4. EXPLANATORY NOTES¹

Shipboard Scientific Party²

INTRODUCTION

This chapter is devoted to a description of the sampling, measurement and core description procedures and methods used during Leg 139. It will help the reader understand the basis for our preliminary conclusions and also help the interested investigator select samples and data for further analysis. This chapter concerns only shipboard operations and analyses described in the site reports in the Initial Results volume of the Leg 139 Proceedings of the Ocean Drilling Program. Methods used by various investigators for shore-based analysis of Leg 139 data will be detailed in individual papers published in the Scientific Results volume.

Site Chapters

Descriptions of individual drilling sites, summaries of operations, and preliminary results are contained in site chapters. The separate sections of the site chapters were written by the following shipboard scientists (authors are listed in alphabetical order; no seniority is implied):

Site Summary: Davis, Mottl

Background and Objectives: Davis, Mottl

Site Geophysics and Geology: Davis, Franklin, Goodfellow, Zierenberg

Operations: Davis, Fisher, Foss, Mottl

Lithostratigraphy and Sedimentology: Baker, Boni, Goodfellow, Krasnov, Marchig, Marumo, Rigsby, Zierenberg

Biostratigraphy: Brunner, Mao

Paleomagnetism: Körner, Oda

Inorganic Geochemistry: Boulegue, Mottl, Wheat

Organic Geochemistry: Simoneit, Whelan

Physical Properties: Gröschel-Becker, Kinoshita, Konuykhov, Villinger

Igneous Petrology: Duckworth, Franklin, Stakes, Zierenberg Sulfide Petrology: Boni, Duckworth, Franklin, Goodfellow, Krasnov,

Marchig, Stakes, Zierenberg

Logging: Becker, Fisher, Langseth

Special Downhole Experiments: Becker, Davis, Langseth, Pettigrew

Heat Flow: Becker, Davis, Fisher, Kinoshita, Langseth, Villinger Summary and Conclusions: Davis, Mottl

Summary core descriptions ("barrel sheets" for sedimentary rocks and visual core descriptions for igneous and massive sulfide rocks) and photographs of each core appear in Section 3 of this volume, summary smear slide tables in Section 4, and thin-section sample descriptions appear in Section 5. Plots of logging data follow each site chapter.

Shipboard Scientific Procedures

Numbering of Sites, Holes, Cores, and Samples

Drilling sites are numbered consecutively from the first site drilled by the Glomar Challenger in 1968. A site number refers to one or more holes drilled while the ship was positioned over one acoustic beacon. Multiple holes may be drilled at a single site by pulling the drill pipe above the seafloor (out of the hole), moving the ship some distance from the previous hole, and then drilling another hole. In some cases, the ship may return to a previously occupied site to drill additional holes.

For all Ocean Drilling Program (ODP) drill sites, a letter suffix distinguishes each hole drilled at the same site. For example, the first hole drilled is assigned the site number modified by the suffix A, the second hole takes the site number and suffix B, and so forth. Note that this procedure differs slightly from that used by the Deep Sea Drilling Project (DSDP) (Sites 1 through 624), but prevents ambiguity between site- and hole-number designations. It is important to distinguish among holes drilled at a site because recovered sediments or rocks from different holes usually do not come from equivalent positions in the stratigraphic column.

The cored interval is measured in meters below seafloor (mbsf); sub-bottom depths are determined by subtracting the drill-pipe measurement (DPM) water depth (the length of pipe from the rig floor to the seafloor) from the total DPM (from the rig floor to the bottom of the hole; see Fig. 1). Echo-sounding data (from the precision depth recorders) are used to locate the site, but they are not used as a basis for any further measurements. Water depths given in the "Operations" and other sections of the site reports are given as drill-pipe measurements from the rig floor. Water depths below sea level can be determined by subtracting the height of the rig floor above sea level from the DPM water depth. The rig-floor height varies from site to site, and is given in the hole depth and location summary tables in each site report.

The depth interval assigned to an individual core begins with the depth below seafloor that the coring operation began and extends to the depth that the coring operation ended for that core (see Fig. 1). For rotary coring (RCB and XCB), each coring interval is equal to the length of the joint of drill pipe added for that interval (though a shorter core may be attempted in special instances). The drill pipe in use varies from about 9.4 to 9.8 m. The pipe is measured as it is added to the drill string and the cored interval is usually recorded as the length of the pipe joint to the nearest 0.1 m. For hydraulic piston coring (APC) operations, the drill string is advanced 9.5 m after each core is taken, the maximum length of the piston stroke.

Cored intervals may not necessarily be adjacent if separated by drilled intervals. In soft sediments, the drill string can be "washed ahead" with the core barrel in place, without recovering sediments. This is achieved by pumping water down the pipe at high pressure to wash the sediment out of the way of the bit and up the annulus between the drill pipe and the wall of the hole. If thin, hard layers are present, then it is possible to get "spotty" sampling of these resistant

¹ Davis, E. E., Mottl, M. J., Fisher, A. T., et al., 1992, Proc. ODP, Init. Repts., 139: College Station, TX (Ocean Drilling Program). ² Shipboard Scientific Party is as given in the list of participants preceding the contents.



Figure 1. Diagram illustrating terms used in the discussion of coring operations and core recovery. layers within the washed interval, and thus to have a cored interval greater than 9.5 m. In practice, this is rare and did not occur during Leg 139. In drilling hard rock, a center bit may replace the core barrel if it is desirable to drill without coring.

Cores taken from a hole are numbered serially from the top of the hole downward. Core numbers and their associated cored intervals (in mbsf) are unique in a given hole. Maximum full recovery for a single core is 9.5 m of rock or sediment contained in a plastic liner (6.6-cm internal diameter) plus about 0.2 m (without a plastic liner) in the core catcher (Fig. 2). The core catcher is a device at the bottom of the core barrel that prevents the core from sliding out when the barrel is retrieved from the hole. For sediments, the core-catcher sample is extruded into a short piece of plastic liner and is treated as a separate section below the last core section, and labeled core catcher (CC). For hard rocks, material recovered in the core catcher is included at the bottom of the last section. In certain situations recovery may exceed the 9.5-m maximum. Recovery greater than 100% may occur when coring in soft sediments (often near the seafloor), using either the APC system or when push-coring with an RCB system, as excess material can be drawn into the core barrel. Apparent recovery greater than 100% may occur also when coring gas-charged sediments with any coring system (APC, XCB, or RCB), as these sediments can expand while depressurizing during recovery (see "Drilling and Operations" section, this chapter).

Each recovered core is divided into 1.5-m sections that are numbered serially from the top (Fig. 2). When full recovery is obtained, the sections are numbered from 1 through 7, with the last section possibly being shorter than 1.5 m (rarely, an unusually long core may require more than 7 sections). When less than full recovery is obtained, there will be as many sections as needed to accommodate the length of the core recovered; for example, 4 m of core would be divided into two 1.5-m sections and one 1-m section. If recovery is less than 100% and there are empty spaces in the core liner between pieces of core, sections are numbered serially from the top and intervening sections are noted as void, whether or not shipboard scientists believe that the fragments were contiguous *in situ*. In rare cases a section less than 1.5 m may be cut in order to preserve features of interest (e.g., lithological contacts).

The core catcher is placed at the top of the cored interval in cases where material is recovered only in the core catcher. However, information supplied by the drillers or by other sources may allow for more precise interpretation as to the correct position of core-catcher material within an incompletely recovered cored interval.

Igneous rock cores are also cut into 1.5-m sections that are numbered serially; individual pieces of rock are then each assigned a number. Fragments of a single piece are assigned a single number, and individual fragments are identified alphabetically. The corecatcher sample is placed at the bottom of the last section and is treated as part of the last section, rather than separately. Scientists completing visual core descriptions describe each lithologic unit, noting core and section boundaries only as physical reference points.

When, as is usually the case, the recovered core is shorter than the cored interval, the top of the core is equated with the top of the cored interval by convention, in order to achieve consistency in handling analytical data derived from the cores. Samples removed from the cores are designated by distance measured in centimeters from the top of the section to the top and bottom of each sample removed from that section. In curated hard-rock sections, sturdy plastic spacers are placed between pieces which did not fit together in order to protect them from damage in transit and in storage; therefore, the centimeter interval noted for a hard-rock sample has no direct relationship to that sample's depth within the cored interval, but is only a physical reference to the location of the sample within the curated core.

A full identification number for a sample consists of the following information: leg, site, hole, core number, core type, section number, piece number (for hard rock), and interval in centimeters measured from the top of section. For example, a sample identification of



Figure 2. Diagram of procedure used in cutting and labeling core sections.

"139-855A-5R-1, 10–12 cm" represents a sample removed from the interval between 10 and 12 cm below the top of Section 1, Core 5 ("R" designates that this core was taken during rotary coring) of Hole 855A during Leg 139.

All ODP core and sample identifiers indicate core type. The following abbreviations are used by Leg 139: R = rotary core barrel (RCB); H = hydraulic piston core (HPC; also referred to as APC, or advanced hydraulic piston core); <math>P = pressure core sampler; X = extended core barrel (XCB); B = drill-bit recovery; and W = wash-core recovery.

Core Handling

Sediments

As soon as a core arrives on deck, a sample is taken from the core catcher and given to the paleontologists for an initial age assessment. The core is then placed on the long horizontal rack on the catwalk, where gas samples may be taken by piercing the core liner and withdrawing gas into a vacuum tube. Voids within the core are sought as sites for gas sampling. Some of the gas samples are stored for shore-based study, but others are analyzed immediately as part of the shipboard safety and pollution-prevention program. Next, the core is marked into section lengths with a felt-tipped pen, each section is labeled, and the core is cut into sections. Whole-round interstitial water (IW) samples are then taken. In addition, some headspace gas samples are scraped from the ends of cut sections on the catwalk and sealed in glass vials for light-hydrocarbon analysis. Each section is then sealed at the top and bottom by gluing on color-coded plastic caps, blue to identify the top of a section and clear for the bottom. A yellow cap is placed on the section ends from which a whole-round sample has been removed, and the sample code (e.g., IW) is written on the yellow cap. The caps are usually attached to the liner by coating the end of the liner and the inside rim of the cap with acetone, and securing the caps with tape.

The cores then are carried into the laboratory, where each section is labeled with an engraver to mark permanently the full designation of the section. The length of the core in each section and the corecatcher sample are measured to the nearest centimeter; this information is logged into the shipboard CORELOG database program.

Whole-round sections are normally run through the multisensor track (MST). The MST includes the GRAPE (gamma-ray attenuation porosity evaluator), *P*-wave logger, and magnetic susceptibility instrument. All three measurements are made on APC cores, but only susceptibility is measured on XCB and RCB cores, which are generally too disturbed to return useful *P*-wave and GRAPE data. Cores of sufficiently soft sediment are equilibrated to room temperature (for approximately 3 hours) and their thermal conductivity is measured (see "Physical Properties" section, this chapter).

Sediment cores are split lengthwise into working and archive halves. The softer cores are split with a wire or saw, depending on the degree of induration. Harder cores are split with a band saw or diamond saw. The wire-cut cores are split from the bottom to top, so investigators should be aware that older material could have been transported up the core on the split face of each section.

The working half of the core is sampled for both shipboard and shore-based laboratory studies. Each extracted sample is logged into the computer database by the location and the name of the investigator receiving the sample. Records of all samples are kept by the curator at ODP. The extracted samples are sealed in plastic vials or bags and labeled. Samples are routinely taken for shipboard physical properties, calcium carbonate (coulometric analysis), total carbon (carbonhydrogen-nitrogen-sulfur [CHNS] elemental analyzer), and X-ray diffraction (XRD) analyses, and the data are reported in the site chapters.

The archive half is described visually. Smear slides are made from samples taken from the archive half and are supplemented by thin sections taken from the working half. Most archive sections are run through the cryogenic magnetometer. The archive half is then photographed with both black-and-white and color film, one whole core at a time. Close-up photographs (black and white) are taken of particular features for site reports, as requested by individual scientists.

Both halves of the core are then put into labeled plastic tubes, sealed, and transferred to cold-storage space aboard the drilling vessel. Cores collected during Leg 139 that were rich in sulfide minerals were sealed in laminated bags made with one layer of aluminum foil sandwiched between two layers of plastic. After inserting a section of core, each bag was evacuated, filled with nitrogen, and placed in a standard D-tube before sealing.

At the end of the leg, the cores were transferred from the ship in refrigerated airfreight containers to cold storage at the Gulf Coast Repository at the Ocean Drilling Program, Texas A&M University, College Station, Texas.

Igneous Rocks

Igneous rock cores are handled differently from sedimentary cores. Once on deck, the core catcher is placed at the bottom of the core liner and total core recovery is calculated by shunting the rock pieces together and measuring to the nearest centimeter; this information is logged into the shipboard CORELOG database. The core is then cut into 1.5-m-long sections and transferred into the lab.

The contents of each section are transferred into 1.5-m-long sections of split core liner, where the bottoms of oriented pieces (i.e., pieces that clearly could not have rotated top to bottom about a horizontal axis in the liner) are marked with a red wax pencil. This is to ensure that orientation is not lost during splitting and labeling. The core is then split into archive and working halves. A plastic spacer is used to separate individual pieces and/or reconstructed groups of pieces in the core liner. These spacers may represent a substantial

interval of no recovery. Each piece is numbered sequentially from the top of each section, beginning with number 1; reconstructed groups of pieces are assigned the same number but are lettered consecutively. Pieces are labeled only on external surfaces. If the piece is oriented, an arrow is added to the label pointing to the top of the section.

The working half of the hard-rock core is then sampled for shipboard laboratory studies. Records of all samples are kept by the curator at ODP. The archive half is described visually, then photographed with both black-and-white and color film, one core at a time. Both halves of the core are then shrink-wrapped in plastic to prevent rock pieces from vibrating out of sequence during transit, put into labeled plastic tubes, sealed, and transferred to cold-storage space aboard the drilling vessel. As with the other Leg 139 cores, they are housed in the Gulf Coast Repository.

DRILLING AND OPERATIONS

Drilling Systems

Three main coring systems were used during Leg 139. The advanced hydraulic piston coring (APC) system combines an oceanographicstyle piston corer with the drill string used as a hydraulic accumulator. The drill string is pressured with the rig pumps (up to 3000 psi) until shear pins fail and the core barrel is driven through the bit and into the sediment for a 9.5-m core. APC cores are taken only in relatively soft sediment and generally are continued until "refusal" is reached. Refusal is usually the point at which excessive force (approaching the tensile limit of the steel) is required to pull the core barrel from the sediment, but sometimes it is defined by the inability to penetrate the sediment an adequate distance to warrant further use of the system. If there is incomplete stroke of the corer, unwelcome "flow-in" disturbance of the core also may result (see below). The APC is most effective in biogenic oozes, where continuous penetration in excess of 300 m has been achieved, and least effective in coarse clastic material or firm seafloor where the softer sediments have been removed. Drill-string rotation is not used in the coring process. After each core is retrieved, the drill string is advanced to the depth appropriate for the top of the next core.

The extended core barrel (XCB) coring system is compatible with the drill string hardware used for APC coring and therefore permits the extension of an APC hole for some distance beyond APC refusal without the requirement for a time-consuming trip of the drill string. The core is cut by a rotating shoe with cutting edges (1 to 2-cm kerf) that extend several centimeters ahead of the main drill bit. Although the inner core barrel rotates with the cutting shoe, the plastic liner inside is isolated from rotation by a system of bearings. The entire barrel is spring-loaded, permitting the cutting shoe to be pushed back to the plane of the main bit's cutting structure if harder rock is encountered. The length of the cored interval is usually 9.5-9.7 m and is determined by the length of the pipe added to the drill string for the core; shorter intervals may be cored if desired. The effectiveness of the XCB currently is limited to soft to medium sediments, but development continues with the goal of extending XCB capability into indurated material. An experimental "hard-rock" XCB shoe was run successfully at Site 856, returning 1.4 m of basalt from the top of an igneous sill.

The main bits used with the APC and XCB coring systems may be 11-7/16-in. roller-cone or 9-7/8-in. to 10-1/8-in. "drag"-type bits. Both designs feature a 3.80-in. opening that permits passage of the APC and XCB core barrels, as well as various other coring and downhole instrumentation packages and logging tools. The roller-cone bits drill by gouging the sediment with teeth that are imbedded in cone-shaped wheels that turn as the drill string is rotated. The drag-type bits machine the sediment away with edges of synthetic, polycrystalline diamond or tungsten carbide. They generally require higher rotational speed but less drill-string weight than the roller-cone bits.

The rotary core barrel (RCB) coring system has been the breadand-butter rock-recovery tool of DSDP and ODP for many years. The RCB system has the ability to obtain representative core samples from many kinds of sediment or rock, but it is not the optimum coring system for some lithologies. It is, however, the only known system that can core an entire sediment column of a kilometer or more and then core crystalline basement rocks without a bit change. The core is trimmed by the rotating cones of a roller-cone bit and must pass through the rotating bit throat before it enters the nonrotating inner core barrel. The inner barrel and its plastic liner are decoupled from drill-string rotation by bearings at top and bottom. As with the XCB, the cored interval is determined by the length of pipe added. Unlike the XCB, the RCB is not compatible with most of the downhole hardware used with the APC system and it is necessary to make a round trip of the drill string and redrill the interval after APC refusal is reached, if continued coring with the RCB is desired.

The bits normally used with the RCB system have four roller cones and are similar in construction to the roller-cone APC/XCB bits. The RCB bit diameter is smaller, 9-7/8 to 10-1/8 in., and the core throat diameter is 2-7/16 in. Because of the small opening and the use of a flapper-type check valve just above the bit, the bit must be dropped by using a mechanical bit release (MBR) before most logging or other tools can pass out of the drill string (see "Downhole Logging" section, this chapter). A variety of tungsten carbide cutting structures are used on RCB bits, depending upon anticipated lithology. Longer, chisel-shaped inserts are used for gouging action in soft to medium material, while shorter chisel- or conical-shaped inserts are used to drill high-compressive-strength rocks through point loading. As a compromise, chisel inserts of medium length are used where lithology is varied or unknown. In those holes during Leg 139 in which high temperatures were expected, special bits with sealed roller bearings were used instead of the usual sealed-journal bearing models.

All of the above systems differ from conventional oil field coring in that the inner core barrels are wireline retrievable. A special high-speed winch and 1/2-in. wire rope are used to retrieve the inner barrel for each core, eliminating the need to trip the drill string. The choice of a coring system is determined by the nature of the material to be cored. The APC nearly always is superior to the rotary systems for soft sediments. If the soft-sediment interval is expected to be thin, quality/quantity of soft cores is not particularly important, or the time of a round trip is to be avoided, RCB coring may begin at the seafloor. Neither the XCB nor the RCB has a clear advantage over the other in soft to medium sediments below the APC refusal point, and each has been known to excel and to fail in a variety of lithologies. The present-day XCB is at an increasing disadvantage to the RCB with greater depth and induration, as the XCB system has a lower rate of penetration, some problems with bit hydraulics, and greater vulnerability to mechanical failure. If any considerable interval of lithified sediments and/or crystalline rocks is anticipated, the RCB system is generally used.

Drilling Characteristics

Drilling Parameters

Because water circulation in the borehole is open, cuttings are lost to the seafloor and cannot be examined. Information concerning sedimentary stratification in uncored or unrecovered intervals may be inferred from seismic data, wireline-logging results, and from an examination of the behavior of the drill string as observed and recorded on the drilling platform. Typically, the harder a layer, the slower and more difficult it is to penetrate. The driller must vary the parameters of weight-on-bit (WOB), rotations per minute (rpm), and circulation rate to produce the optimum outcome in terms of core recovery and rate of penetration (ROP). WOB may range from about 5000 lb in soft, shallow sediments to 40,000 lb in crystalline rocks, and depends upon the type of material being penetrated, the kind of bit in use, and the amount of drill-collar weight available to be applied to the bit. The drill string is usually rotated at 35 to 100 rpm, again depending on the type of bit and the nature of the formation. Typical rates of penetration during Leg 139 ranged from 15 to 20 m/hr in semi-indurated sediment, 5 to 10 m/hr in altered igneous sills, and 2.5 to 5 m/hr in the less altered igneous units.

Circulation rate is critical in that it has a profound effect upon core recovery in soft to medium sediments with the rotary coring systems. Too little drilling fluid at the bit will result in jammed core catchers and a low ROP, while too much will wash the core away. Many holes have a poorly recovered transitional zone in which there seems to be no acceptable compromise. In addition, the velocity of drilling fluid through the annulus must be controlled by the circulation rate to provide adequate hole cleaning while avoiding hole erosion by excessive turbulence in the softer intervals. The parameters of rotary torque and circulating pressure also are monitored as diagnostics to inform the driller of downhole conditions. An increase in the torque required to rotate the drill string may signal hole-cleaning problems, bit failure, or severe hole deviation. The amount of circulating pressure necessary at any one time is determined primarily by the length of the drill string and the amount of restriction at the bit. Changes in pressure may signal successful (or unsuccessful) latch-in of the inner barrel at the bit, hole-cleaning problems, or plugged bit nozzles.

The above parameters are recorded in analog form by the Martin-Decker drilling recorder on the drill floor; the records are available in the Operations office. A computerized TOTCO drilling recorder system that will record drilling data digitally is presently under development.

Drilling Deformation in Piston Cores

Fluidization

Portions of APC cores may be severely disturbed and liquefied, while other sections, above and/or below, may be perfectly undisturbed. This effect is rarely seen when seas are calm, but it becomes increasingly prevalent in higher heave conditions. Even though the entire stroke of the APC takes only about 1 s, the dynamics of drill string and APC interaction are not fully understood. The drill string is not heave-compensated during the APC coring operation. Because the string has elastic properties and is poorly restrained, it is suspected that heave motion induces the fluidization, either due to a reversal of heave direction during the stroke or to heave motion as the core barrel is being withdrawn from the sediment. Fluidization may be induced by causes other than coring operations. In cores where gas hydrate is present, porous sections often are fluidized after the hydrate decomposes (long before the core is split).

Debris at the Tops of Cores

While the length of the APC stroke is 9.5 m, the length of the core chamber is about 10 m. Much of section 1 at the top of the liner often is a mixture of highly disturbed "slush" and pieces of sediment from higher in the section. The following factors contribute to that accumulation.

As the previous APC core leaves a small-diameter hole extending 9.5 m below the main bit, the "shoulder" must be drilled off so that the bit can be positioned at the bottom of the previous cored interval. The reaming of the hole takes place while the next APC is lowered through the pipe, and much of the material falls to the bottom of the hole.

Pump circulation is used for the reaming operation. If the pump keeps operating until the bit reaches the total depth of the hole, the soft sediment in the bottom (top of next core) will be washed away or fluidized. If the pump is shut off before the bit reaches total depth, the debris from the reaming-down is not removed and is cored unless the bit is pushed through it.

The drill string is not heave-compensated during APC coring, and even if it could be, the driller's depth control is not perfect. If the APC "fires" on the upheave, more "soup" is cored than if the bit is shoved into the bottom of the hole at the time. A core chamber of a few centimeters is present from the tip of the cutting shoe to the bottom of the piston even before the corer is actuated. It will be packed with whatever sediment makes first contact with the cutting shoe.

Flow-in Disturbance

This phenomenon occurs only when the APC fails to penetrate the full 9.5 m into sediment and complete its stroke, although its character may be nearly identical to intervals of rough weather disturbance, as described previously. If the corer does not complete its stroke and the core barrel is held frictionally by the sediment, the piston is free to move relative to the barrel until it reaches its mechanical stop. As the piston seal is effective and withdrawal of the barrel is completed by pulling on the piston rod, sediment may be fluidized and drawn into the barrel by syringe action. The flow-in material is characterized by vertical flow lines and the absence of sedimentary structures. Surprisingly stiff sediment occasionally may be involved.

Downwarping

Horizontal beds may be deformed into concave-downward features in otherwise undisturbed APC cores (and to a lesser extent in rotary cores in soft sediment). The effect is caused by frictional contact of the core liner with the sediment during the coring process. The sediment near the edges is dragged downward by the liner in a manner similar to drag features near a fault surface. In severe cases, a rind of sediment may be sheared and highly disturbed while the inner portion of the core remains pristine.

Gas-bubble Disturbance and Expansion

While not actually caused by the coring process, these disturbances result from removing the core from *in-situ* conditions. In very soft sediment containing a relatively large amount of dissolved gas, the formation and expansion of gas bubbles can cause severe disruption and destruction of sedimentary structures to the extent of nearfluidization. Gas voids may also be formed, especially in firmer material, by gas coming out of solution or from decomposing hydrates. If the amount of gas is large, core-catcher shoes and coreliner end caps may be forcibly blown off. Cores may expand by 20% over their original length, with expansion continuing after the core has been cut into sections (leading to a variety of curatorial problems see the "Shipboard Scientific Procedures" section, this chapter). Core expansion is not always caused by gas, as comparison of nongassy cores to logged intervals suggests that there may be measurable expansion due to unloading and mechanical strain relief.

Drilling Deformation in Rotary Cores (XCB and RCB)

Biscuiting

Soft to medium sediment cores may exhibit concave-downward surfaces at periodic intervals of a few centimeters. The external expression on the core is a series of apparently thin, variably colored layers of material. The surfaces of the biscuits are believed to form when torque is applied to the core through friction with rotating surfaces (the RCB bit throat or XCB cutting shoe) as the core is formed. When the torsional strength of the core is exceeded, it fails and spins on its axis, forming the concave surface and a layer of sheared sediment. The length of the "biscuits" is thus roughly proportional to the shear strength of the sediment and tends to increase with depth and induration. When the core can stand up to contact with the full length of the rotating surface, no failures occur and biscuiting ceases.

Grooving

Core-catcher teeth or "dogs" often cause continuous external marks, either longitudinal or spiral, on the cores. This occurs more commonly on RCB cores than XCB cores. If the marks are longitudinal, they are probably the result of rock chips or debris behind one or more of the core-catcher dogs that prevent the dogs from opening fully. Often, for unknown reasons, the RCB inner barrel does not remain stationary with respect to the core and rotates with the outer barrel instead. The result is spiral grooving by the core-catcher dogs that resembles lathe machining. In some cases, a rather severe reduction in core diameter results.

Fracturing and Disintegration

It is not known how much core fracturing results from drilling and coring processes. Sometimes cores are recovered that are so severely fractured and broken that they literally fall apart when the liners are split. In some cases, the brittle failure of the core can be related to preexisting stresses in the rocks. The relief of stresses during the drilling or retrieval operations may lead to brittle failure, which is delayed until after the core is safely in the liner. It is suspected that more immediate failures result in failure to retain/recover core in the barrel. In several of the holes drilled during Leg 139, thermal stresses caused by rapid hole cooling may have exacerbated this problem.

Core Liners

Core liners are loaded into the core barrels before the cutting shoe is attached. After a barrel is retrieved, the liner and recovered core are removed from the barrel so that the core can be sectioned and examined. Three kinds of core liners were available during Leg 139. Standard butyrate liners are transparent and have a melting temperature of about 85°C. Ultem liners are translucent brown and will not melt until about 150°C. Ultem is more brittle than butyrate, however, so the Ultem liners are prone to shatter during coring and splitting. Extruded aluminum metal liners were also fabricated for Leg 139; because they are opaque, metal liners make curation and sampling more difficult.

Reentry Systems

Two types of reentry systems were used during Leg 139: a standard, full-size cone with casing and a smaller, free-fall funnel, which was in one case attached to a short section of drill-in casing. Each system has distinct advantages and disadvantages. The standard reentry system is more robust, requires significantly more advance planning, and is used when there is a long-term objective to return and reenter a hole, or to keep a hole open for an extended period. During Leg 139, full reentry systems were emplaced at Sites 857 and 858 before deployment of instrumented borehole seals (see Davis et al., this volume).

A free-fall funnel is deployed while drilling a single-bit hole if it is decided that scientific or operational objectives require reentry. The funnel is made up around the drill string after some portion of a hole has been drilled but before the pipe is pulled out of the seafloor. The funnel is then dropped down the pipe to land in the hole. As the funnel is not cemented or in any way "attached" to the formation, care must be taken when removing the pipe and reentering that the funnel is not dislodged. Unlike a conventional reentry cone-and-casing system, a free-fall funnel does not help maintain hole stability, except over a short cased interval at the base of the cone. A free-fall funnel can also be attached to the top of a section of drill-in casing, as was done at Hole 856H, to prevent loose sand from hindering drilling and coring operations, and to allow reentry for logging.

Setting a standard reentry cone and casing is a considerably more complex task. First, a "jet-in" test is conducted to determine the depth to which the cone and the first part of the casing string will be set. The jet-in test is usually completed before spudding the RCB exploratory hole. The pipe is lowered to the seafloor and pushed to refusal with the pumps running but without rotation. This test determines the maximum depth at which the conductor casing at the base of the reentry cone can be set. It is important to get this casing into competent formation because the cone and casing are held in place by friction and by the compressive and shear strengths of the seafloor sediments. The RCB exploratory hole is usually drilled next, in part to determine the minimum depth to which casing should be set in order to maintain stability in the reentry hole. All coring and open-hole logging operations for the interval to be cased must be done in the exploratory hole.

The drill string is tripped back to the rig floor, and a reentry cone, 16-in. conductor casing, and a 14-3/4-in. drill bit are made up to the bottom-hole assembly (BHA). The pipe is returned to the seafloor to emplace the cone and conductor casing. After jetting in, the pipe is unlatched from the cone and casing, and the 14-3/4-in. hole is drilled to a few meters beyond the intended casing setting depth for the 11-3/4-in. surface casing. No cores are taken during this phase of drilling. The pipe is tripped back to the rig floor again, and returned to the seafloor with a length of 11-3/4-in. casing a few meters shorter than the depth of the hole. After reentry, the surface casing is lowered through the cone, latched into lower part of the cone, released, and cemented into place. The pipe is then tripped for a standard RCB bit and BHA. A small amount of cement near the base of the casing, the casing shoe, and the cementing plug then are drilled out, and coring may resume from the bottom of the hole. The quality of the hydraulic seal between the open hole beneath the casing shoe and the ocean above (and the mechanical bond of the casing to the formation) depends on the success of the cement job, the length of the casing string, and the hydraulic properties of the formation. The reentry cones used during Leg 139 were modified slightly to accept the instrumented borehole seals described in Davis et al. (this volume).

Pressure Core Sampler

The pressure core sampler (PCS) is a free-fall-deployed, hydraulically actuated, wireline-retrievable pressure coring tool capable of retrieving core samples maintained at bottom-hole pressures. The PCS utilizes both current conventional oil field pressure coring technology and technology developed by DSDP. The PCS is completely compatible with the existing ODP bottom-hole assembly used for the APC and XCB. The PCS is not compatible with the RCB bottom-hole assembly.

The PCS, when free-fall deployed, lands in the BHA. The PCS latches into the BHA and is rotated with the BHA during coring operations in a manner similar to the XCB. The PCS is completely interchangeable with the APC and XCB coring tools, thus allowing a pressurized core sample to be taken at anytime from the mudline down to indurated formations and/or into basement. The PCS recovers a nominal 42-mm-diameter (1.65 in.) core sample, 0.86 m (34 in.) long, at pressures up to 690 bar (10,000 psi).

The PCS contains six main components or subassemblies: latch, actuator, accumulator, manifold, ball valve, and detachable sample chamber. The PCS sample chamber consists of the manifold subassembly, ball valve subassembly, and pressure case. The sample chamber when detached from the PCS is 92.2 mm (3.75 in.) in diameter and 1.8 m (6 ft) long. When the sample chamber is stroked closed and removed from the core barrel, the two sampling ports and their associated integral valves, as well as the integral pressure transducer, are easily accessible. A sampling manifold can be attached to either or both sampling ports for sampling fluids and/or gasses. Once on deck, the detachable sample chamber is removed and placed in a temperature-controlled bath. A sampling manifold is attached and gas and/or fluid samples are then extracted.

SITE GEOPHYSICS AND GEOLOGY

Numerous detailed site surveys were completed before Leg 139. Results of most of these studies have been published previously. Those most relevant to the drilling program, particularly those not published previously, are summarized in the individual site chapters and in Davis and Villinger (this volume). Each type of data is described briefly here, as are data collected during the site survey lines conducted immediately before drilling aboard the *JOIDES Resolution*.

Gravity and Magnetics

The regional plate tectonic regime is defined by magnetic data collected from 1972 to 1985 (Currie et al., 1983; Riddihough, 1985). Trackline spacing over the Middle Valley area is roughly 8 km and data were recorded at 1-min intervals, or about every 200 m along track. Data have been corrected to the IGRF reference field and contoured by R. Currie of the Pacific Geoscience Centre (pers. comm., 1991) and are shown in Davis and Villinger (this volume). Additional data were collected during the pre-drilling site survey conducted aboard the *Resolution*.

Gravity data were also collected at 1-min intervals along the same regional survey lines that the magnetic data were collected, with a Lacoste-Romberg gravimeter (Currie et al., 1983). These gravity and magnetic data augment those collected during earlier surveys at coarser line spacing and with less precise navigational control (e.g., Raff and Mason, 1961; Lucas, 1972; Pearson, 1975).

In addition to sea-surface tows, deep-towed magnetic field data were also collected in 1988 and 1990, primarily in the vicinity of Sites 856 and 858 (M. Tivey, Woods Hole Oceanographic Institution, unpubl. data, 1988, 1990). These data were collected from altitudes above the seafloor ranging from 25 to 150 m. Data were acquired at intervals ranging from a few seconds to one minute, during profiles completed at about 0.5 to 1.5 knots.

Bathymetry

Bathymetry was measured over the valley with a SeaBeam swath echo-sounding system on the National Oceanographic and Atmospheric Administration (NOAA) vessel Surveyor in 1983 and 1985. Lines were navigated with loran-C and were later adjusted using transit satellite fixes. A nominal trackline spacing of 1.8 km provided slightly overlapping sonic coverage from swath to swath, allowing additional relative navigational control. Small adjustments were later applied to force the positions of structural and volcanic features to agree with those determined in subsequent surveys controlled by the global positioning system (GPS). After merging individual swaths and adjusting navigation in this manner, smooth contours were drawn by hand at 10-m intervals. Depths were computed assuming a constant sonic velocity for the water column of 1500 m/s. Data have been published as a series of maps by Currie et al. (1985) and Davis et al. (1987). These data were analyzed in preliminary fashion by Karsten et al. (1986) and are discussed by Davis and Villinger (this volume).

Side-scan Imagery

Two types of side-scan acoustic imagery have been collected over the area. Continuous regional coverage is provided by near-surfacetowed 12-kHz SeaMARC II surveys completed jointly by the Hawaii Institute of Geophysics and the Pacific Geoscience Centre in 1983 and 1985. Individual swaths are 10 km in width and digital resolution across track is about 5 m. More detailed coverage is provided by deep-towed 30-kHz SeaMARC I surveys completed jointly by Lamont-Doherty Geological Observatory and the Pacific Geoscience Centre in 1984, and by Williamson and Associates, the Geological Survey of Canada, and the University of Washington in 1990. Swath widths range from 1 to 5 km, with corresponding crosstrack digital resolution ranging from 0.5 to 2.5 m. Navigational control for the SeaMARC II surveys was provided by transit satellite-adjusted loran-C in 1983, and by GPS-adjusted loran-C in 1985. Navigation is believed to be accurate to within about 100 m. Control for the SeaMARC I surveys was provided by satellite-adjusted loran-C (transit satellite in 1984, GPS in 1990) for ship position, combined with measurements of slant range and depth to the side-scan instruments, or, in parts of the 1990 survey, long-baseline acoustic transponder positioning. In the images shown in this volume, dark areas are those that cause strong backscatter or specular reflections, and light areas are those with smooth seafloor or acoustic shadows. These instruments and data are described in more detail by Blackinton et al. (1983), Chayes et al. (1983), and Davis et al. (1986). The data have been published as a series of maps by Davis et al. (1984, 1987) and Johnson et al. (in press) and are discussed in Davis and Villinger (this volume).

Seismic Reflection Profiles

Single-channel seismic reflection profiling has been conducted during numerous cruises to this area. Results have been presented by McManus et al. (1972), Barr and Chase (1974), and Davis and Lister (1977a). Other more recent results, collected primarily with small (0.65 L) air-gun sources are included in this volume. During the pre-drilling site survey, profiles were made using two 1.3-L (80 in.³) water guns and a Teledyne streamer with a 100-m active section. The towing geometry is shown in Figure 3. Data from this survey were displayed in real time on a Raytheon line-scan recorder and recorded digitally on a Masscomp 561 computer for later display and analysis. Navigation for the data collected after 1985 was provided by or adjusted to GPS; lines collected earlier were navigated with loran-C adjusted to transit-satellite positions.

Three multichannel seismic lines were also shot across the valley along lines directly over the locations of the drill sites. Shot navigation was controlled by an integrated system employing doppler speed, loran-C, and GPS. Data were collected by Digicon, Inc., using an array of 60 air guns totalling 100 L in capacity, and tuned to improve directionality and to simplify the source signature. Signals were received by a 3600-m-long streamer with 144 geophone groups. Shots were spaced every 50 m, providing 36-fold multiplicity for common depth point (CDP) stacks, with a CDP interval of 12.5 m. Migrated sections shown in this volume were processed by Halliburton Geophysical Services, Inc., and have been (1) equalized, (2) filtered to limit velocity, frequency band (nominally 10 to 40 Hz), and dip (45°), and (3) scaled to allow weak arrivals within the sediment section to be imaged along with the extremely high-amplitude, spatially discrete reflections from volcanic horizons. Details of the processing sequence and all parameters are given by Rohr et al. (1992). Near-offset traceby-trace records are also shown in this volume; these are true-amplitude playbacks with no scaling applied. The dominant frequency of the signal is about 35 Hz, providing a one-quarter wave-length resolution of about 10 m.

Heat Flow

Roughly 550 heat flow measurements were made in Middle Valley before Leg 139. Reconnaissance measurements were completed on a regional 10-km grid by Davis and Lister (1977b). More recent data and a preliminary analysis are reported in Davis and Villinger (this volume). These later more detailed measurements were made along multipenetration lines with probes ranging from 2.5 to 4 m in length. Conductivity was measured in situ for a number of penetrations. Heat flow values were computed from the probe temperature data following the scheme described by Villinger and Davis (1987). Measurement spacing along lines in much of the valley is typically a few to several hundred meters; measurements are more closely spaced where local variability is large. In most areas of the valley, heat flow variability combined with the density of the measurements allows heat flow to be contoured at an interval of about 30% of the local values (i.e., 100 mW/m² at 300 mW/m² and 1 W/m² at 3 W/m²). Ship locations were determined using loran-C positions adjusted to transit satellite or GPS. Instrument locations were then estimated from the range and bearing from the ship to the instrument, the average direction of the ship's track, and the correlation of identifiable structural or sedimentary features between the 3.5-kHz pinger record of the probe and ship's 3.5-kHz profiler. About half of the measurements in the vicinity of Site 858 were navigated using a long-baseline acoustic transponder net, also adjusted to GPS coordinates.



Figure 3. Positions of navigational and geophysical elements relative to the drill string on the JOIDES Resolution.

Electrical Resistivity Soundings

Two electrical resistivity experiments have been conducted in Middle Valley, one in the thick section of sediment near the center of the rift in 1984 (Nobes, Law, and Edwards, 1986; Nobes, Villinger, Davis, and Law, 1986) and one over the structures that lie beneath Sites 856 and 858 (Nobes et al., in press). These experiments measured the magnetic field created by an electrical current that was made to flow through the sea and the seafloor. The current was generated by a full ocean-depth vertical dipole source. The results provide information about the electrical resistivity structure of the sediment and upper basement between the magnetometers deployed on ocean bottom and the location of individual, controlled current soundings, down to a depth of about half the distance between the source and receiver. This information constrains the porosity, rock matrix composition, and, to a certain extent, the temperature of the formation. Source-receiver separations range from a few hundred meters to a few kilometers. Sounding locations are typically spaced a few hundred meters apart.

Surficial Sediment and Fluid Sampling

From 1985 to 1990, about 110 piston, gravity, and boomerang sediment cores, ranging in length from 0.5 to 10 m, and one diamond drill core, were collected in Middle Valley. The positions of cores collected before 1986 were determined from loran-C ship positions adjusted to transit satellite fixes. Cores taken after 1986 were positioned relative to either an Oceano long-baseline transponder net or loran-C ship positions.

Sedimentological, mineralogical, and geochemical data from cores collected in 1985 have been analyzed and reported by Davis et al. (1987), Goodfellow and Blaise (1988), and Al-Aasm and Blaise (1991). Results from cores collected between 1986 and 1990 are in preparation (J. Franklin, W. Goodfellow, and J. Lydon, pers. comm., 1991).

Interstitial pore waters were collected in the vicinity of Site 858 in 1988, 1989, and 1990 from piston and gravity cores of unaltered hemipelagic and turbiditic sediment, and from hydrothermally altered sediment. In 1988, pore waters were extracted from 11 cores by centrifuging the sediment or by compacting it with a piston-cylinder squeezer in a hydraulic press. In 1989, pore waters were extracted from eight cores using nitrogen-pressured squeezers and were handled in a nitrogen-charged glove box. Shipboard analyses included pH, alkalinity, and SiO₂. Shore-based analyses included Na, K, Ca, Mg, Cl, F, HCO₃, SO₄, Sr, Ba, Fe, and Zn. Similar analyses were completed on hydrothermal fluids collected from vents during the *Alvin* submersible program described below. Results of these analyses are in preparation (J. Lydon, W. Goodfellow, and J. Franklin, pers. comm., 1991) and a summary of fluid temperatures are included in the "Site 856" and "Site 858" chapters (this volume).

Photographic and Submersible Observations

Photographic surveys of the areas around Sites 856 and 858 were completed as part of investigations conducted in 1985 to 1989. The earliest survey was conducted with a mechanically triggered (trip weight) 35-mm Eggerton camera system (Davis et al., 1987). Later surveys were conducted with a deep-towed camera frame from Lamont-Doherty Geological Observatory that contained silicon-intensified television (SIT) and 35-mm still cameras (J. Franklin, pers. comm., 1991). Data from the TV were telemetered to the ship in real time and recorded on magnetic tape. Temperature, pressure, and salinity data were also collected simultaneously using an Applied Microsystems STD unit. Camera positions in all but the earliest surveys were determined within an Oceano long-baseline acoustic transponder net and corrected to GPS, and have an inaccuracy of about 50 m.

Sites 856 and 858 were also examined during five dives of the *Alvin* in 1990 (J. Franklin, pers. comm., 1991). In addition to visual and photographic observations, high-temperature water samples, detailed magnetic and heat flow measurements, a scanning sonar survey, systematic push-cores and hard-rock samples, and biological samples were collected during the dives. Navigational control was provided by an Oceano long-baseline acoustic transponder system; relative positions are believed to be precise to within about 5 m and accurate to within about 50 m.

Water Column Studies

In 1987, a survey of the water column above Site 858 was completed. A "tow-yo" strategy was used for this work, in which measurements of temperature, pressure, salinity, and particulate concentration were made along a "sawtooth" profile ranging from near the seafloor to 400 m altitude above bottom. Water was sampled at discrete points along this profile and analyzed for Mn and Si₄. This work is reported in Baker et al. (1987).

Underway Geophysics

Before the ship arrived at Site 855, a series of profiles was completed across the highest priority sites in order to verify the position of the structures to be drilled (Fig. 4). Seismic reflection, 3.5-kHz and 12-kHz echo-sounding, and total field magnetic data were collected along the lines, with navigational control provided by GPS. Because of the small size of the structures and the detailed nature of the arrays of holes planned, we had to take into account the relative positions of the GPS antenna, echo-sounding transducers, seismic source and receiver, and moon pool. The geometry we used for the navigational corrections applied in determining the locations of seafloor features at each of the drill sites is shown in Figure 3.

In locating several of the holes, precise positioning with respect to bottom features was accomplished with a TV camera and/or a Mesotech 400-kHz radially scanning sonar. The sonar tool was lowered to within a few meters of the end of drill string and provided a



Figure 4. Site survey tracklines along which 3.5-kHz (A) and 12-kHz (B) echosounding, seismic reflection, and magnetic data were collected before drilling during Leg 139. Mercator projection point: $0^{\circ}0'N$, $0^{\circ}0'S$; 1100.00 m/degree.

local altitude determination and a circular field of view up to 400 m in diameter. Clear backscatter images were obtained on several key features, including an outcropping basalt layer along the fault scarp at Site 855, sloping and blocky massive sulfide outcrops at Site 856, and hydrothemal vents and constructional edifices at Site 858.

On-site Navigation

At several of the Leg 139 sites, detailed arrays of holes were drilled where positioning with respect to seafloor or subseafloor structures was critical. As described above, the survey lines conducted immediately before drilling were precisely navigated in order to verify the positions of previously studied features. Extra care was also taken in positioning the ship and drill string. During drilling operations at any given hole, GPS was logged about every 15 min. Corrections were applied to each position to account for the ship's heading and the distance from the GPS antenna to the moon pool (Fig. 3), and the positions were then averaged. Standard deviations of the individual positions about the averages were less than 0.005 nautical miles, or 10 m; standard errors of the means were typically less than 1 m. The averages for each hole are reported in the "Operations" section of each site chapter in this volume.

The dynamic positioning system for station keeping was controlled by a Honeywell short-baseline acoustic system that ranged to a continuously running pinger (beacon) dropped near the center of operations at each site. This system can operate at distances from a beacon of up to 10% of the water depth, or about 250 m in the case of the Leg 139 sites. Unfortunately, beacon positions could never be determined to better than about 30 m; thus, although the acoustic system provides relative positions to within a few meters, the absolute positions contained larger errors. To tie the acoustic navigation into GPS coordinates, the relative positions of holes at each site were shifted together to match the best average of the GPS hole locations. This method proved optimal for determining the seafloor beacon position. The resulting relative offsets between GPS and acoustic positions at each hole were less than 5 m.

An additional source of inaccuracy in navigation arises from the assumption that the drill string hangs vertically beneath the ship. Information about this source of uncertainty was gained at two holes at Sites 856 and 858 by placing an acoustic beacon on the camera frame during hole survey and reentry operations. The camera frame was found to be generally within 10 m of a position vertically beneath the moon pool. Hole 856G was found to be about 20 m offset (to the south) from the position the moon pool had occupied during drilling; this greater offset could have been caused by the influence of bottom currents on the reentry cone and casing lowered into this hole. Normal offsets are expected to be less than that observed with the camera frame on the string (i.e., less than 10 m).

At Hole 856G, simultaneous loran-C and GPS positions were compared by using fixes collected every 5 min over a period of 1 day. Again, fixes were corrected for antenna position and ship's heading, and averaged. The results show that the loran positions are less scattered than the GPS positions in longitude (standard deviation, loran-C = 0.00003'; GPS = 0.0025') and more scattered in latitude (standard deviation, loran-C = 0.0093'; GPS = 0.0038'). Loran-C positions were displaced from GPS positions to the northwest by 0.164' latitude and 0.436' longitude. A correction was applied to loran-C positions to obtain ship positions whenever GPS reception failed.

LITHOSTRATIGRAPHY AND SEDIMENTOLOGY

The data obtained during the shipboard analysis of each sediment core are summarized in the core description forms or "barrel sheets" (Fig. 5). This information represents field notes taken aboard ship. Because production schedules prohibit modification of the core

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			mhun		cc						

Figure 5. Core description forms ("barrel sheets") used for sediments and sedimentary rocks.

the Leg 139 scientific party are also explained. Visual core descriptions, smear-slide analyses, and thin-section descriptions provide the basic data used to prepare the core description forms. Mineral identifications, determined by X-ray diffraction, are used to augment visual core descriptions. Data on biostratigraphy and magnetic susceptibility are integrated with the sedimentological information.

core description forms. Deviations from those procedures adopted by

Core Designation

Cores are designated using leg, site, hole, core number, and core type as discussed in the "Numbering of Sites, Holes, Cores, and Samples" section (this chapter). In addition, the cored interval is specified in terms of meters below seafloor (mbsf). Depths are corrected—on the basis of drill-pipe measurements (dpm) reported by the SEDCO coring technician and the ODP Operations Superintendent—for the height of the rig floor dual elevator stool above sea level to give true water depth and the correct depth in meters below sea level (mbsl).

Age Data

The geologic age determined from paleontological and/or paleomagnetic results is shown in the "Age" column on the core description form. Detailed information on terms used to report abundance and preservation, as well as information on the zonations, is given in the "Biostratigraphy" section (this chapter).

Classification of Sediments and Sedimentary Rocks

Leg 139 used a modified version of the Ocean Drilling Program's "new sediment classification scheme" (ODP; Mazzullo et al., 1988). This scheme emphasizes descriptive rather than genetic classification. Four basic sediment types were encountered during Leg 139: (1) siliciclastic sediments, (2) mixed sediments, (3) sulfide-rich sediments, and (4) metalliferous and chemical sediments (Table 1). Siliciclastic sediments are composed of more than 60% siliciclastic and volcaniclastic grains and less than 40% pelagic and neritic grains, and contain a higher proportion of siliciclastic than volcaniclastic grains. Mixed sediments are composed of 40% to 60% siliciclastic and volcaniclastic grains and 40% to 60% pelagic and neritic grains. Sulfide-rich sediments are defined as any sediment or sedimentary rock containing 50% or more sulfide. Finally, metalliferous and chemical sediments are a broad category consisting of metal oxides, carbonate minerals, and clay minerals in variable proportions. These sediments are pre-sumably of hydrothermal or hydrogenous origin. The relevant portions of the ODP classification scheme (Mazzullo et al., 1988), with our minor modifications, are presented below.

Principal Names

Each sediment class has a unique set of principal names. For *siliciclastic sediment*, the principal name describes the texture and is assigned according to the following guidelines:

1. The Udden-Wentworth grain-size scale (Wentworth, 1922) defines grain-size ranges and names of the textural groups (gravel, sand, silt, and clay) and subgroups (fine sand, coarse silt, etc.) that are used as the principal names of siliciclastic sediment. Note that the term clay is used only as a grain-size designation and does not denote or imply mineralogical composition.

2. Principal names are listed in order of increasing abundance when two or more textural groups or subgroups are present in a siliciclastic sediment (Shepard, 1954; Fig. 6).

3. The suffix *-stone* is affixed to the principal names *sand*, *silt*, and *clay* when the sediment is lithified.

4. Conglomerate and breccia are used as principal names of gravels with well-rounded and angular clasts, respectively. Degree of lithification is designated by a modifier before the principal name.

Table 1. Outline of sediment classification scheme used for I	Leg 139	(modified after	Mazzullo et
al., 1988).			

Sediment class	Major modifiers	Principal name	Minor modifiers
Siliciclastic sediments	 Composition of grains present in major amounts Grain fabric (gravel only) Sediment color (optional) Degree of lithification (optional) Alteration 	 Gravel, breccia, conglomerate Sand Silt Clay 	 Composition of all grains present in minor amounts Texture and composition of siliciclastic grains present as matrix (for coarse-grained clastic) Authigenic minerals present in minor amounts
Mixed sediments	 Composition of neritic and pelagic grains present in major amounts Texture of clastic grains present in major amounts 	1. Mixed sediments/ mixed sedimentary rock	 Composition of neritic and pelagic grains present in minor amounts Texture of clastic grains present in minor amounts
Sulfide-rich sediments	 Texture: re- sedimented (or not) Composition of nonsulfide grains Degree of lithification 	 Massive sulfide Semi-massive sulfide 	1. Composition of nonsulfide grains present in minor amounts
Metalliferous and chemical sediments	1. Texture	1. Mineral type	1. Composition of other grains present in minor amounts



Figure 6. Ternary diagram showing principal names for siliciclastic sediments (from Shepard, 1954).

For mixed sediment, the principal name describes the degree of consolidation, using the terms mixed sediments or mixed sedimentary rocks.

For *sulfide-rich sediment*, two principal sediment types are recognized on the basis of sulfide concentration (Fig. 7):

- 1. Massive sulfide: contains >75% sulfide minerals.
- 2. Semimassive sulfide: contains 50%-75% sulfide minerals.

The term *resedimented sulfide* is used as a modifier for massive and semimassive sulfide sediments that show evidence of a clastic origin.

Sulfide-containing sediments with <50% sulfide minerals will be described by their principal sediment name with sulfide minerals added as major or minor modifiers as appropriate. In addition modifiers such as *sulfide-cemented*, *vein sulfide*, or *disseminated sulfide* are used for elaboration.

For *metalliferous* and *chemical sediments*, principal names are given on the basis of the predominant mineral species, such as *iron-manganese oxide*.

For other chemical sediments, appropriate names are assigned based upon the predominant mineral species, such as *barite* or *siderite*.

Major and Minor Modifiers

The principal name of each sediment class is preceded by major modifiers, and followed by minor modifiers (preceded by *with*), that describe the lithology of the sediment in greater detail (Table 1). Major and minor modifiers are used most commonly to describe composition and textures of grain types present in major (>25%) and minor (10%–25%) proportions. In addition, major modifiers can be used to describe degree of lithification, grain fabric, alteration, and sediment color. The nomenclature for major and minor modifiers is outlined as follows.

Composition of pelagic grains can be described with the major and minor modifiers: *diatom, radiolarian, spicule, siliceous, nannofossil, foraminifer,* and *calcareous.* The terms *siliceous* and *calcareous* are used generally to describe sediments composed of siliceous or calcareous pelagic grains of uncertain origins.

Composition of neritic grains can be described with the following major and minor modifiers:

1. *Bioclast:* fragment of skeletal remains. Specific names such as molluscan or algal can also be used.

2. Pellet: fecal particles from deposit-feeding organisms.

3. Intraclast: redeposited carbonate-rock fragment or rip-up clast.

Texture of siliciclastic grains is described by the major and minor modifiers *gravel(-ly)*, *sand(-y)*, *silt(-y)*, and *clay(-ey)*. Composition of siliciclastic grains can be described as follows:

1. Mineralogy: modifiers such as *quartz, zeolitic, lithic* (for rock fragments), or *calcareous* are used.

2. Provenance: the source of rock fragments (particularly in gravels, conglomerates, and breccias) can be described by modifiers such as *volcanic*, *sed-lithic* (contains clasts or grains of sedimentary rock), *basaltic*, etc.

Sediment fabric can be described by the major modifiers *grain-supported*, *matrix-supported*, and *imbricated*. Generally, fabric descriptors are applied only to gravels, conglomerates, and breccias.

Degree of consolidation is described using the major modifiers *unlithified* for soft sediment that is readily deformable under the pressure of a finger, *partially lithified* for firm sediment that is incompletely lithified, and *lithified* for hard, cemented sediment that must be cut with a saw.

Grain shapes are described by the major modifiers *rounded*, *subrounded*, *subangular*, and *angular*. Sediment color is determined with the Munsell Chart, a standard color-comparator, and can be employed as a major modifier.

1000/	750/	Sulfide mineral	abundance	050/	100/
	Massive sulfide (with)	(Major modifier) Semi-massive sulfide (with)	₀ (Major modifier) Principal sediment name (with)	(Major modifier) Principal sediment name (with)	10%



Mixed sediments are described using major and minor modifiers indicating composition and texture.

Particular attention is paid to types of alteration. Principal rock names can be modified to indicate their degree and mineralogy of alteration. For the generic example, the modifier can be denoted simply as hydrothermally altered. If a more specific identification of the alteration minerals can be made, the rock name includes the name of the alteration mineral as a major or minor modifier such as chlorite- and albite-altered quartz sandstone or quartz sandstone with albite alteration.

Graphic Lithology

The lithology of the recovered material is represented on the core description forms by a single symbol or by a group of two or more symbols (Fig. 8) in the graphic lithology column. The symbols in a group correspond to end-members of sediment constituents, such as clay or massive sulfide. The constituents are displayed in proportions approximately equal to their respective abundances in the sediment. The most abundant constituent is displayed on the left-hand side of the column and the least abundant constituent is displayed on the right. Where different types of sediment are finely interbedded, symbols given in the column are schematic because the scale of the core description forms does not permit an accurate representation.

SILICICLASTIC SEDIMENTS

Sediment Disturbance

The coring technique, which uses a 25-cm-diameter bit with a 6-cm-diameter core opening, may result in varying degrees of mechanical disturbance of recovered core material. This is illustrated in the drilling disturbance column on the core description form (using the symbols in Fig. 9). Blank regions indicate a lack of drilling disturbance. Drilling disturbance is recognized for soft and firm sediments using these categories:

1. Slightly deformed: bedding contacts are slightly bent.

2. Moderately deformed: bedding contacts have undergone extreme bowing.

3. Highly deformed: bedding is completely disturbed, sometimes showing symmetrical diapir-like or flow structures.

4. Soupy: intervals are water saturated and have lost all aspects of original bedding.

The degree of fracturing in indurated sediments and metamorphic and igneous rocks is described using the following categories:

1. Slightly fractured: core pieces are in place and contain little drilling slurry or breccia.



Figure 8. Key to symbols used in the graphic lithology column on the core description form (Fig. 5).



Figure 9. Symbols used in the drilling disturbance column on the core description form (Fig. 5).

 Moderately fragmented: core pieces are in place or partly displaced, but original orientation is preserved or recognizable (drilling slurry may surround fragments).

3. Highly fragmented: pieces are from the interval cored and probably in correct stratigraphic sequence (although they may not represent the entire section), but original orientation is completely lost.

Drilling breccia: core pieces have lost their original orientation and stratigraphic position and may be mixed with drilling slurry.

Structures

In sediment cores, it can be difficult to distinguish between natural structures and structures created by the coring process, especially in rotary cores. Natural structures are represented graphically in the structure column of the core description form. The symbols used to describe primary physical and biogenic structures (cross laminations, contacts, fining-upward sequences, bioturbation, etc.), compositional structures (fossils, shell fragments), and secondary and diagenetic structures (concretions, nodules, disseminated sulfide, fractures, veins, etc.) are given in Figure 10.

Color

Colors of the recovered material are determined by comparison with the Munsell soil-color charts. Because chemical changes may occur when sediments are exposed to the atmosphere, some colors are ephemeral in deep-sea sediments (Moberly and Klein, 1976). As such, core color is determined immediately after the cores are split. Information on core colors is given in the color column of the core description sheet.

Samples

The position of samples taken from each core for shipboard analysis is indicated in the samples column on the core description form. The symbol "S" indicates the location of samples used for smear-slide analysis. The symbols "I," "W," and "P," designate the location of samples for whole- and half-round interstitial water geochemistry, for whole-round samples taken for individual shipboard scientists, and for physical properties, respectively.

Shipboard paleontologists generally base their age determinations on core-catcher samples, although additional samples from other parts of the core may be examined when required. Examination of such samples may lead to the recognition of zonal boundaries in the core; these are indicated in the appropriate column. All paleontological sample locations are indicated by the symbol "M," even if they are barren.

Smear Slide Summary

Smear slides are generally made at all major changes of lithology and in intervals containing unusual minor lithologies. Thin sections are made in indurated material to determine mineralogy of both major and minor lithotypes. Tables summarizing data from smear slides and thin-section analyses are located in Sections 4 and 5, respectively, in this volume. The tables include information on the sample location, whether the sample represents a major or a minor lithology in the core, and the relative abundances of the various mineral and microfossil constituents. Because smear slide data are generally unreliable for quantitative analyses, relative abundance estimates for Leg 139 smear slides are generally made only to the nearest 10%. Where the abundance is very low, it is recorded as trace (tr).

Lithologic Description—Text

The lithologic description that appears on each core description form consists of three parts: (1) a heading that lists the major lithology (see "Sediment Classification" section, this chapter) present in the core; (2) a more detailed description of these sediments, including data on color, location in the core, significant features, etc.; and (3) a heading and description of minor lithologies, where present, including location (beds may be too thin [<10 cm] to appear in the graphic lithology column).

Magnetic Susceptibility

The magnetic susceptibility log on the core description form is based on routine shipboard analyses. These plots are presented for qualitative comparison only. Additional information concerning procedures for collecting these data is found in the "Physical Properties" section (this chapter).

BIOSTRATIGRAPHY

Sequences cored during Leg 139 are restricted to the late Quaternary and are probably no older than 300,000 to 400,000 yr, so we

Anhydrite nodule

Calcite nodule

Disseminated anhydrite

Disseminated calcite

Carbonate nodule

Dolomite nodule

Pyrite nodule

Sulfide nodule

Totally fractured

Brecciated

Disseminated carbonate

Disseminated dolomite

Disseminated pyrite

Disseminated sulfide

A

А

Ca

Ca

C

С

 \bigcirc

D

P

Ρ

S

S

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er which primary sedimentary	\sim	Load casts
	٠	Lithoclast
aru sequence	\diamond	Isolated pebbles cobbles/dropstones
	A•	Ash or pumice pods
of particle abundance		Ash laver
inae		Non layor
nae (including climbing ripples)	11 1	Micro fault (normal)
nae/beds	12	Micro fault (thrust)
nar laminae/beds	~	Macro fault
ding	\mathbb{X}	Fracture
erval (normal)	7/4	Mineral-filled fracture
erval (reversed)	1F	Injection
dding (normal)	X	Probable compaction fracture
dding (reversed)	SSS	Tension gashes
ontact with graded beds	\odot	Concretions/nodules
lding	\odot	Vugs
bedding		Bioturbation minor
d and contorted bedding	5	(<30% surface area)
ples	33	Bioturbation, moderate (30%—60% surface area)
tact	333	Bioturbation, strong (>60% surface area)
al contact	>>>	Discrete Zoophycos
sharp contact	6	Fossils, general
tification		(megalossiis) Shells (complete)
cks or slump folds		
slump		Shell fragments
cation cracks	\Diamond	Wood fragments
	888 888	Cylindrichnus trace fossil
1	9	Sagarites
e	_	Sagamoo

Figure 10. Symbols used in the sedimentary and tectonic structures column on the core description form (Fig. 5).

relied heavily on assemblage zones in addition to range zones in our biostratigraphy. Dating of the sequences was further complicated by extensive redeposition by turbidity currents. In response and as time permitted, we prepared samples from within cores from units identified as hemipelagic on the basis of sedimentologic criteria, in addition to preparing core-catcher samples. We annotated the barrel sheets with age only where fossils were adequate. Ages assigned in barren or depauperate sequences were flagged by question marks. In these cases, age was inferred based on position relative to fossil-bearing samples.

Foraminifers

The late Quaternary sequences contain transitional and subarctic foraminifers and are best divided into assemblage zones using the ratio of sinistral to dextral coiling forms of Neogloboquadrina pachyderma (Ehrenberg). Bandy (1960) recognized a dextral interval in the Holocene underlain by a sinistral interval in the latest Pleistocene. This zonation was further amended by Brunner and Ledbetter (1989) to include another dextral to sinistral couplet immediately below the Holocene. The lower and middle Pleistocene is subdivided by the coiling zones of Lagoe and Thompson (1988), who defined nine zones (CD8 to CD16) between about 0.6 and 4 Ma. Coiling zones remain poorly defined between the latest Pleistocene and the CD8/CD9 boundary, in large part because drill and piston cores seldom sample this interval in foraminifer-bearing sequences in the transitional to subpolar North Pacific Ocean. A few dextral sequences are reported from this time interval (Ingle, 1973; Kheradpir, 1970; Brunner and Ledbetter, 1989), but their ages are in question. The coiling shifts are controlled by migration of the subarctic and transitional water masses across this region of the North Pacific, and the migrations are closely linked to climatic glacial-interglacial cycles. The dextral intervals may correspond approximately to odd-numbered oxygen isotopic stages as summarized in Table 2 and Figure 11.

Datum	Туре	Age (ka)	Age reference ^a
Mazama Ash	Ash horizon	6.6	1
CD1/DE2.1	^b Coiling change	10	2
CD2.1/CD2.2	^b Coiling change	12	?
CD2.2/CD2.3	^b Coiling change	15	2
CD2.3/CD3	^b Near stage 4	70	3
CD3/CD4	^b Base of stage 5	125	3
?	^c Base of stage 6	184	3
?	^c Base of stage 7	240	3
?	^c Base of stage 8	300	3
?	^c Base of stage 9	335	3
?	^c Base of stage 10	350	3
Loleta Ash	Ash horizon	400	4

Note: CD = interval of dextrally or sinistrally coiled *Nq. pachyderma.* ^a1 = Nelson et al. (1968); 2 = Brunner and Ledbetter (1989); 3 = Imbrie et al. (1984); 4 = Sarna-Wojcicki (1987).

^bCoiling direction change in Nq. pachyderma.

^cOxygen isotopic stage boundaries.

dHypothesized datum.

Twenty-cubic-centimeter samples were oven-dried at 50° C, disaggregated in a hot solution of 1% Calgon, and washed through a sieve with 63-µm openings. The sand-size fraction was inspected for presence of both planktonic and benthic foraminifers. Representatives of all benthic species were picked and a species list was tabulated.

Abundance of planktonic and benthic foraminifers was also estimated qualitatively using the following categories:

A = abundant (>1000 tests in the residue);

C = common (100-999 tests in the residue);

F = few (10-99 tests in the residue);

R = rare (1-9 tests in the residue);

B = barren (no tests present).

Preservational characteristics were divided into three categories based on the extent of breakage and the proportion of delicate to robust tests:

G = good (<25% of specimens were broken and/or delicate specimens were common);

M = moderate (25%-50% of specimens broken and/or delicate specimens rare);

P = poor (samples dominated by fragments and/or delicate specimens absent).

Benthic foraminifers were assigned to the depth classification of marine benthic environments (Table 3) defined by Ingle (1973). Reworking was estimated by noting the presence and abundance of reworked constituents including large neritic diatoms, benthic fora-minifers indigenous to the shelf and upper slope, and other shallow-water fossils.

Table 3. Depth ranges of marine benthic environments.

Benthic environment	Depth range		
Inner shelf	Lowest low tide to 50 m		
Outer shelf	50-150 m		
Upper bathyal	150-500 m		
Upper middle bathyal	500-1500 m		
Lower middle bathyal	1500-2500 m		
Lower bathyal	2500-4000 m		
Abyssal	4000–6500 m		

Calcareous Nannofossils

The biostratigraphic zonations employed in this report is that of the standard calcareous nannofossil zonation (Martini, 1971; Bukry, 1973, 1975; Gartner, 1977; Okada and Bukry, 1980) complemented by the up-to-date zonation proposed by Raffi and Rio (1979), Verbeek (1990), Rio et al. (1990), and Sato et al. (1991) (Fig. 12). Most of them are tied to the geomagnetic-reversal time scale of Berggren et al. (1985).

Calcareous nannofossils were examined in smear slides prepared from sediments. The abundance of nannofossils is designated as follows (under magnification of 1500×):

A = abundant (10.1-100 specimens per field);

C = common (1.1-10 specimens per field);

F = few (1 specimen per 1.1-10 fields);

R = rare (1 specimen per 10.1-100 fields);

B = essentially barren (0-1 specimens in more than 100 fields).

Preservation is indicated by the following:

G = good (specimens slightly etched, show little effects of overgrowth and/or dissolution);

M = moderate (specimens moderately etched, show some effects of overgrowth and/or dissolution, identification of taxa is sometimes impaired);

P = poor (specimens heavily etched, show effects of advanced overgrowth and/or dissolution).

Reworked nannofossils were noted in each sample. Their abundance was recorded by the same scale as that for abundance of in-place calcareous nannofossils.





PALEOMAGNETISM

The main purpose of shipboard paleomagnetic analysis of sediment and basalt cores is to obtain a sequence of polarity transitions for use in determining the age of sediments and basalts. The magnetic field anomaly pattern over Middle Valley shows that it is centered in the normal-polarity Brunhes Chron (\leq 730,000 a) so that no records of geomagnetic reversals were expected. However, numerous investigations on late Quaternary volcanic rocks and different types of sediments have revealed evidence of short-duration excursions and polarity events of the geomagnetic field during the Brunhes Chron (Champion et al., 1988; Hanna and Verosub, 1989). The exact number and the paleomagnetic signature of these events is still in discussion. Toward the goal of identification of possible excursions contained in the unusually expanded late Quaternary sediment section in Middle Valley, the primary components of remanence were isolated using the alternating field demagnetization technique (AF) or thermal demagnetization (TH).

Measurement of Remanent Magnetization

Two magnetometers, a Molspin spinner magnetometer, and a 2-G Enterprises (model 760R) pass-through cryogenic superconducting rock magnetometer were used routinely for the measurement of natural remanent magnetization (NRM) during Leg 139. An AF demagnetizer (model 2G600), capable of producing an alternating field up to



Figure 12. Correlation of nannofossil zones proposed by different authors. LAD = last appearance datum; FAD = first appearance datum.

15 mT, was used on-line with the pass-through cryogenic magnetometer. Both were controlled by a FASTCOM4 multiserial communication board in an IBM-PC-compatible computer. Leg 139 paleomagnetists used a BASIC program modified from the original SU-PERMAG program to measure the archive halves of sediment and rock cores. The spinner magnetometer was controlled by a Macintosh computer and was used to measure magnetization of discrete samples. Discrete samples from the working half of the core were demagnetized with the Schonstedt GSD-1 AF demagnetizer and the TSD-1 thermal demagnetizer.

The superconducting quantum interference device (SQUID) sensors in the cryogenic magnetometer measures the intensity and the direction of magnetization over an interval approximately 20 cm long. Each axis has a slightly different response curve. The size of the sensor limits the spatial resolution somewhat, thereby blurring sharp magnetic transitions. However, the large volume of core material within the sensor region permits an accurate determination of remanence for weakly magnetized samples despite the high background noise related to the motion of the ship. The SQUID electronics were operated at the 1× scale and in the flux-counting mode.

Sediment Remanence

Remanence measurements of sediments were performed by passing continous archive-half core sections through the cryogenic magnetometer. Measurements of NRM and magnetization after AF demagnetization of 5- and 10-mT peak field were taken at 10-cm intervals. Measurements after 15-mT demagnetization field were taken at 2-cm, 5-cm, or 10-cm intervals. The NRM was often dominated by a vertical upward magnetization, presumably acquired during coring.

The magnetostratigraphic interpretation for Leg 139 was based on pass-through measurements of the demagnetized archive halves and checked by progressively demagnetizing discrete samples by AF field. Because measurements are averaged over the broad response regions of the three sensors, deconvolution is required to recover highly detailed changes in magnetization. This work will be done during shore-based studies.

Oriented discrete samples were taken from APC, XCB, and RCB sediment cores by pressing a standard plastic cube box (7 cm³) into the soft core material. For more indurated sediments, cubes were cut out with a spatula before pressing a box or were cut with a saw. Up to three discrete samples per section were taken.

Hard-Rock Remanence

Drilled minicores (1-in. diameter) or 1-in. cubes of igneous rocks and sulfides in the cores were obtained to determine the intensity and polarity of the various "hard rock" units encountered during drilling. Archive-half sections that contained igneous rock pieces >20 cm in length were measured in the cryogenic magnetometer at 2- or 10-cm intervals.

Measurement of Magnetic Susceptibility

Magnetic susceptibility measurements were routinely made on all cores, employing a Bartington Instruments magnetic susceptibility meter (model MS1) with an MS1/CX 80-mm whole-core sensor loop set at 0.47 kHz. The susceptibility meter was on line with the gammaray attenuation porosity evaluator (GRAPE) and the *P*-wave logger (PWL) on the multisensor track (MST). In addition to characterizing the cored sediments, susceptibility data were used for correlation between holes and sites. The magnetic susceptibility of the core sections was measured as part of the physical properties program (see "Physical Properties" section, this chapter). Magnetic susceptibility of discrete igneous rock samples was measured using the same susceptibility meter with a 36-mm dual frequency loop in the low frequency mode.

Koenigsberger Ratio (Q-ratio)

From the observed NRM intensity and the susceptibility, the Q-ratio of the igneous rock samples was calculated by using the present strength of the geomagnetic field at this position (0.56 Gauss, based on IGRF80).

$$Q = J_0 / (\chi_0 \times H),$$

where J_0 is the NRM intensity per unit volume, χ_0 is the susceptibility, and H is the Earth's magnetic field at this location. The Q-ratio is commonly used to determine the source of *in-situ* magnetization and is important in identifying the source of the magnetic anomalies observed at sea level. Values up to the current field, and values greater than 1, imply a magnetization dominated by induced magnetization parallel to the current field, and values less than 1 imply a magnetization dominated by remanent magnetization.

FLUID GEOCHEMISTRY

Interstitial water was obtained from sediments by squeezing, by *in-situ* extraction using the water sampler temperature probe (WSTP), and by grinding in contact with distilled water followed by squeezing. Water occupying the borehole also was sampled from one hole, 858F, in which upflow was anticipated.

Squeezing

Interstitial waters were squeezed from whole-round sections of sediment cores 6 to 10 cm long, and from quarter-round sections up to 20 cm long. Whole-rounds were cut from cores as soon as they arrived on deck. Quarter-rounds were taken from the working halves of cores several hours to days later only when additional samples were needed. Sediment from whole-rounds was immediately extruded from the core liner, scraped with a Teflon-coated stainless steel spatula to remove the outer, contaminated layer, and placed in a titanium squeezer similar to the steel squeezer designed by Manheim and Sayles (1974). The squeezer and samples were handled with plastic gloves to avoid contamination. Sediments were squeezed in a Carver hydraulic press at pressures up to 2.8 MPa. Interstitial water was collected directly from the squeezer into a 50-mL all-plastic syringe, from which the various aliquots for analysis were ejected through an on-line, 0.2-µm polysulfone filter mounted in a Gelman "acrodisc" disposable filter holder. No attempt was made to equilibrate the sample with the in-situ temperature before squeezing. Squeezed interstitial water samples were designated "IW" samples.

In-situ Extraction

Interstitial water was extracted *in situ* with the WSTP tool (Barnes, 1988), which may simultaneously measure sediment temperature. The tool is lowered on the coring wire to the end of the drill string, where it locks onto an assembly just above the bit. While the tool descends, the hole is flushed with drilling fluid (usually surface seawater) with the bit just off the bottom to keep the hole free of fill. After the sampler is latched into place, the bit is lowered into the bottom with the filter assembly projecting about 1 m past the bit. A timer-operated valve opens and interstitial water is drawn under negative relative pressure through the filter and into the sampler.

The filter assembly was lengthened to 22 cm for Leg 139 (Fig. 13) and is narrower than in an earlier version of the tool. These modifications reduced fracturing of the formation and produce a filter surface area of 200 cm^2 . Two types of filters were employed on Leg 139. A low-temperature filter was made of 1-µm polyester mesh sandwiched between two layers of 80-µm titanium screen and held together with epoxy. This filter was designed for use at temperatures up to about 85° C. Above this temperature the polyester mesh and epoxy will melt. The screen was originally coated with Mo-oxide; most of this coating was burned off by exposing the mesh to the flame from a propane torch until it stopped giving off black smoke. Additional attempts to remove all traces of the coating by prolonged heating in a furnace were unsuccessful. Soaking the mesh in a variety of solvents also failed, as any compound capable of removing the Mo-oxide also etched away part of the screen, making it too coarse and weak to be useful for filtering.

A high-temperature filter was made from one layer of 80-µm titanium screen (as above) and one layer of 2-µm stainless steel screen, held with high-temperature epoxy. It is thought that this filter will operate at temperatures well in excess of the operational limit of the WSTP (200° C).

A third experimental filter was tested early in the cruise. This ultra-high-temperature design included three layers of woven fiberglass wrapped tightly around the inner titanium sleeve over the sampling tubing and held in place by a wrap of titanium wire. This filter was developed because fiberglass will not melt below about 1200° C. On deployments during the early part of Leg 139 this filter failed to retain fine particles which quickly plugged the inlet tube. Its use was therefore discontinued.

Pore water enters the sample reservoir via 1/16-in. titanium tubing after passing through the filter assembly. The tube is held in a groove cut into a titanium sleeve that fits around the thermistor probe shaft. The sleeve, tubing, and filter are covered by a second titanium sleeve. This outer sleeve provides support and abrasion protection for the filter, and is perforated approximately every centimeter with 1/2-cm holes to allow fluid to pass. The titanium sample coil that holds 10 mL of fluid and is connected to a titanium sample coil that holds 10 mL of fluid. This in turn is connected to a copper sample coil that holds 46 mL. Except for the copper coil, all of the connectors and valves are titanium or Teflon. A one-way valve is connected to the other end of the copper coil, which allows fluid to pass into a stainless steel overflow cylinder. This overflow cylinder generates negative relative pressure when the sampling valve is open downhole, as this cylinder is normally filled with air when the tool is sent downhole.

The procedure for water sampling with the WSTP is unchanged from that used during earlier legs. The fluid path is back-filled with distilled water before deployment and the overflow cylinder is exposed to atmospheric pressure. A timer is set to open the valve after a fixed time, exposing the sampling line and chamber to ambient pressure. The timer also closes the valve after a prearranged time interval has passed. The length of time required to fill the WSTP probably varies depending on lithology and the water content of the sediment, but the valve is kept open for about 10 min. The tool is recovered after the sample valve has closed. A check valve below the sample coils maintains fluid pressure in the coil at 1000 psi.

When the tool is returned to the lab, the cover for the chamber containing the sample coils is carefully removed and any "overflow" water present is collected and designated as a "BO" sample. This fluid includes the distilled water that occupied the space inside the titanium tubing (4 mL) and the sample coils (56 mL) before deployment, plus all fluid in excess of 60 mL collected downhole. If a small fluid sample (<60 mL) is collected by the tool, the overflow fluid will be nearly all distilled water, and the sample will be diluted. If a large volume is collected (>60 mL), then the fluid trapped in the sample coils is from either the formation or the borehole. Water from the overflow cylinder is analyzed, as it often is useful for determining the concentration of the major and minor species that are dissolved in pore water. In particular, this aliquot sometimes shows higher alkalinity- and calciumto-chloride ratios than the undiluted aliquot from the titanium coil, indicating that calcium carbonate has probably precipitated in the latter. The amount of dilution of the overflow aliquot can usually be determined from its chlorinity relative to that of the undiluted sample. Whether the tool samples pristine, in-situ pore water depends on how deeply it is pressed into the formation, how permeable the sediment is, and whether the formation cracks during insertion of the probe.



Figure 13. Photograph of the WSTP filter assemblies used during Leg 139. The top of the figure shows a fully assembled filter. Below this is a titanium filter cover, a titanium and polyester filter, and a titanium support sleeve. These components fit over the stainless steel thermistor probe in the center of the photograph. Below the probe are retaining nuts, washers, and Teflon seals for the filter. At the bottom of the photograph are a fiberglass filter wrapped over a titanium support sleeve and held in place with titanium wire, and another filter cover.

Water from the titanium sample coil was filtered $(0.2 \,\mu\text{m})$ and used for determination of major and minor dissolved species. These samples were designated "BC." The copper coil was hermetically sealed for later analysis of helium isotopes and dissolved gases. These samples were designated as "BG" samples.

The GRIND Technique

Interstitial water also was obtained using the ground rock interstitial normative determination (GRIND) technique, which was developed on Leg 139 for highly lithified samples from Sites 857 and 858 that would yield no pore water on squeezing, even after several hours at the maximum pressure of 2.8 MPa that can be safely generated with the Carver press. In the GRIND technique, the freshly collected sample is fragmented and then ground with distilled water in a ball mill. The ground mixture is then squeezed like a typical sample and the effluent is analyzed.

Whole-round samples of altered basalt and lithified sediment were collected and processed as soon as possible after core recovery. Typically one subsample was broken off and squeezed while another was ground. The subsample to be ground was blotted with a paper towel, wrapped tightly in parafilm, and stored refrigerated to prevent it from drying out before it could be processed, usually about a day after collection. The sample was then placed in double plastic bags and fragmented to subcentimeter size with a hammer. About 35 g was then weighed out, which conveniently filled the sample chamber for the ball mill. The fragments were placed in the chamber, a measured volume of distilled water was added, and the mixture was ground for 15 min in the ball mill. The optimal amount of water was found to be equal to the porosity multiplied by the mass of the sample. If a greater amount was used, the ground mixture was too fluid to transfer to the squeezer and extract efficiently. The optimal grinding duration was found to be 15 min. Shorter periods did not adequately crush the sample, and longer periods may enhance reaction between water and sample. After grinding, the mixture was squeezed to extract the water, which was then filtered and analyzed.

Chemical data generated using the GRIND technique can be normalized to the chlorinity estimated from neighboring samples from which pore water was expelled by squeezing. If no chlorinity values are available for comparison, plots of the ratio of chemical species to chlorinity as a function of depth will help reveal trends. Artifacts that are produced using the GRIND technique are poorly known at present. More than 20 samples were both squeezed and ground during Leg 139, however, and the results of the two methods compare very well for most species, as reported in the "Site 857" and "Site 858" chapters (this volume).

Borehole Water Sampling

A single 1-L water sample was taken at 102 mbsf in the open borehole of Hole 858F using the Los Alamos titanium sampler. The sampler was deployed on the wireline and the depth cited is probably accurate only to within 10 to 20 m because of wireline stretch. The identifier for the borehole water sample is "LA."

Analytical Methods

Interstitial water samples were analyzed immediately upon recovery for pH, alkalinity (by potentiometric titration), salinity (by refractive index), and, when odor was detected, hydrogen sulfide (by colorimetry using methylene blue [Parsons et al., 1984] and by sulfide-selective electrode). Aliquots were refrigerated and analyzed within a few days for magnesium (by colorimetric titration), calcium (by titration with a calcium-selective electrode using EGTA as a titrant), chlorinity (by potentiometric titration with silver nitrate), sulfate (by ion chromatography), silica, phosphate, and ammonium (by colorimetry), and potassium (by flame atomic emmision spectrophotometry). Most of these are standard ODP techniques, as detailed by Gieskes and Peretsman (1986). We used IAPSO as our primary standard for determination of calcium, magnesium, chlorinity, and sulfate. Other analyses employed reagent grade chemicals as suggested by Gieskes and Peretsman (1986).

Because we suspected that hydrogen sulfide was oxidizing during squeezing and before analysis, we also measured it in some samples while the pore water was still in contact with the sediment, using an electrochemical technique. We used 10 cm3 of sediment that had been collected immediately on core retrieval in an all-plastic syringe and transferred into a glass vessel that contained 20 mL of a NaOH(0.01 M)-NaCl (0.55 M) solution, all of which had been purged with nitrogen. A sulfide-selective electrode (Ag/Ag₂S) and a doublejunction electrode were set in the sample-solution slurry and the potential was measured while the slurry was stirred. Stable measurements were typically obtained within 10 min of sampling. The electrode was standardized with sulfide solutions of known concentration, added to 20 mL of the same NaOH-NaCl solution and subsequently titrated with a standardized mercuric chloride. The concentration of hydrogen sulfide in the standard was then calculated using a Gran plot. Final calculations of the concentration in the pore-water samples included a correction for porosity of the wet sediment, as measured in the physical properties laboratory. Precision was estimated to be better than 10% in the 0.001 to 10 mmol/kg range. Measurements of hydrogen sulfide by this method yielded higher concentrations than did colorimetric determinations of pore water squeezed from sediment, probably because of oxidation of hydrogen sulfide during squeezing. The WSTP sample from Hole 858D yielded a sulfide concentration of the same order of magnitude as concentrations determined on these basified sediment slurries in contact with the electrochemical cell.

ORGANIC GEOCHEMISTRY

Shipboard organic geochemistry during Leg 139 was conducted to provide real-time monitoring of volatile hydrocarbons, hydrogen sulfide, and other gases for safety considerations and as an initial characterization of the content and type of gases, for monitoring the thermal alteration of bitumen, and for evaluating the types, amounts, and maturity of the sedimentary organic matter. These analyses provide a basis for the preliminary site summaries and background for the more detailed shore-based studies.

Gas Analyses

The compositions and concentrations of hydrocarbon and other gases were monitored in the sediments at intervals of generally one per core. The gases were extracted from bulk sediments utilizing head-space sampling techniques. To measure disseminated gas, a sediment sample (5–10 cm³ sampled by cork borer or syringe) was taken as the core arrived on deck, sealed in a Kapak bag, and frozen or extruded immediately into a glass vial that was closed with a septum and metal crimp seal. Sedimentary rocks deeper in the holes were chipped and similarly sealed. The vial was then heated to 60° C and kept at this temperature for 45 min before gas analysis.

Gas-pocket (expansion void) samples were obtained as the core arrived on deck, by releasing gases from visual pockets into preevacuated and sealed glass tubes (vacutainers). For this purpose, one end of an injection needle was inserted through the rubber stopper of the vacutainer and the other end through the plastic core liner into the gas pocket.

All headspace gas and vacutainer samples were injected with a gas-tight syringe into one of the following gas chromatographs depending on gas concentration:

1. A Hach-Carle AGC Series 100 Model 211 gas chromatograph (GC) equipped with a flame ionization detector (FID) and a $1.8-m \times 0.32$ -cm stainless steel column packed with Poropak N:Q (80%:20%, respectively);

2. A Hewlett-Packard Model 5890A modified natural gas analyzer (NGA) gas chromatograph fitted with FID and thermal conductivity detector (TCD) for analyses. The gas chromatographic system employs a 1.8-m × 0.32-cm stainless steel column packed with Poropak T, a0.9-m×0.32-cm stainless steel column with a 13X molecular sieve, a 1.8-m × 0.32-cm stainless steel column packed with 80/100mesh Hayesep R (acid washed), and a 30-m × 0.25-mm capillary column coated with DB-1 (J&W, Inc.). Appropriate automatic valve switching, controlled by two Hewlett-Packard Model 3393A integrators which also record and integrate the count rates, allows the columns above to be used sequentially. This provides a rapid capability to determine hydrogen sulfide, oxygen, nitrogen, carbon dioxide, carbon monoxide, carbon disulfide, and hydrocarbons from methane to hexanes. The separation on the TCD portion of the Hewlett-Packard GC system was done isothermally. Helium was used as carrier gas. Separation of hydrocarbons on the FID portion of the GC was done by programming a temperature change from 40° to 100°C at 8°C/min. The TCD injector and detector temperatures were 80° and 150° C, respectively, and the corresponding temperatures for the FID were 150 and 250°C, respectively. All gas concentrations are reported in parts per million (volume/volume).

Bitumen Analyses

Initial screening of sediment extracts was performed on the solvent supernatant from the fluorescence extraction, which was removed and concentrated for analysis. Additional wet sediments were extracted with methanol and n-hexane (1:2) by shaking, subsequent centrifugation (2000 rpm), and removal of the hexane supernatant. Freeze-dried sediment samples were gently ground in an agate mortar, and about 500 mg of each was weighed out and transferred into 1-dram screwcapped vials. All vials for bitumen extract analyses had Teflon-lined caps. Normal hexane (C₆H₁₄, 2 mL) was added and the suspension shaken occasionally for about 2 hr. The clear supernatant solution was pipetted into a second vial and the extraction was repeated with another 1-mL aliquot of n-C6H14. Combined extracts were evaporated under nitrogen blow-down at about 40°C to volumes of 10 to 40 µL. A 1- to 3-µL sample was then injected using normal GC protocol. Hydrocarbons were identified by comparison of the retention times with those of authentic standards. The final quantification of the results is based on the weight of dry sediment and the aliquot used in the injection. Relative yields were calculated from the integration of this total GC signal area multiplied by the dilution factor (the numbers in the tables in the site chapters in this volume are $\times 10^6$). Solvent blanks and drilling greases were also analyzed.

The Hewlett-Packard Model 5890A GC was fitted with a $30\text{-m} \times 0.25\text{-mm}$ capillary column coated with DB-1. The temperature was programmed as isothermal for 3 min at 30° C, 10° C/min to 220° C, 4° C/min to 300° C, and as isothermal for 15 min, with the injector at 250° C, FID at 300° C. Helium was used as the carrier gas.

Fluorescence

Fluorescence measurements can indicate the presence of aromatic compounds in petroleum and its products (e.g., Wyman and Castaño, 1974). Fluorescence of pyrolysis products (bitumen) is an approximate indicator of the evolution of the petroleum potential of a sediment. It reflects the aromaticity of the hydrocarbons in the bitumen (Curray, Moore, et al., 1982). Fluorescence data were measured on bulk sediment samples taken from each core as isopropanol or methanol/*n*-hexane extract solutions. The fluorescence intensity was estimated under a UV lamp (Curray, Moore, et al., 1982) and the extract color was also monitored.

Elemental Analyses

Sediments were analyzed on board for inorganic carbon (in carbonate) and for total carbon, hydrogen, nitrogen, and sulfur. The total organic carbon (TOC) content of the sediments was then calculated by subtraction of the inorganic carbon content from the total carbon content. It should be noted that the presence of refractory carbonates (e.g., dolomite) introduces errors due to incomplete dissolution in the coulometric method, so that reliable shipboard analyses of TOC were not possible on these samples. The analyses were performed on sediment samples collected for this purpose and shore-based TOC analyses will be conducted on residues from headspace gas analyses. Sediments were freeze-dried and ground in an agate mortar before analysis.

Total inorganic carbon was determined using a Coulometrics 5011 coulometer equipped with a System 140 carbonate carbon analyzer. Depending on carbonate content, 15 to 70 mg of ground and weighed sediment was reacted in a 2N HCl solution. The liberated CO_2 was titrated in a monoethanolamine solution with a color indicator, while the change in light transmittance was monitored with a photodetection cell.

Total carbon, hydrogen, nitrogen, and sulfur were determined using a Carlo Erba NA 1500 CNS analyzer. Bulk samples were combusted at 1000° C in an oxygen atmosphere with addition of vanadium pentoxide in tinfoil sample holders, converting organic and inorganic carbon into CO_2 and sulfur to SO_2 . These gases, along with the water and nitrogen that were also generated, were then separated by gas chromatography and measured with a thermal conductivity detector.

SEDIMENT GEOCHEMISTRY AND ALTERATION

Twenty-cubic-centimeter samples of sediment were taken at a typical interval of one per section (approximately every 1.5 m) for chemical analysis, adjacent to the physical properties (PP) samples. About one per core (approximately every 9 m) of these chemistry samples was analyzed for major and trace elements by X-ray fluores-cence (XRF) and for total carbon, hydrogen, nitrogen, and sulfur by CHNS analyzer. Typically, one sample per section was analyzed for inorganic (carbonate) carbon by coulometry and for mineralogy by X-ray diffraction (XRD) on bulk and oriented samples.

Major and Trace Element Analyses by XRF

Major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, Mn, P) and trace elements (Ba, Ce, Cr, Ca, Nb, Ni, Rb, Sr, V, Y, Zn, Zr) were determined by XRF, on fused disks and pressed powders, respectively. The XRF system aboard ship is a fully automated, wavelengthdispersive, ARL 8420 spectrometer using a 3-kW rhodium X-ray tube as the excitation source for both major and trace elements. For major elements, a 5-cm3 subsample of wet sediment was disaggregated and suspended in 250 mL of deionized water to remove sea salts, allowed to settle, and dried in a 60°C oven after the supernatant water had been siphoned off. Samples with porosity <20%, as estimated from physical properties data, were semilithified and were not washed, as their pore-water contact was too low to affect their bulk composition significantly. For trace elements, 8-cm3 subsamples were freeze-dried without washing. Each subsample was then ground for 5 to 10 seconds (s) in a tungsten-carbide container in the Spex shatter box, to approximately 200 mesh. The subsample for major elements was then dried for 12 hr at 110° C, weighed, ignited in a quartz crucible at 900° C for 5 hr, and weighed again to calculate loss on ignition. Six grams (preweighed ashore) of dry, lanthanum-doped (20% La2O3) lithium tetraborate flux (Spex #FF28-10) was then mixed with 500 mg $(\pm 0.5 \text{ mg})$ of the ignited powder that had first been ground gently in a clean agate mortar. Care must be taken to mix the flux in well and not to let the mixture touch the lid of the Qorpak bottle. The mixture was then placed in a platinum-gold crucible and heated at 1100° C for 6 to 10 min in a modified Claisse Fluxer apparatus (Norrish and Hutton, 1969). The molten mixture was then poured into a Pt-Au mold to form a disk. This procedure reduces matrix effects and variations in background. The 12:1 flux-to-sample ratio makes matrix corrections unnecessary for normal sediment compositions. Hence the relationship between X-ray intensity and concentration becomes linear and can be described by:

$$C_i = (I_i \times m_i) - b_i,$$

where

 C_i = concentration of oxide *i* (wt %),

 I_i = net peak X-ray intensity of oxide *i*,

 m_i = slope of calibration curve for oxide *i* (wt%), and

 b_i = apparent background concentration for oxide *i* (wt%).

The slope m_i was calculated from a calibration curve derived from the measurement of well-analyzed reference rocks (BHVO-1, G-2, AGV-1, JGB-1, JP-1, Br, and DRN). The background b_i was determined either on blanks or derived by regression analysis from the calibration curves.

The subsample for trace element determination was pressed into a pellet. Six grams of dry sediment powder was mixed with Liquid Binder (100 mg of polymeric binder per cubic centimeter of sediment) and pressed into an aluminum cap with 7 tons of pressure. A minimum of 5 g of sample ensures that the pellet will be "infinitely thick" for rhodium K-series radiation. An off-line calculation program based on routines from Bougault et al. (1977) was used for the computation of trace element concentrations from measured X-ray intensities.

Carbon, Hydrogen, Nitrogen, and Sulfur

Inorganic carbon was determined using a Coulometrics 5011 coulometer equipped with a System 140 carbonate carbon analyzer. In this method 15 to 70 mg, depending on carbonate content, of freeze-dried, ground, and weighed sediment is reacted in a 2N HCl solution. The liberated CO_2 is titrated in a monoethanolamine solution with a colorimetric indicator, while monitoring the change in light transmittance with a photodetection cell. Some carbonate nodules were reacted with H₃PO₄ in order to dissolve them more effectively.

Total carbon, hydrogen, nitrogen, and sulfur were determined using a CHNS analyzer (model NA 1500) from Carlo Erba Instruments. In this method, 5 to 10 mg of freeze-dried, ground, and weighed sediment is mixed with vanadium pentoxide in a tin capsule and combusted at 1700°C in an oxygen atmosphere. The oxidized gases that result are passed into a stream of helium, separated by gas chromatography, and measured using a thermal conductivity detector.

Organic carbon was calculated as the difference between total carbon and total inorganic carbon, or by separate analysis using a Rock-Eval, as described in the "Organic Geochemistry" section (this chapter).

Mineralogy by XRD

Mineralogy of the sediments was determined using a Philips ADP 3520 X-ray diffractometer for the XRD analysis. Instrument conditions were as follows: CuK α radiation with Ni filter, 40 kV, 35 mA, goniometer scan from 2° to 32° 2 θ , step size 0.02°, count time 2 s. Bulk samples were freeze-dried, ground, and mounted in random orientation in aluminum planchettes.

Clay-size fraction was separated from 20 cm³ of wet sediment by suspension in deionized water followed by centrifugation. Clay-size suspensions were pipetted on the surface of a glass slide and allowed to air dry, producing an oriented mount. Glycolation was also used to identify clay minerals.

SULFIDE PETROLOGY

Because sulfide in seafloor massive sulfide deposits can occur as soft sediments or as indurated rock, the manner in which this material is curated, sampled, described, and analyzed overlaps procedures established for both sediment and igneous and metamorphic rock (see "Sedimentary Petrology" and "Igneous Petrology" sections, this chapter). We consider sulfide deposits separately here because of the large range of lithologies, textures, and minerals observed during Leg 139, and the diversity of depositional settings.

Core Curation and Shipboard Sampling

Soft sulfide sediment was split by cutting the plastic liner with a sharp knife and pulling a stainless steel wire through the core. In cases where the core consisted of sulfide clasts set in a soft sediment matrix, the soft core between clasts was split with a stainless steel knife, the core was opened, and the indurated clasts were cut with a rock saw. Cores were designated using leg, site, hole, core, section, and core type as discussed in the "Introduction" section (this chapter).

Sulfide-rock cores were examined before cutting for structural orientation, bedding angles, mineral textures, vein distribution, and hydrothermal alteration. Wherever possible, vertical core orientation was preserved by marking the base of individual pieces. Each core was numbered and sampled in a similar way to igneous and metamorphic rocks (see "Igneous Petrology" section, this chapter).

The archive half of hard-rock sulfide cores was described on a specially devised form, generally similar to that devised for igneous rocks (HARVI), and was photographed before storage. Closeup photographs were taken to illustrate representative structures and textures. Nondestructive magnetic susceptibility measurements were made on whole cores whereas thermal conductivity measurements were made on the working half of the core. The working half was sampled for shipboard polished sections and polished thin sections, physical properties, magnetic studies, CHNS analyses, and Cu, Zn, and Pb analyses by atomic absorption spectroscopy (AAS) following total dissolution. Because sulfide minerals oxidize rapidly under atmospheric conditions, both the archive and working halves of sulfide cores were placed in airtight plastic aluminum-foil-laminated bags that were then evacuated, flushed with nitrogen, and sealed.

Visual Core Descriptions

Unconsolidated sulfide sediment was described on sediment visual core description (VCD) forms and barrel sheets. The sulfide sediment was described similarly to other sediment using a modified version of ODP's new sediment classification scheme (ODP; Mazzullo et al., 1988).

In order to describe sulfide-rich sediment, the range of lithologies, structures, textures, and minerals was expanded. Sulfide sediment where sulfide minerals were dominant (i.e., >50%) was divided on the basis of grain size into sulfide breccia, sulfide sand, sulfide silt, and sulfide clay. Clast modifiers include the major hydrothermal minerals pyrite, pyrrhotite, sphalerite, chalcopyrite, barite, amorphous silica, talc, hydrothermal clay, carbonate, and iron oxide. These clasts potentially include material precipitated directly from hydrothermal fluids both on and near the seafloor and earlier precipitated sulfide that has been veined and replaced by later hydrothermal fluids.

Sulfide rock was described using the VCD form for igneous and metamorphic rocks ("Igneous Petrology" section, this chapter) which was modified to accommodate sulfide rocks. The left column of each VCD is a graphic representation of the archive half of core showing major structures and textures. A horizontal line denotes a plastic spacer and vertically oriented pieces are indicated by an upwardpointing arrow. Samples for shipboard analysis are indicated as follows: D = X-ray diffraction, F = X-ray fluorescence or flame atomic absorption spectroscopy, T = polished thin section or polished section, P = physical properties analysis, M = paleomagnetic analysis, and S = smear slide.

All visual descriptions were generalized and entered into a form that contains the following information:

- 1. The leg, site, hole, core, type, section, and piece number.
- 2. Major minerals and their abundance and characteristics.
- 3. Minor minerals and their characteristics.
- 4. Trace minerals.
- 5. Textural description.
- 6. Structures (i.e., veins, fractures, size, orientation).
- 7. Interpretations, sketches, etc.

Classification of Hard-Rock Sulfide Samples

Sulfide samples from Holes 856G and 856H were classified according to the macroscopic descriptive attributes of the core. Sulfide is classified into six types on the basis of the content of principal minerals, as determined by hand sample examination, and the most prominent textural attributes. Disaggregated sulfide-rich sediment, whether formed by seafloor weathering or fragmented during drilling, is referred to as sulfide sand and is not included in the classification scheme. The mineral content and textural attributes of representative samples of each type were confirmed using polished thin-section petrographic data. The principal opaque minerals-pyrite, pyrrhotite, and magnetite-are generally distinguishable macroscopically. However, sphalerite in some samples is difficult to distinguish from magnetite due to overgrowth and replacement of sphalerite by magnetite. Middle Valley sulfide samples contain both chalcopyrite and isocubanite, which commonly occur in microscopic exsolution-like intergrowths. These phases are not distinguishable in hand specimen and could not always be distinguished by shipboard petrography; the term chalcopyrite is used to describe Cu-Fe sulfide in these rocks regardless of the relative proportion of chalcopyrite and isocubanite. Pseudomorphic replacement of pyrrhotite by pyrite is common in these samples, and made visual estimates of the abundance of pyrite and pyrrhotite less certain.

Identification of the non-opaque minerals was more difficult and is primarily based on observations from polished thin sections. Dark green, vug-filling material is an intergrowth of amorphous silica and a green clay with high birefringence, tentatively identified as a smectite-group mineral. The white silicate filling vugs contains cloudy amorphous silica intergrown with a colorless, low-birefringence mineral that is tentatively identified as chlorite. Coarser grained silicate minerals in some vugs have a relief and birefringence similar to mixed-layer illite-smectite. The petrographic identification of minerals in polished thin sections could not be confirmed by XRD at the time of core description due to equipment malfunction. In addition, variable amounts of the interstitial minerals were lost from the polished thin sections during preparation. As a result, the descriptions of the silicate minerals in sulfide samples are not totally representative or complete.

The determination of sulfide textures is more subjective. Various terms used conventionally by sulfide petrographers are defined in Table 4. For example, "grain size" refers primarily to the size of mineral aggregates, and not individual grains or crystals. The size of individual crystals of each mineral species except pyrrhotite is almost impossible to determine by direct visual observation. Thus "finegrained" refers to either individual mineral grains or aggregates of 0.2 mm diameter or less, and "coarse-grained" to grains or aggregates of more than 0.8 mm. In the case of pyrrhotite pseudomorphically replaced by pyrite, the grain size refers to the size of the original pyrrhotite grain and not the very fine-grained crystals of pyrite replacing pyrrhotite. The grain-size of the silicate minerals (referred to as "gangue minerals" by sulfide petrologists) is usually indeterminate macroscopically. Microscopic examination revealed silicate grain sizes are usually less than 0.05 mm and that much of the silicate gangue is amorphous. Sulfate and carbonate grain sizes refer to individual grains, however.

Division of sulfidic rocks into distinct types results in at least a few samples falling into the "boundary" areas between types. Also, some samples contain contacts between sulfide types. For these, two types were assigned, with the dominant assemblage listed first.

This classification system applies only to the sulfide-bearing rocks recovered during Leg 139. Mineralogical and textural features of sulfides found at other areas, including both sedimented and volcanic-dominated ridges, are at least in part different from those obtained during Leg 139.

Term	Description
Atoll texture	The surrounding of one mineral by another resulting in "islands" of one mineral within a "sea" of another.
Botryoidal	Having the form of a bunch of grapes; a surface of spherical shapes.
Boxwork	A network of intersecting crystals deposited in cavities formed by dissolution of other sulfide minerals.
Chalcopyrite disease	Discontinuous lamallae and inclusions of chalcopyrite within sphalerite, similar to an exsolution texture, but formed by replacement of sphalerite by chalcopyrite.
Collomorphic/colloform	A bulbous, finely laminated texture, usually seen in pyrite, formed by the rhythmic precipitation of ultrafine material.
Crustiform	Layered encrustation of minerals precipitated on a pre-existing framework.
Cuspate	A sharp scallop-shaped projection texture.
Dendritic	A mineral deposited in a branching pattern.
Felted	Lath-shaped cystals interwoven in an irregular fashion.
Framboids	Microscopic aggregates of spheroidal pyrite grains that coalesce to resemble a raspberry.
Gangue	Minerals other than oxide and sulfide phases occurring in sulfide samples, generally silicate and carbonate minerals.
Groundmass	Cf. matrix.
Interstital	In between the main mineral phases, infilling pore spaces.
Interstice	An opening or space between minerals.
Massive	Homogeneous monomineralic aggregate.
Mesh network	Cf. reticulate.
Poikiolitic	Small grains of one mineral included within a single larger grain of another mineral.
Porphyroblastic	Recrystallized euhedral minerals within a finer grained primary matrix.
Pseudomorph	Replacement of a mineral by another mineral that retains the original crystal form.
Pyritohedron	A dodecahedral crystal of pyrite.
Reticulate	Replacement texture forming a porous network that often encloses remnants of the original mineral.
Skeletal	Microscopic development of the outline of a crystal, with incomplete infilling.
Vermicular	Occurring in a worm-like form intergrown with another mineral, similar to myrmekitic.

Table 4. Summary of textural terms used to describe sediments and rocks.

The various types are determined without any particular reference to stratigraphic or genetic relationships. The major characteristics of the different types are summarized in Table 5.

Polished Thin-section and Polished Section Descriptions

Polished thin sections and polished sections of sulfide sediment and sulfide rocks were examined in order to refine visual observations, and to document textural relationships and mineralogy in greater detail. Mineral name, mineral and void percentages, size, textural descriptions, and general comments on the different sulfide minerals were tabulated. The terminology was consistent with that used for megascopic descriptions. Polished thin-section and polished section descriptions are included in the Section 5 of this volume.

Atomic Absorption Analyses

Sulfide rock and sediment were sampled routinely from each section for shipboard chemical analyses. Because sulfide minerals react with platinum crucibles and the X-ray fluorescence unit has not been calibrated to analyze sulfide-rich samples, Cu, Zn, and Pb were determined on a selected suite of samples by AAS. Calibration standards for each elements were prepared by diluting 1000-ppm Fisher Scientific standards to the optimum range within the linear portion of the calibration curve. From about 50 cm³ of sample that was ground to minus 200 mesh, 1 g was weighed and dissolved in a mixture of HNO₃, HCl, and HF, and brought to an initial volume of 100 mL. The dissolution procedure was modified after Bouvier (1991) and is presented in Table 6. No attempt was made to retain Ba in solution and the solutions were not filtered. In several samples, a white to pale gray precipitate remained despite three repeats of the

Table 5.	Classification	of sulfide	rocks	from	Leg	139
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dissolution procedure described in Table 6. The composition of this residue is unknown, but is probably barite.

Base metal analyses were performed on a Varian SpectrAA-10/20 using an air-acetylene flame. Wavelength settings, slit width, and gas flow were controlled manually. Element concentrations were calculated automatically from the calibration curve.

Carbon-Hydrogen-Nitrogen-Sulfur Analyses

CHNS analyses were performed on a selection of sulfide samples determined by AAS for transition metals. Analytical procedures are the same as those used to analyze sedimentary rocks (see "Sediment Geochemistry and Alteration" section, this chapter).

IGNEOUS AND METAMORPHIC ROCKS

Core Curation and Shipboard Sampling

Hard rock samples were examined for structural orientations and sediment-rock contacts were examined for chilled margins, baked sediment, and alteration aureoles before cutting. Each contiguous piece was numbered sequentially from the top of each core section and labeled. Broken core fragments that could be fitted together were reassembled into pieces; each fragment was lettered consecutively from the top down (e.g., 1A, 1B, and 1C). Composite pieces often occupied more than one section. Plastic spacers were placed between pieces with different numbers. The presence of a spacer, therefore, may represent a substantial interval of no recovery. If it was evident that an individual piece had not rotated about a horizontal axis during drilling, an arrow was added to the label pointing to the top of the section. Azimuthal orientation of the core was not possible due to the free rotation of samples about a vertical axis within the barrel,

Туре	Color and texture	Sulfide/oxide mineralogy	Gangue mineralogy	Metal content	Major features
1. Homogeneous massive fine- grained pyrrhotite	Earthy bronze, homogeneous massive, fine- grained	Po: 60%-80% Py: 0%-30% Mt: <5% Cp: 2%-6% Sp: 0%-5%	Smectite/amorphous silica, carbonate	Moderate Cu and Zn	Color, fine-grained, homogeneous texture. High Py content.
2. Homogeneous massive fine- grained pyrite- pyrrhotite	Brown to dark bronze, metallic luster, homogeneous massive, fine-grained	Py: 30%-65% Po: 0%-60% Mt: 0%-15% Hm: 1%-3% Cp: 0.1%-5% Sp: 0.1%-5%	Smectite/amorphous silica, carbonate	Low to moderate Cu and Zn, generally lower than type 1	Homogeneous texture, similar to type 1 but with higher Po content
 Homogeneous medium- to coarse- grained pyrite- pyrrhotite 	Yellowish bronze, homogeneous, medium- to coarse- grained	Py: 30%-70% Po: <20% Cp: 1%-5% Sp: 0%-3% Mt: 10%	Smectite/amorphous silica, carbonate	Low to moderate Cu and Zn	Medium- to coarse-grained texture, ubiquitous Mt, variable Cu and Zn contents
 Heterogeneous and veined coarse- grained pyrite- pyrrhotite 	Yellowish bronze, heterogeneous and veined, coarse- grained	Py: 10%–50% Po: 0%–40% Mt: 5%–15% Sp: 2%–20% Cp: 2%–5%	Chlorite/smectite, amorphous silica	Moderate to high contents of Cu and Zn	Heterogeneous texture, porphyritic appearance, irregular veins, high Zn and Cu contents
5. Massive colloform and vuggy pyrite	Yellowish bronze, metallic luster, massive, colloform and vuggy; reticulate	Py: 80%–90% Po: trace	Amorphous silica, chlorite, carbonate	Low Cu and Zn	Colloform and vuggy texture, metallic luster, low base-metal content
 Sediment with sulfide veining 	Variable, gray with bronze veins. Sediments with sulfide veins.	Py: 5%–80% Po < Py Sp: 0%–20% Cp: 0%–5%	Hemipelagic sediment	Locally high Cu and Zn contents in veins	"Stringer" sulfide texture

Reagents:	1. Concentrated HCl, HNO ₃ , and HF
	2. EDTA
	3. NH ₄ OH
Apparatus:	1. Hotplates (up to 150° C)
	2. Teflon beakers (preferably 100 mL)
	3. Teflon stirring rod
	4. 100-mL volumetric flasks
	5. Centrifuge tubes
	6. 5-mL pipette
	7. Glass vials for weighed samples
Digestion procedures:	1. Clean 10 teflon beakers by soaking in 10% HCl.
	Weigh about 1.000-g portion of sample into a glass vial labeled with both sample number and laboratory number. Samples should be ground in steel instead of in tungsten carbide grinding containers.
	 Transfer sample from glass vial to labeled teffon beakers and rinse out the sample container with about 5 ml of deionized water. Rinsing should be done twice and the total volume of water should not exceed about 5 mL.
	Swirl the water in the beaker until the sample powder is wet.
	 Cautiously and incrementally add 10 mL of concentrated HNO₃. Sulfide-rich samples tend to froth so be careful to avoid splattering the sample.
	6. Evaporate to dryness at about 150° C: to avoid forming insoluble Fe-oxides, do not exceed 185° C.
	 Remove each beaker from the hotplate and add 10 mL of concentrated HCl and 10 mL of HF. Take to near dryness.
	8. Again, remove each beaker, add 10 mL of concentrated HCl, and take to dryness.
	 Add 35 mL of H₂O and 10 mL of HCl, and heat to dissolve. Place a watch glass on each beaker to reduce evaporation.
	10. Remove from hotplate, add 5 mL of 0.8% EDTA solution, and cool to room temperature. The EDTA is to keep barium in solution.
	 If residue remains, repeat steps 7 to 10. Fusion of residue with lithium metaborate may be necessary if residue remains after repeating steps 7 to 10.
	 Transfer to a 100-mL volumetric flask, rinse beaker at least twice to remove any residue, and bring up to volume with deionized water.
	13. Determine samples for Cu, Zn, and Pb using AAS methods.

Table 6. Dissolution procedures for massive sulfide.

Notes: This digestion procedure is based on a total acid dissolution technique for rocks by Bouvier (1991). Because it is not feasible to measure all elements at sea, we decided to focus on the important metals, particularly Cu, Zn, and Pb. As a result, the total dissolution procedures of Bouvier (1991) have been modified.

although the fragments of each piece were marked and cut with a consistent orientation. After the vertical core orientation was noted, the pieces were split with a diamond saw into archive and working halves. Cores containing igneous rocks were split along an azimuth that allowed important features and structures to be represented in both the working and archive samples, especially mineralization, structures, and veins. The cores were cut perpendicular to any primary foliation or fault plane.

Each lithologic unit of the working half of the core was sampled (where recovery permitted) for shipboard measurement of physical properties, magnetic studies, XRF, XRD, CHNS, and thin-section studies. Magnetic susceptibility was measured on the whole cores before splitting and thermal conductivity was measured on the archive half of the split core. Where feasible, cubes or minicores for physical properties measurements were taken immediately adjacent to samples used for chemical analyses and polished thin sections. The archive half was described on the VCD form and was photographed before storage. During this description, small quantities of vein and vesicle fillings were sampled from the working half for XRD analysis to confirm mineral identity.

Visual Core Descriptions

VCD forms were used in the documentation of the igneous rock cores (see Section 3 of this volume). The left column is a graphic representation of the archive half. A horizontal line across the entire width of the column denotes a plastic spacer. Vertically oriented pieces are indicated on the form by an upward-pointing arrow to the right of the piece. Shipboard samples and studies are indicated in the column headed "shipboard studies," using the following notation: XRD = X-ray diffraction analysis; XRF = X-ray fluorescence analysis; TS = petrographic thin section; PP = physical properties analysis; and PM = paleomagnetic analysis.

To ensure consistent and complete descriptions, the visual core descriptions were entered into the computerized database HARVI. The database is divided into separate data sets for fine-grained rocks and coarse-grained rocks. Fine-grained rocks include all extrusions, and shallow intrusions which are aphyric or phenocrystic with a primarily glassy or cryptocrystalline matrix. Coarser grained rocks include samples that are holocrystalline and whose groundmass minerals are large and equigranular or poikiloblastic. Coarse-grained rocks include the centers of large sills or dikes and are not necessarily cumulate in texture. Each record is checked by the database program for consistency and completeness and is subsequently printed in a format that can be directly pasted onto the barrel sheet with the graphic representation of the core.

When describing sequences of rocks, the core was subdivided into lithologic units on the basis of changes in texture, grain size, mineral occurrence and abundance, rock composition, and rock clast type. Rocks for which the protolith is completely obscured by metamorphism (e.g., an actinolite schist or greenstone) were given separate lithological names. If the original rock type is discernible, the prefix "meta" or the term "altered" is used as a modifier with the name of the protolith. Any changes in mineralogy or structure associated with elevated (above seafloor) temperatures or tectonic activity were classified as "metamorphism." When describing the total relative proportion of primary and secondary minerals, the general term "alteration" was used to include all secondary minerals. Given that the hydrothermal metamorphism characteristic of this area grades from seafloor conditions to greenschist grade, this classification reduced the subjective division between "metamorphism" and "alteration" which might otherwise obscure the similarity of processes. For each lithologic unit and section, the following information was recorded in the database system:

1. The leg, site, hole, core number, core type, and section number.

2. The unit number (consecutive downhole), position in the section, number of pieces of the same lithologic type, the rock name, and the identification of the describer.

3. The Munsell color of the dry rock and the presence and character of any structural fabric including deformation. Symbols for tectonic structures are provided in Figure 10 (see "Lithostratigraphy and Sedimentology" section, this chapter).

4. The number of mineral phases visible with a hand lens and their distribution within the unit, together with the following information for each phase: (1) abundance (volume percentage), (2) size range in millimeter, (3) shape, (4) degree of alteration, and (5) further comments.

5. The groundmass texture: glassy, fine grained (<1 mm), medium grained (1–5 mm), or coarse grained (>5 mm). Grain size changes within units were also noted.

The presence and characteristics of secondary minerals and alteration products.

7. The abundance, distribution, size, shape, and infilling material of vesicles (including the proportion of vesicles that are filled by alteration minerals).

The rock structure: whether the flow is massive, pillowed, thin or sheetlike, brecciated, or a hyaloclastite.

9. The relative amount of rock alteration, expressed both in the description and next to the graphic description of the archive half. Rocks were classified as fresh (<2%), slightly altered (2%–10%), moderately altered (10%–40%), highly altered (40%–80%), very highly altered (80%–95%), and completely altered (95%–100%). These grades of alteration were expressed in columnar form as F, S, M, H, V, and C, respectively. The type, form, and distribution of alteration was also noted.

10. The presence of veins and fractures, including their abundance, width, mineral fillings or coatings, orientation, and associated wall rock alteration. The orientation of veins and fractures with respect to the core axis was measured with a protractor, such that the plane parallel to the core axis is considered 0°. The relationship of the alteration and vein filling minerals with respect to veins and fractures was also noted. Vein networks and their mineralogy were indicated adjacent to the graphic representation of the archive half.

11. Other comments, including notes on the continuity of the unit within the core and on the interrelationship of units.

Basalt and diabase are termed aphyric (<1%), sparsely phyric (1%-2%), moderately phyric (2%-10%), or highly phyric (>10%), depending upon the proportion of phenocrysts visible with the hand lens or binocular microscope. Basalts are further classified by phenocryst type (e.g., a moderately plagioclase-olivine phyric basalt contains 2%-10% phenocrysts, mostly plagioclase, with subordinate olivine). More specific rock names were given where chemical analyses or thin sections were available.

Lavas erupted on the seafloor typically show (1) a sparsely crystalline glassy margin overlying (2) a variolitic (synonymous with spherulitic) zone of quench phases, which may then grade into (3) a coarser microlitic zone towards the interior of the flow. In many samples, these zones are not well defined and may be expressed as alternating layers or areas. Varioles commonly show a sheaf-like or radial form, and microlites commonly show crystal clustering networks in areas of microlitic texture. The term intergranular refers to groundmass textures where individual crystals are granule-shaped with little intergrowth. Intersertal texture refers to granule-shaped crystals or glass that occupy interstices between unoriented feldspar laths.

Lavas intruded within the sedimentary pile may be characterized by baked or indurated sediment attached to glassy margins, both in intact flows or as random pieces. An abundance of glassy margins in a given section is taken to be indicative of a flow margin. Magmas intruded within sediments (either sills or dikes) may also appear as dismembered glassy flow breccias within a sediment host. The sediment will be contact metamorphosed at both the top and bottom contacts of a sill. Observation of contact relationships is especially important.

A breccia is defined as any rock composed of angular broken rock fragments held together by mineral cement or a fine-grained matrix. These can be volcanic or tectonic (fault breccia) in origin. Volcanic breccias are characterized by fragments of broken, but not crushed, basalt in a glassy, commonly altered matrix. A fault breccia is characterized by fragments that are cataclastically deformed (crushed under brittle conditions) by movement along the fault. A cataclasite results from extensive dynamic metamorphism during which there is fracture and rotation of mineral grains or mineral aggregates, accompanied by extensive bending, breaking, and granulation of minerals. Larger crystals set in a matrix of fine-grained crushed grains produced under these conditions would have a mortar texture.

Visual core descriptions of igneous rocks are given in Section 3 (this volume) and descriptions of each rock unit are available from the computerized database at the ODP repositories. A summary of the textural terms used is given in Table 7.

Thin-section Descriptions

Thin sections of igneous rocks were examined to complement and refine the hand-specimen observations. The percentages and textural descriptions of individual phases were reported in the computerized database HRTHIN. The same terminology was used for thin-section descriptions as was used for the megascopic descriptions. Thin-section descriptions are included in Section 5 (this volume) and are also available from the ODP computerized database. A table summarizing the thin section data is provided for each core.

Table 7. Summary of textural terms used in the description of igneous rocks.

Altered	Replacement of primary minerals by secondary minerals at low temperatures and static conditions associated with exposure to cold sea water on the seafloor.					
Alteration	The total percentage of primary minerals replaced by secondary minerals (includes metamorphic minerals).					
Breccia	Rock that has been brittlely deformed, frequently veined, but may also be pieces in sediment host.					
Cataclasite	Brittlely deformed rock characterized by fracture and rotation of the mineral grains, accompanied by extensive granulation.					
Coarse-grained rocks	Holocrystalline matrix, includes diabase, microgabbro, and gabbro.					
Fine-grained rocks	Aphyric or cryptocrystalline matrix, typically pillow basalts and margins of dikes or sills.					
Foliation	Any planar structure visible in the rock. Cores were always split vertical to any foliation plane.					
Metabasalt	Fine-grained rock containing secondary minerals that formed at elevated temperatures.					
Metamorphosed	Replacement of primary igneous minerals by secondary minerals or deformation which occurs at conditions different from the seafloor.					
Microlitic	Partially crystalline zone typical of the interiors of large pillow basalts in which the groundmass minerals are small but euhedral and identifiable.					
Oriented	Piece large enough that it did not roll vertically in the core barrel and retains original vertical orientation.					
Variolitic	Partially crystalline zone adjacent to glassy chilled margin of pillow basalt, typically with spherulitic plagioclase and clinopyroxene.					

X-ray Diffraction Analyses

A Philips ADP 3520 X-ray diffractometer was used for the XRD analysis of mineral phases. Ni filtered CuK α radiation generated at 40 kV and 35 mA was used. Peaks were scanned from 2° to 32° 2 θ , with a step size of 0.02°, and a counting time of 2 s per step. Samples were ground to <200 mesh in either a Spex 8000 Mixer Mill (in tungsten carbide) or an agate mortar and pestle. The powder was then pressed into the aluminum sample holders or smeared onto glass plates for analysis.

X-ray Fluorescence Analysis

Before analysis, samples were crushed in a Spex 8510 shatter box using tungsten carbide. Where recovery permitted, at least 20 cm³ of material was ground to ensure a representative sample. The tungsten carbide barrel introduces considerable W contamination and minor Ta, Co, and Nb contamination, resulting in the powder becoming unsuitable for instrumental neutron activation analysis (INAA). Niobium contamination resulting from grinding in the tungsten carbide barrel has been determined to be below 1 ppm (D. Sims, pers. comm., 1990). Key samples that were to be used for shore-based as well as shipboard analysis were ground instead in an automated agate mortar and pestle, to avoid the W, Ta, Co, and Nb contamination resulting from use of the tungsten carbide barrel.

A fully automated wavelength-dispersive ARL8420 XRF (3 kW) system equipped with a Rh target X-ray tube was used to determine the major oxide and trace element abundances of whole-rock samples. Analyses of the major oxides were performed on lithium borate glass disks doped with lanthanum as a "heavy absorber" (Norrish and Hutton, 1969). The disks were prepared from 500 mg of rock powder that had been ignited for 3 hr at 1025° C and mixed with 6.000 g of preweighed (on shore) dry flux consisting of 80% lithium tetraborate and 20% La₂O₃. This mixture was then melted in air at 1150° C in a Pt-Au crucible for about 10 min and poured into a Pt-Au mold using a Claisse Fluxer. The 12:1 flux to sample ratio and the use of the lanthanum absorber made matrix effects insignificant over the normal range of igneous rock compositions. Hence, the relationship between X-ray intensity and concentration becomes linear and is described by:

$$C_i = (I_i \times m_i) - b_i,$$

where C_i = concentration of element i (wt%), I_i = peak X-ray intensity of element i; m_i = slope of calibration curve for element i (wt%/counts per second), and bi = apparent background concentration for element i (wt%).

The slope m_i was calculated from a calibration curve derived from the measurement of well-analyzed reference rocks (BEN, BR, DRN [from Geostandards, France], BHVO-1, AGV-1 [from the U.S. Geological Survey], JGB-1, JP-1 [from the Geological Survey of Japan], AII-92-29-1 [from Woods Hole Oceanographic Institution/Massachusetts Institute of Technology], and K1919 [from Lamont-Doherty Geological Observatory]). The background b_i was determined by regression analysis from the calibration curves.

Systematic errors resulting from short-term or long-term fluctuations in X-ray tube intensity and instrument temperature were addressed by counting an internal standard between no more than six unknowns in any given run. Repetitive analyses of the shipboard standard derived from the calibration curves used are given in Table 8. The intensities of this standard were normalized to its known values, providing correction factors to the measured intensities of the unknowns. To reduce shipboard weighing errors, two glass disks were prepared for each sample. Accurate weighing was difficult on board the moving platform of the *JOIDES Resolution*, and was performed with particular care as weighing errors could be a major source of imprecision in the final analysis. Weights within 0.5 mg (\pm 0.1%) were considered acceptable. Five weight measurements were taken for each sample and the average used as the true weight. Loss on ignition was determined by drying the sample at 110°C for 8 hr, and then by weighing before and after ignition at 1030°C in air.

Trace element determinations were made on pressed-powder pellets prepared by pressing (with 7 MPa of pressure) a mixture of 5.0 g of dry rock powder (dried at 110° C for >2 hr) and 30 drops of polyvinyl alcohol binder into an aluminum cap. A modified Compton scattering technique based on the intensity of the Rh Compton peak was used for matrix absorption corrections (Reynolds, 1967).

Replicate analyses of rock standards show that the major element data are precise within 0.5% to 2.5%, and are considered accurate to $\approx 1\%$ for Si, Ti, Fe, Ca, and K, and between 3% and 5% for Al, Mn, Na, and P. The trace element data are considered accurate to between 2% and 3% or 1 ppm (whichever is greater) for Rb, Sr, Y, and Zr, and between 5% and 10% or 1 ppm for the others. The accuracy of Ba and Ce is considerably less, and they are reported primarily for purposes of internal comparison. Precision is within 3% for Ni, Cr, and V at concentrations >100 ppm, but 10 to 25% at concentrations <100 ppm. Analytical conditions for the XRF analyses are given in Table 9.

Carbon-Hydrogen-Nitrogen-Sulfur Analyses

CHNS analyses were performed on selected mineralized or altered igneous rocks. These analyses were included to permit assessment of variations in water content and sulfur content. Samples were typically splits from the XRF powders. Analytical procedures are identical to those used for sedimentary rocks (see "Lithostratigraphy and Sedimentology" section, this chapter).

PHYSICAL PROPERTIES

Physical properties data collected aboard the *JOIDES Resolution* from core material recovered by drilling are a valuable link between geophysical site survey data, downhole logging measurements, and lithologic units identified visually and analytically throughout the core. Integration of all of these types of data characterizes the geological and physical state of the subseafloor around the borehole. The Leg 139 physical properties program was designed to quantify the physical changes in cored sections of sediment and basalt resulting from alteration due to high temperatures and hydrothermal fluid flow in the thickly sedimented, slowly spreading Middle Valley of the Juan de Fuca Ridge. The resulting data set also provides important constraints for estimating the thermal and hydrologic regime in the sediment and upper igneous crust in this hydrothermally active rift.

Measurements during Leg 139 included compressional wave velocity, bulk density, grain density, porosity, thermal conductivity, and volume magnetic susceptibility. Electrical resistivity data were collected for the pore-fluid geochemists' calculation of formation factors. All discrete physical property measurements (index properties, thermal conductivity, velocity) were made at a frequency of two per section (approximately every 0.75 m) in the shallower parts of holes and once per section deeper. In XCB and RCB holes the sampling frequency was reduced to one per section or even one per core, depending on the homogeneity of the material and the amount of core disturbance. Where the sedimentary lithology was uniform throughout the cored interval, samples were taken once every other section. Undisturbed material of each lithology was selected. A study of the relatively fine-scale variation of physical properties within well-defined turbidite sequences was conducted at Hole 856A. Cubes of sulfide and basalt were selected in consultation with the sulfide and igneous petrologists, usually adjacent to thin-section specimens. Representative samples were taken as often as core recovery allowed and were shared with the paleomagnetists.

A discussion of physical property analyses with respect to equipment, methods, errors, correction factors, and coring disturbance is presented by Boyce (1973, 1976). The specific analytical methods and calculations used by Leg 139 physical properties specialists are those recommended by the physical properties subgroup of the ODP Shipboard Measurements Panel (1991).

Core Flow and Shipboard Analyses

The suite of whole-core analyses performed on newly recovered cores varied according to the type of drilling method used. Pseudocontinuous records of compressional wave velocity (via the P-wave logger, or PWL), density (via the gamma-ray attenuation porosity evaluator, or GRAPE) and volume magnetic susceptibility were obtained by logging unsplit APC core sections with the multisensor track system (MST). The sampling intervals were normally in the range of 2 to 5 cm, depending on the sensors used. The GRAPE was not operational until Hole 856G but was used routinely on APC cores from Hole 857A onward. APC core sections were normally scanned twice, before and after 3-4 hr of thermal equilibration, to determine whether temperature, which was measured with a thermocouple before each run, affected physical properties significantly. The APC MST data recorded for the equilibrated scans were saved as prime data; the other APC data were acquired for comparative purposes only. Because PWL velocity and GRAPE data are sensitive to drilling disturbance, only volume magnetic susceptibility was initially measured on XCB and RCB cores. However, test runs on non-APC cores showed that GRAPE data provided valuable, semiguantitative wholecore density information for selection of measurement and sample locations and for hole-to-hole correlation, and routine GRAPE scans were reinstated. Both measurements were made immediately after core recovery. The XCB and RCB cores were then left to equilibrate thermally before thermal conductivity measurements were made.

Thermal conductivity was measured on unsplit sections of sediment after they had equilibrated thermally. These measurements were discontinued in hard rock or indurated sediment which could not be penetrated with the needle probe or with a small drill bit. Needleprobe analyses were then performed on split slabs of material in a saltwater bath.

Electrical resistivity of soft and semilithified sediment was measured from Hole 857A onward immediately after the cores were split. Joris Gieskes (Scripps Institute of Oceanography [SIO]) kindly supplied an apparatus similar to the Schlumberger formation tester for these measurements.

Velocity measurements were made next on the working halves of sediment cores. The computer-controlled digital sound velocimeter (DSV) introduced on Leg 138 was used to determine velocities in soft and variously indurated sediment. The manually controlled Hamilton frame velocimeter (HFV) was employed if the DSV transducer blades could not easily penetrate the sediment without producing large cracks. Split core was analyzed in the liner with the HFV until the pressure required to seat the transducers on the sample fractured the sediment. Robust pieces of lithified sediment, basalt, and sulfide were removed from the liner and subjected to HFV velocity measurements before thermal conductivity was measured with the half-space method. Lithified sediment, basalt and sulfide samples were also cut into oriented parallel-sided cubes and their directional velocities measured with the HFV.

Samples for index properties measurements were taken with a 20-cm³ sample scoop immediately after velocity analyses were completed on split soft-sediment cores. A fraction of each sample (about 10 cm^3) was set aside for shore-based grain size and clay mineralogy analyses. Cubes of indurated sediment, basalt, and sulfide were cut from the core at the same locations where representative thin sections were requested by the igneous and sulfide petrologists. Physical properties measured in the laboratory have not been corrected for *in-situ* pressure or temperature, as this will be attempted later following a comparison with downhole logs.

Multisensor Track

Individual unsplit APC core sections were placed horizontally in the MST sample boat, which moved the sections past the magnetic susceptibility, GRAPE, and P-wave sensors. Whole-core volume magnetic susceptibility was measured with Bartington Instruments' model MS1 susceptibility meter adapted with an MS1/CX 80-mm whole-core sensor loop set at 0.465 kHz. The width of the impulseresponse peak at half maximum is less than 5 cm. Measurements were performed at a sensitivity range of 1.0 and in the cgs mode at 2.0-cm intervals. The susceptibility of discrete samples (cubes) was measured with a sensor unit (type MS1B) attached to the Bartington meter. The MST reports the whole-core susceptibility of samples in cgs units; all data from completely filled cores were converted to volume normalized SI units by multiplication with a conversion factor of 4π (12.57). No correction was made for partially filled liners, voids, or the coil-toinner core liner diameter ratio of 0.825. The MnO2 standard was not used for calibration. Magnetic susceptibility data were helpful in selecting measurement locations for thermal conductivity analyses and sampling sites in holes where turbidites were abundant.

The GRAPE (Boyce, 1976) was used to continuously measure the wet-bulk density of whole cores at 2-cm intervals. The bulk density of the sample (in g/cm³) is determined by comparing the attenuation of gamma rays through the core with attenuation through an aluminum or quartz standard (Boyce, 1976). An aluminum standard was used for calibration every 24 hr during routine whole-core use. The nondestructive GRAPE method was used routinely on APC cores and the first few XCB cores recovered in each hole. In general, deeper XCB and RCB cores contained annular air spaces between the core and liner, and/or gaps in the recovered core, which rendered them less suitable for the GRAPE since its calibration is for full diameter core only. Drilling mud sometimes also filled this annulus and the spaces between "biscuits" in XCB cores, resulting in lower apparent bulk densities. However, GRAPE data obtained from XCB and RCB cores were valuable indicators of general density trends between cores and holes.

The PWL sends a short, 500-kHz compressional wave pulse through the core at a repetition rate of 1 kHz via transmitting and receiving transducers aligned perpendicular to the core axis. Measurements were taken at 2.5-cm intervals; water was applied to the exterior of the core liner and to the transducer surfaces to improve acoustic contact between the transducers and the liner. A pair of displacement transducers monitored the separation of the P-wave transducers as each section proceeded along the track. Variations in the outside diameter of the core liner therefore did not degrade the accuracy of the measured velocities. The system was calibrated with distilled water and glycol standards at least once per APC hole. Use of the PWL was generally limited to APC and the uppermost XCB cores in each hole since compressional waves is transmitted optimally only in cores that completely fill the liner. PWL data were filtered to remove the effects of gas, voids, core ends, and weak signal strength. Data were averaged over 0.2- to 0.5-m intervals before plotting.

Thermal Conductivity

Thermal conductivity on soft sediments or hard rocks was measured either with the needle-probe full-space method of Von Herzen and Maxwell (1959) or the half-space method of Vacquier (1985). Data from both methods were collected with the computer-controlled WHOI Thermcon-85 data acquisition unit and stored on a PC.

True thermal conductivity values for shipboard standards, originally determined at ODP or published in open literature, were tested by divided bar at the USGS (A. Fisher, pers. comm., 1990). These values (\pm standard deviation), used on Leg 139, are as follows: black rubber = 0.54 ± 0.02 W/(m·K), red rubber = 0.96 ± 0.05 W/(m·K), fused silica = 1.38 ± 0.07 W/(m·K), macor = 1.61 ± 0.08

Run	Na ₂ O	MgO	MnO	TiO ₂	K ₂ O	SiO ₂	CaO	Fe ₂ O ₃	Al_2O_3	P_2O_5	Total
Q	2.23	6.93	0.17	2.83	0.54	50.59	11.49	12.42	13.78	0.28	101.26
R	2.20	6.95	0.17	2.81	0.54	50.51	11.46	12.39	13.62	0.27	100.92
S	2.27	6.90	0.17	2.80	1.27	50.57	11.43	12.31	13.76	0.28	101.76
U	2.28	6.84	0.17	2.80	0.54	50.15	11.49	12.32	13.65	0.28	100.52
V	2.26	6.89	0.17	2.81	1.23	50.39	11.44	12.33	13.81	0.28	101.61
W	2.30	6.90	0.17	2.81	0.53	50.09	11.47	12.41	13.63	0.27	100.58
Z	2.34	6.89	0.16	2.82	0.54	50.31	11.52	12.42	13.87	0.28	101.15
BB	2.24	6.89	0.17	2.81	0.53	50.34	11.46	12.42	13.59	0.27	100.72
CC	2.31	6.80	0.17	2.79	0.54	50.42	11.52	12.41	13.76	0.28	101.00
EE	2.28	6.80	0.17	2.79	0.53	50.06	11.46	12.40	13.68	0.28	100.45
GG	2.31	6.96	0.16	2.81	0.53	50.08	11.47	12.43	13.81	0.28	100.84
HH	2.24	6.79	0.16	2.78	1.23	49.99	11.53	12.39	13.71	0.28	101.10
JJ	2.29	6.92	0.17	2.80	0.53	50.42	11.43	12.39	13.63	0.27	100.85
MM	2.24	6.88	0.17	2.82	0.53	50.69	11.55	12.40	13.75	0.28	101.31
NN	2.24	6.86	0.17	2.83	0.53	50.59	11.55	12.46	13.67	0.28	101.18
00	2.34	6.86	0.16	2.81	1.23	50.65	11.48	12.38	13.86	0.28	102.05
00	2.30	6.89	0.17	2.82	1.23	50.39	11.45	12.43	13.73	0.28	101.69
SS	2.20	6.84	0.17	2.80	0.53	50.28	11.47	12.40	13.66	0.27	100.62
UU	2.28	6.87	0.18	2.81	0.54	50.48	11.54	12.40	13.76	0.28	101.14
VV	2.25	6.84	0.17	2.81	0.54	50.73	11.57	12.36	13.88	0.28	101.43
XX	2.30	6.92	0.17	2.81	0.53	50.13	11.45	12.38	13.86	0.28	100.83
YY	2.30	6.84	0.16	2.80	1.25	50.10	11.42	12.35	13.81	0.28	101.31
AAA	2.55	6.73	0.18	2.83	0.53	49.73	11.45	12.35	13.80	0.28	100.43
BBB	2.58	6.85	0.17	2.83	0.56	50.46	11.49	12.38	13.77	0.28	101.37
DDD	2.53	6.76	0.17	2.80	0.56	50.78	11.48	12.40	13.87	0.28	101.63
EEE	2.62	6.76	0.17	2.81	0.55	50.30	11.46	12.39	13.77	0.28	101.11
FFF	2.61	6.86	0.17	2.82	0.56	50.64	11.46	12.46	13.87	0.28	101.73
GGG	2.52	6.94	0.17	2.81	0.56	50.61	11.53	12.42	13.81	0.28	101.65
HHH	2.58	6.92	0.17	2.81	0.55	50.76	11.46	12.43	13.83	0.28	101.79
Ш	2 59	6.86	0.16	2.80	0.55	50.56	11.52	12.40	13.89	0.28	101.61
KKK	2.58	6.88	0.17	2.80	0.55	50.76	11.48	12.41	13.89	0.28	101.80
LLL	2.57	6.88	0.21	2.82	0.55	50.47	11.46	12.40	13.91	0.28	101.55
MMM	2 59	6.90	0.17	2.81	0.56	50.29	11.57	12.39	13.73	0.28	101.29
000	2.66	6.76	0.19	2.81	0.56	50.67	11.47	12.40	13.88	0.28	101.68
ppp	2.57	6.89	0.17	2.83	0.58	50.36	11 47	12.42	13.67	0.28	101 24
000	2 59	6.98	0.17	2.84	0.56	50.47	11.50	12.39	13.88	0.28	101.66
222	2 56	6.78	0.16	2.82	0.56	50.64	11 47	12.38	13.93	0.29	101.59
TTT	2.63	6.79	0.17	2.81	0.56	50.66	11.48	12.48	13.82	0.28	101.68
IIIII	2.65	6.85	0.17	2.82	0.56	50.75	11 47	12.42	13 72	0.28	101.69
www	2.50	6.82	0.17	2.83	0.56	50.76	11.53	12.46	13 74	0.28	101.74
XXX	2.64	6.86	0.17	2.82	0.57	51.00	11.48	12 37	13.91	0.28	102.10
YYY	2.61	6.84	0.17	2.83	0.56	50.53	11 49	12.49	13.68	0.28	101 48
AB	2.61	6.86	0.17	2.85	0.56	50.67	11.49	12.49	13.80	0.28	101.46
AC	2.01	6.87	0.17	2.02	0.56	50.69	11.49	12.50	13.60	0.20	101.00
AD	2.73	6.84	0.17	2.01	0.57	50.72	11.48	12.43	13.75	0.28	101.80
AF	2.64	6 78	0.19	2.83	0.57	50.74	11.45	12.44	13.56	0.28	101.00
ALI	2.04	6.83	0.17	2.05	0.57	50.00	11.45	12.44	13.80	0.20	102.00
AL	2.73	674	0.17	2.01	0.56	50.90	11.40	12.44	13.00	0.29	101.35
AI	2.75	6.84	0.17	2.01	0.50	50.47	11.50	12.30	13.80	0.29	101.33
AK	2.70	6.80	0.17	2.00	0.58	50.74	11.45	12.40	13.60	0.29	101.77
AL	2.70	6.70	0.17	2.02	0.57	50.60	11.45	12.42	13.01	0.20	101.00
AN	2.12	6.90	0.17	2.19	0.57	50.09	11.40	12.37	13.04	0.20	101.39
-74.15	2.01	0.80	0.17	2.81	0.58	30.88	11,47	12.38	15.07	0.28	101.65

Table 8. Repetitive analyses of shipboard internal standard derived from the calibrations used for whole-rock analysis.

W/(m·K) and Hole 504B basalt = 2.05 ± 0.10 W/(m·K). On the transit to the first drill site all available needle probes, including those dedicated to half-space measurements, were calibrated over fixed time intervals against these standard values. The 60–240-s time interval was chosen because (1) before 60 s the temperature vs. log (time) data rarely vary linearly, and (2) after about 240 s the thermal front from the heated needle tends to "feel" the edge of smaller, more conductive samples. Plots of measured thermal conductivities vs. ideal (standard) conductivities for full-space probe #17 and half-space probe #205 are given as examples of calibration results (Fig. 14). Full-space measurements utilized black rubber, red rubber, fused silica, and macor standards; red rubber, macor, and Hole 504B basalt were used as half-space standards. The resulting calibration curves were applied when determining the final values of thermal conductivity. Scatter in basalt standard conductivity values increased during the cruise; the standard should, perhaps, be replaced. All thermal conductivity data are reported in units of W/(m-K), and have an estimated error of 5% to 10%.

Before measuring thermal conductivity, the cores were left at room temperature for about 3-4 hr to equilibrate thermally. Up to four needle probes were inserted into full sediment cores through holes drilled into the unsplit core liners. An additional probe was inserted into a conductivity standard to monitor probe behavior. Before the measurement was started the temperature drift in the section was evaluated with the thermistors in the sediment. If the temperature within a core drifted less then 0.04° C/min, the measurement was started by applying a current to the heater wire for 5 min. Thermal conductivities were determined from the temperature rise vs. the logarithm of time. Typically, temperatures from the time interval between 60-240 s after the start of heating were fitted to the curve

EXPLANATORY NOTES

Table 8 (continued).

Run	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Cr	v	$\text{TiO}_2(\%)$	Ce	Ва	Rh1 ^a	Rh2 ^a
N	19	242	28	398	8	111	137	114	299	315	2.79	5	175	17.82	16.75
Т	19	240	27	402	9	112	141	116	299	324	2.78	4	172	17.79	16.89
X	19	237	26	408	10	115	141	117	291	318	2.78	5	180	17.73	16.92
Y	20	238	26	410	10	115	142	114	296	322	2.81	4	184	17.84	16.97
AA	19	235	27	407	9	116	147	118	309	328	2.80	9	171	17.85	17.06
DD	19	231	26	405	9	115	148	118	294	330	2.78	6	179	17.76	16.99
FF	19	231	26	405	9	116	145	118	310	330	2.79	2	172	17.71	17.05
п	19	230	26	408	9	113	145	118	308	326	2.78	6	174	17.77	17.17
KK	19	228	26	409	10	116	145	119	305	326	2.78	6	175	17.79	17.16
LL	19	229	27	407	10	114	148	117	295	324	2.78	8	169	17.78	17.19
PP	20	228	26	408	10	114	146	119	306	321	2.78	5	180	17.86	17.21
RR	19	233	26	408	10	116	144	116	307	328	2.78	0	180	17.81	17.14
TT	19	229	26	403	10	112	143	117	316	309	2.77	3	179	17.69	17.18
WW	19	232	27	407	10	116	146	119	306	328	2.80	9	179	17.81	17.09
ZZ	19	231	26	405	9	113	144	116	308	321	2.78	3	185	17.76	17.07
CCC	19	229	26	408	10	115	150	117	308	325	2.78	12	171	17.83	17.06
111	19	231	27	411	9	115	148	117	310	328	2.79	0	175	17.90	17.22
NNN	19	229	27	407	9	116	145	117	299	318	2.80	5	173	17.75	17.17
RRR	24	178	26	389	8	115	143	114	301	320	2.74	80	297	17.19	17.24
VVV	19	230	26	408	10	111	146	116	309	325	2.77	0	179	17.75	17.04
ZZZ	19	230	27	407	10	113	143	116	313	323	2.79	9	167	17.75	17.11
AG	19	232	26	407	10	112	148	117	310	319	2.76	8	171	17.76	17.10
AE	19	229	26	405	10	113	144	115	313	321	2.78	8	175	17.70	17.21
AM	19	229	29	408	9	112	145	114	291	322	2.76	5	166	17.70	17.08

^a Measured values for Rh peaks used for matrix absorption correction.

$$T(t) = (q/4\pi k) \cdot ln(t) + A + Bt,$$

where:

k = thermal conductivity (W/[m·K]),

 $T = \text{temperature } (^{\circ} \text{C}),$

t = time since heater on (s),

q = heat input per length of the needle per time (W/m s),

A = offset (associated with thermal contact resistances), and

B = linear ("drift") term.

A narrower time window was used on the few occasions where the temperature rise vs. log of time curve was very nonlinear. The thermal conductivity value was then calculated by a least-squares fit of the measured temperature data to the above equation.

Thermal conductivity of lithified sediment and rock was also measured on split cores. We used a needle probe partially embedded in a slab of insulating material, following the half-space method of Vacquier (1985). The flat surface of a selected sample of split core was polished with fine sandpaper and placed on top of the slab. The sample and slab were immersed in a saltwater bath to maintain a uniform temperature, to avoid cooling by evaporation, and to keep the sample saturated. Samples were generally removed from the working half and stored in a beaker of saltwater while awaiting analysis. Each sample was then placed on an epoxy/probe base in the bath until it reached thermal equilibrium with the water. Thermal conductivity was calculated using the same theory as for full-space measurements, but additional corrections were applied to account for the geometry of the experiment.

Electrical Resistivity

The "Dalrymple" resistivity apparatus lent to the Leg 139 physical properties group by Joris Gieskes of SIO functioned as follows. A fixed-voltage, 1-kHz square wave generated by two Heathkit Model IP-18–regulated power supplies was input to a voltage-proportional current amplifier. This circuit generated a constant current (10, 100, or 1000 μ A) signal which was applied across the outer generating electrodes of a four-electrode probe. The resulting potential across the inner receiving electrodes, which is proportional to resistance, was

measured with a high-impedance voltmeter. The formation factor is calculated as the ratio of two readings. The first reading is obtained by inserting the electrodes into the unconsolidated split sediment core. The second reading is the reference measurement and is made by immersing the electrodes in surface seawater that is contained in a split core liner. Cubes of basalt and sulfide used for velocity and index property determinations were archived for shore-based electrical resistivity measurements.

Compressional Wave Velocity

Compressional wave (*P*-wave) velocity was measured on halfround or discrete samples using two different systems. Unlithified to moderately lithified sediment was analyzed with a Dalhousie University/Bedford Institute of Oceanography digital sound velocimeter (DSV). The Hamilton frame velocimeter (HFV) was used when the DSV blades were difficult to insert into lithified sediments and/or cracked them. Two measurements per section were made immediately adjacent to the thermal conductivity measurements, wherever possible. The HFV was routinely used to measure velocities of basalt and sulfide samples.

Digital Sound Velocimeter

Operation of the DSV is detailed in Mayer et al. (1987) and Courtney and Mayer (in press). Velocities are calculated from the traveltimes of acoustic signals between two pairs of piezoelectric transducers inserted into the split sediment cores. The electrical excitation signal is a 2- μ s square wave. Measurements were made along the core axis, with the transducers separated by about 7 cm. Measurements parallel to bedding, with a transducer separation of 3.9 mm, were made on APC cores at Site 858 and other APC reference core material recovered during the cruise.

A dedicated microcomputer controls all velocimeter functions, including the processing of transmitted and received signals after they are digitized by a Nicolet 320 digital oscilloscope. The DSV software calculates sediment velocity based on user selection of the first arrival. Thermistors in the transducers used to monitor temperature during measurements have not yet been interfaced with the rest of the system.

Table 9.	XRF anal	ytical condition	ons during L	eg 139.
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Element								Total	count time (s)
	Line	Crystal	Detector ^a	Collimator	Peak angle (°)	Background offset (°)	Peak	Background	
SiO ₂	Κα	PET(002)	FPC	Coarse	109.10	0	40	0	
TiO ₂	Κα	LiF(200)	FPC	Fine	86.16	0	40	0	
Al ₂ O ₂	Κα	PET(002)	FPC	Coarse	144.49	0	100	0	
Fe On	Κα	LiF(200)	FPC	Fine	57.53	0	40	0	
MnO	Κα	LiF(200)	FPC	Fine	63.03	0	40	0	
MgO	Κα	TLAP	FPC	Coarse	44.88	±0.80	200	400	
CaO	Κα	LiF(200)	FPC	Coarse	113.18	0	40	0	
Na ₂ O	Κα	TLAP	FPC	Coarse	54.73	-1.20	200	200	
K ₂ O	Κα	LiF(200)	FPC	Fine	136.66	0	40	0	
P2O5	Κα	Ge(111)	FPC	Coarse	141.00	0	100	0	
Rh	K-C	LiF(200)	Scint	Fine	18.60	0	100	0	
Nb	Κα	LiF(200)	Scint	Fine	21.39	±0.35	200	200	
Zr	Κα	LiF(200)	Scint	Fine	22.54	±0.35	100	100	
Y	Κα	LiF(200)	Scint	Fine	23.83	±0.40	100	100	
Sr	Κα	LiF(200)	Scint	Fine	25.15	±0.41	100	100	
Rb	Κα	LiF(200)	Scint	Fine	26.60	±0.60	100	100	
Zn	Κα	LiF(200)	Scint	Fine	41.81	±0.40	60	60	
Cu	Κα	LiF(200)	Scint	Fine	45.02	±0.40	60	60	
Ni	Κα	LiF(200)	Scint	Coarse	48.64	±0.60	60	60	
Cr	Κα	LiF(200)	FPC	Fine	69.38	±0.50	60	60	
Fe	Κα	LiF(220)	FPC	Fine	85.73	-0.40 + 0.70	40	40	
v	Κα	LiF(220)	FPC	Fine	123.20	-0.50	60	60	
TiO ₂	Κα	LiF(200)	FPC	Fine	86.16	±0.50	40	40	
Ce	Lα	LiF(220)	FPC	Coarse	128.35	±1.50	100	100	
Ba	LB	LiF(220)	FPC	Coarse	128.93	±1.50	100	100	

Note: All elements analyzed under vacuum on goniometers 1 and 2, at generator settings of 60 kV and 50 mA. ^a FPC = flow proportional counter using P_{10} gas; scint = NaI scintillation counter.

^b Total Fe as Fe₂O₃.

The transducer separation was evaluated by performing a distilled water calibration several times at each hole. The distance between transducers was measured with digital vernier calipers and entered into the calibration program along with the core temperature. The computer determines a value of sound velocity in distilled water based on standard equations (Shipboard Scientific Party, 1992) for the measured temperature, and then calculates the transducer separation using the signal traveltime.

Hamilton Frame Velocimeter

Where the sediment was too consolidated to allow measurements with the DSV, velocity was measured with the HFV perpendicular to the core axis through the core liner; a correction was applied for the effects of the liner. Distilled water was used to improve the acoustic contact between the sample and the transducers. Measurements on half-round samples, both in and out of the liner, were always made in the c-direction, which is approximately parallel to bedding. This could introduce a systematic bias in velocity data if the core material is anisotropic (which was the case at Site 857). In order to address this problem, we obtained parallel-sided cubes as index property samples from all material that was coherent enough to be cut with the doublebladed saw. Velocities were then measured in the a-direction (along core axis), b-direction (across core parallel to the split face of the working half), and c-direction (through core perpendicular to the split face of the working half). Anisotropy was calculated following the expression of Carlson and Christensen (1979):

$$A = 200 (V_h - V_v) / (V_h + V_v),$$

where anisotropy (A) is the ratio of the velocity difference to the mean velocity expressed as a percentage. For V_{ν} we used velocities measured in the a direction; V_h values are averages of velocities obtained in the b- and c-directions. Results of anisotropy studies are discussed in the site reports.

The 500-kHz signal for the HFV is generated by a Tektronix FG 501A function generator. Sample thickness was measured using a variable lead-screw resistor attached to the calipers that hold the sample between the transducers on the Hamilton frame. Resistivity was read with a Tektronix DM 5010 digital multimeter-counter/timer system. A Nicolet oscilloscope was used to digitize waveforms from the HFV and traveltimes were read directly from the screen. As the epoxied surface of the lower stationary receiving transducer used at the start of the cruise was not level, the samples had to be carefully positioned before measurement.

The HFV transducers and calipers were calibrated with aluminum standards of known velocity and thickness. Zero-delay times were calculated by measuring the velocity of these aluminum standards and then performing a linear regression on the resulting traveltime vs. distance data. Thickness and zero-time corrections were applied to the data, and the compressional velocity was then calculated by

Velocity_{sample} = Thickness_{sample}/Corrected traveltime_{sample},

where:

Thickness_{sample} = Total thickness - liner thickness (mm), and

Corrected traveltimesample = total traveltime - liner traveltime -

zero-delay time (µs).

All velocity data are reported in units of meters per second (m/s) and are estimated to be accurate within $\pm 2\%$ (Boyce, 1976). Delamination of the potting compound and faulty signal quality required the replacement of one top transducer and two bottom transducers. Calibration procedures were repeated after each exchange.

Sonic velocity of basalt and sulfide samples was measured as follows. A 1.5-cm cube was cut using a double-bladed rock saw. When the axial orientation was known, velocity was measured in all three directions of



Figure 14. Examples of calibration data for dedicated full-space and half-space thermal conductivity needle probes. Thermal conductivity data measured by full-space probe #17 (top) are compared to ideal values for black rubber, red rubber, fused silica, and macor standards derived from divided bar tests. Half-space probe #205 (bottom) was calibrated against ideal values for red rubber, macor, and Hole 504B basalt measured by divided bar. Conductivities were determined over a time interval of 60–240 s in all cases. The error bars in each plot indicate one standard deviation of all measurements made during Leg 139; the least-squares best fit is also shown. Ideal thermal conductivity values for all standards are presented in the text.

the core to determine velocity anisotropy within the cored materials. At least three velocity determinations were made across each face of the sample, and the resulting averages are reported for each direction.

Index Properties

Index properties (wet- and dry-bulk density, grain density, water content, and porosity) were calculated from measurements of wet and dry weights and wet and dry volumes of about 10 cm^3 of sediment or rock. Wherever possible, samples were taken immediately adjacent to the positions where the other discrete physical properties were measured. Sediment samples were placed in small aluminum beakers and weighed, with a precision of about 0.02 g, using a calibrated Scientech 202 electronic balance. Total weight of wet samples plus beakers was about 15-20 g; dry weights were about 10-15 g. Wet volumes were measured using a Quantachrome helium Penta-Pycnometer with small sample inserts. Volume calibrations were performed on the pycnometer while in port. Samples were oven-dried

at $110^{\circ} \pm 5^{\circ}$ C for 24 hr to drive off free water (ASTM, 1989). Dry weights and volumes were then measured with the same balance and pycnometer. Chunks of indurated sediment and cubes or minicores of sulfide and basalt were treated slightly differently. Inserts of a different geometry were required for these samples, as was recalibration of the Penta-Pycnometer. Porosities and void ratios for these samples were determined indirectly from wet and dry weights and dry volumes. The pycnometer was recalibrated again with the standard, beaker-compatible inserts before unlithified sediment samples were measured.

The equations used to calculate index properties are discussed in the ODP Shipboard Measurements Panel report (1991) and by Boyce (1976). The definitions and units used for the index properties are:

1. Porosity (%) = $100 \cdot \text{volume of water/volume of wet sediment.}$ 2. Wet-bulk density (g/cm³) = weight of wet sediment/volume of wet sediment.

3. Grain density (g/cm^3) = weight of dry sediment/volume of dry solid fraction.

4. Dry water content (%) = $100 \cdot$ weight of water/dry weight of sediment.

5. Void ratio (unitless) = volume of water/volume of dry solid fraction.

Salinity-corrected physical properties were computed for all samples by assuming a pore-water salinity of 3.5%, and by subtracting the estimated weight and volume of the residual salt (Hamilton, 1971).

The accuracy of the results generated by the standard formulae for salt correction was calculated by assuming typical weights and volumes of materials with known porosities and grain densities. Values of bulk density, grain density, and porosity calculated with these formulas are systematically too high (by about 1%) for material with a porosity ranging from 20% to 70%.

DOWNHOLE LOGGING

The downhole logging program on Leg 139 was designed to characterize the geophysical, geochemical, and structural properties of the sediments and rocks drilled. Interpretation of the continuous, *in-situ* measurements made by the logging tools can yield a stratigraphic, lithologic, geophysical, and mineralogic characterization of the site. *In-situ* downhole measurements in open holes have several advantages over laboratory core measurements. Logs continuously and rapidly measure physical and geochemical properties of the surrounding formation. In addition, the properties are measured at stresses and temperatures that are more representative of *in-situ* conditions than are laboratory measurements. In fact, comparison of logging data with the correlative laboratory data can delineate changes of the physical properties of sediments and rocks due to changes in stress, and comparison of logs with lithologies can help to accurately locate core samples relative to the seafloor and relative to each other.

Logging is usually done after coring in a hole is complete. A large number of different logging tools were available during Leg 139, including those routinely supplied by Schlumberger and special tools provided by Lamont-Doherty Geological Observatory. For efficiency, related logging tools are usually coupled together in "tool strings" so that a number of measurements can be made on a single lowering. The sensors in each tool continuously monitor one or more properties of the formation. Schlumberger data are recorded at 15-cm (0.5 ft) intervals as the tools are moved up or down the hole. Up to four tool strings of Schlumberger sensors were used at Leg 139 sites: (1) one or two geophysical tool strings, (2) a geochemical tool string, and (3) a formation microscanner string (Fig. 15). A self-contained internally recording temperature tool can be attached to the bottom of all tool strings except the formation microscanner string. This temperature tool can measure temperatures up to 70°C.



Figure 15. Schematic diagram of standard Schlumberger logging tool strings.

Four high-temperature tools were put on board expressly for Leg 139. Two are wireline tools: the Geophysical Surveying Company's pressure, temperature, and flow tool, which is designed to operate at temperatures up to 375° C, and the Bureau Recherche Geologique et Mineralogique tool, which measures temperatures up to 400° C. On Leg 139 both of these tools were limited to measurements in holes of 260° C or less because that is the upper limit of temperature tolerance of the wireline currently on the *Resolution*.

For temperatures above 260° C two remote recording (memory tools) were available: the Geophysical Research Company tool (on loan from the Geothermal Research Division of the Sandia National Laboratory) records only temperatures, but can work to temperatures up to 420° C for exposures less than 3 hr. A high-temperature Kuster tool that makes an etched record of temperature vs. pressure on a stainless steel base was available as a backup.

Standard Schlumberger Logging Tools

Geophysical Tool Strings

Two combinations of tools were used to measure the physical properties of the formation: the seismic stratigraphy string and the lithoporosity string. The former is made up of the (1) natural gammaray tool, (2) long-spacing digital sonic tool, and (3) dual induction tool. The latter consists of the (1) natural gamma-ray tool, (2) hightemperature lithodensity tool, and (3) compensated neutron porosity tool. Note that the natural gamma-ray tool is run on every tool string to provide a profile that can be used as a basis for correlation between logging runs and between holes (see Table 10 for a brief description of the logging tools used on Leg 139).

Geochemical Tool String

The geochemical tool string used on Leg 139 included the (1) natural gamma-ray tool, (2) induced gamma-ray spectroscopy tool, and (3) aluminum clay tool. Data related to the relative concentrations of silicon, calcium, iron, sulfur, hydrogen, and chlorine can be determined aboard ship with data from the gamma-ray spectroscopy tool. Additional shore-based processing is required to obtain weight abundances of these six elements, plus the abundances of gadolinium and titanium. Weight percentages of potassium, uranium, thorium, and aluminum can be determined by combining data from natural gamma-ray and gamma-ray spectroscopy tools.

Formation Microscanner String

The formation microscanner string consists of the (1) formation microscanner, (2) natural gamma-ray tool, and (3) general purpose inclinometry tool. The formation microscanner produces highresolution images of the resistivity of the borehole wall rock, which reveal the detailed sedimentary and/or structural features of the formation (Ekstrom et al., 1986). The resolution of this tool under ideal conditions is about 1.25 mm. The inclinometer tool provides precision information on the position and orientation of the formation microscanner string in the hole.

The raw formation microscanner data must be processed on shore to obtain complete, spatially oriented images. However, limited processing can be accomplished at sea. Formation microscanner results allow detailed correlation between core samples and logging results, orientation of cores, mapping of fractures, faults, Table 10. Summary description of standard logging tools used in the Ocean Drilling Program.

Name of tool	Acronym	Function
1. Caliper log	CALI	Measures radius of borehole.
2. Dual-induction log	DIT	Measures resistivity at three radial depths.
3. High-temperature lithodensity tool	HLDT	Measures density of formation using gamma-ray scattering.
4. Long-spacing sonic tool	LSS	Measures compressional wave velocity over 3.6-m intervals.
5. Borehole compensated sonic tool	BHC	Measures compressional wave velocity over two overlapping intervals.
6. Formation microscanner	FMS	Makes high-resolution resistivity image of the borehole wall.
7. General purpose inclinometer tool	GPIT	Used with FMS to give hole orientation and tool position.
8. Compensated neutron porosity tool	CNT	Measures porosity by backscattering of neutrons.
9. Natural gamma-ray tool	NGT	Detects natural gamma radiation of formation, yields K, U, and Th abundances.
10. Gamma spectrometer tool	GST	Active gamma-ray spectrometer with 14-MeV neutron source; measures Ca, Si, Fe, S,
		Ti, H, Cl, and gadolinium.
11. Aluminum clay tool	ACT	Measures aluminum content by gamma-ray output from the formation after activation by a californium source.

foliations, and bedding planes. The formation microscanner can also be used to estimate stress in the borehole from its precise measurements of borehole shape.

Log Data Quality

The quality of log data may be seriously degraded in sections of excessively large diameter borehole or by rapid changes in diameter. Resistivity and velocity measurements are less sensitive to borehole effects, whereas the nuclear measurements (density, neutron porosity, and both natural and induced spectral gamma ray) are most seriously impaired, because of the large attenuation of the neutrons by the borehole fluid. Corrections can be applied to the original data in order to reduce the effects of these conditions and, generally, any departure from the conditions under which the tools were calibrated.

Small depth mismatches between logging runs in a single hole can impair the results in zones of rapidly varying lithology. On Leg 139 the hydraulic heave compensator which adjusts for ship motion was not operating, so that logs taken during periods of significant heave were degraded. Certain types of logging tools such as the borehole televiewer were not used because the images obtained are seriously degraded by oscillatory motion in the hole.

Log Analysis

During logging, incoming data were monitored on an oscilloscope and simultaneously recorded on digital tape in the Schlumberger logging unit. After logging, the Schlumberger tapes were read by the Masscomp computer system or the Vaxstation 3200 in the downhole measurements laboratory and reformatted to a file format compatible with the Terralog log-interpretation software package. The Terralog system of programs allows a wide assortment of log manipulations and plot options. The log analysis and interpretation varies for each site. Some log interpretation is carried out aboard ship; further analysis and interpretation are undertaken after the cruise, using a companion system at Lamont-Doherty Geological Observatory.

IN-SITU TEMPERATURES

Scientific Objectives

Measurements of temperature were of primary importance to the main objective of Leg 139, characterizing the hydrogeology of a sedimented spreading center. The thermal state of the sediments and basaltic crust is strongly influenced by, and is thus a good indicator of, fluid flow in this setting. Pore-fluid chemistry is also strongly influenced by advection, and many geochemical tracers are at least an order of magnitude more sensitive to the effects of fluid flow than is formation temperature. In combination, analyses of thermal and chemical gradients provide indications of fluid flow over a wide range of velocities. Techniques used for *in-situ* pore-fluid sampling during Leg 139 are covered in the "Fluid Geochemistry" section (this chapter). Several borehole-temperature logging tools were also used during Leg 139; these are described in the "Downhole Logging" section (this chapter).

Water Sampler Temperature Probe Measurements

The WSTP is a hybrid of two other tools, the Uyeda temperature tool (Yokota et al., 1980) and the Barnes fluid sampler (Barnes, 1979) (Table 11). A second generation WSTP became available during ODP Leg 110 with improved sampling capabilities and a stouter temperature probe (Barnes, 1988). A third version of this tool was introduced during Leg 139 in anticipation of encountering extremely hightemperature, corrosive fluids. The Leg 139 iteration of the WSTP does not have the pressure sensing capabilities available with the previous generation, as the section of the tool which contained the pressure transducers is now occupied by a high-temperature, high-pressure electrical feed-through which hydraulically isolates the tool electronics from the probe tip.

Table 11. Specifications of temperature measurement instruments used during Leg 139.

Tool	Thermistor housing	Sensor resolution	Recording interval
APC tool	Steel annular cylinder, ID: 0.0617 m, OD: 0.0907 m	0.01° C	Programmable generally 5 s
WSTP	Steel cylindrical probe, OD: 0.0127 m	0.01° C	4.369 s

Note: OD = outer diameter; ID = inner diameter.

The original Uyeda temperature tool had a thin, stainless steel probe which was pushed ahead of the bit into the undisturbed sediments at the bottom of a hole. The second generation tool had a probe tip with a minimum diameter of 1.3 cm which extended 8.3 cm past a 5.1-cm diameter pore-fluid filter block. The new WSTP probe includes a temperature-probe tip which is slightly longer and wider overall, although it ends with the same diameter (Fig. 16 and Table 11). Because the filter assembly has been made longer to improve fluid sampling performance, but tool length has been kept constant, the new temperature probe extends just 3.5 cm past the end of the filter. During Leg 139, we fabricated a 2.7-cm diameter sleeve which fits over the temperature probe, for use



Figure 16. Scale cross sections of the WSTP probe assembly, configured for temperature only, and for temperature and water sampling. All dimensions are in centimeters. The probe tips extend 1.1 m ahead of the bit when latched in place.

when temperatures only were needed from the instrument. This sleeve is run instead of the filter assembly, to reduce the time constant of the probe and improve the geometry of the measurement so that (1) the frictional heat pulse associated with insertion of the probe can be assumed to approximate more closely a line source of heat, and (2) insertion of the instrument is less likely to fracture semilithified sediments.

Because the digital package used to record thermistor resistances has a fixed range of 0-30 k-ohm, it was necessary to include two thermistor circuits with partially overlapping ranges to cover the entire anticipated temperature range with adequate resolution for Leg 139 (Fig. 17). The data logger contains one recorder for each circuit, with a sampling interval of 4.369 s. All components meet military specifications (maximum working temperature 125° C) allowing measurements of *in-situ* temperatures up to about 200° C, as long as the electronics are cooled by continuous circulation around the tool. Additional WSTP modifications include complete rewiring with high-temperature conductors, connectors, and pass-throughs.

In operation, the WSTP is mounted inside a core barrel and lowered down the drill pipe by wireline while the bit is held above the bottom of the hole. The tool is held briefly above mudline to measure the temperature of bottom water. The tool is then lowered and latched into place, with the probe tip extending 1.1 m ahead of the bit. The drill string is lowered and the probe is forced into the bottom of the hole. A colleted delivery system allows the probe to retract back up inside the bit should the formation prove to be too hard for penetration. With an APC/XCB bottom-hole assembly, the bit can be decoupled from the tool after penetration so that the probe will not be disturbed by drill-string heave.

The driller can continue fluid circulation during the station if necessary to keep the hole clear of fill, as circulation of cold bottom water in the hole will have little influence on measured temperatures at times less than a few hours after drilling, so long as the probe penetrates at least 50 cm (Fisher and Hounslow, 1990). Insertion of the probe significantly disturbs formation temperatures, and as the instrument can not be left in position to allow this disturbance to decay completely, extrapolation to thermal equilibrium is required. Data reduction methods are described later in this section.

The relatively short length of the narrow probe appears to allow only a few minutes of undisturbed measurements before a thermal disturbance is conducted down from the larger-diameter section above, limiting the accuracy of temperature extrapolations to about $\pm 0.1^{\circ}$ – 0.2° C. Because the exact depth of penetration of the tool is never known, all temperatures measured with the WSTP must be considered lower bounds on *in-situ* conditions. From the shape of the temperature-time records and from comparison with nearby measurements it is often possible to determine if the tool was pressed into fill at the bottom of a hole or if the formation cracked upon insertion. A review



Figure 17. Performance curves for two typical thermistor circuits used in the WSTP tool during Leg 139. The two circuits allow a temperature range of $0^{\circ}-200^{\circ}$ C to be covered with a nominal resolution of about 0.01°C. The "low-temperature" thermistor (solid line) has a nominal resistance of 10 k-ohm at room temperature, and can be used to determine temperatures with high precision over a range of about $0^{\circ}-70^{\circ}$ C; this thermistor was calibrated to 100° C, but resolution falls off as this temperature limit is approached. The "high-temperature" thermistor circuit (dashed line) has a nominal resistance of 100 k-ohm at room temperature (with two 50-k-ohm thermistors wired in series) but resistance on this circuit falls below 30 k-ohm (and is thus discernable with the data loggers) as temperatures increase to 60° C. The overlap between the ranges of the two thermistor circuits allows data recorded on the separate channels to be compared.

of thermal data obtained with this type of probe during DSDP is given by Hyndman et al. (1987).

APC-tool Temperature Measurements

The new advanced piston core heat-flow coring shoe (APC tool) was also used during Leg 139 (Table 11, Fig. 18). This tool is used for measuring *in-situ* sediment temperatures during regular piston-coring operations. The instrument contains an electronics section, composed of three circuit boards and two battery packs, built into a cylindrical frame (Fig. 18). This frame fits inside an annular cavity in a special coring shoe. Two steel prongs extend from the base of the frame and anchor the electronics in place inside the shoe. Inside one of the two prongs is a platinum resistance-temperature device (RTD) which has been calibrated over a range of -20 to 100° C, with resolution of 0.01° C. The RTD prong is coated with thermally conductive grease to assure a good contact with the wall of the cutting shoe. The instrument runs on standard camera batteries which are readily available and easily replaced.

The tool is programmed after it has been inserted into the coring shoe, and repeated deployments can be run without removing the tool or batteries. The tool contains a microprocessor and 32 kilobytes of nonvolatile memory, and is run off a PC through an interface box. The tool operating system is downloaded from the computer, and the user defines a table of events, which includes the measurement frequency and total time of operation. During Leg 139, data were generally collected at a 5-s time interval. Between individual measurements, and optionally for extended periods, the tool can be programmed to "sleep" to conserve power.

After programming and starting the test sequence, a crossover subassembly with O-rings seals the cavity containing the electronics. The shoe is then placed at the front end of a core barrel and lowered down the pipe. The shoe is typically held just above the mudline to measure the temperature of bottom water, then lowered into the bottom-hole assembly. The core barrel is deployed in the standard way, fired out through the bit using hydraulic pressure from the rig pumps, but it is left in place for 10 min instead of being retrieved immediately, so that the tool can begin thermal equilibration with the formation. After the core barrel is returned to the ship, the coring shoe is removed and the temperature data are uploaded to the PC for reduction.

Data Reduction

Although the WSTP and APC tools have different geometries, the methods used for analysis of recovered temperature data are similar. For the WSTP, the thermal response of a cylindrical probe to a pulse



Figure 18. Photograph of (left to right) the APC tool electronics, an APC coring shoe, connecting cable, batteries, and interface box.

of heating (or cooling) is given by Bullard (1954). The equivalent theory for the APC tool is discussed by Horai and Von Herzen (1985). For both instruments, synthetic type-curves are constructed, based on tool geometry, sampling interval, and the thermal properties of the tools and surrounding sediments. Both tools have thermal time constants of several minutes under normal conditions, requiring that the probes be kept in bottom for at least 10–15 min in order to allow extrapolation of the temperature curves with confidence.

The theoretical decay curves simulate the instantaneous change in temperature (heating or cooling) of the sediment following probe penetration, but in practice a finite time is required for the sensors to reach a maximum temperature. As a result, the effective origin time of the thermal pulse is delayed as a function of tool and sediment properties. In addition, the recorders sample temperatures at fixed intervals, leaving the exact penetration time uncertain. An effective penetration time and an extrapolated temperature are estimated by shifting the time axis of the theoretical thermal decay curves to fit the actual data. Temperatures from the first 5-10 measurements (20–50 s) following penetration commonly do not follow the theoretical curves, but later parts of the records usually provide a very

good match (Fig. 19). The choice of which data should be included in the matching, and which time shift should be used, is partly subjective; it is probably best to use as much of the actual decay curve as possible. The variations in extrapolated temperatures that result from choosing different time intervals and time shifts can be used to estimate errors associated with the temperatures finally assigned to represent *in-situ* conditions.

SPECIAL DOWNHOLE EXPERIMENTS

A number of special downhole experiments were planned for the reentry holes drilled at Sites 857 and 858 during Leg 139. Most of these special experiments were directed at assessing the hydrogeological state of the sediments and crust penetrated by the reentry holes. Besides standard logging (see "Downhole Logging" section, this chapter), the downhole experiments planned for these reentry holes included:

temperature logging with a variety of high-temperature tools;
 packer inflations to determine bulk permeability;



Figure 19. Examples of temperature/time and curve-fit records. **A.** A good temperature/time record for a measurement in cool sediments. The heat pulse resulting from insertion of the probe is clearly visible. The WSTP probe is pushed into the sediments while the APC tool is fired in along with a core barrel. **B.** Measured and modeled temperatures from the same run as in (A). The modeled temperature curve extrapolates to 13.03° C. **C.** A good temperature/time record for a measurement in warm sediments. The frictional heat pulse is barely apparent. **D.** Measured and modeled temperatures from the same run as in (C). The modeled curve extrapolates to an undisturbed temperature of 59.36° C.

3. flowmeter/packer/injection experiments to determine fine-scale permeability; and

4. installation of long-term instrumented borehole seals.

The temperature logging tools are discussed in "Downhole Logging" section (this chapter), and the instrumented borehole seals are described in detail in a separate chapter by Davis et al. (this volume). The methods for the packer and flowmeter experiments are described in this section.

Packer Experiments

Average formation permeabilities were measured using a resetable drill-string packer manufactured by TAM International and described by Becker (1986, 1988). This packer incorporates inflatable rubber elements to isolate a section of the hole and can be configured as a single or a straddle packer. For the measurements during Leg 139, it was configured with either one or two elements and used as a single-seal packer to isolate the zone between the bottom of the hole and the seal (Fig. 20). At the two reentry holes, downhole temperatures were considerably higher than the packer seals could withstand. Therefore, the packer was inflated in casing near the seafloor, where temperatures were cooler, and used to measure the average permeability of the entire open-hole interval (Fig. 20).

The packer is actuated using a "go-devil" that is dropped down the drill string into the packer inflation subassembly. The go-devil also carries recorders to monitor downhole fluid pressures in the isolated, pressurized zone during the experiment; these pressures are the primary data from which permeability is calculated. Two types of pressure recorders were used during Leg 139: (1) mechanical "K-3" gauges made by Kuster, and (2) electronic "ERPG-300" gauges made by Geophysical Research Corporation. The K-3 gauges record analog pressure mechanically by scratching a metal chart; the ERPG-300 gauges record in electronic memory 10,000 digital pressure values sampled at 8.64-s intervals over one day. The data from these gauges are not available until the go-devil is retrieved upon completion of the experiment. However, the entire drill string as well as the isolated zone was pressurized during testing, and a pressure transducer at the rig floor was also used to provide a real-time indication of downhole events. Throughout the packer measurements, pumping rates and total volumes pumped were also measured at the rig floor.

Once the packer was inflated, two kinds of experiments were used to determine the permeability of the isolated interval: pressure pulse or "slug" tests and constant-rate injection tests. Figure 21 shows examples of the pressure records obtained during these kinds of experiments. The methods used were similar to those described by Anderson and Zoback (1982), Hickman et al. (1984), Anderson et al. (1985), and Becker (1989, 1990, 1991) in conducting packer experiments in Holes 395A and 504B during the DSDP and ODP. Injection tests generally disturb the pressure field in the formation around the hole much more than slug tests, and were therefore conducted after the slug tests at appropriate inflation depths.

Slug Test Procedures

The slug tests were conducted following the methods for the "modified" slug test of Bredehoeft and Papadopulos (1980), which is an adaptation of the slug test method of Cooper et al. (1967) and Papadopulos et al. (1973) for formations with relatively low permeabilities. In the modified slug test, a short pressure pulse is applied to the fluid in the zone isolated by the packer, and the decay of this pulse is monitored as fluid flows from the borehole into the isolated formation. The decay of such a pressure pulse is described by the equation:

$$P(t)/P_0 = F(\alpha, \beta)$$



Figure 20. Sketch of the inflatable drill-string packer as deployed during Leg 139. A. A single packer element incorporated in the bottom-hole assembly, before inflation or after deflation. B. Cut-away sketch of the inflated packer showing go-devil, pressure recorders, and tested interval between the casing shoe and the bottom of the hole. During inflation of the packer, the go-devil directs fluids pumped from the rig floor into the inflation elements; once the packer is inflated, the go-devil position is shifted such that fluids pumped from the rig floor are directed into the tested interval.

where *P* is pressure in excess of the initial undisturbed value, P_0 is the initial pressure increase, α is a dimensionless parameter that depends on the storage coefficient (*S*), and porosity (ϕ) of the isolated formation, β is a dimensionless parameter that depends on the transmissivity (*T*) and permeability (*k*) of the formation, and *F* is a complicated infinite integral. More specifically,

$$\alpha = \pi a^2 S / V_w C_w \rho_w g, \beta = \pi T t / V_w C_w \rho_w g,$$

$$S = b \phi C_i \rho_i g, \text{ and}$$

$$T = b k \rho_i g / \mu,$$



Figure 21. Pressures vs. time recorded in the zones isolated in Hole 735B during one of three packer inflations conducted during Leg 118 (Becker, 1991), illustrating the characteristic responses to both slug and injection tests.

where t is time, g is gravitational acceleration, a is the radius of the hole in the isolated zone, b is the height of the isolated zone, C_i , ρ_i , and μ are, respectively, the compressibility, density, and dynamic viscosity of the fluid in the isolated zone, and C_w and ρ_w are the compressibility and density of the fluid in the total pressurized volume, V_w .

To process the pressure data measured during slug tests, we followed the standard curve-fitting method described by Cooper et al. (1967) and Papadopulos et al. (1973), as follows. A plot of the decay of measured pressures vs. log time was superposed on a family of type-curves of $F(\alpha,\beta)$ vs. log β calculated for various values of α spanning several orders of magnitude. The data plot was then shifted along the abscissa of the type-curve plot to visually determine the value of α for which the data best fit the type curve. Then the transmissivity and average permeability of the tested interval could be calculated from the correspondence between the values of time and β for the best-fit curve, using the definitions for β and transmissivity given above.

As noted by Cooper et al. (1967), Papadopulos et al. (1973), Bredehoeft and Papadopulos (1980), and Hickman et al. (1984), the calculated type-curves are relatively insensitive to changes in α and much more sensitive to changes in β . Thus, this procedure yields relatively poor estimates of the storage coefficient and porosity, but reasonable determinations of transmissivity and average permeability.

Constant-Rate Injection Tests

In a relatively permeable formation, a slug test will decay quite rapidly, and a better determination of permeability can be obtained by conducting a constant-rate injection test. In this experiment, borehole pressure within the isolated zone is monitored as fluids are pumped into the formation at a constant rate. The rise of pressure as injection proceeds quickly becomes linear with the log of time, according to the following equation (Horner, 1951; Matthews and Russell, 1967):

$$P(a,t) = (q\mu/4\pi kb)\ln(\tau\phi\mu C_i a^2/4kt),$$

where q is the flux of injected fluids, τ is Euler's constant, and the remaining parameters are defined above. The average permeability of the isolated zone can be determined directly from the slope of a plot of pressure vs. log time, given the measured constant injection rate.

Properties of the Fluids in the Pressurized System

The transient pressures measured during both slug and injection tests depend on the properties of the pressurized fluids, particularly viscosity and compressibility, which vary with both temperature and pressure. For the temperature dependent viscosity of seawater, we used Gartling's (1977) equation, $\mu(10^{-3} \text{ Pa-s}) = 16.68T^{-0.8987}$, with T in °C. As noted by Neuzil (1982), the effective compressibility of the fluid in a shut-in hole is sometimes greater than that of the pure fluid (seawater in this case), because of (1) compliance of the drill string and test equipment and (2) air possibly trapped in the system. While every effort was made during Leg 139 to purge all air from the drill string, pump, and connecting plumbing, small amounts of air may have remained in the system. Such trapped air would increase the effective system compressibility, and cause the transmissivity and bulk permeability calculated in a slug test to be erroneously high. Therefore, we carefully recorded the volumes pumped downhole during slug tests, so that the effective compressibility of the pressurized system could be determined using the definition of compressibility, C = dV/VdP, and be accounted for in the calculation of formation permeability.

In-situ Permeability vs. Calculated Bulk Permeability

Both slug and injection tests involve an important assumption that the permeability of the rock in the zone isolated by the packer is uniform and isotropic. This assumption is probably not valid for the formations penetrated during Leg 139 where permeability may be dominated by isolated fractures. Nevertheless, it probably "becomes more valid as the scale of the permeability tests [i.e., the length of the zone isolated by the packer] increases with respect to the spacing of the fractures" (Hickman et al., 1984; Parsons, 1966). The permeabilities computed here are average Darcian or equivalent porous-medium permeabilities, denoted as bulk permeabilities, obtained by applying the theory for uniformly permeable media. If the *in-situ* permeability is indeed dominated by isolated fractures, the actual hydrologic conductivities of such fractures may be orders of magnitude greater than the bulk transmissivities reported here.

Flowmeter/Injection Experiment

The flowmeter/injection experiment was run in order to assess the fine-scale variation of permeability and the contribution of faults and fractures to the bulk values measured with the packer. The flowmeter/injection method utilizes constant-rate injection into a hole sealed by the packer and simultaneous logging of pressure, flow, and hole size with depth to arrive at a detailed vertical profile of permeability. This method was originally proposed by Hufschmied (1984) and has been evaluated and successfully conducted in subaerial holes (e.g., Morin et al., 1988; Hess, 1989; Molz et al., 1989).

There are fundamental differences between the way this experiment is performed in a subaerial hole and the way it must be performed in an ODP hole. In the former case, all fluid injected into the hole at the wellhead can be assumed to enter the formation. In the ODP case, fluid injected down the drill string from pumps aboard the ship may escape back up the annulus to the open ocean unless a packer is used to seal the annulus (Fig. 22). Adapting this experiment for ODP use required designing a new packer go-devil that would ride on the logging cable as the flowmeter tool was lowered into the hole before packer inflation. This go-devil was required first to enable packer inflation, and then to release the logging cable so the flowmeter log could be conducted as fluid was injected into the formation.

Two flowmeter tools were available for this experiment during Leg 139. The primary tool (Fig. 22) was built for the experiment by Comprobe and incorporated a pressure sensor with a range of



Figure 22. Sketch of the flowmeter/injection experiment after inflation of the packer. Dashed lines with arrows represent fluids pumped from the rig floor and into permeable zones of the formation.

10,000 psi, spinner flowmeter, and a caliper with a maximum reading of 15-in. hole diameter. The nominal resolution of the pressure sensor is 0.01% of the full-scale reading of 10,000 psi. The range and resolution of the spinner flowmeter depend on the diameter of the hole and require calibration at the beginning of the experiment by pumping at known rates while the tool remains in the casing. In the event of a failure of this tool, the high-temperature Japex PTF tool (described in the "Downhole Logging" section, this chapter) could be substituted, as long as hole size information was also collected using the Schlumberger logs.

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