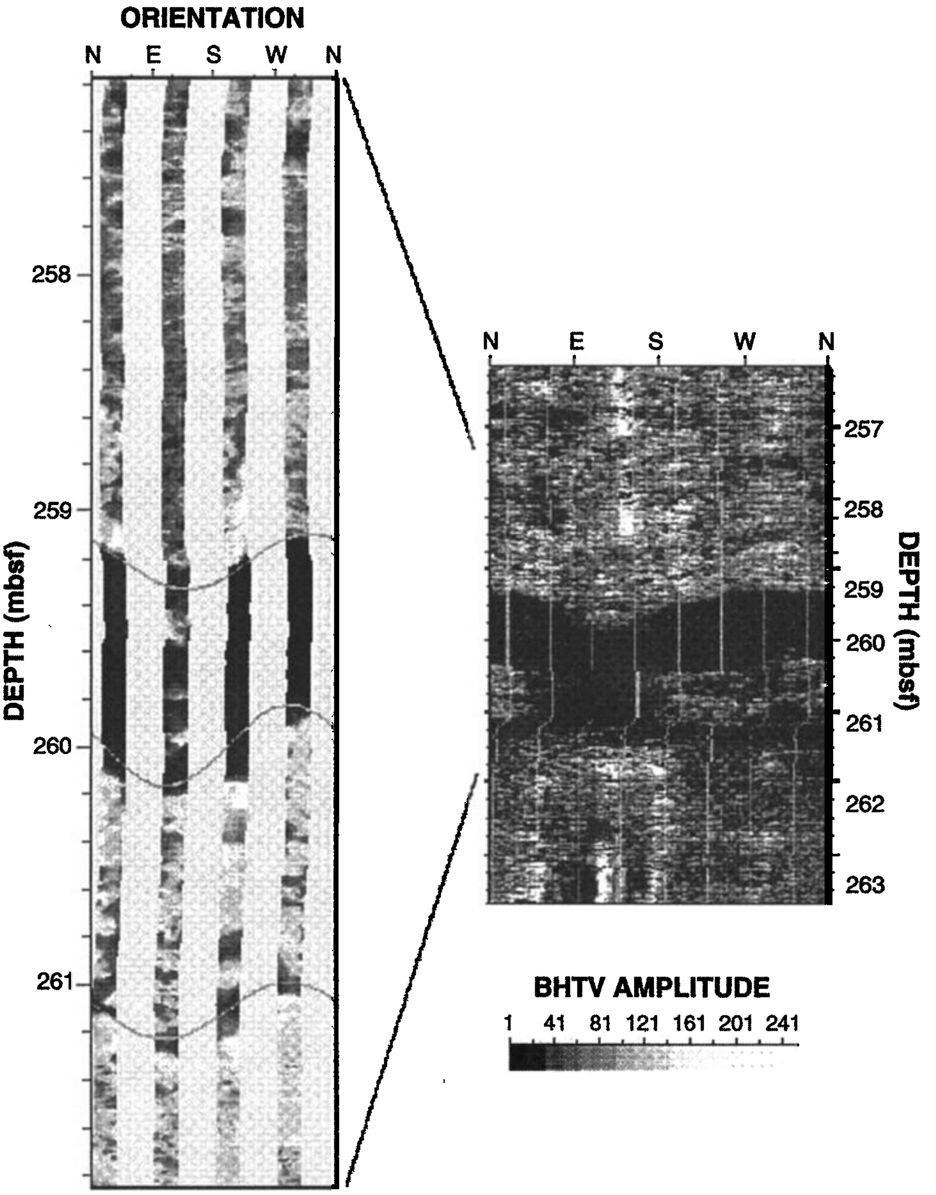

Figure 21. Wire line log images of a fault within an accretionary prism in ODP Hole 829A in the western Pacific [after *Chabernaud*, 1994; *Krammer et al.*, 1994]. Images from (left) FMS and from (right) Borehole Televiewer tools both indicate an 80-cm-thick east dipping fault zone that is electrically conductive and acoustically absorbing because of high water content.

that record a greater variety of measurements and larger volumes of data.

In the future, long-term observations lasting 5 years or more will become possible in hydraulically sealed and instrumented boreholes. As more long-term observatories are emplaced, new experiments will be designed between nearby, instrumented boreholes to trace lateral hydrologic properties and sample in situ fluids. These observations could reveal geochemical and biological activity unique to high-temperature environments that exist only after ambient conditions have recovered. Advances in drilling technology will also enable wireline measurements in open holes that have not previously been made in the oceans; borehole imaging tools with improved resolution, nuclear magnetic resonance tools, and wireline fluid samplers are all existing technologies that are currently incompatible with current ODP drilling operations. Such tools may also be deployed by wireline reentry but require dedicated seagoing expeditions. The installation of broadband seismic observatories across the world's oceans, for example, will require a considerable effort simply for the deployment of borehole seismometers in existing holes. Wire line reentry may be used to acquire vertical seismic profiles, dipole shear sonic logs, and high-energy nuclear logs behind casing in existing holes. The acquisition of log data while drilling, however, may be used with little additional time to address scientific questions in new ways. Simply employing a new strategy that uses LWD to drill closely spaced holes could be used to produce three-dimensional maps of the in situ properties where holes are typically unstable, such as in the shallowest subseafloor section, through slide failures and fault zones, or in young oceanic crust. As drilling technologies continue to advance, logging in highly deviated holes in conjunction with a riser, something that has never been attempted for scientific drilling objectives or in the deep ocean, will be possible. With a riser, ship motions can also be compensated for more effectively, improving the quality of the downhole data and the reconciliation of depth with core samples.

All the downhole data discussed in this review and those still to be recorded in the future will require archiving and retrieval systems that are consistent with core sample and surface data and that enable simple access for all ocean drill sites. The development of such a database is currently in progress for existing core and downhole data through the ODP but will require advancement as new data continue to be acquired.

CONCLUSIONS

In the last decade, measurements made with downhole technologies have provided crucial data that have led to the resolution of a variety of scientific problems in marine geology and geophysics. Downhole measurements provided data for magnetostratigraphy and the chronology of Milankovitch cycles in sedimentary sequences and their correlation with paleoclimatic changes; these will be important when drilling in new geologic environments, such as in the Arctic and Antarctic, where complete core recovery is not certain. Continued improvement in the resolution of orbital and suborbital cycles by logging with the FMS and other downhole tools may reveal climate and sea level cycles as short as 2000–3000 years in areas with rapid sedimentation. Logs have contributed significantly to studies of the upper oceanic crust and its chemical composition, hydrothermal alteration, and seismic stratigraphy. Using wireline tools in previously undrilled sections of the lower ocean crust and deep into continental margins will undoubtedly provide new data to test models of the deformation at the boundary between the continents and oceans, the structure and complete stratigraphy of the oceanic crust, and the depth and nature of hydrothermal exchanges between the crust and the ocean. The reentry and hydraulic sealing of boreholes after the drilling ship leaves has expanded the acquisition of data to measure temporal variations of downhole thermal and fluid properties; however, the circulation of fluids in submarine formations is still poorly understood. In addition to the proven technologies, new wireline tools, such as one that samples in situ fluids, and extended periods of downhole temperature and fluid monitoring may provide new data to define the formation permeability and the rate and volume of fluid exchange below the seafloor.

Using logging-while-drilling technology, in situ properties, such as porosity, have been measured in fault zones that act as fluid conduits in accretionary prisms. This technology will become increasingly important as core recovery becomes more difficult, such as when deep holes are drilled through accretionary prisms at several locations to study the lateral distribution of porosity and tectonic deformation. Downhole data are most representative of in situ conditions when they are acquired immediately after drilling or days to years later after conditions have returned to their predrilling state. Using these strategies, high-resolution formation properties and transient and long-term temporal fluid variations will be possible to observe. During the next decade of research in marine geology and geophysics, such downhole measurements are poised to expand the scientific opportunities that will come from programs in new frontier environments planned for ocean drilling.

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