# 2. EXPLANATORY NOTES<sup>1</sup>

## Shipboard Scientific Party<sup>2</sup>

## INTRODUCTION

This chapter is devoted to a description of the sampling, measurement, and core description procedures and analytical methods used during Leg 147.

#### Authorship

The "Introduction and Principal Results" chapter was authored by Mével, Gillis, and the Shipboard Scientific Party. 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 - Gillis, Mével, Shipboard Scientific Party

Operations - Allan, Gillis, McDonald, Mével, Pollard

Sediments - Allan, Natland

- Igneous Petrography Allan, Arai, Dick, Falloon, Malpas, Miller, Natland, Pedersen, Prichard, Puchelt
- Metamorphism Früh-Green, Gillis, Kelley, Lécuyer, Manning, Mével

Structure - Boudier, Célérier, Kennedy, MacLeod

- Geochemistry Allan, Arai, Dick, Falloon, Früh-Green, Gillis, Kelley, Lécuyer, Malpas, Manning, Mével, Miller, Natland, Pedersen, Prichard, Puchelt
- Paleomagnetism Kelso, Kikawa, Pariso, Richter
- Physical Properties Iturrino, McDonald

Downhole Measurements - Célérier, MacLeod, McDonald

Appendixes - Shipboard Scientific Party

Following the text of each site chapter are summary core descriptions (barrel sheets for sedimentary rocks, visual core descriptions for igneous and metamorphic rocks); thin-section descriptions; and photographs of each core. Additional tabulated igneous, metamorphic, and structural data are given as appendixes on the back-pocket CD-ROM.

#### 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.

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. Distinguishing among holes drilled at a site is important, because recovered 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 assigned to individual cores 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). Water depths below sea level are determined by subtracting the height of the rig floor above sea level from the DPM water depth. The depth interval assigned to an individual core begins with the depth below the seafloor at which the coring operation began, and extends to the depth that the coring operation ended for that core (see Fig. 1). For rotary coring (RCB), each coring interval is equal to the length of the joint of drill pipe added for that interval (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. However, coring intervals may be shorter and may not be adjacent if separated by drilled intervals (washed intervals).

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 usually unique in a given hole; however, this may not be true if an interval must be cored twice, because of caving of cuttings or other hole problems. The maximum full recovery for a single core is 9.5 m of rock 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 being retrieved from the hole. Most cores cut during Leg 147 were recovered within Cr-plated or steel-lined core barrels without a plastic liner; these are noted in the "Operations" section of each site chapter.

Each recovered core is divided into 1.5-m sections that are numbered serially from the top (Fig. 2); 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. 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, as many sections as are needed are created 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. In rare cases, a section of less than 1.5 m might be cut to preserve features of interest (e.g., lithologic contacts). The core-catcher 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 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 that do not fit together to protect them from damage in transit and in storage; therefore, the centimeter interval

<sup>&</sup>lt;sup>1</sup>Gillis, K., Mével, C., Allan, J., et al., 1993. Proc. ODP, Init. Repts., 147: College Station, TX (Ocean Drilling Program).

<sup>&</sup>lt;sup>2</sup> Shipboard Scientific Party is as given in the list of participants preceding the contents.



Sub-bottom bottom

Represents recovered material

Bottom felt: distance from rig floor to seafloor

Total depth: distance from rig floor to bottom of hole (sub-bottom bottom) Penetration: distance from seafloor to bottom of hole (sub-bottom bottom) Number of cores: total of all cores recorded, including cores with no recovery

Total length of cored section: distance from sub-bottom top to sub-bottom bottom minus drilled (but not cored) areas in between

Total core recovered: total from adding a, b, c, and d in diagram

Core recovery (%): equals total core recovered divided by total length of cored section times 100

Figure 1. Diagram illustrating terms used in the discussion of coring operations and core recovery.

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 the section. For example, a sample identification of "147-894A-1R-1 (Piece 3, 10–12 cm)" represents a sample removed from Piece 3 in the interval between 10 and 12 cm below the top of Section 1, Core 1 (R designates that this core was taken during rotary coring) of Hole 894A during Leg 147.

All ODP core and sample identifiers indicate core type. The following abbreviations are used: R = rotary core barrel (RCB); B = drill-bit recovery; W = wash-core recovery; and M = miscellaneous material. R, M, and W cores were cut on Leg 147.

## **Core Handling**

#### Sedimentary Rocks

Once on deck, the core is cut into labeled sections. Each section is then sealed at the top and bottom by gluing on color-coded plastic caps: blue to identify the top of the section and clear for the bottom. The caps are usually attached to the liner by coating the end liner and the inside rim of the cap with acetone; then the caps are taped to the liners. The cores are carried into the laboratory, where the sections are again labeled, using an engraver to permanently mark the full designation of the section. The length of the core in each section and the core-catcher sample are measured to the nearest centimeter; this information is logged into the shipboard CORELOG database program.

Cores of soft material are split lengthwise into working and archive halves. The archive half is photographed with both black-andwhite and color film, a whole core at a time. Close-up photographs



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

(black-and-white) are taken of particular features for illustrations, as requested by individual scientists. The archive half is described visually using the VCD computerized data input barrel sheet program. Smear slides are made from samples taken from the archive half and are supplemented by thin sections taken from the working half. The working half of the core is sampled for both shipboard and shorebased laboratory studies. Each extracted sample is logged into the sampling computer database program by the location and the name of the investigator receiving the sample. Records of all removed samples are kept by the curator at ODP. The extracted samples are sealed in plastic vials or bags and labeled.

Both halves of the core are then put into labeled plastic tubes, sealed, and transferred to cold-storage space aboard the drilling vessel. At the end of Leg 147, 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. For samples collected within a lined core barrel, 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 core-log database. These samples are then transferred to 1.5-m-long split core liners. For samples collected within an unlined core barrel, core is pulled from the core barrels using a wire hook, transferred into 1.5-m-long split core liners, and then measured for total recovery. During transferral to the split core liner, 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 done to ensure that orientation is not lost during the splitting and labeling process. If continuous lengths of hard rock >20 cm are recovered, whole-round sections are run through the multisensor track (MST). The MST includes the GRAPE (gamma-ray attenuation porosity evaluator), *P*-wave logger, and magnetic susceptibility instrument. Generally, only GRAPE and susceptibility data are obtained from RCB cores.

The core is then split with a diamond saw into archive and working halves, taking care to represent key core features in both 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 (e.g., 1A, 1B, 1C, etc.). 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. As all pieces are free to turn about a vertical axis during drilling, orientation of the core by azimuth is not possible.

The archive half is drawn on the hard-rock visual core description form, noting size, shape, orientation, and special features of each piece (see "Igneous-metamorphic Core Description" section, this chapter). Three additional core logs noting igneous lithology, pervasiveness of metamorphism, and principal structural features are constructed, as are detailed core description spreadsheet logs. Most archive sections greater than 20 cm in length are run through the cryogenic magnetometer. As with sediment recovery, the archive half is then photographed with both black-and-white and color film, one core at a time. Close-up photographs (black-and-white) are taken of particular features for illustrations in the summary of each site, as requested by the shipboard scientific party.

After the cores were described, the working halves were sampled once a day for shipboard thin sections, physical properties, magnetic studies, X-ray fluorescence (XRF), and carbon-hydrogen-nitrogensulfur analyses. Analytical methods are described later in this chapter, and the data are reported in the site chapters. Where recovery permitted, samples were taken from representative lithologic units for XRF analyses of major and selected trace elements. Additional samples were taken for XRF analyses from selected alteration zones. During Leg 147, samples also were taken from the working halves for shore-based laboratory studies. Each extracted sample was logged into the computer database by the location and the name of the investigator receiving the sample. The extracted samples were sealed in plastic vials or bags and labeled. Records of all samples are kept by the curator at ODP.

Both halves of the core were 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. All Leg 147 cores are housed in the Gulf Coast Repository.

## **IGNEOUS-METAMORPHIC CORE DESCRIPTION**

### **Visual Core Description**

Modified Visual Core Description (VCD) forms that summarize the igneous, metamorphic, and structural features of the core were used during Leg 147 (Fig. 3 and 4). The left column of the form is a graphic representation of the archive half. A horizontal line across the entire width of the column denotes a plastic spacer glued between rock pieces inside the liner. Oriented pieces are indicated on the form by an upward-pointing arrow to the right of the piece. Shipboard samples and studies are indicated on the VCD in the column headed "Shipboard Studies" using the following notation: X = X-ray fluorescence analysis; T = petrographic thin section; M = paleomagnetic analysis; P = physical properties analysis; and D = X-ray diffraction. Lithologic units were distinguished on the basis of igneous criteria and are numbered consecutively downhole. Three additional columns were added to the VCD forms during Leg 147 to record igneous lithology, the intensity of metamorphism, and structural features.

Data from the VCDs were entered into the HARVI computerized database and are available from the computerized database at the ODP repositories. The database is divided into separate data sets for finegrained and coarse-grained rocks. Each record is checked by the database program for consistency and completeness, and is subsequently printed in a format that can be pasted directly onto the barrel sheet for curatorial handling. For each lithologic unit and section, the following information was recorded in the HARVI database system:

A. the leg, site, hole, core number, core type, and section number; B. the unit number (consecutive downhole), position in the section, number of pieces of the same lithologic type, the rock name, nature of the igneous contact, and the identification of the observer;

C. the color of the dry rock;

D. the mineral phases visible with a hand lens and their distribution within the unit, together with the following information for each phase: (1) abundance (volume %); (2) size range in mm; (3) shape (anhedral, subhedral, or euhedral); (4) degree of alteration; and (5) further comments if appropriate;

E. the texture of the rock defined by absolute grain size: finegrained (<1 mm), medium-grained (1-5 mm), or coarse-grained (>5 mm); grain-size changes within units were noted; and relative grain size (equigranular and inequigranular);

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

G. the presence and characteristics of secondary minerals, including their mode of occurrence (void-filling or replacive), association with primary minerals, depositional sequences and overprinting relations, and relationship with rock fabric;

H. the intensity of metamorphism, expressed as the percentage of primary phases replaced by secondary minerals: fresh (<2%); slightly metamorphosed (2%-10%); moderately metamorphosed (10%-40%); highly metamorphosed (40%-80%); and pervasive (80%-100%). This scale for the intensity of metamorphism is graphically represented in a column on the VCD forms as F, S, M, H, and P, respectively; these features are graphically represented in a column on the VCD forms;

I. the presence of veins and fractures, including their abundance, width, mineral fillings or coatings, presence of halos within the adjacent rock;

J. the presence of structural features, including: the orientation of igneous contacts, igneous layering, magmatic fabrics (igneous foliations etc.), solid-state fabrics, cataclastic features, fractures and faults, and veins;

K. other comments, including notes on the continuity of the unit within the core and on the interrelationship of units.

#### **Thin-Section Descriptions**

Thin sections were described to complement and refine the macroscopic descriptions recorded in the VCDs and HARVI database. The rock name, texture and grain size, and a description of primary and secondary mineralogy in terms of modal abundances and mineral habit were recorded on a Thin-Section Description Form (TSDF). Descriptions of textures, overprinting relations, and microstructural features were included in the comment section of the TSDF. Modal abundances were determined by counting at least 1500 points using an automatically advancing stage with an attached counter and/or by visual estimation, and readjusted to add up to 100%. These data were recorded 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 the appendixes and are also available from the ODP computerized database.

## Spreadsheets

In addition to the VCDs, and HARVI and HRTHIN databases, several spreadsheets were designed to facilitate data presentation and to record additional data that were not readily included in the HARVI



#### 147-894G-12R-2

## **UNIT 11: GABBRONORITE**

#### Pieces 1-11

COLOR: Light gray. LAYERING: None, although coarse and fine intervals appear regularly but relationships suggest contacts between these intervals are generally irregular but tend to be vertical or subvertical. DEFORMATION: Minor veining. Steep mineral (magmatic) foliation defined by euhedral to subhedral tabular plagioclase, visible in Pieces 9, 10, and 11. PRIMARY MINERALOGY: Olivine decreasing in amount in this portion of Unit 11. Large euhedral orthopyroxene are more common. Trace apatite in thin section. Plagioclase - Mode: 55%. Crystal size: 0.8-5 mm. Crystal shape: Tabular euhedral to subhedral. Crystal orientation: Partly foliated. Percent replacement: 10% (rare)\_00%. Comments: Grain size is 5–10 mm in coarse intervals and 0.8 to 1 mm in fine intervals. Clinopyroxene - Mode: 20%-25%. Crystal size: 1-10 mm. Crystal shape: Anhedral Crystal orientation: None Percent replacement: 50%-70%. Comments: Grain size is 5-10 mm in coarse intervals and 1-3 mm in fine intervals. Orthopyroxene - Mode: 15%-20%. Crystal size: 1-10 mm. Crystal shape: Anhedral Crystal orientation: None, except minor foliation. Percent replacement: 50%. Comments: grain size is 5-10 mm in coarser intervals and 1-3 mm in fine intervals with the exception of few <1 cm oikocrysts. Oxides - Mode: 1% Crystal size: 3-6 mm. Crystal shape: Anhedral Crystal orientation: None. Olivine - Mode: Trace. Crystal size: 1 mm. Crystal shape: Subhedral. Crystal orientation: Weak foliation in some pieces. Secondary MixeraLogy: Piece 4 contains 2-cm wide pervasively altered zone with secondary plagioclase, fibrous green amphibole after pyroxene. Magmatic vein in Piece 9 is bounded by 3 mm wide alteration zone defined by white secondary plagioclase, amphibole and chlorite. Rare (0.5%) sulfide. Orthopyroxene is in some places rimmed by cummingtonite. Piece 4 contains a 2 mm-wide prehnite + chlorite + zeolite vein with a 0.5 mm chlorite rim. Discontinuous veins of mixed layer clays also present. Total percent: <40% Texture: Alteration is heterogeneous down core, with 5-10 fibrous amphibole after clinopyroxene. Plagioclase altered up to 100% to secondary plagioclase. Clinopyroxene up to 100% to fibrous amphibole. Orthopyroxene to fi-Vein material: In Pieces 4C, 4D, 4E, 4F, 9, 10A, and 10C as 2-mm wide straight veins of chlorite and actinolite with aggregates of quartz and second-ary plagioclase in vein centers. Sinuous isolated veins (0.1–0.3 mm) are of actinolite and chlorite, quartz and actinolite or chlorite, actinolite and prehnite ADDITIONAL COMMENTS: Alternation of fine and coarse gabbronorite visible in some pieces (9, 10, 11). Coarse patches are almost pegmatitic; fine patches preserve a magmatic foliation steeply dipping and in general approximately parallel to coarse-fine boundaries, which are diffuse over a few mm. In Piece 11 the boundary appears at a higher angle to the foliation

Figure 3. Example of hard-rock Visual Core Description Form used during Leg 147.

#### EXPLANATORY NOTES



Figure 4. Hard-rock legend with patterns for the different lithologies and structural symbols.

and HRTHIN databases. These spreadsheets are described in the "Igneous Petrography," "Metamorphism," and "Structural Geology" sections (this chapter) and are included in the appendixes on the associated CD-ROM.

#### SEDIMENT CORE DESCRIPTION

Sedimentary cores are handled differently from igneous rock cores. Shipboard scientists were responsible for visual core logging and thin-section descriptions of sedimentary material. Core liners were not routinely run in the core barrels during Leg 147, and some of the sediment cores were removed by pushing or with the aid of a hose. Therefore, most sedimentary structures were disturbed.

#### Visual Core Descriptions

The visual core description (VCD) forms for sedimentary rocks summarize the data obtained during shipboard analysis of each core and are generated using the ODP in-house Macintosh application "VCD." The following discussion explains the ODP conventions used in compiling each part of the core description forms and the use of "VCD" to generate these forms. Note that these VCDs differ from those used for igneous rocks (Fig. 5).

Core descriptions are initially recorded by hand on standard VCD forms, which record observations at the section scale. Characteristics of the core are illustrated in seven columns and summarized in text form.

The graphic lithology column is a graphic representation of the archive half. The lithology of the material recovered is represented on the core description forms by up to three symbols in the graphic lithology column (Fig. 6). Where an interval of sediment or sedimentary rock is a homogenous mixture, the constituent categories are separated by a solid vertical line, with each category represented by its own symbol. Constituents accounting for <10% of the sediment in a given lithology (or others remaining after the representation of the three most abundant lithologies) are not shown in the graphic lithol-

SI	TE 894 H	101	_E	A CORE	= 1	R	-	CORED 0.0 - 6.0 mbsf
Meter	Graphic Lith.	Section	Age	Structure	Disturb	Sample	Color	Description
1		1		* * * * * * * * * * *	WWW 00000 WWW 0000	т	10YR 6/4 10Y 5/1 5G 4/1 10Y 5/1 10G 4/1	FORAMINIFER-BEARING IGNEOUS LITHIC BRECCIA Minor Lithology: FORAMINIFER OOZE at the top of the core contains 40% sand-sized grains with minor clay derived from altered igneous rocks. Foraminifer content increases up section. General Description: Matrix supported angular clasts consist of diabase fragments up to 5 cm. Matrix
3 4 6		3			WWWW 0000 WWWW 000		2.5Y N4/0	consists of poorly sorted sand-, silt-, and clay-sized fragments derived from altered chloritic igneous material with minor (<10%) foraminiferal and nannofossil ooze. There are rare fragments of fine-grained and glassy basalt. Fining-upward sequences are probably induced by drilling.

Figure 5. Example of core description form ("barrel sheet") used for sediments and sedimentary rocks during Leg 147.

ogy column but are listed in the lithologic description section of the core description form. In an interval comprising two or more sediment lithologies that have quite different compositions, such as in thin-bedded and highly variegated sediments, the average relative abundances of the lithologic constituents are represented graphically by dashed lines that vertically divide the interval into appropriate fractions, as described above. The graphic lithology column shows only the composition of layers or intervals exceeding 20 cm in thickness.

No information was placed in the age column as no paleontologists sailed on Leg 147.

Sedimentary structures in sediment cores, natural structures and structures created by the coring process can be difficult to distinguish. Natural sedimentary structures observed are indicated by symbols entered in the structure column of the core description forms (Fig. 7).

Sediment disturbance resulting from the coring process is illustrated in the disturbance column on the core description forms (using symbols in Fig. 7). Blank regions indicate a lack of drilling disturbance. The degree of drilling disturbance is described for soft and firm sediments using the following categories:

1. Slightly disturbed: bedding contacts are slightly bent.

Moderately disturbed: bedding contacts have undergone extreme bowing.

Highly disturbed: 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 sediments is described using the following categories:

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

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

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;

#### PELAGIC SEDIMENTS

#### Calcareous Nanno-foram or ossil ooze Foraminiferal ooze foram-nanno ooze CB1 CB2 CB3 ous ooze Nannofossil chall Foraminiferal cl CB4 CBS CB Nanno-foram or foram-nanno cha Calcareous chalk Limeston CB CB8 CB9 Siliceous Diatom-radiolarian Diatom ooze Radiolarian ooze or siliceous ooze SB SB2 SB3 Diatomite Radiolarite Porcellanite 4444444 ~~~~ <u>\_\_\_\_</u> AAAAAA 4444A SB6 SB4 SB5 Siliceous clay/ Cher Spiculite claystone .... \$\$ w VV 5 -.... .... SB7 SB8 SB9 NERITIC SEDIMENTS Boundstone Grainstone Packstone Wackeston PPPPPPP PPPPPP PPPPPP PPPPPPP PP P N1 N2 N3 N4 Rudstone Mudstone FFFFFF FFFFFFF FFFFFFFF FFFFFFF N5 NE N7 CHEMICAL SEDIMENTS Sapropels SR6 SB7 SR9 Halite Anhydrite G

#### Figure 6. Key to symbols used in the "graphic lithology" column on the core description form shown in Figure 5.

F3

SILICICLASTIC	SEDIMENTS		
Clay/claystone	Shale (fissile)	Sand/silt/clay	Silt/siltstone
T1	T3	T4	T5
Sand/sandstone	Silty sand/sandy silt	Silty clay/clayey silt	Sandy clay/ clayey sand
10000000000			
T6	Τ7	T8	T9
Gravel	Conglomerate	Breccia	
SSSSSSSSS	8888888		
	66666666	6666666	
	8888888		
SR1	SR2	SR3	
VOLCANICLAS	TIC SEDIMENTS		
Volcanic ash/tuff	Volcanic lapilli	Volcanic breccia	
20.0.0.0.0.0	Estatetetetete		
V1	V2	V3	
SPECIAL ROCK	TYPES		
Matic igneous	Silicic igneous	Metamorphics	
	+++++++++++++++++++++++++++++++++++++++	ままままままま	
	+++++++++++++++++++++++++++++++++++++++	<u>+++++++</u>	
0.010101010101	+*+*+*+*+*+*+	TTTTTT	
SR4	SR5	SH8	
MIXED SEDIME	NTS		
Symbol for least abundant component	->	<ul> <li>Symbol for most abundant compone</li> </ul>	ent
	LIŢL		
	Symbol for component	of	
	interneoiate abbridanc	e	
CONCRETIONS			
(Mn) = Manganese	(P) = Pyrite	(B) = Barite	) = Zeolite
Drawn cir	cle with symbol (others	s may be designated)	
ADDITIONAL S	YMBOLS		
0000000000	155555555	00000000	1000000
888888888	88888888	8888888	
800000000	N666666	66666666	1000000000
AS1	AS2	AS3	AS4
NNNNNN		Realized	
	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX	6333333	
<u> </u>		222222222	
AS5	AS6	AS7	AS8
50000000i			
0000000			

.....

AS12

8.8

8

AS11

8

.....

AS10

20

E1

E2



Figure 7. Symbols used for drilling disturbance and sedimentary structure on core description forms shown in Figure 5.

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

#### Samples

The position of samples taken from each core for shipboard sedimentological analysis, and of whole-round samples removed from the core, is indicated in the samples column on the core-description form (Fig. 5). The symbol D indicates the location of X-ray diffraction samples, and the symbol T indicates the location of thin-section samples.

# Color

The hue and chroma attributes of color were determined by comparison with Munsell Soil Color Charts (Munsell Soil Color Charts, 1971) as soon as possible after the cores were split, because redoxassociated color changes may occur when deep-sea sediments are exposed to the atmosphere. Information on core colors is given in the color column on the core description forms.

## Lithologic Description - Text

The lithologic description that appears on each core description form consists of three parts: (1) a heading that lists all the major sediment lithologies observed in the core, (2) a heading for minor lithologies, and (3) a more detailed description of these sediments, including the location in the core of significant features. Descriptions and locations of thin, interbedded, or minor lithologies that cannot be depicted in the graphic lithology column are included in the text.

#### **Classification of Sediments and Sedimentary Rocks**

With one exception, Leg 147 used the sediment classification scheme of the Ocean Drilling Program (Shipboard Scientific Party, 1990a; Mazzullo et al., 1987). Ooze is defined as unlithified calcareous and/or siliceous pelagic sediments in the ODP classification system; during Leg 147, we used ooze symbols in the VCD lithology column when the sediment was texturally a clastic sediment but composed of pelagic grains. However, we chose to name pelagic sediments "sands" or "silts" when obvious sorting had occurred.

A granular sediment is classified by designating a principal name and major and minor modifiers. The principal name of a granular sediment defines its granular-sediment class; the major and minor modifiers describe the texture, composition, and fabric.

For granular 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 sub-groups (fine sand, coarse silt, etc.).

2. Principal names are listed in order of increasing abundance when two or more textural groups or subgroups are present.

3. The suffix -stone is affixed to the principal names sand, silt, and clay if the sediment is lithified. Conglomerate and breccia are used as principal names of lithified or unlithified gravels having well-rounded and angular clasts, respectively.

## **Major and Minor Modifiers**

The principal name of a granular-sediment class is preceded by major modifiers and followed by minor modifiers (preceded by "with") that describe the lithology of the granular sediment in greater detail. 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 and to describe grain fabric (e.g., matrix supported).

## **IGNEOUS PETROGRAPHY**

#### **Rock Classification**

The igneous rocks were classified on the basis of grain size and the abundance of primary minerals. Based on grain size the rocks were subdivided into aphanitic (only phenocrysts can be distinguished by the naked eye) and phaneritic rocks (all principal minerals can be distinguished by the naked eye). Mafic aphanitic rocks were termed basalt. Basalts were aphyric (<1%), sparsely phyric (1%–2%), moderately phyric (2%–10%), or highly phyric (>10%), depending upon the abundance of phenocrysts. Basalts were further classified by phenocryst type (e.g., a moderately phyric olivine plagioclase basalt contains 2%–10% phenocrysts, mostly plagioclase, with subordinate olivine).

The mafic and ultramafic phaneritic rocks were classified according to Streckeisen (1974) (Fig. 8). The existence of additional mineral phases was shown by a mineral name qualifier (e.g., oxide gabbro or amphibole gabbro), with >5% of that mineral present to use the qualifier.

#### Igneous Lithology

For a complex sequence of plutonic rocks, stratigraphic interpretations are difficult because of overprinting of magmatic and tectonic processes during the formation of the sequence. This uncertainty is amplified by post-magmatic alteration and faulting. The lithostratigraphic units adopted here are mappable divisions defined by changes in modal mineralogy as encountered downhole. This includes abrupt, intrusive boundaries and gradational mineralogical variations. Criteria for these divisions are discussed in the "Igneous Petrography of Holes 894F and 894G" section, "Site 894" chapter (this volume), and the "Igneous Petrology" section, "Site 895" chapter (this volume).

Tabulations include for each unit: lithology; top and bottom recorded with reference to core, section, and piece; curated depth and thickness; and expanded depth. Also included are notes on grain size and textural variations, accessory phases, and contact relationships.



Figure 8. The classification of plutonic rocks that have plagioclase, pyroxene, and olivine as principal components (after Streckeisen, 1974).

Parts of the core drilled but not cored and mixed lithology rubble recovered after reaming and washing the hole are included in the tabulation, but are not considered lithologic units. Calculated expanded depths are based on the algorithm:

expanded depth = depth to top of core + [(curated position in core/total curated length of core recovery) · (length of cored interval)].

This algorithm is based on the assumption that the recovery is representative in proportion and composition of all lithologies drilled in a cored interval. This expansion is only included to enhance graphic representation.

# **Primary Silicate Minerals**

The principal rock-forming minerals were silicates, comprising plagioclase, olivine, clinopyroxene, orthopyroxene, and amphibole. For each of these minerals, the following data were recorded: (1) amount of the silicate mineral in percent, (2) size of mineral grains (measured along the longest axis in mm), (3) the shape of the mineral grains using the terms euhedral, subhedral, and anhedral. If the minerals were euhedral or subhedral, their shapes were described using terms like equant, tabular, platy, etc. (Fig. 9). The size and aspect ratio of plagioclase and pyroxene (clinopyroxene and orthopyroxene) for Site 894 was recorded on a spreadsheet (Fig. 10) located on the accompanying CD-ROM.

## **Igneous Textures**

The texture of igneous rocks represents the geometrical relationships between the main component crystals (and any amorphous materials). Crystallinity, granularity (the absolute and the relative sizes of crystals), crystal shapes and arrangement of crystals are the main properties of texture. The great majority of rocks described were holocrystalline, and the granularity of the rock is, therefore, the first property noted for macroscopic textural features. These rocks were described either as phaneritic or aphanitic.

The absolute ranges of grain size in the rocks were recorded using the terms: very coarse-grained (crystal diameters >30 mm), coarse-



Figure 9. Atlas of crystal forms for igneous minerals.

grained (crystal diameters 5-30 mm), medium-grained (crystal diameters 1-5 mm), and fine-grained (crystal diameters <1 mm). The rocks were subdivided on the basis of relative grain size into equigranular and inequigranular rocks. The equigranular rocks were described as: panidiomorphic granular (bulk of the crystal was euhedral and of uniform size), hypidiomorphic granular (bulk of the crystal was subhedral and of uniform size), or allotriomorphic granular (bulk of the crystals was anhedral and of uniform size). The inequigranular rocks were described as: seriate (crystals of the principal minerals show a continuous range of sizes), porphyritic (relatively large crystals were surrounded by finer-grained groundmass), glomeroporphyritic (a porphyritic texture where the phenocrysts were clustered in aggregates), poikilitic (relatively large crystals of one mineral [oikocryst] enclose numerous smaller crystals of one or more other minerals [chadacrysts]), ophitic/subophitic (a poikilitic texture in which the randomly arranged chadacrysts were elongate and were wholly, or partly, enclosed by the oikocryst), or intergranular (the spaces between plagioclase laths were occupied by one or more grains of pyroxene [± olivine and opaque minerals]). If there was a marked random change in texture within a lithologic unit, it was described as varitextured.

#### **Oxides and Sulfides**

The characteristics of the oxide and sulfide minerals in the core were recorded both on the HARVI and HRTHIN databases.

Oxides and sulfides were classified on the basis of type and texture and, where possible, identified as primary or secondary. The total percentage of these minerals was visually estimated, and the maximum grain size was quoted in millimeters. Magnetite and ilmenite were undifferentiated in hand specimen. Hematite staining was recorded on partially altered olivine. Among the sulfides, an attempt was made to differentiate pyrite and chalcopyrite in hand specimen.

The texture of the oxide and sulfide minerals was described in terms of the habit of the mineral and its relationship with adjacent minerals. Their form was generally described as euhedral, subhedral, or anhedral, and was further subdivided on the basis of shape (Fig. 9). Mineral association was based on either a majority relationship with primary igneous minerals, secondary minerals, or other oxides or sulfides.

#### **Igneous Structure**

In plutonic rocks, igneous structures can be especially important in defining the mechanism of crystallization of the primary mineralogy. Igneous fabric was recorded in the HARVI and HRTHIN databases as homogeneous (or unstructured), varitextured where an abrupt and random variation in texture occurred (in places from coarse [pegmatitic] to very fine grained), layered where distinct sheet-like cumulate

units exist, and laminated where thin (<1.0 cm), sharply defined units occurred. Where visible, graded layers were defined as modal if the primary mineralogy showed gradational changes, grain size where there was a gradual increase or decrease in the size of primary mineral crystal, or textural where there was a gradational change in texture (e.g., from poikilitic to granular). The sense of grading is related to stratigraphic direction. Normal stratigraphic grading was recognized as either from coarse to fine grain size upward or from dark to light mineralogy upward in a layer. Reverse grading was considered the opposite. Where crystal alignment of probable igneous origin was observed, this was recorded as foliated or lineated. The morphology of the layers was recorded as planar when flat, curved planar when simply curved, or irregular planar when more complicated. The orientation of any planar structure was recorded by measuring apparent dips and strike and calculating true dip (see "Structural Geology" section, this chapter).

## **Thin-Section Description**

Thin sections of igneous rocks were examined to complement and refine the hand-specimen observations. In general, the same type of data was collected from thin sections as from visual description, and a similar terminology was used. Some additional textural features were recorded. Aphanitic rocks were distinguished either as microcrystalline (crystals can be identified in thin section with a petrographic microscope) or as cryptocrystalline (crystals are too small to be identified with a microscope). Crystal sizes were measured using a micrometer scale. The presence of inclusions, overgrowth, and zonation was noted, and the apparent order of crystallization was suggested. The presence of accessory minerals such as apatite and zircon was noted.

The oxides and sulfides in each thin section were described in terms of size, abundance, mineralogy, shape, texture, and their association with each other and with the host silicate minerals. Where possible, the origin of oxides and sulfides (primary or secondary) was noted. The percentage of oxides and sulfides present was visually estimated.

## METAMORPHISM

## Introduction

Visual core descriptions of metamorphic and vein characteristics were conducted together with igneous and structural documentation of the core. This information was recorded to provide three types of data: (1) the extent of replacement of igneous minerals by metamorphic, or secondary minerals; (2) the extent to which metamorphic minerals contribute to any subsolidus fabric found in the core; and (3) the abundance and character of veins and associated wall-rock alteration, or vein haloes. The timing of metamorphic crystallization, the overprinting relationships between secondary minerals, and the crosscutting relationships of veins were reported in the comments of the HARVI database. To ensure accurate core descriptions, thin-section petrography of representative samples was integrated with visual core descriptions where possible. Identification of vein-filling material was checked with X-ray diffraction (XRD).

For each core section, the following information was recorded in metamorphic mineral and vein log spreadsheets given on the accompanying CD-ROM (Figs. 11 and 12): the leg, site, hole, core number, core type, section number, piece number (consecutive downhole), and position in the section. Igneous lithologies, as defined above, were recorded in the mineral and vein spreadsheets. Table 1 lists abbreviations for lithology, color, and mineralogy that were used in the spreadsheets.

#### Macroscopic Description

The metamorphic mineral spreadsheet given on the accompanying CD-ROM (Fig. 11) summarizes the macroscopic core description of secondary mineralogy. This data is also given in the HARVI database.

C 2R 2R 4R	S	Р	cm	1 1		A Real Property lies and the second se					
2R 2R 4R			em	mbsi	Lith	Unit	max. mm	avg. mm	max. mm	Avg. mm	Aspect ratio
2R 4R	1	1	3	28.63	OG	1	5	3	5	2.5	4.8
4R	2	19A	140	31.5	OG	3	4.5	3	4	2	4.4
	ĩ	2	10	45.1	Rubble	-	6	3	3	2	3.9
4R	î	10	58	45 58	GN	4	12	4	4	2	4.2
4R	î	15	107	46.07	GN	4	8	4	65	3	35
AR	2	7	36	46.68	GN	4	6	3	3.5	2	3.2
AD	2	é	44	46.00	CN	7	28	5	9	5	26
AD	2	11	86	40.77	CN	4	6.5	35	25	25	2.0
4R	2	1	10	47.19	OCN	4	0.5	3.5	5.5	2.0	3.7
SR CD	1	2	12	50.12	CN	5	5.5	4	4	2	3.9
OK	1	1.	4	54.84	GN	0	1.5	4	5	3	4.2
OK	1	4A	50	55.5	GN	0	12.5	4	5	2	3.4
6R	1	8A	83	55.63	GN	6	9	5.5	11	3	3.5
6R	2	1	13	56.36	GN	6	12.5	5.5	12	5	2.7
6R	2	5C	61	56.84	GN	6	9	4	3.5	1	3.5
6R	2	10	115	57.38	GN	6	6	3.5	3.5	1	3.7
6R	2	10	121	57.44	GN	6	7.5	5	5	2.5	2.9
7R	1	9	45	65.25	GN	6	8	4	6.5	2.5	3.7
7R	1	14	94	65.74	GN	6	12.5	5.5	11	4.5	3.2
7R	2	1	10	66.31	GN	6	9.5	5	7	3	3.5
8R	ĩ	2	14	68 64	GN	6	7	4	11	3.5	3.1
8R	î	10	127	69.76	GN	6	7.5	25	7	3	2.0
8D	2	10	97	70.80	CN	6	5	2.0	5	3	3.2
OP	2	60	20	70.09	CN	6	11.5	3	6.5	1	2.0
OD	4	15	59	74.79	GN	0	11.5	4	0.5	4	3.0
9R	1	15	102	75.42	GN	0	1	3.5	5	2.5	5.5
9R	2	IB	18	75.79	GN	6	9	3.8	9.5	4	3.4
9R	2	5D	105	76.67	GN	6	7.5	3	4.5	2.5	3.5
9R	4	12	140	79.71	OGN	7	6	3.5	4.5	2	3.7
10R	1	17	125	80.36	G	8	6	3	3	1.5	3.8
11R	2	8	74	86.31	GN	9	8.5	3	3	1.5	3.8
11R	2	12	123	86.8	GN	9	6.5	3	3.5	2	3.6
11R	3	1	4	87.05	GN	9	10	4.5	6.5	4	3
11R	3	9	66	87.67	OGN	10	5	3	5	2.5	3.1
12R	1	2	22	94.02	GN	11	9	4	7	3	2.8
12R	1	6	47	94 49	GN	11	6	3	6	3	2.6
12R	î	12D	122	94.8	GN	11	10	5	10	5	3
12R	2	QA	04	06.26	GN	11	6	3	0	Ă	25
12P	õ	0A	04	06.26	GN	11	2	1	2	1	4
120	õ	11	140	06.71	CN	11	4	2	2	15	3.4
120	2	7.4	140	90.71	CN	11	10	5	12.5	7.5	2.9
120	2	27A	00	97.41	ON	11	10	2	12.5	25	4.1
128	5	80	81	98.22	GN	11	4	3	4	2.5	4.1
12R	4	3	24	98.48	GN	11	1	4	0	2.5	3.4
12R	4	14	132	99.57	GN	11	7.5	5	5	3	3.9
12R	5	1	4	99.79	GN	11	11	4	5	3	3.3
12R	5	11B	125	101	GN	11	10	3	4	3	3.2
12R	6	1	6	101.2	GN	11	9	4	4	2.5	3.7
12R	6	5C	44	101.6	GN	11	9	4	8.5	2.5	3.8
13R	1	4	26	103.7	GN	11	7	4	6	3	3.7
13R	1	6	39	103.8	GN	11	11	6	10	5	2.8
13R	1	14	127	104.7	GN	11	6	3	6	4	2.5
13R	2	1	8	104.9	GN	11	14	9	15	8	3.3
13R	2	5	36	105.1	GN	11	12	4	7	3	4.4
13R	2	104	119	106	GN	11	10	5	8	35	3
138	3	1	12	106.4	GN	11	8	4.5	11	4	30
130	3	2	31	106.4	CN	11	10	5	12	5	27
120	2	4	31	100.5	CN	11	10	5	12	36	2.7
138	2	2	40	106.7	GN	11	10	5	0	3.3	2.1
1.5K	3	Э	04	106.9	GN	11	8	2	/	3.5	3

Figure 10. Example of the grain size spreadsheet used for Site 894. C = core; S = section; P = piece number; cm = cm from top of the section; mbsf = meters below seafloor; Lith = lithologi; Unit = lithologic unit; max. mm = maximum size in millimeters; avg. mm = average size in mm. Lithologic types: G = gabbro; OG = olivine gabbro; GN = gabbronorite; OGN = olivine gabbronorite; B = basalt.

Primary phases and the secondary minerals that replace them were noted, and the volume percent of each phase was estimated in hand specimen and checked by modal analysis of thin sections. Portions of pieces where primary textures were ambiguous or obliterated by secondary minerals were termed patches. Characterization of these patches in the metamorphic mineral spreadsheet included mineralogy, size, and an estimate of volume.

Alteration intensity was classified as follows: fresh (<2%), slight (2%–10%), moderate (10%–40%), high (40%–80%), and pervasive (80%–100%). A column on the (VCD) shows the variation in alteration intensity in the core. Note that alteration intensities are independent of changes in lithologic units defined by igneous features.

## **Description of Metamorphic Fabric**

Where metamorphic minerals are included in fabric elements such as shear zones, mylonites, or foliations, textures and associated minerals were recorded in the HARVI database. Of special interest was where the original igneous character was modified by subsolidus deformation. Textural features noted included identities and abundance (volume %) of porphyroclasts, neoblasts, and minerals associated with the fabric.

Breccias were defined as intervals of angular fragments in which clast rotation could be documented. Portions of the core crosscut by dense vein networks may appear to be "brecciated," but if matrix clasts cut by the veins were not rotated, these features were described as net veins (see below). Characterization of breccias included clast lithology and secondary mineralogy, matrix mineralogy, and abundance of clasts and mineral phases.

## **Description of Veins**

Veins were defined as linear cracks partially or completely filled by secondary minerals. Fractures were taken to be linear cracks with

1 able 1. Static and uynamic metamorphism appreviations	Table	1. Static and	I dynamic	metamorphism	abbreviations
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	1	Mineralo	egy		Texture/Fabric	С	olor
ab act amph anth ap arg atg ben bi br	albite actinolite amphibole anthophyllite apatite aragonite antigorite benitoite biotite brucite	hb hgr idd ilm liz mgs mt np olv opx	homblende hydrogrossular iddingsite ilmenite lizardite magnesite magnetite neptunite olivine olivine	bx cat dv fol fr grm myl sb sz uc	breccia cataclastic densely veined foliated fractured groundmass mylonite shear band shear zone ultracataclastic	bl blk br dk gr lt w	blue black brown dark green light white
cc chal chl chy cly cpx csp cu cum cz ep FeOx fu gar	chalcopyrite chlorite chlorite clay clinopyroxene chrome spinel native copper cummingtonite clinozoisite epidote iron oxide fuchsite garnet	ox plg pre py pyrh qtz scpx ser spl tlc tr tt ves zeo	oxides plagioclase prehnite pyrite pyritotite quartz secondary clinopyroxene secondary plagioclase talc tremolite titanite vesuvianite zeolite				

no mineral fill. The term halo was used to describe spatially related alteration of rock matrices adjoining cracks. Note that both veins and fractures may have haloes.

At Site 894, a vein spreadsheet (Fig. 12) was used to assist in recording information about veins and their associated alteration haloes in the core. Individual vein types were identified by color and mineralogy. Data on abundance, width (mm), orientation, and texture and abundance of vein-filling minerals were recorded for each piece containing one or more veins. In pieces with more than one vein, veins were numbered sequentially from the top of the piece in conjunction with recording data for the structural spreadsheets (see below). Documentation of vein-related alteration haloes included halo type (based on color and mineralogy), halo width, and abundance of haloes as percentage of the piece containing them.

A key parameter in the characterization of vein-related metamorphism is linear vein density (number of veins per unit distance). Calculation of linear vein densities from cored rocks is problematic for two reasons. First, the probability of intersecting veins is a strong function of vein orientation, such that, in a network of veins with varying orientations, the densities of those at a high angle to the axis of the core will have a higher apparent density than those at a low angle. Second, core is typically recovered as centimeter- to decimeter-sized pieces that may or may not represent the entire cored interval. In archiving the pieces, spacers are placed between each piece of core, and measurements relating the distance from the top of a section of core to a feature of interest may or may not include the artificially added space between pieces. The discrepancy between curated core length and cumulative length of recovered pieces is illustrated in Figure 13.

We adopted two conventions to characterize vein density consistently. First, vein locations were measured at the centers of the pieces rather than at either side to establish a consistent measuring location and minimize problems associated with locating veins that do not intersect the side of a piece (Fig. 13). This location was entered in the vein spreadsheets under the column of cm'. In combination with the distance from the top of each section to the top and bottom spacers bounding the piece (cmt and cmb in the vein log respectively), cm' allows relocation of particular veins. To calculate vein densities, we added the actual lengths of each piece (top to bottom), not including the spacers. Because the sum of all piece lengths represents total recovery, calculated vein densities reflect the density actually observed in the rocks recovered and do not include arbitrary space introduced during curation. For example, Figure 13 shows that the sum of the lengths of each piece, or cumulative piece length, is 26 cm. The three veins found in this section thus yield a linear vein density of 0.12 veins cm<sup>-1</sup>.

## **Thin-Section Description**

Detailed petrographic descriptions were made on board to aid identification and characterization of metamorphic and vein mineral assemblages. For each thin section, textures of metamorphic minerals were described. Abundances were either visually estimated or determined by point counting. This information was recorded in the HRTHIN database. The modal data allowed accurate characterization of the extent of metamorphism and helped to make more accurate the macroscopic and microscopic visual estimates of alteration extent.

# STRUCTURAL GEOLOGY

## Introduction

Systematic structural studies have yet to become standard procedure on ODP legs. Occasional exceptions have included, for example, Legs 131 (Nankai Trough) and 134 (New Hebrides Trench), during which specific objectives that potentially could be addressed by such studies had been identified from the outset. Because of this piecemeal approach to the structural geological description of ODP core, there has been little standardization either of methodology or nomenclature. For Leg 147, we adopted a convention for the measurement and description of core that is an adaptation of those developed on Legs 118, 131, 135, and 140. This section explains the terminology used for the macroscopic and microscopic description of structures in the core, details the convention adopted for the measurement of planar and linear structural features, and the means by which the reorientation of such features to geographical coordinates was attempted.

#### **Macroscopic Core Description**

The intention of the structural core description records is to identify and describe in a systematic and quantitative way all the structural information present in the core, and to record its orientation. All material, from both working and archive halves, was examined, although orientation measurements were largely made on the archive half. Depths were recorded at the intersection of a feature with the center-line of the core; and where several features of the same type occurred at the same depth or in the same core piece, feature numbers

				Inte	erval										_	After					Total	
					ci vai	-	Lith	After						After		other and			AD		alteration	V
Hole	С	S	Р	т	В	Lith	Unit	Olivine	%	After plag	%	After cpx	%	opx	%	unknown	%	Patches	cm	%	(%)	Comments.
B B	1	1	1 2	0.0 2.0	2.0 8.0	G G	$1 \\ 1$	Ξ	-	spl, chl spl, amph	90 70	=	0 0	-	-	amph,chl amph,chl	100 60	-	-	Ξ	95 60	Fine anastomosing networks of cly + gr- amph veinlets, 1mm in width, medomiantly cutting placing large
в	1	1	3	9.0	14.0	G	1	_		spl,amph	70	amph	40			amph,chl	80		_	_	65	Similar to Piece 1; anastomosing veinlets of gr-amph, 0.2 mm.
B*	1	1	3	8.0	12.0	G	1	-		spl, amph, cly	83	amph, scpx, cly?	90			amph	36		-	-	91	Anastomosing veinlets of fibrous green- yellow amphibole.
D	2	1	1-2	0.0	18.0	в	2	-	-		—	-			_	-			-	-	0	Fresh aphanitic basalt.
E	2	1	2	9.0	12.0	G	1			spl?	?	amph, chl	40		-			1.1.2		_	40	
E	3	1	1-4	0.0	25.0	G	3	-		spl	15	amph	60	_	—	amph	30		-		40	3 pieces.
E*	3	1	4	19.0	21.0	G	3	-	-	spl,amph,cl y, chl	68	amph, scpx, cly, FeOx?	92		-	-			-		56	Plagioclase is cut by fine chl pale green fibrous amphibole veinlets.
E	3	1	5-6	26.0	39.0	B	3		-	spl	50	amph, chl	30	_	-				-		30	2) 2)
E	3	1	7-11	41.0	82.0	G	3			spl,amph	75	amph	80	_	_				_		80	Amph veinlets cut plagioclase; discontinuous splag + gr-amph veinlets (3-5 mm).
E*	3	1	8	50.0	53.0	G	3	—	-	spl,amph,cl y ep	53	amph, scpx chl, FeOX, cly?	88	_	_	_		-	_	-	70	Alteration is heterogeneous. Sample is cut by a discontinuous chlorite veinlet w/minor fibrous amphibole, and a veinlet of clav?.
E*	3	1	10	70.0	73.0	G	3		-	spl,amph,ch l cly	55	amph, Scpx FeOx, cly?	87		Η.	-		_	-		75	Trace epidote, sample is cut by .45 m wide prehnite veinlet that is bounded locally by low-birefringence chlorite. Also cut by a very fine veinlet of calcite .16mm in width.
F*	1	1	1	2.0	9.0	G	1	-	-	spl,cly,chl	80	amph,chl, scpx				cly,qtz	45					Foliated cataclastic gabbro with alternating zones of ultracataclasites
F F	1 2	1	3-7 1-2	15.0 0.0	41.0 22.0	G G	1 1	$\equiv$	Ξ	spl,chl spl	70 65	amph amph	50 50	1	Ξ	Ξ	0 0	-	Ξ		65 60	Cut by fine chlorite? veinlets. Piece 1 cut by amph veinlet, Piece 2 cut
F*	2	1	1	5.0	7.0	G	1	-	-	spl,amph	90	chl,scpx, amph,mt	80	-		-					43	by splag-amph veinlets. Brown and olive green amphibole after cpx. Cut by actinolite and chlorite veinlets.
F	2	1	3	26.0	35.0	G	1			spl,cly	75	amph	50	_			0		-		80	
F* F	2 2	1 1	3 4-7	32.0 36.0	35.0 57.0	G G	1		$\equiv$	spl,cly spl,cly	65 95	chl,amph, scpx amph, chl	90 90	_	$\equiv$	cly cly	30 5		-	-	73 95	Cataclastic gabbro. Highly altered cataclasite. Piece 7
F*	2	1	7	54.0	56.0	G	1	-	-	spl,cly	90	amph, chl	90		_	-			-	-	-	contains mylonite(?) zone. Cataclastic gabbro cut by 2 distinct shear
F	3	1	1	1.0	6.0	G	1	-	_	spl, ep	80-	amph, chl	60	_	-	-		100	-	-	70-80	zones. Cut by chlorite veinlet. Incipient fractures.
F	3	1	2-3	6.0	15.0	G	1	-	-	spl	40	amph, chl	30	-	—	chl	5		—	-	40	
F	2	1	4	4.0	21.0	G	1	_	_	spi	40	ampn, chi	50		_	chi	5		_		43	
F	3	1	5	21.0	21.0	G	1	_	_	col	30	amph chl	20		_	chl	10		_	_	55	Secondary plag patchy
F*	3	1	5	30.0	33.0	G	1	_	=	spl	30	amph, chl, scpx	40	—	=	<u> </u>		700 700	=	_	33	Local microshearing. Sample is cut by
F F	3 3	$\frac{1}{1}$	6 7	34.0 39.0	39.0 45.5	G G	$\frac{1}{1}$	_	_	spl spl, ep	10 100	chl amph	40 40		Ξ	1		chl	Ξ	20	75	Contains ultracataclastic shear zone. Clast-supported breccia, matrix defined by chl + ep.
F	3	1	7	39.0	45.5	G	1	-	-	-	$\sim$				-	-	-	ep	·	10		
F	3	1	8	45.5	51.0	G	1			0.000			-	1.171	-	qtz,ep	40	epi	-	50	100	Matrix-supported breccia, matrix defined by chl + ep.

Figure 11. Example of the metamorphic mineral spreadsheet used during Leg 147. C = core; S = section; P = piece number; T = top of interval measured in cm from top of the section; Lith = lithology; Lith Unit = lithologic unit; After olivine, After plag, After cpx, After opx = secondary phases replacing olivine, plagioclase, clinopyroxene, orthopyroxene, respectively; % = percentage of the primary mineral actually replaced; AD = average diameter. \* = Sample description based on thin-section analysis. Lithology abbreviations are given in Figure 10; mineral abbreviations are listed in Table 1.

#### EXPLANATORY NOTES

									Vein	Width	Length	Halo	
н	С	S	Р	cmt	cmb	cm'	Lith	Unit	color	(mm)	(cm)	minerals	Comments
E	3	1	11	76.0	82.0	79.0	G		pale green	0.3	6.0		Anastomosing veinlets coalescing as one vein system
E	3	1	11	76.0	82.0	81.0	G		pale green	0.1	3.5		
F	1	1	4	19.0	23.0	19.5	Ğ	1	white	0.5	2.0		Forms small lense
F	2	1	1	0.0	10.2	51	Ğ	î	lt green	01	95		
F	2	î.	20	13.5	22.8	18.0	G	÷.	lt green	0.1	80		On fracture surface
F	2	î	20	13.5	22.0	20.5	G	1	lt green	0.1	4.0		On Interare Surnee
F	ñ	1	20	26.0	24.5	21.0	G	1	n green	0.1	2.0		Terminetes in a cataclastic/braccia
г	2	1	Ja	20.0	54.5	51.0	G	1	pare green	0.1	5.0		Zone
F	3	1	1	0.0	6.0	0.5	G	1	dk green	0.2	4.5	spl in plg	Straight
F	3	1	1	0.0	6.0	1.2	G	1	dk green	0.2	4.5		0
F	3	1	1	0.0	6.0	2.0	G	î	dk green				Some open space
F	3	1	2	6.0	9.0	64	G	î	dk green	0.1	25		a sine of su of sus
F	3	î	3	9.0	15.0	11.0	G	1	dk green	0.5	Mar.		
F	3	÷.	3	0.0	15.0	12.5	G	î	dk green	0.5			
F	2	1	2	9.0	15.0	12.5	G	1	dk green	0.5			
F	2	1	3	9.0	15.0	14.0	0	1	dk green	0.5			12
P	3	1	4	15.0	21.0	18.0	G	1	green	2.0	5.5		Anastomosing veins
F	3	1	5	21.0	34.0	21.0	G	1	white	1.0	8.0		1 main vein, numerous discontinuous veins
F	3	1	6	34.0	30.0	35.0	G	1	dle aroon	1.0	25		discontinuous venis
F	2	1	12	67.5	39.0	55.0	G	1	dk green	1.0	2.5		Several exectomoring vains in hy
r r	2	- ÷	14	07.5	05.0	08.5	0	1	dk green	1.0	4.0		Several anastomosing venis in ox
r	2	1	14	11.5	85.0	81.5	G	1	white	2.0	0		Dense spi veins up to .5cm wide
F	3	1	15	85.0	91.0	86.0	G	1	dk green	1.0	3.0		
F	3	1	16	91.0	91.0	97.5	G	1	brown		5.0		brownish vein (carb?). Some plg bx 3 pieces, cataclastic
F	3	1	19	116.0	123.5	118.0	OG	3	lt green	1.0	5.0		Chl selvage
F	3	1	20	123,5	132.0	123.5	В	3	lt green	0.5	3.5		Chl selvage
G	1	1	1	0.0	6.0	1.5	OG	1	dk green	2.5	2.0		Irregular width
G	1	1	2	6.0	17.0	8.5	OG	1	dk green	0.8	6.5		This vein and next linked by 3rd, smaller vein
G	1	1	2	60	17.0	95	OG	1	dk green	0.5	52		
Ğ	1	î	2	6.0	17.0	90	OG	î	dk green	0.5	20		
Ğ	2	î	2	127.0	50.0	57.0	P	2	ukgreen	20	2.4		1 years off yoin 1 connects with 2
G	2	÷.	0	55.0	50.0	57.0	D	2	white	0.4	2.4		1 very son, veni i connects whit 2
G	2	1	0	55.0	39.0	57.0	D	4	white green	0.4	6.0		2
0	2	1	9	33.0	77.0	02.0	Б	2	white	0.8	0.0		1
G	2	1	9	59.0	77.0	70.0	в	2	lt green	0.5	5.3		2
G	2	1	9	59.0	77.0	71.0	в	2	white	0.8	4.5		3 sinuous
G	2	1	9	59.0	77.0	73.0	B	2	brown green	0.8	5.5		4 cut by 3
G	2	î	ó	59.0	77.0	62.0	B	2	lt green	0.1	3.0		5 cuts 1
č	2	÷.	10	77.0	92.0	78.0	D	2	it green	0.1	3.0		5, cuts 1
č	2	1	16	122.0	107.0	125.0	D	4	ak green	0.2	2.5		C1
G	2	1	10	123.0	127.0	125.0	B	2	It green	1.0	2.8		Sinuous
G	2	1	17	127.0	135.0	132.5	В	2	It green	0.8	2.0		
G	2	1	18	135.0	144.5	138.0	В	2	yellow green	0.8	4.8		1, zonation
G	2	1	18	135.0	144.5	142.0	в	2	lt green	0.4	4.8		2
G	2	2	3	9.0	16.0	10.0	В	2	dk green /	0.8	5.5		White lens-shaped patches of
G	2	2	2	0.0	16.0	12 5	р	2	white dlt brown	0.5	2.1		Terminates into vein 1
0	4	2	3	9.0	10.0	13.5	в	2	ak brown-	0.5	2.1		reminates into vein 1
G	2	2	4	17.0	22.0	18.0	в	2	lt green	0.3	5.5		

Figure 12. Example of the vein spreadsheet used for Site 894. H = hole; C = core; S = section; P = piece number; cmt = location of the top of the piece in the core; <math>cm' = the location of a vein within a piece; Lith = lithology; Unit = lithologic unit. Lithology abbreviations are given in Figure 10.

were assigned for convenience (e.g., vein #1, vein #2, etc.), although we stress that these have no chronological significance. Wherever possible, this was done to ensure compatibility with the shipboard metamorphic petrology descriptions (see above). Core was drawn, and features noted and measured by hand on a working structural VCD form (Fig. 14); data also was entered into the HARVI database and structural data spreadsheets given on the accompanying CD-ROM (Fig. 15). Thin-section descriptions were recorded on separate sheets, as discussed below.

In an attempt to achieve consistency of nomenclature, a working terminology for macroscopic features was developed that subdivides them for the purposes of initial core description as follows:

-igneous contacts

-magmatic fabrics (igneous foliations etc.)

-fractures and faults

-veins

By subdividing core features thus, it is not implied that these features fall into distinct pigeonholes. Clearly there is gradation and even overlap, but particular aspects were emphasized by adding modifiers, descriptive comments, and sketches. They are discussed in more detail below. For Site 894 we attempted a pseudo-quantification of the intensity of penetrative fabrics and non-penetrative deformation on the working structural VCD form (Table 2; Figs. 14 and 15), in a similar manner to that attempted on Leg 118. However, the system was not found to be very informative and therefore was not used at Site 895.

## Nomenclature

The nomenclature used for penetrative rock fabrics in gabbros from Site 894 is based upon but extensively modified from that established for the gabbros of Leg 118 (Robinson, Von Herzen, et al., 1989). A further distinction is made between fabrics defined by the preferred orientation of the long axes of inequant crystals, formed in response to magmatic flow, and crystal lattice fabrics formed by solid-state deformation processes.

<sup>-</sup>igneous layering

<sup>-</sup>solid-state fabrics

<sup>-</sup>cataclastic features



Figure 13. Schematic core showing method of locating veins and method of calculating vein density. The values cmt, cmb and cm' allow relocation of individual veins (see text for definitions of these parameters). For pieces with more than one vein, such as Piece 2, veins are numbered sequentially from the top of the piece.

The strength of the magmatic flow fabric can be considered in terms of the degree of preferred orientation of the maximum length of inequant minerals (here typically the cumulus phase or phases) in a plane perpendicular to the foliation and parallel to the lineation (if present). Quantification of the intensity of the fabric goes beyond the scope of our shipboard studies, so only subjective judgments were made, based on hand specimen, and checked, wherever possible, by thin-section description. We have, therefore, made only a qualitative subdivision of this fabric, from grades 0 to 3, as outlined in Table 2. This subdivision was noted under column M on the visual core descriptions for Site 894 and, later, on the structural data spreadsheet.

A deformation log for solid-state (plastic) deformation fabrics (under column D on our VCDs and structural spreadsheet) is included (Table 2), following previous convention in defining six "grades" of deformation from 0 to 5. This subdivision encompasses both penetrative and nonpenetrative fabrics, recognizing, of course, that a complete gradation exists between the two. In contrast to the Leg 118 gabbros, however, no evidence for solid-state deformation was observed in any of the Site 894 cores.

We emphasize that no direct or quantitative relationship between the intensity of deformation (in terms of percentage strain) and texture is implied for any of the deformation logs, although in general they are clearly consistent with increasing degrees of deformation. The principal advantage of these classification schemes is that they allow different observers to make consistent observations and, therefore, allow a semi-quantitative estimation of the *relative* variations in fabric development from interval to interval or site to site.

For brittle deformation we have distinguished between the process of cataclasis (i.e., the translation, rotation, and consequent grain-size reduction of finite volumes of rock in response to shear) and simple fracturing on a discrete surface. Although the deformation processes are different, the macroscopic appearance of mylonites and cataclasites may be very similar; hence we have attempted to erect a classification scheme for cataclastic textures that parallels that of the solid-state deformation fabrics (again, from 0 to 5 under column C; Table 2).

Fractures and faults are distinguished from each other on the basis of reasonable evidence for displacement in the latter (and accordingly rated 2 as opposed to 1 under column F on our VCDs). Reasonable evidence for displacement includes truncation or offset of passive markers and observation of slickenlines, although care was necessary to distinguish the latter from drilling-induced polishing and striation of vein and fracture surfaces. The presence of fault gouge or breccia also was taken as an indication of displacement, but was noted on our VCDs and spreadsheet in the cataclasis column.

Veins are characterized by their fill, width, and presence or absence of an alteration halo; their study was made in close conjunction with the shipboard metamorphic petrologists. The subdivision used during Leg 147, from 0 to 3 (Table 2), differed slightly from the other deformation features in reflecting the intensity of veining in any one core piece. Occurrence of a solitary vein with demonstrable offset across it would, therefore, rate a 1 in the vein column (V) but 2 in the fault/fracture column of our VCD and spreadsheet (Figs. 14 and 15).

#### Measurement of Structures

Planar features traversing the core can be measured in several ways. We adopted the convention established on Leg 135 (MacLeod et al., 1992; Parson et al., 1992), which is itself an adaptation of the systems of measurement used during Legs 131 and 134. The plane normal to the axis of the borehole is referred to as the apparent horizontal plane. On this plane a  $360^{\circ}$  net is used with a pseudo-north (000°) at the bottom line of the working half of the core, the same convention as that used for shipboard paleomagnetic studies (Fig. 16). The face of the split core, therefore, lies in a plane striking  $090^{\circ}-270^{\circ}$  (core coordinates) and dips vertically. An apparent dip can be measured on this surface (using a protractor-based instrument similar to that described in the Leg 131 *Initial Reports* (Taira, Hill, Firth, et al., 1991; Fig. 17A) and its sense indicated, whether toward  $090^{\circ}$  (E) or

Table 2. Deformation categories used in macroscopic core description.	

Category:	0	1	2	3	4	5
Magmatic	Isotropic: no shape fabric	Weak shape fabric	Moderate shape fabric	Strong shape fabric		
Ductile	Crystallographic fabric absent	Weakly foliated	Strongly foliated	Porphyroclastic (proto)mylonite	Mylonite	Ultramylonite
Cataclastic	Undeformed	Dense anastomosing fracturing and incipient brecciation.	Well-developed fault brecciation; rotation of clasts with minor trans- lation possible	Protocataclasite: rotation, trans- lation and grain size reduction necessary	Cataclasite	Ultracataclasite
Fracturing	Unfractured	Minor fracturing, no observable displacement	Minor observable displacement (i.e. = fault)	Major faulting		
Veins	No veins	Occasional veins (= filled fractures)	Moderate veining	Intense vein networks		

Structural visual core descriptions:

Site 894	Hole:	G	Core:	GR	Section	: 1	OBS:	CJM		Da	ate:	25	Dec
Piece # ARCHIV	(E	Feature	Descr	iption	FINE-M	DIUM	GRAINED					155.	2
cino		NOF			ISOTROP 1	C	HKOUGHOU	T	м	D	С	F	۷
#1		ORIENTED							0	0	0	0	0
#2	2	ORIENTED	(0.34	nm ch	lonte vein )			t	0	0	0	1	(
#3	$\geq$	ORIENTED						Ī	0	0	0	0	0
14		VEINS:						ł	_	-		_	_
#4	E to meet a to a	$ \begin{array}{c}         0 45 E \\         0 35E \\         0 35E \\         0 72 w \\         vel \\         0 35C \\         0 35C \\         0 35C \\         0 35C \\         0 400 \\       $	48 N 25 N 68 town 5 20 5 21 N 5 21 N 5 21 N 6 24 19 10 10 10 10 10 10 10 10 10 10	0 0 1 1 1 1 1 1 1 1 1 1 1 1 1	2 may dark o 2 man light o 2 man light o 3 man dar 0.3 man dar 0.4 lonte + chlorite + the lerite +	green ch actinolit Green clay & F & green clay & green clay the green cla timolite ock alt or green ite prehnite	llonite e e hlenite chlenite y prob. + chlenite eration chlonite		0	0	Ø	(	2
#5 +	Chill for	VEIN 3: 55 W 3 42 V 45 47 45 43 6 32 7 63 8 70 9 48 10 68	334 3 3 N 3 25 N W	shr. 1 170 . 139 . 355 20 cur . 173 . 223	0.3 m chlo, 1.2 mm dore 0.3 mm chlo ? chlo ? chlo ? chlo ? chlo ? chlo ? 0.3 mm ch > 0.3 mm ac By Vein (E 2 mm chl 0.2 mm chl	nte-pred green ch onite - pr onite - cl lorite - p hlorite - p timolite onte - pred chlorite -	imite ionite-prohm chaite ay rehaite schaite haite clay	ke	0	0	0	1	2
#6	フ	NO T ORIEN TED					,		0	0	0	1	1

Figure 14. Layout of the working Structural Visual Core Description form.

_															_							Comb	Ined		Lin	_	Comb	ined Lin	
				Feature				Feature	Feature	Sense	Offset						App		App		App	Conto	incu		Lan		Como	uicu Lin	el Second Second
н	С	S	Р	loc (cm	) mbsf	Lith	Unit	type	number	of shear	(cm)	М	D	С	F	v	dip 1	Dir	dip 2	Dir	strike	strike	dip	plunge	pitch	azim	azim	plunge	Comments
EFFFFFFFF	3R 1R 2R 2R 2R 2R 2R 2R 2R 2R		10 1 2 3 3 3 7	69 5 7 16 22 30 29 33 56	19.59 0.05 9.37 9.46 9.52 9.60 9.59 9.63 9.86	G G G G G G G G G G G	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	vein fol cataclas fault vein fault fault cataclasite ultracataclas	1 2	norm norm	0.4		000000000000000000000000000000000000000	0 5 0 0 0 0 0 4 5	1 2 2 1 2 0 0	1 0 1 1 1 0 0	82 70 85 63 54 83 59 18 30	¥EE¥¥E¥¥¥	38	N	11 0 169 144 154 199 357 168	191 0 349 144 154 19 177 247 168	82 70 85 68 57 83 59 40 31	80		S	180	80	Thin felsic veins forming zone ~lcm wide Foliated porphyroclastic shear zone Dark shear band displacing small felsic vein Minor oxid on fracture plane, no slicks Thin felsic vein Fracture with pale blue-greenish material cutting cataclasite Fracture with pale blue-greenish material cutting cataclasite Band of moderate-severe cataclasis cut by minifaults Ultracataclasite with porphyroclasts of ?amph
F	3R	1	4	19	19.09	G	1	ultracataclas	6			0	0	5	0	0	35	w	30	N		220	42						Cataclasite with pale greenish mineral
F	3R	1	6	37	19.27	G	1	ultracataclas	5			0	0	5	0	0													
F	3R	1	9	54	19.44	G	1	ultracataclas				0	0	5	0	0													
000000000000000000000000000000000000000	IR R R R R R R R R R R R R R R R R R R	111111111111111222222222222222222222222	2 2 3 5 5 5 9 9 9 9 15 15 8 18 8 3 3 7 7 7 7 7 10 10 0 10 11 11 11 11 15 15 15 17 19 19 19 19 19 19 3 3	$\begin{array}{c} 11\\ 12\\ 18\\ 37\\ 41\\ 60\\ 120\\ 114\\ 138\\ 13\\ 14\\ 32\\ 32\\ 40\\ 30\\ 58\\ 65\\ 77\\ 73\\ 70\\ 102\\ 107\\ 98\\ 121\\ 137\\ 102\\ 107\\ 98\\ 121\\ 137\\ 102\\ 102\\ 102\\ 102\\ 102\\ 102\\ 102\\ 102$	18.71 18.72 28.78 28.97 29.01 29.20 29.24 29.27 29.20 29.24 29.20 30.25 30.86 30.86 30.86 30.86 31.15 31.55 31	OG OG B B B B B B B B B B B B B B B B B	1 - N N N N N N N N N N N N N N N N N N	vein vein vein vein vein vein vein vein	1 2 1 2 1 2 3 1 2 1 2 1 2 2 3 4 5 1 2 3 4 1 2 5 6 8 1 2 3 4 1 2 5 6 8 1 2 3 4 1 2 5 6 8 1 2 3 4 1 2 5 6 8 1 2 5 1 2 2 5 2 5				$\begin{smallmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 &$	$\begin{smallmatrix} 0 & 0 \\ 0 $	1 1 1 1 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1	$\begin{smallmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 0 \\ 1 & 1 \\ 1 $	8 13 57 50 60 49 4 58 18 86 65 18 86 67 4 2 23 11 63 53 9 39 21 8 4 16 32 7 16 32 18 4 18 18 18 18 18 18 18 18 18 18	¥¥¥в¥ва ¥¥¥вая¥¥Х¥вавав¥вев¥¥¥¥ёвавав¥ ¥¥	38 22 59 42 52 52 34 3 52 20 34 14 23 6 8 5 9 8 20 50	ZZ ZZS ZZ¥Z ZZS ZSSSSSSS ZS	356 346 348 70 10 4 329 32 32 347 349 334 334 335 356	260 240 346 346 305 346 305 274 70 188 302 274 70 190 184 9 3 2 233 205 347 205 347 205 347 205 347 205 347 205 344 168 304 220 172 205 344 205 346 344 205 345 345 355 345 345 345 345 345 345 34	38 257 56 16 42 54 56 86 20 54 88 40 54 83 48 52 71 55 66 47 25 24 56 81 63 64 57 55 66 75 56 75 56 75 75 75 75 75 75 75 75 75 75		N87				Vein 1 cuts vein 2 Vein 2 cut by vein 1 Principal vein Vein 3 cuts vein 4 Vein 4 cut by vein 3
G	2R	3	3	17.5	31.78	OG	3	cataclas	3					2	2	1	42	W	11	S		168	43						3, 4, 6 and 7 all bounding fault breccia; prob. conjugate

Figure 15. Example of the structural spreadsheet. H = hole; C = core; S = section; P = piece number; feature loc cm = location of the feature from the top of the section in cm; lith = lithologic unit; M = magmatic flow fabric index; D = solid-state deformation fabric index; C = cataclastic textures index; F = fractures and faults index; V = vein index; app dip dir = apparent dip direction; lin = lineation. Lithology abbreviations are given in Figure 10.

 $270^{\circ}$  (W) (Fig.17B). A second apparent dip at  $90^{\circ}$  to this may be measurable on the curved part of the core, or (if convenient) by making a vertical cut in the  $000^{\circ}$ – $180^{\circ}$  plane (Fig. 17C); alternatively, a strike measurement may be taken directly from a cut made in the apparent horizontal plane (Fig. 17D). If the way the fracture, vein, etc. lies relative to the cut or broken surface of the core is convenient, the dip and strike can be measured directly. Direct strike measurements were preferred wherever possible as they are much more precise; the derivation of a plane by the combination of two apparent dips is subject to great uncertainty in the resultant strike if the dip of the plane is shallow (Fig. 18). Note that the right-hand rule convention (i.e., that the dip direction is  $90^{\circ}$  clockwise from the strike) was used throughout and dip direction identifiers not used: such identifiers become inconvenient when attempting to correct core to true coordinates (see below).

Mineral foliations and planar igneous contacts were measured in exactly the same way. Linear structures such as slickenlines were measured either directly, by their azimuth and amount of plunge, or indirectly, by means of their pitch on a previously measured plane. Reference also was made to various physical and magnetic properties of the core (specifically, anisotropies of seismic velocity and magnetic susceptibility, respectively) to help characterize and constrain rock fabrics post-cruise (see "Paleomagnetism" and "Physical Properties" sections, this chapter).

"True" dips and strikes (still relative to core coordinates) were derived from the apparent measurements stereographically, using the Stereonet plotting program of R.W. Allmendinger, Version 4.25, on an Apple Macintosh computer. The two apparent dip orientations were entered as lines, and the computer generated the great circle of cylindrical best fit to both lines. The orientation of this great circle gave the "working dip direction" and true dip of the observed structure, which was recorded on the structural spreadsheet. All measurements assume that the core was vertical; no correction for borehole deviation was made. The magnitudes and directions of deviation of the Leg 147 boreholes are poorly constrained. The only information comes from general purpose inclinometry tool (GPIT) data from the upper part of Hole 894G (~45–80 mbsf); these data show this portion of the hole to be deviated by approximately 4° only (see "Downhole Measurements" section, "Site 894" chapter, this volume).

#### Methods of Core Orientation

One of the principal limitations of core-based structural studies is that the core pieces are not oriented with respect to azimuth. In the absence of azimuthal data, it is not possible to assess directly the significance of, for example, microstructures, petrofabrics, or fault



Figure 16. Definition of artificial core coordinate system.



Figure 17. Methods of measuring planar core features.



Figure 18. Estimation of uncertainties involved in strike measurements derived from the combination of two apparent dips.

kinematic data from the core in the context of larger-scale tectonic features inferred by other geological or geophysical means. Many other core-based studies, particularly of paleomagnetism, are similarly hampered. Previous workers often have attempted to use the primary magnetization vector of core samples to reorient core, assuming that this vector is coincident with the present-day Earth's field; however, this neglects the possible effects of secular variation and assumes that no tectonic rotation of the sample, be it on a local or regional scale, has occurred.

A second means of core reorientation is to compare distinctive planar features in the core (e.g., igneous layering or regular vein or fracture sets) with their representations on downhole log images from the same interval. The Formation MicroScanner (FMS) downhole logging tool, described in the "Downhole Measurements" section (this chapter), generates high-resolution electrical images of the borehole wall. These images are oriented with respect to geographical coordinates, because the tools carry triaxial magnetometers. Comparison of the features in the core reference frame to geographical coordinates. Paleomagnetic data also can be reoriented in the same way and provide a means of detecting tectonic rotations. The methodology of core reorientation using downhole logs is described in detail in



Figure 19. Orientation of cuts necessary to obtain correctly oriented thin sections for structural purposes.

MacLeod et al. (1992; and in press), and applied for structural data from Leg 135 by MacLeod (in press) and for paleomagnetic data by Sager et al. (in press) and MacLeod et al. (1992; and in press). Its principal disadvantages are its inapplicability if there are no distinctive markers in the borehole and that detailed comparison with the logs can only be made post-cruise. On board ship we were therefore restricted to attempting reorientation of core pieces relative to the primary magnetization vector of core samples.

## **Thin-Section Descriptions**

Thin-section billets of basement lithologies recovered during Leg 147 were examined to: (1) confirm macroscopic descriptions of magmatic, ductile, and brittle structures; (2) provide information on the kinematics of such deformation; (3) determine time relationships between deformation and dynamic metamorphism; and (4) provide coverage of major structural zones and a representative section of downhole variations.

Where possible, sections were oriented with respect to the core (i.e., the original attitude of the vertical is preserved) and samples were cut perpendicular to the foliation and parallel to any extensional lineation, as this is the plane that best displays both shear-sense indicators and the preferred dimensional orientation of minerals (Fig. 19). To ensure consistent and complete description of microscopic features, a checklist has been used for all thin sections described. This information was entered on a standardized structural form (Table 3), and summarized in the HRTHIN database.

# GEOCHEMISTRY

# X-ray Fluorescence Analyses

Samples considered by the shipboard party to be representative of individual lithologic units or of unusual composition were analyzed for major and selected trace elements by X-ray fluorescence (XRF). The shipboard XRF system (Applied Research Laboratory 8420) is a fully automated wavelength-dispersive spectrometer employing a 3-kw rhodium target X-ray tube as the excitation source for both major and trace elements. Trace elements were analyzed on the shipboard system; hardware problems necessitated running major element samples at Woods Hole Oceanographic Institute.

#### Table 3. Terminology used in working thin-section description form for structural data.

Leg 147 Site 894			
Core, section, piece:			
Rock name:			
Oriented?:			
Observer:			
MAGMATIC FABRIC			
Textural Type: 1, 2, 3, or 4			
Layering: defining minerals			
Foliation: defining minerals			
Euhedral minerals:			size:
Interstitial minerals:			size:
Poikilitic minerals:			size:
SOLID-STATE DEFORMATION			
Textural type: I, II, III, IV, V			
Foliation: defining minerals			
Porphyroclasts:			size:
	substructure:		
	shape or/and crystallographic fabric		
Recrystallized minerals:		% age:	size:
	grain boundary texture:		
	crystallographic fabric:		
Timing of deformation (pre/syn/post meta- morphism):			
DEFORMATION STRUCTURES:			
Magmatic: tiling, magmatic shear bands			
Ductile: mechanical twinning, mylonitic bands; S-C fabrics, kinematic indicators, undulose extinction			
Brittle: microfaulting, cataclastic deforma- tion, vein filling minerals:			
Sense of shear:			
Time relationships: ductile/brittle events			
Comment/sketches:			

The Leg 147 analytical conditions and procedures during trace element analysis followed those reported in Storms, Batiza, et al. (1993).

## Crushing and Grinding

Following cutting by either water-cooled saws or 1-in.-diameter diamond drill cores, samples were wet-ground on diamond abrasive wheels to remove saw marks or any unwanted material. For estimating sampling errors due to sample size (Clanton and Fletcher, 1976), the exact weight for each sample was recorded along with the analyses. After grinding, the samples were sonicated in methanol for 10 min and then in distilled water until the enclosing water stayed clear. This procedure was followed by drying at 110°C in an oven for at least two hours. Larger samples were reduced to less than 0.5-cm diameter by crushing in a low trace-element steel mortar and collar (Rock Labs "Little Smasher"), whereas smaller samples were crushed between teflon discs by pressure in a press. The crushed rock fragments were then ground in an agate mortar to <200 mesh, with final pulverization in a tungsten carbide Shatterbox grinding vessel.

## **Major Elements**

Major elements were determined using the X-ray fluorescence facility at Woods Hole Oceanographic Institution, which is equipped with a Phillips PW 1404 automated spectrometer and accompanying software. Rock powders were fused with a lithium tetraborate-base flux following a combination of techniques outlined in Schroeder et al. (1980). The major element adsorption coefficients calculated from the Rasberry-Heinrichs equation were empirically determined on reference rocks and used to correct background-corrected intensity ratios of unknowns before determining actual concentrations.

#### **Trace Elements**

Trace elements were determined on powder pellets made by mixing 5 to 7 g of fresh oven-dried rock powder with 30 drops of polyvinyl alcohol binder and pressing the mixture into an aluminum cap with 7 tons of pressure. A minimum of 5 g basalt or gabbro ensured that the sample was indefinitely thick for the Rh K series radiation (20 KeV). Trace element concentrations based on calculation routines modified from Norrish and Chappell (1967), Reynolds (1963, 1967), and Walker (1973) were computed using the following relationship:

$$C_i = (I_i \cdot A_i)/m_i$$

where  $C_i$  = the concentration (ppm) of element *i*,  $I_i$  = the net peak intensity (counts/s) of element *i* corrected for nonlinear background and spectral interferences,  $A_i$  = the mass absorption coefficient for element *i*, and  $m_i$  = the calibration factor (ppm/counts/s) of element *i*.

The calibration factor for each element was determined on a wide range of rock and mineral standards. Analysis of the standard BHVO during Leg 147 is given in Table 4. See Leg 111 XRF Explanatory Notes (Becker, Sakai, et al., 1988) for more details of the off-line computer program used for these calculations.

## Preparation of Inter-laboratory Reference Materials

To facilitate future comparison of Leg 147 geochemical data generated at many different laboratories, multiple inter-laboratory geochemical reference materials were generated during Leg 147, one gabbro from Site 894 and one mixed mafic and ultramafic sand and gravel from Site 895 (see "Geochemistry" section, "Site 895" chapter, this volume). Powders were prepared following the procedures outlined for XRF analysis. These samples were complemented by the basaltic standards BAS 140 (Dick, Erzinger, Stokking, et al., 1992) and BAS 142 (Storms, Batiza, et al. 1993). Analytical results from the participating labs will be reported in the Leg 147 *Scientific Results* volume.

# Loss on Ignition, Water, Carbon Dioxide, and Sulfur Analyses

Loss on ignition (LOI) is normally determined by heating the oven-dried (110°C) sample to 1025°C for 4 hr. During this process of ignition, water (crystalline and constitutional) is expelled, carbon dioxide is released from carbonates and eventually from organic matter, sulfur from sulfides is oxidized to sulfur dioxide, and sulfur trioxide is released from sulfates present (barite, gypsum, and anhydrite). All of these reactions cause a loss on ignition. At the same time, a gain of weight is produced by the oxidation of ferrous iron to ferric oxide, which causes the weight to increase by 11.1% of the percentage of contained ferrous iron.

To better understand the LOI results, 50 to 80 mg of each sample was combusted at 1010°C and analyzed in a Carlo Erba NA 1500 CHNS analyzer by gas chromatography. The results were obtained after oxidation of all relevant constituents to the respective gaseous oxides. The CHNS analyzer reports the results as H, C, N, and S; we report these here as  $H_2O$ ,  $CO_2$ , and S. No detectable nitrogen was found in rocks analyzed during Leg 147. Detection limits for nitrogen were 0.01% for 30 mg of sample. Various amounts of Isotiourea (from Carlo Erba) were used as the calibration standard; the compound Sulfanilamide (from Aldrich Chemicals), the NBS standard NBS1646 Estuarine Sediment, and the United States Geological Survey (USGS) standard Cody Shale were used to test accuracy and reproducibility of the method.

## PALEOMAGNETISM

Paleomagnetic measurements were performed on minicore samples and, when available, on continuous pieces from the recovered drill core. Minicore samples were chosen to be representative of the lithology and alteration mineralogy of the Leg 147 cores, and were vertically oriented. In addition, an effort was made to select samples near important structural features so they could be oriented using paleomagnetic directions. At least one minicore sample was taken from each section of core for shipboard study. However, sections that consisted only of small, unoriented fragments were not sampled. Subsequent to splitting individual pieces of the core, ODP convention for rotary cores follows that of an oriented piston core (see Fig. 20). That is, +X (north) is into the face of the working half of the core, +Y (east) points toward the right side of the face of the working half of the core, and +Z is down. During standard ODP rotary drilling, individual pieces of the core are free to rotate within the core barrel and, thus, are not oriented with respect to north or to each other. Therefore, the only true orientation is with respect to the vertical dimension.

#### **Measurement of Remanent Magnetization**

A 2-G Enterprises (Model 760R) pass-through cryogenic rock magnetometer was used to measure remanent magnetization of both the minicores and continuous core pieces. The superconducting quantum interference device (SQUID) sensors in the cryogenic magnetometer measure the intensity and direction of magnetization throughout an interval approximately 20 cm long; portions of the archive half of the core that were greater than this length were measured at 5-cm intervals. During Leg 147, the SQUID electronics were operated in the flux-counting mode. An alternating field (AF) demagnetizer (Model 2G600) capable of producing an alternating field up to 20 mT was used on-line with the pass-through cryogenic magnetometer. The magnetometer, the demagnetizer, and their common stepper motor transport system were operated over serial interfaces by software on an IBM PCcompatible computer. The software was an ODP customization of a vendor (2-G) distributed QuicBasic program originally called SUPER-MAG. Measurements of natural remanent magnetization (NRM) were performed after demagnetization levels of 2, 4, 6, 8, 10, 12, 15, and 18



Figure 20. Orientation diagram and terminology used for physical properties measurements.

mT. Because of the potential for overheating the coils, demagnetization was not performed at 20 mT.

For minicore samples, AF demagnetization at higher fields was performed with a single-axis Schonstedt Geophysical Specimen Demagnetizer (Model GSD-1) at 20.0, 25.0, 30.0 mT and upward (to a maximum of 100 mT) in 10-mT steps until the specimen decreased to below 10% of the NRM intensity, and a stable inclination was identified. In addition, thermal demagnetization was performed on selected samples using a Schonstedt Thermal Specimen Demagnetizer (Model TSD-1) and steps of 100, 200, 300, 400, 450, 500, 525, 550, 575, and 600°C.

#### Measurement of Magnetic Susceptibility

Whole-core magnetic susceptibility (k) was measured at 2-cm intervals on sections of the core that contained relatively long pieces (i.e., greater than about 15 cm) using a Bartington Instrument susceptibility meter (Model MS1). The susceptibility sensor is a MS1/CX 80-mm loop set at 4.7 kHz and mounted in line with the GRAPE and *P*-wave logger on the multisensor tract (MST). The sensors on the MST are calibrated to measure whole cores. Portions of the recovered core that are not perfectly cylindrical will result in a volume error and were eliminated from the database. The susceptibility measurements obtained from the MST showed good agreement with measurements made on minicores. The magnetic susceptibility of minicores was measured using a Kappabridge KLY-2 (see below). Values of initial volume susceptibility were used in conjunction with the values of the

intensity of NRM to calculate the Koenigsberger (Q) ratio of the samples. A field value of 0.033 mT was assumed for Site 894 so that  $Q = J_0 \mu_0 / kH$  where  $\mu_0$  is the permeability of free space.

#### Anisotropy of Magnetic Susceptibility

The volume susceptibility (k) and the susceptibility tensor ( $k_{ij}$ ) were measured on standard-sized minicores (2.4 × 2.2 cm, volume 11 cm<sup>3</sup>) using a Kappabridge KLY-2 (Geofyzika Brno). The Kappabridge is a semi-automatic autobalance inductivity bridge with a high sensitivity (4 × 10<sup>-8</sup>) and an accuracy of ±0.1% within one measuring range. The induced magnetization of the specimens is determined in 15 positions in a field of 300 A/m and then combined to the susceptibility tensor. The principal magnitudes and directions of  $k_{ij}$  were obtained by the diagonalization of the tensor; the principal directions are given by the eigenvectors and the principal magnitudes by the eigenvalues. The bridge is interfaced with an IBM PC-compatible computer. Data are collected and processed by the FORTRAN-77 program ANI20 by V. Jelinek.

#### **Rock Magnetic Measurements**

In addition to standard paleomagnetic measurements, we completed measurements of low-temperature magnetic susceptibility on a small number of minicores from the Leg 147 cores. Low-temperature magnetic susceptibility was measured to determine and quantify the sources of magnetic susceptibility. The temperature dependence of magnetic properties in a temperature interval between 77 K (liquid nitrogen temperature) and room temperature was used to analyze the sources of magnetic fabrics. Most of this additional work was done after completion of the physical property measurements, during which the samples were heated to about 110°C, and this may have had a limited effect on the magnetic properties of the samples.

## PHYSICAL PROPERTIES

Shipboard measurements of physical properties provide information that aids characterization of lithologic units, correlation of lithology with downhole logging results, and interpretation of seismic surveys and other geophysical data. The goal of the physical properties program of Leg 147, in addition to providing a link between lithologic and geophysical data, was to identify the physical signals in igneous rocks that result from different magmatic and metamorphic events.

Several types of measurements were performed on the wholeround core sections. Measurements of bulk density and magnetic susceptibility were provided by the multisensor track (MST). The MST incorporates a gamma-ray attenuation porosity evaluator (GRAPE), a compressional-wave core logger (PWL), and a magnetic susceptibility monitor. The PWL was not used during the leg, because this

LEG	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Cr	v
Gladney and Roelandts (1988)	19	180	26	420	10	113	140	120	300	310
142 (9 runs) <sup>a</sup>	18	182	26	399	8	110	144	122	290	330
147	20	182	26	396	9	112	137	123	290	300
147	20	180	26	398	9	111	138	123	292	305
147	20	182	26	395	9	112	139	122	292	303
147	20	182	26	397	8	117	139	121	287	307
147	20	182	26	395	9	113	138	123	291	310
147	20	180	25	398	9	113	138	124	291	303
147	19	180	25	400	8	112	139	123	288	295
147	19	181	26	398	9	113	138	123	288	310
147	19	184	25	405	9	112	137	123	286	306
147	19	179	26	401	9	114	139	123	289	303
147	20	180	25	398	9	113	139	122	291	295

Table 4. Trace element analysis of the BHVO reference standard following Leg 147 calibration.

<sup>&</sup>lt;sup>a</sup>Storms, Batiza, et al. (1993).

tool measures compressional-wave velocities through the liner before penetrating the whole-round samples, and the liner-rock contact is usually poor, giving rise to extremely low velocities.

Physical properties measured on minicore samples obtained from the split cores included compressional-wave velocity, thermal conductivity, electrical resistivity, and index properties. Samples were chosen to be representative of the core and in zones with the least amount of fracturing. Measurements and samples were obtained generally at the frequency of one per core section. Thin sections were obtained from some samples to link petrologic features to the physical properties measured during the leg. Experimental details are described below and in the cited references.

# **Compressional-wave Velocity**

The pulse transmission method was used to determine the compressional-wave velocity using piezoelectric transducers as sources and detectors in a screw-press Hamilton Frame described by Boyce (1976). Calibration measurements were performed using leucite (leucite  $V_p$  = 2.745 km/s) and aluminum (aluminum  $V_p = 6.295$  km/s) minicores to determine the zero displacement time delay inherent in the measuring system. The traveltimes in each material were measured five times through a range of different lengths and plotted as a reduced time vs. sample length graph, where the reduction velocity is the nominal velocity of the calibration sample (Fig. 21A). The average intercept time at zero length for both materials, reduced at their nominal velocities, is the delay time for the particular set of transducers. This technique is similar to that used during previous hard rock legs (Becker, Sakai, et al., 1988; Dick, Erzinger, Stokking, et al., 1992) and is preferable to taking a single reading at zero length. Early tests indicated that the flatness and parallelism of the specimens determined the accuracy and reproducibility of the measurements. Accordingly, the samples were prepared with both sides flat and parallel to within 0.01 mm. This small tolerance resulted in sharply defined first arrivals of the direct P-wave mode. The calibration measurements were repeated five times to provide an estimate of error in measuring traveltime. These errors are expressed in terms of 2 standard deviations reduced to a common velocity of 6 km/s, a typical velocity for the rocks seen on this leg. If it is assumed the errors are Gaussian, this becomes the 90% confidence limit. There is no obvious change in error with sample length (Fig. 21B). The average error at the 90% confidence limit error is ±0.12 km/s at a 6.0 km/s velocity.

Compressional-wave velocities were measured in two orthogonal directions (A and C transmission directions) as shown in Figure 20. Two types of minicores (25 mm in diameter and 15–40 mm long) were used in this apparatus: (1) samples drilled vertical or parallel to the core axis before splitting (A), and (2) samples normal to the core-splitting plane (C) and usually at an angle to foliation.

## Multisensor Track (MST)

The MST incorporates the GRAPE and magnetic susceptibility devices in scans of the whole-round core sections. Individual wholeround core sections were placed horizontally on the MST, which moves the section through the two sets of sensors. Finally, the data were edited for measurements performed in between samples and for intervals with poor recovery.

The basic theory of gamma-ray attenuation states that, if the gamma-ray energy is within certain limits (0.2 to 1.02 MeV), the rays passing through the rock material will be attenuated by Compton scattering (Evans, 1965; Evans and Cotterell, 1970; Boyce, 1976). The following equation is the basis for attenuation of a parallel gamma-ray beam in an ideal slab absorber (Evans, 1965):

$$I = I_0 e^{-\mu dr} \tag{1}$$



Figure 21. Calibration plots used for the Hamilton Frame velocimeter. A. Zero length intercept. B. Error repeatability. Open circles = leucite; filled circles = aluminum.

$$\rho = (1/\mu d) \ln(I_0/I), \tag{2}$$

where:

*I* is the intensity of the gamma-ray beam that penetrates the absorber with no loss of energy;

 $I_0$  is the source intensity;

 $\rho$  is the bulk density in g/cm<sup>3</sup>;

 $\mu$  is the Compton mass attenuation coefficient in cm<sup>2</sup>/g; and

*d* is the thickness of the sample in cm.

The GRAPE uses a <sup>137</sup>Cs source to perform measurements of bulk density at 0.5-cm intervals and compares the attenuation of gamma rays through the cores with the attenuation through an aluminum standard (Boyce, 1976). The GRAPE data are most reliable in advanced hydraulic piston corer (APC) cores. For rotary core barrel (RCB) cores, errors can occur when samples do not have a uniform thickness and when cores are not continuous. Therefore, continuous GRAPE data obtained at the beginning of Leg 147 were not useful because of significant changes in thickness and the overall poor recovery.

A GRAPE Special 2-Minute Count technique (Boyce, 1976) was then used to determine wet-bulk densities. These GRAPE measurements were performed on whole-round samples. All counts for the samples and accompanying air (background) counts were made in duplicate and averaged. Average grain density values from gravimetric measurements were used to correct the wet-bulk density determined by the GRAPE for deviation of the grain density of the sample from that of quartz. The precision estimated for this technique is  $\pm 1.5\%$  (Boyce, 1976).

One of the basic problems with using equation 2 to determine wetbulk density is that all minerals do not have the same attenuation coefficient. For example, water has an attenuation coefficient that is 10% greater than quartz, or for a quartz coefficient equivalent to  $0.100 \text{ cm}^2/\text{g}$ the water coefficient will be  $0.110 \text{ cm}^2/\text{g}$  (Evans, 1965; Boyce, 1976). The MST magnetic susceptibility procedures are included in the "Paleomagnetism" section (this chapter).

#### **Index Properties**

Index properties (bulk density, grain density, water content, porosity, dry density) were calculated from measurements of wet and dry sample weights and dry volumes. Samples of approximately 10 cm<sup>3</sup> were taken for determination of index properties. In addition, whole core determination of bulk density was measured using the GRAPE on the MST on cores that partially filled the liner.

Sample mass was determined aboard ship to a precision of ±0.01 g using a Scitech electronic balance with a computer averaging system to account for ship motion. The sample mass was counterbalanced by a known mass such that only mass differentials of less than 5 g usually were measured. Volumes were determined using a Quantachrome Penta-Pycnometer, which is an instrument specifically designed to measure the volume and true density of the samples by employing Archimedes' principle of fluid displacement. The displaced fluid is helium, which assures penetration into crevices and pores approaching one Angstrom (10-10 m) in dimension. Purge times of 5 min were used to approach a helium-saturated steady state condition. The Quantachrome pycnometer measures volumes to an approximate precision of ±0.02 cm3. Sample volumes were repeated until two consecutive measurements yielded volumes within 0.02 cm3 of each other. A reference volume was run with each group of samples during the first several hundred tests. The standard was rotated between cells to check for systematic error. Preliminary results of this exercise suggest the pycnometer is fairly stable for a given cell inset or sleeve. However, changing sleeves or insets offset the standard calibration by 0.1 cm<sup>3</sup>.

#### Water Content

The determination of water content followed the methods of the American Society for Testing and Materials (ASTM) designation (D) 2216 (ASTM, 1989). As outlined in ASTM D2216, corrections are required for salt when measuring marine samples. Samples were saturated in seawater and placed in a vacuum for 24 hr to achieve in-situ wet conditions. All measurements were corrected for salt assuming a pore salinity of 35%. In addition to the recommended water content calculation, the ratio of the pore fluid mass to the dry sediment mass (% dry mass) presented in ASTM D2216, a calculation of the ratio of pore fluid mass to total sample mass also was reported (% wet mass). The equations for each water content calculation are as follows:

$$W_c (\% \text{ dry mass}) = (M_t - M_d)/(M_d - rM_t)$$
 (3)

$$W_c$$
 (% wet mass) =  $(M_i - M_d) \cdot (1 + r)/M_i$  (4)

where:

 $M_t$  = total mass (saturated);  $M_d$  = dry mass; r = salinity.

#### **Bulk Density**

Bulk density ( $\rho$ ) is the density of the total sample, including the pore fluid (i.e.,  $\rho = M_t/V_t$ , where  $V_t$  is the total sample volume). The total mass ( $M_t$ ) was measured using the electronic balance, and the total volume was calculated using the mass of pore fluid ( $W_w$ ), the volume of the pore fluid ( $V_w$ ), and the dry sample volume as expressed by the following equations:

$$W_w = (M_t - M_d)/s \tag{5}$$

where:

 $M_d = dry mass;$ 

s = salt factor = (1000 - salinity)/1000 = 0.965allowing the calculation of the pore water volume ( $V_w$ ),

$$V_w = W_w / \rho_w \tag{6}$$

where:

$$\rho_w = \text{density of pore water} = 1.0245 \text{ g/cm}^3$$
.

Then the total wet volume  $(V_t)$  was calculated using the following equation:

$$V_t = V_w + V_d, \tag{7}$$

where:

 $V_d$  = dry volume (directly measured with the pycnometer)

and permits the direct calculation of bulk density values using  $\rho = M_t/V_t$ .

#### Porosity

The porosity  $(\eta)$  was calculated using:

$$\eta = (W_c \times \rho)/((1 + W_c) \times \rho_w)$$
(8)

#### Grain Density

Samples were dried for 24 hr at 110°C, and the grain density was determined directly on selected intervals from the dry mass (Scitech balance) and dry volume (pycnometer) measurements. Both mass and volume were corrected for salt as follows:

$$\rho_{\text{grain}} = (M_d - m_s)/(V_d - (m_s/\rho_{\text{salt}}))$$
(9)

where:

$$V_d$$
 = dry volume;  
 $p_{salt}$  = density of salt (2.257 g/cm<sup>3</sup>);  
 $m_s$  = mass of salt in the pore fluid, or

$$m_s = \text{salinity} \cdot W_w.$$
 (10)

#### **Thermal Conductivity**

Core samples were measured nondestructively for thermal conductivity in the shipboard laboratory. Specimens were obtained from the archive half to prevent samples used for chemistry analyses from being contaminated with the EE&G thermally conductive compound. This procedure was used previously during Leg 140 (Dick, Erzinger, Stokking, et al., 1992) and is documented in the shipboard thermal conductivity manual. Thermal conductivity measurements were performed using the half space method over a 6-min interval with a heated needle probe placed between the sample and a slab of low conductivity material (Sass et al., 1984; Vacquier, 1985). All halfspace measurements were conducted in a water bath to keep the samples saturated, to improve the thermal contact between the needle and the sample, and to reduce thermal drift during the tests. The samples were polished with 240 and 600 grit on a glass plate to smooth the contact area, and thermally conductive compound was used to improve the thermal contact. This method is most convenient for the hard-rock cores, which were cut in the form of a half-round cylinder, as this shape is easily adapted to the apparatus.

The theory of the method closely approximates the heating of a line source in a plane separating half-spaces of the sample material and a thermal insulator, which in turn is a relatively straightforward extension of the method of heating a uniform full-space by a line source (Jaeger, 1956; Von Herzen and Maxwell, 1959). Thermal conductivity is calculated from the rate of temperature rise in the probe while a heater current is flowing. The temperature rise in the probe should vary logarithmically with time as:

$$T(t) = (q/4\pi k) \ln(t) + \text{constant}$$
(11)

where:

k = thermal conductivity;

T and t = the temperature and time, respectively;

q = the heat generated per unit length of the probe.

From Equation 11, the thermal conductivity is derived from the slope of temperature vs. the logarithm of time (Fig. 22). If the substrate on which the sample is placed were a perfect thermal insulator, the rise in temperature with time at the needle probe would be exactly twice that experienced by the probe in an infinite medium having the same thermal conductivity of the sample. In practice, the poorly conducting substrate absorbs a fraction of the heat during measurement, the amount of which depends on the ratio of sample to substrate conductivity. For most rock samples measured during Leg 147, this ratio was sufficiently large (>15–20) that the adjustment from the simple theory is a relatively small correction. This correction was determined by carefully measuring materials whose conductivity was known and close to those measured in the samples.

The data collection and reduction procedures for half-space tests are identical to those for full-space tests. Thermal conductivity probes were calibrated by conducting measurements on three standards of known thermal conductivities. The standards used were red rubber, fused silica, and macor ceramic, all provided by ODP, with known thermal conductivities of 0.96, 1.38, and 1.61 W/m°C, respectively. Thermal conductivity readings with the different probes used during Leg 147 are summarized in Table 5. A linear regression of known thermal conductivity,  $k_{corr}$ , to probe reading,  $K_{meas}$ , indicates a correction given by  $k_{corr} = b + mK_{meas}$  for specific needles used for all the measurements (Fig. 23). This correction was applied to all readings made during Leg 147.

# **Electrical Resistivity**

A new resistivity device consisting of a nylon holder and springloaded stainless steel sensors was used during Leg 147. The holder was designed to have the same diameter as the sample to minimize leakage along the sides of the sample, and the sensors were polished to maintain an even contact with the minicore. The measurements were performed in water-saturated samples wrapped in teflon tape. For consistency, the measurements were made with the ends of the minicores slightly dampened.

The device applies a 5-volt alternating current across the electrodes and measures the drop in potential through the sample. The device outputs the resistance of the saturated sample in terms of the potential drop in mV. In determining sample resistivity, the potential is first converted into resistance by dividing it by the instrument current. The resistance is then converted to resistivity by multiplying by the instrument cell constant. The cell constant was defined for every sample as the cross-sectional area divided by the length of the sample. These measurements were used to determine the formation factor and to estimate porosity.

#### DOWNHOLE MEASUREMENTS

#### General

After coring is completed, a combination of sensors is lowered downhole to monitor the physical and chemical properties of formations adjacent to the borehole. Interpretation of these continuous, in-situ measurements can yield a stratigraphic, lithologic, structural,



Figure 22. Typical plot of temperature vs. In time used for the calculation of the thermal conductivity values.

Table 5. Calibration measurements for the thermal conductivity needle probes.

Probe #	Standard	Runs	Thermal conductivity W/m°C	Probe reading <sup>a</sup> W/m°C	Standard deviation W/m°C
207					
	Red rubber	10	$0.96 \pm 0.05$	0.947	0.031
	Fused silica	10	$1.38 \pm 0.07$	1.389	0.039
	Macor ceramic	10	$1.61 \pm 0.08$	1.594	0.017
322					
	Red rubber	10	$0.96 \pm 0.05$	0.993	0.035
	Fused silica	10	$1.38 \pm 0.07$	1.307	0.072
	Macor ceramic	10	$1.61 \pm 0.08$	1.646	0.018
205					
	Red rubber	8	$0.96 \pm 0.05$	0.950	0.020
	Fused silica	10	$1.38 \pm 0.07$	1.373	0.026
	Macor ceramic	9	$1.61 \pm 0.08$	1.613	0.029

Note: Based on probe readings and standard deviations obtained from the calibration standards, only needle probes #205 and #207 were used during Leg 147.

a Denotes mean value from number of runs.

geophysical, and geochemical characterization of the hole. Six combinations of downhole sensors are available (Fig. 24):

1. the Schlumberger "quad combo": the long-spaced digital sonic tool (LSS-SDT), the natural gamma-ray spectrometry tool (NGT), the high-temperature lithodensity tool (HLDT), and the phasor dual induction tool (DIT) to which is attached the Lamont-Doherty Earth Observatory (LDEO) temperature logging tool (TLT);

 the Formation MicroScanner (FMS) tool string, composed of the general purpose inclinometry tool (GPIT) and micro electrical scanning tool (MEST), together with the NGT;



Figure 23. Calibration plot used for the thermal conductivity needle probes.



Figure 24. Sketch of the logging tool string combinations used during Leg 147. Weight refers to weight in air of the total string minus TLT. Diameter not to scale with length. Acronyms are listed in Table 6. Zero refers to tool zero depth.

3. the Schlumberger geochemical combination, consisting of an NGT, an aluminum activation clay tool (AACT) and an induced gamma-ray spectrometry tool (GST), to which also is attached the LDEO temperature logging tool;

4. the LDEO digital borehole televiewer (BHTV), designed by Deutsche Montan Technologie;

5. the Schlumberger well seismic tool (WST);

6. the dual laterolog tool (DLT), the NGT, and the LDEO temperature logging tool.

Table 6 lists the tools used in the above combinations, the main logs they produce, their approximate vertical resolution and range of depth of investigation. The NGT is run on all combinations to provide a common basis for depth correlations, except on the BHTV because of connection incompatibilities. The DLT is better suited than the DIT to the high electrical resistivity (Schlumberger, 1989) of igneous rocks but is too large to be combined in the quad-combo; thus, it has to be run separately. The FMS and the BHTV images provide continuous data about structural elements and hole shape and to help place the core pieces back in depth and orientation.

Throughout the acquisition of downhole measurements, data are transmitted to the surface by the 7 conductor logging cable, displayed in real time and simultaneously recorded. The temperature tool (TLT) is an exception to this because its data are recorded internally and downloaded only after logging. Many downhole data become quickly available on board ship, but a few require further processing, which is done onshore after the end of the leg.

During Leg 147 poor hole conditions precluded the acquisition of most of the above logs. No logging was possible at all at Site 895; at Site 894 an abbreviated logging program included the HLDT, LSS-SDT, NGT, TLT, BHTV, and FMS (NGT, GPIT, MEST) only (see "Downhole Measurements" section, "Site 894" chapter, this volume). A brief description of those tools that were used and their applications is given below according to the physical properties they measure. More detailed information can be found in Hearst and Nelson (1984), Serra (1984), Timur and Toksöz (1985), Ellis (1987), and Schlumberger (1989).

## Sonic Velocity

The LSS-SDT (Fig. 25) uses two acoustic transmitters and two receivers to record the full waveform of sound waves that travel along the borehole wall over source-receiver distances of 2.4, 3.0, and 3.6 m. Compressional-wave velocity is determined in real time by a threshold-measuring technique that attempts to detect the first arrival by first break criteria. Occasionally, this technique fails, and either the threshold is exceeded by noise, or the amplitude of the first compressional arrival is smaller than the threshold. The latter effect is known as cycle skipping and creates spurious spikes on the sonic log. Such problems may often be eliminated by reprocessing the data; in some cases, however (as with Site 894: see "Downhole Measurements" section, "Site 894" chapter, this volume), the artifacts are too severe for a reliable formation signal to be isolated.



Figure 25. Sketch of the Schlumberger long-spacing sonic tool (LSS). T = transmitter; R = receiver; U = upper; L = lower.

#### Table 6. Downhole tools and principal logs.

Tool acronym	Tool name	Method	Measurement	Vertical resolution (cm)	Depth of investigation range (cm)	Log acronym
CALI	Caliper	4 bow arms	Hole diameter			CALL HD
DIT	Dual-induction tool	Induction	Deep resistivity	200	120-150	ILD, IDPH
			Medium resistivity	150	60-80	ILM, IMPH
		Spherically focussed	Shallow resistivity	75	30-40	SFLU
	current	Internal temperature			ITEM	
DLT	Dual laterolog	Focussed current	Deep resistivity	60	> 200	LLD
	Dani mitrorog	r ordstord current	Shallow resistivity	60	< 100	LLS
SS-SDT	Long spacing sonic digital tool	3 travel intervals	Traveltime Full sonic P-wave	61	5-75	LTT1, 2, 3, 4, DTLN, DTLF WF1, 2, 3, 4
IGT	Natural gamma-ray tool	Natural gamma ray	Total gamma ray	45	30-50	SGR, CGR
		s and a gamma sul	U. Th. K	45		URAN, THOR, POTA
ILDT	High-temperature litho-density tool	Gamma-ray scattering	Density Photoelectric effect	45	20-70	RHOB, DRHO PEFL, PEFS
SST	Gamma spectrometry tool	Induced gamma ray	Ca, Si, Fe, S, H, Cl	45	20-70	CCA, CSI, CFE, CSUL, CHY, CCHL
ACT	Aluminum activation clay tool	Induced gamma ray	AI	45	20-70	UWAL, ALUM
INT	Compensated neutron tool	Neutrons backscattering	Porosity	45	20-70	NPHI, TNPH, ENPH
MS	Formation MicroScanner	Image of the borehole	Resistivity	0.5	25	
<b>MEST</b>	Micro electrical scanning tool	caliper	Hole diameter			C1,C2
GPIT	General purpose	Magnetometer	Magnetic field	4		FX, FY, FZ, FNOR
inclinometry tool	Accelerometer	Acceleration	4		AX, AY, AZ, AN	
	2009/2012/2012/2014 <b>*</b> 100/201		Inclinometry	4		FINC, AZIM, DEVI, P1AZ, RB, HAZI
BHTV	Borehole televiewer	Sonar image of borehole	Traveltime	0.5	0	
LT	Temperature logging tool	Thermistors	Temperature, pressure			
MS	Auxiliary measurement	Hole fluid	Temperature,			
	service	measurements	resistivity			
TCCB	Telemetry cartridge		2994500 (2020) 2025. 			

Compressional-wave velocity is controlled primarily by porosity and diagenesis; decreasing porosity or increasing lithification causes velocity to increase.

#### Gamma Ray

#### Natural Gamma-ray Tool

The NGT measures the natural gamma radiation of the formation by a scintillation detector (Lock and Hoyer, 1971). The gamma-ray spectrum is divided into five discrete energy windows, and counts are recorded for each window.

Most natural gamma rays are emitted by the radioactive isotope  ${}^{40}$ K and radioactive isotopes of the U and Th decay series; processing of the window counts gives elemental abundances of K, U, and Th. Because these elements are generally most abundant in clays, the gamma-ray log can be used to estimate the clay content of the formation.

#### High-temperature Lithodensity Tool

The HLDT (Fig. 26) uses a gamma-ray source (0.66 MeV 137Cs) to induce a back-scattered flux of gamma rays that is measured at fixed distances from the source. It also records a photoelectric effect factor (PEF). The radioactive source and detector array are located in a skid pressed against the borehole wall by a single spring-loaded caliper arm. This caliper has a maximum extent of approximately 18–19 in. (~48 cm).

Attenuation of these induced gamma rays is mainly caused by Compton scattering and, therefore, controlled by the density of electrons in the formation. Formation density is extrapolated by assuming that the atomic weight of most rock-forming elements is approximately twice the atomic number. Photoelectric absorption occurs in the energy window below 150 keV and depends on the energy of the incident gamma ray, the atomic cross section, and the nature of the atom. The PEF measurement is almost independent of porosity and, therefore, can be used directly as a matrix lithology indicator. Excessive roughness of the borehole wall allows drilling fluid between the skid and the formation and, consequently, leads to underestimated density measurements. Approximate corrections can be applied using caliper data.

#### **Borehole Inclination and Magnetometer Measurement**

Three-component magnetometers are included both in the GPIT, which is part of the FMS string, and in the BHTV string. They are used to derive the orientation of the downhole sensors within the borehole, the orientation (azimuth and deviation) of the borehole itself, and the magnetic field inclination, declination and intensity. The GPIT also contains a three-component accelerometer to compensate for instrument accelerations along the borehole axis during data acquisition.

#### **Electrical Images**

The FMS (composed of the GPIT and MEST) was introduced by Schlumberger in 1986 to measure the electrical resistivity of the borehole with an array of sensors sufficiently dense to produce high-resolution borehole resistivity images (Ekstrom et al., 1986). Because ODP operations require logging tools to run through the drill pipe (4.125 in.), a modified, smaller-diameter tool was specifically designed by Schlumberger and introduced on ODP Leg 126 (Shipboard Scientific Party, 1990b and 1990c; Pezard et al., 1990). The ODP FMS (Fig. 27A) has four orthogonal pads that are pressed against the borehole wall; each pad (Fig. 27B) carries an array of 16 electrodes (Fig. 27C). The electrodes spacing (Fig. 27C)-together with a vertical sampling distance of 2.5 mm and processing that corrects the offset rows to one level, thus doubling the horizontal resolution-yields a vertical resolution of 5 mm and a horizontal resolution of 1.25 mm; moreover, if there is sufficient resistivity contrast, features of the order of microns across may be detected. The 16 conductivity traces from one pad are displayed side by side, then coded into an image. The four images (one from each pad) typically cover only about 25% of the borehole (depending upon hole diameter); that coverage can be increased by running the tool twice. The FMS works properly only in holes of diameter less than 15 in. (37 cm). The electrode currents probe





Figure 26. Schematic drawing of the Schlumberger high-temperature lithodensity tool (HLDT) (after Schlumberger, 1989).

the conductivity of the rock to a depth of a few centimeters into the borehole wall. They thus respond to variations in physical and chemical properties of the rock such as porosity or surface conduction when conductive clay minerals (e.g., smectites) are present.

Initial processing of the data into images can be done on board ship using proprietary Schlumberger software on the Downhole Measurement Lab LDEO VAX 3100 workstation. Further processing and interpretation of the FMS images is usually performed post-cruise. Magnetometer data that are recorded by the GPIT allow orientation of these images with respect to magnetic North.

Applications of the FMS images include: identification and mapping of fractures, faults, and foliations; determination of strike and dip of structures; lithologic discrimination; detailed correlation of coring and logging depth; and orientation of cores (Serra, 1989; Pezard et al., 1990; Pezard et al., 1992; MacLeod et al., 1992, and in press). The FMS also can be used to determine in-situ principal horizontal stress directions from the precise measurement of borehole diameter by two orthogonal calipers. In an isotropic, linearly elastic rock subject to differential stresses, breakouts form along the borehole wall in the direction of least principal horizontal stress as a result of stress concentrations (Bell and Gough, 1979; Morin et al., 1990).

## **Acoustic Images**

The BHTV (Fig. 28) is an ultrasonic tool that produces an acoustic image of the borehole wall. The BHTV used during Leg 147 is a digital tool designed by Deutsche Montan Technologie (DMP), Germany, and first introduced during ODP Leg 134. A transducer emits broadband (600–1300 kHz) ultrasonic pulses that are directed toward the borehole wall by a rotating mirror. Amplitude and traveltime of the reflected signals are then recorded 128 times per mirror revolution. The typical 6 revolutions per second of the mirror in conjunction with the tool upward movement of 1.5 m/s allows the entire borehole wall to be scanned with a resolution of 0.5 mm for hole diameters of approximately 20 cm. Data are presented in the form of an unwrapped image of the borehole wall both in amplitude and time. Magnetometer

Figure 27. Sketch of the four-pad Schlumberger Formation MicroScanner (FMS) designed for ODP (from Shipboard Scientific Party, 1990b). A. Complete tool. B. Pad configuration. C. Sensor array geometry; dimensions are in millimeters.

data that also are recorded by the BHTV tool string allow these images to be oriented.

The amplitude of the reflected signal depends essentially on the roughness of the borehole wall but also on the reflection coefficient of the borehole fluid-rock interface, the position of the BHTV tool in the borehole, and the shape of the borehole. Fractures or lithologic variations in the drilled rocks can be recognized easily in the amplitude image. The traveltime images give detailed information about the shape of the borehole and, thus, can be considered sophisticated "caliper log" data. The BHTV data can be used to build borehole horizontal cross sections that, if breakouts are identified, can determine the principal horizontal stress directions; to detect fractures; and to re-orient cores. These data complement the FMS resistivity images, but have the advantage of providing complete coverage of the borehole wall.

#### **Temperature Measurement**

The LDEO temperature logging tool (TLT) is a self-contained tool that can be attached to the base of any of the Schlumberger tool combinations. Data from two thermistors and a pressure transducer are collected every 0.5 s and are recorded in an internal Tattletale computer. After logging, the data are transferred from the tool to a shipboard computer for analysis. The two thermistors provide complementary information: the fast-response thermistor, though relatively less accurate, is very precise, and thus able to detect small abrupt temperature excursions (caused, for example, by fluid flow from the formation); the slow-response thermistor is more accurate but less precise and can be used to estimate temperature gradients on the scale of the borehole. Data are recorded as a function of time and of pressure; conversion to depth is made with reference to the latter.

Because logging is typically performed soon after drilling, and hence soon after widespread forced water circulation during drilling,



Figure 28. Schematic drawing of the LDEO-DMT borehole televiewer (BHTV); scale is not respected.

the water temperatures measured by the TLT are not in equilibrium with the formation temperatures; thus, it is common to observe a gradual warming of the TLT temperatures as logging proceeds. The temperatures taken from the last logging run are the closest to formation temperature, but even these should be considered minimum estimates. Techniques to extrapolate the measured temperature to equilibrium formation temperature have been proposed by Jaeger (1961) and Burch and Langseth (1981). The formation temperature gradient obtained from these data, coupled with the conductivity measurements done on core samples, yields an estimate of heat flow at the well.

## **Data Quality**

Downhole data quality may be seriously degraded in excessively large diameter sections of borehole, or by rapid changes in hole diameter. Electrical resistivity and velocity measurements are the least sensitive to such borehole effects; nuclear measurements (density, neutron porosity, and both natural and induced spectral gamma rays), on the other hand, are much more seriously impaired because of the large attenuation by the borehole fluid. However, processing can reduce these borehole effects to some extent.

Different logs may have small depth mismatches caused by cable stretch or ship heave during recording. To minimize such errors, a hydraulic heave compensator adjusts for ship motion in real time, and the NGT is run with all tools when possible to provide a common basis for log correlations.

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<sup>\*</sup> Abbreviations for names of organizations and publication titles in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

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