Schmincke, H.-U., Weaver, P.P.E., Firth, J.V., et al., 1995 Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 157

3. EXPLANATORY NOTES¹

Shipboard Scientific Party²

INTRODUCTION

This chapter summarizes shipboard core handling and analytical procedures on which our preliminary conclusions are based. This information concerns only shipboard operations and analyses described in the site reports in this *Initial Reports* volume.

Authorship of Site Chapters

The sections of the site chapters were written by the following shipboard scientists (listed in alphabetical order):

Principal Results: Schmincke, Weaver Background and Objectives: Schmincke, Weaver Seismic Stratigraphy: Funck, Lykke-Anderson Underway Geophysics: Funck, Lykke-Anderson Operations: Firth, Grout Lithostratigraphy: Carey, Goldstrand, Lebreiro, Rothwell, Schneider, Sumita, Taniguchi, Wallace Biostratigraphy: Brunner, Howe, Maniscalco, Sblendorio-Levy Paleomagnetism: Fuller, Herr Petrography, Mineralogy, and Geochemistry of Volcaniclastic Sediments: Carey, Goldstrand, Lebreiro, Rothwell, Schneider, Sumita, Taniguchi, Wallace Inorganic Geochemistry: Gérard, Jarvis Organic Geochemistry: Lindblom Physical Properties: Baraza, Coakley, Funck, Hood Downhole Measurements: Bristow, Lykke-Anderson Sediment Accumulation Rates: Brunner, Fuller, Herr, Howe, Maniscalco, Sblendorio-Levy

For brevity, we have omitted some general information that has appeared in past *Initial Reports* volumes and kept our notes as short as possible. Reference is made to other *Initial Reports* volumes and technical notes for detailed description of methods where appropriate.

Shipboard Procedures

When core arrived on deck, core catcher samples were taken for biostratigraphic analysis, and gas samples were taken immediately for analysis as part of the shipboard safety and pollution prevention program (SSPP). The core was then cut into sections, whole round samples were taken for shipboard interstitial-water analyses, and headspace gas samples were immediately scraped from the ends of cut sections and sealed in glass vials for light hydrocarbon analysis.

After core sections were run through the MultiSensor Track (MST; see "Physical Properties") and thermal conductivity was measured, the sections were subsequently split into working and archive halves. The working half of each core was sampled for both shipboard and shore-based laboratory studies; the archive half was described visually. Most archive sections were run through the cryogenic magnetometer. The archive half was then photographed a whole core at a time in both black-and-white and color, and blackand-white close-up photographs were taken of particular features for illustration in each site summary.

Both halves of the core were then placed into labeled plastic tubes, sealed, and transferred to cold storage space aboard the drilling vessel. At the end of the leg, the cores were transferred from the ship into refrigerated trucks and then to cold storage at the Bremen Core Repository of the Ocean Drilling Program, in the Federal Republic of Germany.

The numbering of sites, holes, cores, and samples followed the standard ODP procedures. For example, Sample 157-950A-10X-1, 10–12 cm, represents a sample removed from the interval between 10 and 12 cm below the top of Section 1, Core 10 (X designates that this core was taken with the XCB system) of Hole 950A during Leg 157. In short, ODP descriptors are interpreted as follows: leg-hole-core (+ coring type letter)-section, interval (in centimeters).

Cored intervals are referred to in meters below seafloor (mbsf); these are determined by subtracting the rig-floor height above sea level (as determined at each site) from the drill-pipe measurement from the drill floor.

SEDIMENT CORE DESCRIPTION FORMS

The sediment core description forms, or barrel sheets, summarize the sedimentological data obtained during shipboard analysis of each sediment core. A detailed log showing the thickness and nature of each sedimentary unit produced for all MAP and VICAP sites is discussed and illustrated at the end of this chapter.

Graphic Lithology Column

Leg 157 used a slightly modified version of the lithological classification scheme of Mazzullo et al. (1988) that is outlined in the "Sediment Classification" section of this chapter. The only significant modification is a further subdivision of volcaniclastic sediment into *fine ash* and *coarse ash*. Sediment type is represented graphically on the core description forms using the symbols illustrated in Figure 1.

In the "Graphic Lithology" column, a maximum of three different lithologies (for interbedded sediments) or three different components (for mixed sediments) can be represented within the same interval of core. Percentages are rounded to the nearest 10% and only lithologies that constitute at least 10% of the core are shown. Only lithologic units 20 cm or more thick are represented. Minor lithologies present as thin interbeds within the major lithology are shown by a dashed vertical line dividing the lithologies. Components present as minor fractions of the main lithology are shown by a continuous vertical line.

Schmincke, H.-U., Weaver, P.P.E., Firth, J.V., et al., 1995. Proc. ODP, Init. Repts., 157: College Station, TX (Ocean Drilling Program).

²Shipboard Scientific Party is given in the list preceding the Table of Contents.



Figure 1. Key to symbols used in the graphic lithology column on the core description form.

Sedimentary Structures

A key to the symbols used in the sedimentary structure column on Leg 157 is given in Figure 2. We used the generic terms *slightly*, *moderately*, and *strongly bioturbated* where the cause of sediment mottling was clear. However, we used the terms *mottled* and *strongly mottled* where the cause of mottling was unclear or apparently chemical in origin. The term *mottled* may therefore indicate penecontemporaneous or post-depositional changes to the sediment, including chemical haloes and other diagenetic effects. Original sedimentary structures may have been destroyed in cores that have been severely disturbed by drilling.

Sediment Disturbance

Observations of drilling-related disturbance over an interval of 20 cm or more are recorded by the symbols shown in Figure 2. The disturbance categories used were the same as those used on Leg 135 (Parson, Hawkins, Allan, et al., 1992) and the reader is referred to the "Explanatory Notes" of that *Initial Reports* volume for full description of the categories used.

Samples

The positions of samples taken from each core for analysis are indicated by letters in the "Samples" column of the core description form:

S = smear slide T = thin section M = micropaleontology sample I = interstitial water sample

O = organic geochemistry sample

Smear Slide and Thin-section Summary

Tables summarizing data from smear slides and thin sections appear at the end of each site chapter. Smear slide tables include information about the sample location (site, hole, core, section number, and interval in centimeters); whether the sample represents a dominant (D) or a minor lithology (M) in the core; and the estimated percentage ranges of sand, silt, and clay, together with all identified components. Thin section tables include information about sample location, type of rock, and the abundance and types of lithic, crystal, and biogenic components. Clast information includes the abundance of phenocrysts and type, nature of the groundmass, occurrence of structural features, and the type and abundance of secondary minerals.

Color

Color, hue, and chroma attributes were determined with a handheld Minolta CM-2002 spectrophotometer as soon as possible after the cores were split. This instrument measures reflected visible light in thirty-one 10-nm-wide bands ranging from 400 to 700 nm. Reflectance measurements were taken for all intervals of visually similar color in all cores. However, over certain intervals, measurements were made at a close spacing (usually 5 cm) for specific studies. Colors of indurated sediments were determined from wet samples.

Lithologic Description

The lithologic description consists of a brief summary of the major lithologies observed, followed by a summary of the minor lithologies. The color (approximated to the closest category in the shipboard visual core description [VCD] barrel sheet construction program), composition (as determined from smear slides), sedimentary structures or other notable features are described, and the distribution of these features in the core is indicated.

The terminology for the thickness of sedimentary beds and laminae follows McKee and Weir (1953): very thick bedded (>100 cm), thick bedded (30–100 cm), medium bedded (10–30 cm), thin bedded (3–10 cm), very thin bedded (1–3 cm), thickly laminated (>0.3 cm), and thinly laminated (<0.3 cm). Some beds of medium thickness and all thin or very thin beds of a minor lithology may be described in the Description" column, although the beds may be too thin (<20 cm) to appear in the "Graphic Lithology" column.

Drilling Disturbance Symbols Sedimentary Structures Soft sediments 1< Veins Interval over which primary sedimentary structures occur Slightly disturbed Load casts **↑**F Fining-upward sequence ٠ Lithoclast i 1c Coarsening-upward sequence Moderately disturbed Isolated pebbles 0 î Reduction of particle abundance cobbles/dropstones Δ Ash or purnice pods Planar laminae 3 Highly disturbed Ash layer A Cross-laminae (including climbing ripples) 1/ Micro fault (normal) Wavy laminae/beds 000 1/2 Micro fault (thrust) Soupy Wedge-planar laminae/beds Cross-bedding Macro fault X Hard sediments Δ Fracture Graded interval (normal) V 1/ Mineral-filled fracture Slightly fractured Graded interval (reversed) HA Injection ... Graded bedding (normal) X Probable compaction fracture ... Graded bedding (reversed) + Moderately fractured ×5 ... Tension gashes Scoured contact with graded beds L \odot Flaser bedding Concretions/nodules >> 8 Ø Lenticular bedding Highly fragmented Vugs nn Convoluted and contorted bedding Bioturbation, minor 3 ××× (<30% surface area) m Current ripples Drilling breccia Bioturbation, moderate 33 Sharp contact (30%-60% surface area) Gradational contact Bioturbation, strong Scoured, sharp contact 333 (>60% surface area) 17 Cross-stratification >>> Discrete Zoophycos trace fossil Slump blocks or slump folds 6 Fossils, general (megafossils) 2 Contorted slump slump folds 0 Shells (complete) Š Mud/desiccation cracks Ø Shell fragments Scour 4 a Wood fragments Imbrication 1 * Cylindrichnus trace fossil Clastic dike Figure 2. Symbols used for drilling disturbance and 9 19 Sagarites Water-escape pipes sedimentary structures on core description forms.

Genetic Logs

A new type of graphic log was devised to allow rapid overview of the principal lithology. The logs were done principally by the cochiefs quickly after the splitting of the cores, and visualized using the MacDraw program. For the MAP sites the main purpose was to portray graphically the main sediment types: organic, volcanic, and calcareous turbidites, and pelagic clays, muds, and oozes. These simplified graphic logs then allowed for quick calculation of the relative proportions of sediment types and calculation of sedimentation rates. A condensed version of the MAP genetic logs is included in sedimentology sections while the full set appears on the CD-ROM (back pocket, this volume).

Sediments in the VICAP sites varied much more in the lithology compared to the MAP sites because of the broad range in composition, textures, and structures of the volcaniclastic sediments ranging from thin ash-fall layers to debris flow deposits exceeding 50 m in thickness. The abundance of sediments consisting of both volcanic and nonvolcanic components mixed in all proportions presented a particular problem in devising and applying a simple graphic key. Consequently, the key to clarify the sediments was updated repeatedly. An example of a genetic log from Site 956 is shown in Figure 3 along with the key used for Site 956. The logs for all sites are included on the CD-ROM (back pocket, this volume).

SEDIMENT CLASSIFICATION

Classification of Sediments and Sedimentary Rocks

The slightly modified version of the Ocean Drilling Program sediment classification scheme (Mazzullo et al., 1988) used on Leg 157 is described below. This classification scheme recognizes two principal sediment types: granular and chemical. Chemical sediments were not encountered during Leg 157.

Classes of Granular Sediments

Variations in the relative proportions of different grain types define five major classes of granular sediments: pelagic, neritic, siliciclastic, volcaniclastic, and mixed (Fig. 4). Pelagic grains comprise the skeletal remains of open marine siliceous and calcareous microfauna and microflora (e.g., radiolarians, planktonic foraminifers, nannofossils) and associated organisms. Neritic grains include calcareous grains and skeletal remains (e.g., bioclasts, shallow-water benthic foraminifers, peloids) of nonpelagic origin. Siliciclastic grains are mineral and rock fragments derived from plutonic, sedimentary, and metamorphic rocks. Volcaniclastic grains include those of pyroclastic (direct products of magma degassing) and epiclastic (detritus derived from erosion of volcanic rocks) origin.

Classification of Granular Sediment

Granular sediment is classified by a principal name designation with additional 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, fabric, or roundness of the grains (Table 1).

Principal Names

Each granular-sediment class has a unique set of principal names. A summary of these principal names is presented in Table 1. For a complete discussion see Mazzullo et al. (1988).

We modified the classification of Mazzullo et al. (1988) with regard to principal names of volcaniclastic sediments. Volcaniclastic sediments have been subdivided into two groups: pyroclastic and ep-



with ashes equivalent to ignimbrite P1. The basalitic tirfs below are shown with the hyaloclastite patterns except where they are fine-grained (dotted pattern). Bedding in the otherwise massive hyaloclastite debris flow is shown by horizontal lines.

Figure 3. Example of genetic log used for VICAP sites and key to symbols used in the graphic lithology log.

iclastic. The names and ranges of three grain size groups for pyroclastic material (from Fisher and Schmincke, 1984) are as follows:

1. Volcanic breccia: clasts >64 mm in diameter.

2. Lapilli: clasts 2-64 mm in diameter; when lithified, described as lapillistone.

3. Ash: grains <2 mm in diameter; when lithified, described as tuff.

We further subdivided the ash component of the Mazzullo et al. scheme into two size classes: material ranging 1/16 to 2 mm in grain size (equivalent to sand in siliciclastic sediments) is described as *coarse ash* and material less then 1/16 mm (silt and clay-size) is termed *fine ash*. *Coarse tuff* and *fine tuff* are the terms used for lithified equivalents of these size ranges. For epiclastic sediments the principal name is based on grain size using the same nomenclature as



Figure 4. Diagram showing classes of granular sediment (after Mazzullo et al., 1988).

the classification for siliciclastic sediments (Udden-Wentworth grain size scale).

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 (Table 1). Major and minor modifiers most commonly describe composition and grain size of particles present in major (>25%) and minor (10%-25%) proportions. In addition, major modifiers can describe degree of lithification, grain fabric, grain shape, and sediment color. The principal modifiers used in the classification of volcaniclastic sediments include lithic (rock fragments), vitric (glass, pumice, or hyaloclastite), crystal (mineral phases and fragments), and modifiers describing the composition of the lithic grains and crystals (e.g., basaltic or feldspar). For a complete discussion of major and minor modifier nomenclature, see Mazzullo et al. (1988).

BIOSTRATIGRAPHY

Introduction

Leg 157 shipboard biostratigraphy was based on the examination of both calcareous nannofossils and planktonic foraminifers. During Leg 157, many turbiditic and volcaniclastic sequences were drilled making core-catcher analyses unreliable in many cases. We therefore sampled the hemipelagic sediments from the split cores wherever possible, thus enhancing the biostratigraphic resolution. In cases where the hemipelagic sediments were barren we sampled the finer grained parts of turbidites to provide a coarser age control.

Time-scale/Magnetobiostratigraphic Framework

On Leg 157 we used the composite magnetic polarity time scale devised for ODP Leg 154. This time scale is a composite of four previous time scales (see "Paleomagnetism," this chapter, and Curry, Shackleton, Richter, et al., 1995, for more details). Figure 5 shows the correlation of the calcareous nannofossil and planktonic foraminiferal zones to the composite magnetostratigraphic time scale used here.

Calcareous Nannofossils

Zonation and Datum Levels

For Leg 157, the low latitude CN zones of Bukry (1973, 1975) and Okada and Bukry (1980) were used (in preference to the alternative Martini, 1971, zonation) because of their higher resolution in some parts of the time scale. Table 2 lists the calcareous nannofossil datum levels used on Leg 157 and their estimated ages (from Curry, Shackleton, Richter, et al., 1995). Additionally, six calcareous nannofossil datum levels from Young et al. (1994) were added to Table 2. An estimated age was calculated for these added datum levels by using linear interpolation between the nearest geomagnetic reversal boundaries. Figure 5 shows the correlation between the magnetostratigraphic time scale and the nannofossil zones used on this leg.

Methods

Standard nannofossil smear slides were prepared from unprocessed sediment and examined at ×1250 magnification using a transmitted light microscope, equipped with polarizing and phase contrast facilities.

Overall nannofossil abundance in a sample was recorded as follows (viewed at $\times 1250$):

VH = very high; more than 100 specimens per field H = high; 50–100 specimens per field M = moderate; 10–50 specimen per field L = low; 1–10 specimens per field VL = very low; 1 specimen per 1–10 fields B = barren; no nannofossils present

Species abundance was recorded as follows (viewed at ×1250):

A = abundant; >100 individuals in a field of view (FOV) C = common; >10 individuals in a FOV F = few; 1–10 individual in a FOV R = rare; 1 individual in 10 FOV VR = very rare; 1 individual in 100 FOV

Letter codes G (good), M (moderate), and P (poor) are used to denote the preservational state of nannofossils (see full definitions in Curry, Shackleton, Richter, et al., 1995).

Foraminifers

We used the subtropical zonation of Berggren (1977) and Berggren et al. (1983) for the Quaternary and Neogene sequences. A list of datum levels appears in Table 3, which follows Berggren et al. (1985) and Chaisson and Leckie (1993) with various modifications (Shackleton et al., 1995; Weaver and Clement, 1986; Weaver and Raymo, 1989). Figure 5 shows the correlation between the magnetostratigraphic time scale and the planktonic foraminiferal zones used on this leg.

We used benthic foraminifers to determine the source of turbidites, water depth, and water mass in pelagic intervals (Haake et al., 1982; Lutze, 1980; Lutze and Coulbourn, 1984; Martin, 1981; Mathieu, 1972, 1988; Murray et al., 1986).

Sample size was standardized by volume so specimen abundances could be compared between samples: core catcher samples were 20 cm³ and samples from split cores were 10 cm³. Unlithified samples were washed through a 63 μ m sieve with tap water and dried quickly under heat lamps. Lithified samples were broken into small pieces with a hammer, washed on a stack of sieves with 1 mm and 63 μ m

Sediment class	Major modifiers	Principal name	Minor modifiers		
Pelagic sediment	Composition of pelagic and neritic grains present in major amounts Texture of clastic grains present in major amounts	Ooze Chalk Limestone Radiolarite Diatomite Spiculite Chert	Composition of pelagic and neritic grains present in minor amounts Texture of clastic grains present in minor amounts		
Neritic sediment	Composition of neritic and pelagic grains present in major amounts Texture of clastic grains present in major amounts Degree of lithification	Boundstone Grainstone Packstone Wackestone Mudstone Floatstone Rudstone	Composition of neritic and pelagic grains present in minor amounts Texture of clastic grains present in minor amounts		
Siliciclastic sediment	Composition of all grains present in major amounts Grain fabric (gravels only) Grain shape (optional) Sediment color (optional) Degree of lithification (optional)	Gravel, breccia, conglomerate Sand Silt Clay	Composition of all grains present in minor amounts Texture and composition of siliciclastic grains present as matrix (for coarse- grained clastic)		
Volcaniclastic sediment	Composition of all grains present in major amounts Texture of clastic grains present in major amounts Degree of lithification (optional)	Pyroclastic: Volcanic breccia Lapilli Coarse ash/tuff Fine ash/tuff Epiclastic: Volcanic Conglomerate Ig-lithic breccia Volcanic sand Volcanic sand	Composition of all volcaniclasts present in minor amounts Composition of all neritic and pelagic grains present in minor amounts Texture of clastic grains present in minor amounts		
Mixed sediments	Composition of neritic and pelagic grains present in major amounts Texture of clastic grains present in major amounts	Mixed sediments/ mixed sedimentary rock	Composition of neritic and pelagic grains present in minor amounts Texture of clastic grains present in minor amounts		

Table 1. Outline of granular-	ediment classification sch	eme (modified from	Mazzullo et al.	, 1988).
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openings, dried under heat lamps, boiled in a 1% (by weight) Calgon solution, and rewashed on a 63 μ m screen. The following abundance categories were estimated for groups and taxa from a visual examination of the sand-size constituents in the dried sample:

A = abundant; >1000 grains per 10 cm^3

 $C = \text{common}; 101-1000 \text{ grains per } 10 \text{ cm}^3$

 $F = few; 11-100 grains per 10 cm^3$

 $R = rare; 1-10 \text{ grains per } 10 \text{ cm}^3$

B = barren

We also noted the dominant constituent in the sand-size fraction; these data are available from the ODP database.

Preservation was estimated as follows:

G = good; >90% of the specimens intact; delicate species abundant

M = moderate; 30%–90% of the specimens unbroken and few delicate specimens present

P = poor; <30% of specimens intact and no delicate specimens present

Benthic foraminifer depth zones were adapted mainly from Lutze (1980) and Lutze and Coulbourn (1984) on the northwest African continental margin. A major biogeographic boundary near 23°N latitude divides the slope and shelf into north and south provinces above 1000 m (Lutze and Coulbourn, 1984).

Neritic (north) = shelf and upper slope; 0–200 m Neritic (south) = shelf and upper slope; 0–200 m Upper bathyal (north) = upper slope; 200–500 m Upper bathyal (south) = upper slope; 200–500 m Middle bathyal (north) = middle slope; 500–1000 m Middle bathyal (south) = middle slope; 500–1000 m Lower bathyal to abyssal = lower slope, rise, and abyssal plain; >1000 m

PALEOMAGNETISM

For magnetostratigraphy on Leg 157, the natural remanent magnetization (NRM) of archive half sections was measured on the 2G Enterprises 760R magnetometer using a standard 10 cm reading interval, with alternating field (AF) demagnetization up to 25 mT. Discrete samples from the working half were measured, with demagnetization up to 50 mT to establish demagnetization behavior in higher fields. Stepwise thermal demagnetization was also employed for selected discrete samples to determine blocking temperatures. The magnetic susceptibility was measured for each whole core section as part of the MST analyses. Anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM) measurements, along with bulk susceptibilities, were used as controls to determine whether changes in NRM intensity were related to changes in geomagnetic field or to variations in magnetic mineralogy.

Rock magnetic measurements were also made on the discrete samples to obtain data for standard plots to characterize the magnetic phases present and the remanence they carry. These included acquisition and demagnetization (AF and thermal) of IRM and ARM and bulk susceptibility.

The anisotropy of magnetic susceptibility (AMS) was measured with the Kappabridge KLY 2.03 as a fabric indicator for flow directions in sediments.



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Table 2. Age estimates of nannofossil datum levels used on Leg 157, adjusted to the Leg 154 time scale (from Curry, Shackleton, Richter, et al., 1995).

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$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	LO Discoaster surculus	CN12c	NN17	2.61	3
Do Disconsite numberCN12 b2.763LO Sphenolithus spp.CN12 aNN163.773LO Reticulofenestra pseudoumbilicusCN11aNN154.3910FO Discoaster tamalisCN10bN144.7910FO Ceratolithus sugosusCN10bS.344FO Ceratolithus rugosusCN10bS.344LO Triquetrorhabdulus rugosusCN10bS.344Plicoene/Miocene boundaryS.38LOLO Amaurolithus amplificus6.54LO Amaurolithus amplificus6.54LO Amaurolithus amplificus6.54FO Amaurolithus amplificus6.84FO Discoaster quinqueramusCN9b7.34FO Discoaster surculus7.84FO Discoaster oublichiiCN8aN1118.4FO Discoaster loeblichiiCN8aN118.4FO Discoaster loeblichiiCN8aN109.4A FO Discoaster hamatus9.64FO Discoaster hamatus9.64FO Discoaster hamatus9.64FO Discoaster hamatusS.64FO Discoaster hamatus9.64FO catinaster colitusCN6NN810.7LO Coccolitus miopelagicus11.34FO common Discoaster kuglerii11.34FO common Discoaster kuglerii12.74FO Discoaster kuglerii12.74FO Calcidiscus macintyrei (211 µm)12.24 <t< td=""><td>LO Discoaster tamalis</td><td>CN12b</td><td>11117</td><td>2.76</td><td>ä</td></t<>	LO Discoaster tamalis	CN12b	11117	2.76	ä
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FO Sphenolithus heteromorphus CN3 18.1 7 LO Sphenolithus belemnos NN4 18.4 7 FO Sphenolithus belemnos CN2 19.7 7 LO Triquetrorhabdulus carinatus NN3 23.1 7 FO Discoaster druggii CN1c NN2 23.3 8 LO acme Sphenolithus delphix 23.7 9 Miocene/Oligocene boundary 23.8 12 FO Sphenolithus oamaruensis 28.1 12 FO Chiasmolithus oamaruensis 36.9 12 FO Rativulóntores 42.2 12	FO Calcidiscus premacintyrei			17.4	6
LO Sphenolithus belemnos NN4 18.4 7 FO Sphenolithus belemnos CN2 19.7 7 LO Triquetrorhabdulus carinatus NN3 23.1 7 FO Discoaster druggii CN1c NN2 23.3 8 LO acme Sphenolithus delphix 23.7 9 Miocene/Oligocene boundary 23.8 L LO Dictyococcites bisectus 23.8 12 FO Sphenolithus ciperoensis 28.1 12 FO Chiasmolithus oamaruensis 36.9 12 FO Rativulformetra umbilicure 42.2 12	FO Sphenolithus heteromorphus	CN3		18.1	7
FO Sphenolithus belemnos CN2 19.7 7 LO Triquetrorhabdulus carinatus NN3 23.1 7 FO Discoaster druggi CN1c NN2 23.3 8 LO acme Sphenolithus delphix 23.7 9 Miocene/Oligocene boundary 23.8 12 LO Dictyococites bisectus 23.8 12 FO Sphenolithus ciperoensis 28.1 12 FO Chiasmolithus omaruensis 36.9 12 FO Raticulfornestra umbilicure 42.2 12	LO Sphenolithus belemnos	(1) 10	NN4	18.4	7
LO Triquetrorhabdulus carinatus NN3 23.1 7 FO Discoaster druggii CN1c NN2 23.3 8 Lo acme Sphenolithus delphix 23.7 9 Miocene/Oligocene boundary 23.8 12 LO Dictyococcites bisectus 23.8 12 FO Sphenolithus oamaruensis 28.1 12 FO Reticulformetra umbilitour 36.9 12	FO Sphenolithus belemnos	CN2	10.00	19.7 .	7
FO Discoaster aruggit CN1C NN2 23.5 8 LO acme Sphenolithus delphix 23.7 9 Miocene/Oligocene boundary 23.8 LO Dictyococcites bisectus 23.8 12 FO Sphenolithus ciperoensis 28.1 12 FO Chiasmolithus oamaruensis 36.9 12 FO Raticulaforectra umbiliture 42.2 12	LO Triquetrorhabdulus carinatus	CDU	NN3	23.1	/
LO acme sphenolinus delphix 23.7 9 Miocene/Oligocene boundary 23.8 LO Dictyococcites bisectus 23.8 FO Sphenolithus ciperoensis 28.1 FO Chiasmolithus oamaruensis 36.9 FO Rativulgemeetra umbilicure 42.2	10 Discoaster druggu	UNIC	NN2	23.5	8
Milocener/Ongocene boundary 23.8 LO Dictyococcites bisectus 23.8 FO Sphenolithus ciperoensis 28.1 FO Chiasmolithus camaruensis 36.9 LO Destructioner 42.2	Niesene (Oliesene heunder)			23.1	9
FO Encryococcues disectus 25.8 12 FO Sphenolithus cipercoensis 28.1 12 FO Chiasmolithus comaruensis 36.9 12 FO Raticulation comparison 42.2 12	1 O Distussessitas hisastus			23.8	12
FO Chiasmolithus communities 36.9 12 FO Reliandeformetre and 12	EO Sphanolithus ciparoansis			28.1	12
EO Patieulofenestra umbilious 42.2 12	FO Chiasmolithus camaruaneis			36.9	12
1 O Renculojenestra unionicas 42.2 12	FO Reticulofenestra umbilicus			42.2	12

Notes: Additional datum levels have been interpolated from Young et al. (1994). FO = first (evolutionary) occurrence; LO = last (evolutionary) occurrence. References: 1 = Thierstein et al. (1977), 2 = Raffi et al. (1993), 3 = Backman and Shackleton (1983), 4 = Raffi and Flores (1995), 5 = Backman et al. (1990), 6 = Gartner (1992), 7 = Olafsson (1991), 8 = Berggren et al. (1985), 9 = Fornacini et al. (1990), 10 = Young et al. (1994), 11 = Sato and Takayama (1992), 12 = Curry, Shackleton, Richter, et al. (1995).

Magnetic Polarity Reversal Time Scale

Shipboard paleontologists and paleomagnetists decided to use a magnetic polarity time scale that is a composite of four previous time

Figure 5. Diagram showing the correlation between the magnetostratigraphic time scale and the nannofossil zones of Okada and Bukry (1980) and Martini (1971), and the planktonic foraminiferal zones of Berggren (1977, 1983) and Blow (1969). After Curry, Shackleton, Richter, et al. (1995). Datum levels are tied to the paleomagnetic time scale, but zones are not necessarily inter-correlated.

Table 3. Age estimates of	planktonic foraminiferal da	atum levels used on Leg 15	7, adjusted to the Leg	154 time scale (fron	a Curry, Shac	kleton, Richter,
et al., 1995).						

Event	Zone (5)	Zone (6)	Age (Ma)	References	Event	Zone (5)	Zone (6)	Age (Ma)	References
	×.,	(-)	0.6					0	n anna an anna an anna an an an an an an
LO Globorotalia tosaensis			0.6	1	FO Globigerinoides obliquus extremus			8	4
LO Globigerinoides fistulosus			1.7	1	FO Globorotalia plesiotumida		N17	8.2	4
Pleistocene/Pliocene houndary			1 77	1	FO Neogloboquadrina humerosa			8.28	1
Theistocenest nocene boundary			1.77		LO Globoquadrina dehiscens			9.99	3
LO Globigerinoides obliquus extremus			1.88	2, 3	FO Neogloboquadrina acostaensis	M11	N16	9.99	3
FO Globorotalia truncatulinoides	N22	N22	1.92	2, 3	LO Paragloborotalia mayeri		N15	10.3	4
FO Globorotalia inflata			2.19	2, 3	LO Globorotalia praemenardii			10.7	4
Reappearance of Pulleniatina (Atlantic)			2.3	3	FO Globigerina nepenthes	M9/M10	N14	10.8	4
LO Globorotalia exilis			2.3	3	FO Globigerina apertura			10.8	4
LO Globorotalia miocenica	PL6		2.37	2,3	FO Globigerina decoraperta			11.2	4
LO Globorotalia puncticulata			2.5	2,3	LO Fohsella fohsi s.l.			11.8	4
LO Globorotalia pertenuis			2.6	1	FO Globorotalia lenguaensis			12.3	4
LO Globorotalia multicamerata	PL5		3	1	FO Fohsella fohsi robusta		N13	12.7	1
LO Dentoglobigerina altispira	PL5		3.09	2.3	FO Fohsella fohsi s.l.			13.5	4
LO Globorotalia conomiozea			3.1	1	LO Globorotalia praescitula			13.8	4
FO Sphaeroidinella dehiscens s.s.		N19/N20	3.12	1	FO Fohsella praefohsi		N11/N12	14	4
LO Sphaeroidinellopsis spp.			3.12	i	LO Globorotalia archeomenardii			14.2	4
LO Sphaeroidinellopsis seminulina	PI 4		3.15	23	LO Fohsella peripheroronda	M8		14.6	1
FO Globorotalia tosaensis	1.443		3.2	4	FO Fohsella peripheroacuta		N10	14.7	4
FO Globigerinoides fistulosus			3.2	4	FO Globorotalia praemenardii			14.9	4
FO Globorotalia crassula			3.24	7	FO Orbuling spp.		N9	15.1	1
FO Globorotalia partenuis			3.47	1	FO Orbuling suturalis	M7		15.1	1
1 O Globorotalia margaritae	DI 2		2 70	1	FO Globorotalia archeomenardii			15.5	4
LO Gibborolatia margaritae	PLS		2.09	1	FO Globigerinoides diminutus	M62		16.11	i
Pulleniating (S to D coiling shapes)			5.98	1	10 Globigerinoides altianerturus	14101		16.2	4
FO Cloborotalia missonia			4.04	4	EO Procorbuling sicana	MS	N8	16 39	í
LO Clobaratalia plasiatumi da			4.04	5	FO Globorotalia miozea	MA	140	16.58	î
LO Gioborolalla plesiolumiaa	DI O		4.4	4	10 Cloborotalia zaolandica	1414		16.58	î
LO Globigerina nepenines	PL2		4.03	2, 3	LO Globorotalia pseudomiorea			16.58	1
EO Giobigerinolaes selgiel			4.69	1	EO Globorotalia himagogg			16 77	1
FO Globorotalia puncticulata			4.69	2, 3	LO Catangudras stainforthi			17.15	1
FO Globorotalia crassaformis s.s.			4.78	3	LO Catanzidan dissimilia		N17	17.13	1
LO Globorotalia cibaoensis			2	4	EO Clabostalia and and		187	17.33	1
LO Neogloboquadrina acostaensis			5.1	4	FO Globorolalla zealanaica	142		17.33	1
Pliocene/Miocene boundary			5 38	1	FO Globorolalia pseuaomiozea	MS		17.33	1
Theenervice outlineary			5.50		LO Globorotalia semivera			17.33	1
LO Globorotalia juanai			5.4	4	LO Globorotalia incognita			17.33	1
LO Globoquadrina baroemoensis			5.4	4	FO Globorotalia praescitula		110	17.39	1
LO Globoquadrina dehiscens	PL1		5.6	4	FO Globigerinatella insueta		No	18.7	4
FO Globorotalia tumida		N18	5.71	1	LO Globoquadrina binaiensis			19.1	4
FO Globigerinoides conglobatus			5.82	1	FO Globigerinoides altiaperturus			20.56	1
LO Globorotalia lenguaensis			5.82	1	LO Paragloborotalia kugleri	M2	N5	21.55	1
FO Globorotalia cibaoensis			5.82	1	FO Globoquadrina binaiensis	100000		22.1	4
Neogloboauadrina acostaensis (S to D)			6.43	1	FO Globoquadrina dehiscens	MIb		23.29	1
FO Globorotalia margaritae	M13		6.64	2.3	FO Globorotalia incognita			23.29	1
FO dextral menardine globorotaliids			6.6	1	LO Globigerina angulisuturalis			23.29	1
Neogloboauadrina acostaensis (D to S)			67	î	LO Globorotalia pseudokugleri			23.29	1
FO Globorotalia conomiozea	M12		67	î	FO Paragloborotalia kugleri	M1		23.75	1
I O sinistral menardine globorotaliide	MIL		7.26	i	LO Globorotalia mendacis			23.75	1
FO Globorotalia juanaj			8	4	FO Globigerinoides primordius		N4	24.5	4
FO Candeina nitida			8	4			1000	2560	14

Notes: 1 = Berggren et al. (1985), 2 = Weaver and Clement (1986, 1987), 3 = Weaver and Raymo (1986), 4 = Chaisson and Leckie (1993), 5 = Blow (1969), as modified by Kennett and Srinivasan (1983), 6 = Berggren (1977) and Berggren et al. (1983).

scales: Shackleton et al.'s (1990) astronomically tuned time scale, for the interval between 0 and 2.6 Ma; Hilgen's (1991a, 1991b) astronomically tuned time scale, for the interval between 2.6 Ma and 5.23 Ma; Shackleton et al.'s (1995, their table 17) time scale (partially astronomically tuned), for the interval between 5.23 and 14.8 Ma; and finally Cande and Kent's (1992) seafloor-spreading-based time scale for beyond 14.8 Ma. These four separate time scales are compatible and should not introduce artificial discontinuities in calculated sedimentation rates at the points they have been joined. Absolute ages used in the Leg 157 magnetic polarity time scale are summarized in Table 4.

Laboratory Procedures

The procedures followed those of previous ODP legs (e.g., Leg 155 *Initial Reports*, "Explanatory Notes"). The 2-G 760R, with a 7.7 cm (3 in.) access diameter, was employed in the pass-through measurement of the archive half of the core sections. The cryogenic magnetometer was also used in the pass-through mode to measure remanence in up to seven spatially separated discrete samples from zones of particular interest using a discrete sample measuring pro-

gram. Discrete sample remanence measurements were made also with a Molspin Minispin spinner magnetometer. The two instruments were also cross-calibrated and compared with a standard sample measured previously at the University of California-Santa Barbara (UCSB) laboratory. A Schonstedt Alternating Field Demagnetizer (GSD-1) and Schonstedt Thermal Demagnetizer (TSD-1) permitted demagnetization to levels of 100 mT and 800°C, respectively. However, beyond 50 mT, AF demagnetization was found to be unsatisfactory on test samples. IRM acquisition was accomplished with an ASC Impulse Magnetizer (IM-10), which can generate transient direct current (DC) fields of up to 1.2 T. A DTECH Partial Anhysteretic Remanent Magnetizer was used to impart ARMs at 100 mT AF in ambient DC fields of 1 mT intensity.

The Kappabridge KLY-2 Magnetic Susceptibility System was used to measure AMS and bulk susceptibility on discrete samples at the rate of one sample per core section.

Core Orientation

During advanced hydraulic piston corer (APC) drilling, core orientation was achieved with a Tensor orientation tool. Data from the

Table 4. Ages accepted for the magnetic polarity time scale.

Boundary	Name	Age	Reference	Boundary	Name	Age	Referenc
C1n	Brunhes (o)	0.78	1	C5Ar.1n (t)		12.605	3
Clr.ln	Jaramillo (t)	0.99	i.	C5Ar.1n (o)		12.637	3
Clr.ln	Jaramillo (o)	1.07	1	C5Ar.2n (t)		12,705	3
22n	Olduvai (t)	1.77	i	C5Ar.2n (o)		12.752	3
C2n	Olduvai (o)	1.95	1	C5AAn (t)		12.929	3
2An.1n	Gauss (t)	2.60	12	C5AAn (o)		13.083	3
2An.1r	Kaena (t)	3.04		C5ABn (t)		13 252	3
2An Ir	Kaena (o)	3.11	2	C5ABn (o)		13 466	3
2An 2r	Mammoth (t)	3.22	2	C5ACn(t)		13 666	3
2An 2r	Mammoth (o)	3 33	2	C5ACn(0)		14 053	3
72 Ar	Gilbert (t)	3.58	2	C5ADn (t)		14 159	3
3n In	Cochiti (t)	4.19	ź	C5ADn (c)		14.607	3
² 2n 1n	Cochiti (c)	4.10	2	C5RpIn(0)		14.800	3 4
220.20	Numinals (1)	4.29	2	C5Bn.In (t)		14.800	5,4
22-2-	Numivak (t)	4.48	2	C5Bn.1n (0)		15.029	4
22-2-	Nunivak (0)	4.02	2	C5Bn.2n (t)		15.058	4
22-2-2-	Sidurjan (t)	4.80	2	C5Bn.2n (0)		16 025	7
_3n.3n	Sidurjan (o)	4.89	2	CSCn.In (t)		16.055	4
.3n.4n	Thvera (t)	4.98	2	C5Cn.In(0)		16.318	4
.3n.4n	Invera (o)	5.23	2, 3	C5Cn.2n(t)		10.552	4
.3A.n1 (t)		5.875	3	C5Cn.2n (0)		10.515	4
3A.n1 (0)		6.122	3	C5Cn.3n(t)		10.383	4
.3A.n2 (t)		6.256	3	C5Cn.3n (0)		10.755	4
3A.n2 (0)		6.555	3	C5Dn (t)		17.310	4
3Bn (t)		6.919	3	CSDn (o)		17.650	4
3Bn (o)		7.072	3	C5En (t)		18.317	4
24n.1n (t)		7.406	3	C5En (o)		18.817	4
C4n.1n (o)		7.533	3	C6n (t)		19.083	4
24n.2n (t)		7.618	3	C6n (o)		20.162	4
C4n.2n (o)		8.027	3	C6An.1n (t)		20.546	4
24r.1n (t)		8.174	3	C6An.1n (o)		20.752	4
C4r.1n (o)		8.205	3	C6An.2n (t)		21.021	4
C4An (t)		8.631	3	C6An.2n (o)		21.343	4
C4An (o)		8.945	3	C6AAn (t)		21.787	4
C4Ar.1n (t)		9.142	3	C6AAn (o)		21.877	4
4Ar.1n (o)		9.218	3	C6AAr.1n (t)		22.166	4
24Ar.2n (t)		9.482	3	C6AAr.1n (o)		22.263	4
C4Ar.2n (o)		9.543	3	C6AAr.2n (t)		22.471	4
25n.1n (t)		9.639	3	C6AAr.2n (o)		22.505	4
5n.2n (o)		10.839	3	C6Bn.1n (t)		22.599	4
5r.1n (t)		10.943	3	C6Bn.1n (o)		22.760	4
25r.1n (o)		10.991	3	C6Bn.2n (t)		22.814	4
5r.2n (t)		11.373	3	C6Bn.2n (o)		23.076	4
(5r.2n (o)		11,428	3	C6Cp ln (t)		23.357	4
5An.1n (t)		11.841	3	$C6Cn \ln (o)$		23.537	4
5An.1n (o)		11 988	3	C6Cn.2n(t)		23,678	4
5An.2n (t)		12,096	3	C6Cn 2n (o)		23,800	4
"5An 2n (o)		12 320	3	evenium (0)			

Notes: 1 = Shackleton et al. (1990), 2 = Hilgen (1991a and 1991b), 3 = Shackleton (1994, table 17), 4 = Cande and Kent (1992). Abbreviations: t = top, o = onset.

Tensor tool was corrected for local magnetic variation before its use in the computation of remanence field directions and AMS vector orientations. Oriented discrete samples were taken from the working half cores by pressing sample cubes into the soft sediment. A thin stainless steel spatula was used to cut into the more lithified sediment zones before insertion of the sample cubes to minimize sediment deformation. In lithified material, samples were obtained either by cutting cubes or drilling cylinders.

PETROGRAPHY, MINERALOGY, AND GEOCHEMISTRY OF VOLCANICLASTIC SEDIMENTS

Core Curation and Description

Core sections from Sites 953–956 that contained volcaniclastic sediments and rocks were handled, split, and labelled according to standard ODP procedures for sediments. Visual core description forms were used to document these cores (see site summaries), with particular emphasis on the abundance, texture, and composition of vitric, lithic, and crystal components. Definition of the terms used can be found in the "Sediment Core Description" and "Sediment Classification" sections (this chapter) and in Mazzullo et al. (1988). Per-

centages and textural descriptions of individual components from thin section examination are included in the appendixes.

X-ray Fluorescence (XRF) Analysis

A fully automated wavelength-dispersive ARL8420 XRF (3 kW) system equipped with a Rh target X-ray tube was used to determine the major and trace element abundances of whole-rock samples. Analytical procedures were similar to those followed on Leg 142 (Storms, Batiza, et al., 1993) with the following exceptions. Samples were cleaned in methanol with an ultrasonic cleaner, rinsed in deionized water, and dried at 110°C for 12 hr. Ignition time was 4 hr and temperature was 900°C for rock powders, and fused disks were prepared by melting at 1075°C for 8 min. Loss on ignition (LOI) was determined by drying the sample at 110°C for 12 hr and then weighing before and after ignition at 1025°C in air. Instrument conditions for the XRF analyses are given in Table 5. A wide variety of rock and sediment standards were used for major and trace element calibration, including alkali basalts and syenites that are similar in composition to volcaniclastic sediments recovered during Leg 157. Means and standard deviations of major and trace element analyses of alkali basalt standard BE-N are given in Table 6.

Replicate analyses of rock standards show that the major element data are precise within 0.5% to 2.5%, and are considered accurate to

Table 5. XRF operating conditions	, analytical error	r estimates, and	detection limits
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Oxide or element	Line	Crystal	Detector	Collimator	Peak angle (°2θ)	Background offset (°20)	Count time on peak (s)	Count time on background (s)	Analytical error (rel%)	Detection limit
Major elem	ents (wt%)									
SiO	K-alpha	PET	FPC	Medium	109.21		40		0.5	0.03
TiO	K-alpha	LIF200	FPC	Fine	86.14		40		2.6	0.01
Al ₂ Ô ₂	K-alpha	PET	FPC	Medium	145.12		100		0.6	0.01
Fe ₂ O ₂	K-alpha	LIF200	FPC	Fine	57.52		40		1.1	0.01
MnO	K-alpha	LIF200	FPC	Fine	62.97		100		6.5	0.005
MgO	K-alpha	TLAP	FPC	Medium	45.17	±0.80	150	150	1.5	0.01
CaO	K-alpha	LIF200	FPC	Medium	113.09		40		1.2	0.005
Na ₂ O	K-alpha	TLAP	FPC	Medium	55.10	-1.20	150	150	3.0	0.03
K ₂ Ô	K-alpha	LIF200	FPC	Medium	136.69		100		0.8	0.01
P2O5	K-alpha	GE111	FPC	Medium	141.04		100		9.8	0.01
Trace elem	ents (ppm)									
Cr	K-alpha	LIF200	FPC	Fine	69.35	-0.50	100	50	2.6	1.3
Ni	K-alpha	LIF200	Scint	Fine	48.67	-0.60	100	50	2.3	1.2
Cu	K-alpha	LIF200	Scint	Fine	45.03	-0.55	100	50	4.8	1.4
V	K-alpha	LIF220	FPC	Fine	123.06	-0.50	100	50	0.7	21.5
Zn	K-alpha	LIF200	Scint	Fine	41.81	-0.55	100	50	1.0	2.5
Sr	K-alpha	LIF200	Scint	Fine	25.15	-0.40	100	50	0.9	0.6
Ba	L-beta	LIF220	FPC	Medium	128.78	-1.50	100	50	1.8	6.3
Rb	K-alpha	LIF200	Scint	Fine	26.62	-0.60	100	50	0.7	1.0
Y	K-alpha	LIF200	Scint	Fine	23.80	-0.40	100	50	3.0	1.0
Zr	K-alpha	LIF200	Scint	Fine	22.55	-0.35	100	50	1.0	0.6
Nb	K-alpha	LIF200	Scint	Fine	21.40	+0.35	200	100	4.6	0.9
Ce	L-alpha	LIF220	FPC	Medium	128.16	-1.50	100	50	3.2	3.4

Notes: All major elements measured using a rhodium X-ray tube operated at 30 kV and 80 mA. Trace elements are measured using a rhodium X-ray tube operated at 50 kV and 50 mA. Detector: FPC = flow proportional counter (P10 gas); Scint = NaI Scintillation counter. Matrix absorption corrections for trace and some major (Ti, Fe, Mn, Ca) elements were made using the intensity of the Rh Compton scattering peak (Reynolds, 1967).

Table 6. Precision of XRF major and trace element analyses for standard BE-N.

<u>5</u> :	Pref. value		Standard deviation	Relative
	BE-N	Mean	(10)	(%)
Major element	ts (wt%)			
SiO ₂	39.58	39.80	0.162	0.4
TiO ₂	2.70	2.73	0.044	1.6
Al ₂ Ô ₂	10.43	10.14	0.039	0.4
Fe ₂ O ₃ *	13.30	13.15	0.196	1.5
MnO	0.210	0.20	0.006	2.9
MgO	13.62	13.63	0.064	0.5
CaO	14.37	14.39	0.043	0.3
Na ₂ O	3.30	3.15	0.033	1.0
K ₂ Ô	1.440	1.46	0.005	0.3
P205	1.090	1.07	0.005	0.5
Total	100.04	99.73	0.360	0.4
Trace element	s (ppm)			
Cr	360.0	376.9	5.0	1.3
Ni	279.0	276.8	5.9	2.1
Cu	NA	75.8	3.1	4.1
v	NA	228.3	4.4	1.9
Zn	NA	122.1	2.5	2.1
Sr	1370.0	1364.5	13.7	1.0
Ba	1025.0	1003.2	7.0	0.7
Rb	47.0	39.5	1.5	3.9
Y	30.0	27.0	0.6	2.4
Zr	278.0	277.3	2.9	1.0
Nb	NA	110.5	1.1	1.0
Ce	152.0	157.6	6.4	4.1

Note: NA = not available.

~1% for Si, Ti, Fe, Ca, and K, and between 3% and 5% for Al, Mn, Na, and P.Trace element data are considered accurate between 2% and 3% or 1 ppm (whichever is greater) for Rb, Sr, Y, and Zr, and between 5% and 10% or 1 ppm for the others. The accuracy of Ba and Ce is considerably less, and they are reported primarily for purposes of internal comparison.Precision is within 3% for Ni, Cr, and V at concentrations >100 ppm, but 10% to 25% at concentrations <100 ppm.

Classification of Igneous Rocks

The igneous rocks encountered on Leg 157 differ significantly from most igneous rocks drilled previously at other ODP sites because the volcanism of the Canary Islands, from which the majority of the rocks were derived, is dominantly alkalic. In addition, igneous rocks were encountered only as clasts making assignment to larger rock bodies generally difficult or impossible. The most common mafic rock in the Canary Islands is alkalic basalt (sensu lato); the most abundant phenocrysts are clinopyroxene, olivine, and plagioclase. Dark volcanic rocks were therefore called basalts when chemical or thin section information was not available, but the term was modified where possible with the names of phenocryst phases in order of increasing abundance. In cases where thin section and/or concentrations of major and trace elements of fresh to slightly altered rocks were available, an attempt was made based on Hoernle and Schmincke (1993a) and the general classification of Le Bas et al. (1986) to distinguish nephelinitic/basanitic from alkalic and tholeiitic rocks.

Volcanic rocks of intermediate composition (mugearites, benmoreites, tephrites) were difficult to classify and were named intermediate rocks; they are commonly light gray when fresh, finegrained, and only sparsely porphyritic.

Three main groups of highly evolved felsic volcanic rocks occur on the central Canary Islands and were encountered in the cores:

Group 1: low-silica rhyolites and silica-oversaturated trachytes (only the Miocene Mogan Group on Gran Canaria)

Group 2: slightly silica-undersaturated trachyphonolites (Fataga Group on Gran Canaria)

Group 3: highly silica-undersaturated phonolites (Roque Nublo Group on Gran Canaria; also present on Tenerife with some transitions between rock groups on both islands)

These different groups were particularly useful as chemostratigraphic markers because of their distinctive mineralogical associations and trace element signatures. The dominant phenocryst phase in all felsic volcanic rock groups is an orthoclase feldspar, whereas the chief mafic phenocryst phase in Group 1 volcanics is alkali amphibole (and minor clinopyroxene and hypersthene in the lower units). Dark mica (phlogopite-biotite) is the most common mafic phenocryst in Group 2 rocks. Clinopyroxene, more calcic amphibole, and sphene are common mafic phenocrysts in Group 3 rocks. In the absence of thin-section or geochemical data the evolved rocks were simply classified as felsic rocks.

Geochemical data for volcaniclastic sediments were also used to discriminate between the three groups of felsic rocks as sediment sources. SiO₂ decreases from ~70 wt% (Group 1) to ~55 wt% (Group 3), whereas alumina varies from ~10–14 wt% (Group 1) to ~22 wt% (Group 3), and total alkalies strongly increase from ~10–11 wt% (Group 1) to ~16 wt% (Group 3). Zr/Nb ratios were especially useful for distinguishing the various groups, as Zr/Nb is generally between 6 and 8 in Group 1 rocks, but mostly <4 in Group 2 and 3 rocks.

INORGANIC GEOCHEMISTRY

Interstitial-water Sampling and Analysis

Shipboard interstitial water analyses were performed on 5- to 20cm-long whole-round sections that were cut and capped immediately after the core arrived on deck. Samples were generally taken from the bottom of sections three, four, or five of every core down to 100 mbsf, every second core to 200 mbsf, and every third core below that.

Interstitial waters were extracted from sediments using titanium squeezers (Manheim and Sayles, 1974). Prior to squeezing, the sediment was extruded from the core liner, the surface was scraped to remove the potentially contaminated exterior layer, and the cleaned sample was placed in a squeezer on top of a Whatman No. 1 filter paper. A PTFE disc and a titanium piston were placed on top of the sample in the cylinder, and up to 240 MPa (35,000 psi) pressure was applied with a hydraulic press. Interstitial water was collected in a plastic syringe attached to the bottom of the squeezer assembly and filtered through a 0.45 μ m polycarbonate filter. Samples were transferred to plastic vials pending shipboard analyses; aliquots for shorebased analyses were placed in acid-washed plastic tubes or glass ampoules and heat-sealed.

Interstitial water samples were analyzed immediately after extraction for salinity, determined as total dissolved solids (TDS) using a Goldberg optical hand-held refractometer (Reichart), and for pH and alkalinity by Gran titration with a Brinkmann pH electrode and a Metrohm autotitrator (Gieskes et al., 1991). Batches of samples were analyzed subsequently for chloride by titration, and for ammonium and silica by colorimetric methods using a Milton Roy Spectronic 301 spectrophotometer, following the analytical techniques described by Gieskes et al. (1991). International Association of Physical Sciences Organizations (IAPSO) standard seawater was used for calibrating most methods. The precision of these analyses, expressed as 1σ percentage relative standard deviations (% RSD) from the means of multiple determinations of IAPSO standard seawater or a synthetic standard (NH₄, Si), run at regular intervals within an analytical batch, were as follows:

Alkalinity: <1.5 Ammonia: <5 Chloride: <0.3 Silica: <3

Calcium, magnesium, potassium, sodium, and sulfate were determined by ion chromatography (IC) using a Dionex DX-100 instrument. Samples were prepared as 1/200 dilutions. Instrumental calibration utilized variable dilutions of IAPSO and, for high Ca sites, IAPSO spiked with appropriate amounts of 1000 μ g/mL Ca standard solution (Fisher Scientific Atomic Absorption Calcium Reference Solution). Ion Pac AS4 and Dionex CS12 columns were used for anion and cation analysis, respectively. The precision of these analyses (% RSD) was around 1% for sodium, potassium, calcium, magnesium, and sulfate. By reference to triplicate determinations of IAPSO run within sample batches, accuracy was better than 2% for all elements.

Calcium and magnesium were additionally determined by titration in a suite of nine samples from Site 950. Good agreement was achieved between the two methods, although better precision (0.5% RSD) was attained by titration. A small analytical bias was observed, with both Ca and Mg data obtained by ion-chromatography being on average 1%–2% lower than those obtained by titration. Given the uncertainties introduced by sampling and pore-water extraction procedures, the wide concentration ranges expected, and the considerable time benefits of using the instrumental method, the ion chromatographic data were judged to be acceptable for routine analysis, and this method was used for all pore-water samples.

Lithium and strontium were determined in selected samples using a Varian SpectrAA-20 atomic absorption spectrometer. Samples were diluted 1/5 with nannopure water; lanthanum chloride was added as an ionization suppressant for the determination of strontium. Lithium was determined by emission, and strontium by absorption, using an air-acetylene flame. Precision was better than 2% RSD for both elements. Chemical data for interstitial waters are reported in molar units.

Inorganic Carbon Determination in Sediments

Inorganic carbon was determined using a Coulometrics 5011 Carbon Dioxide Coulometer equipped with a System 140 carbonate carbon analyzer. A known mass (40–50 mg) of freeze-dried ground sediment was reacted in a 2M HCl solution. The liberated CO_2 was titrated in a monoethanolamine solution with a colorimetric indicator, while the change in light transmittance was monitored with a photodetection cell. The percentage of carbonate was calculated from the inorganic carbon content assuming that all carbonate occurs as calcium carbonate. The precision of these analyses, based on multiple determinations of a pure carbonate standard was <1% RSD.

Nitrogen, Carbon, and Sulfur Determination in Sediments

Total nitrogen, carbon, and sulphur of sediment samples were determined using an NCS analyzer, Carlo Erba Instruments Model NA 1500. Mixtures of vanadium pentoxide and crushed freeze-dried samples (~5 mg) were combusted in an oxygen atmosphere at 1000°C, converting total (organic and inorganic) carbon to CO_2 , sulphur to SO_2 , and nitrogen to NO_2 , which was reduced to N_2 using copper. The gases were separated by gas chromatography and measured with a thermal conductivity detector. The precision of these analyses was better than 3% RSD. Total organic carbon (TOC) was calculated by difference between total carbon (TC) from the NCS analyzer and inorganic carbon from the Coulometer.

XRD Analysis of Sediments

Shipboard mineralogy was determined by X-ray diffraction (XRD) analyses of bulk sediments. Subsamples of interstitial water squeeze cakes, plus some additional representative samples, were freeze-dried and ground in an agate mortar and pestle. A Phillips PW1710 diffractometer employing Ni-filtered CuK alpha radiation at 40 kv and 30 mA, was scanned from 2–70° 20 at 0.015°/s for routine analysis. Clay mineralogy was determined onshore by XRD analysis of oriented air-dried, glycolated, and heated (500°C for 4 hr) materials, at the Laboratoire de Pétrologie Minéralogie ORSTOM Bondy (France), using a Siemens diffractometer with Ni-filtered CuK alpha radiation, at 40kv and 30mA.

ORGANIC GEOCHEMISTRY

Shipboard organic chemistry during Leg 157 was conducted to supply real-time monitoring of hydrocarbon gases for safety and for the initial characterization of the content and type of gases and organic matter in sediments. These analyses provide a basis for the preliminary site summaries and background for more detailed shore-based studies. Methods and instruments are described in more detail by Emeis and Kvenvolden (1986), and in the "Explanatory Notes" of the Leg 146 *Initial Reports* volume (Shipboard Scientific Party, 1994).

Sampling for Headspace Gases

During Leg 157, the compositions and concentrations of hydrocarbons and other gases were monitored generally at intervals of one per core, using the headspace method (HS) (details in the "Explanatory Notes" of the Leg 156 *Initial Reports* volume, in press). The vacutainer method was only used in a few cores at Site 955 where gas pockets provided adequate sample volumes for analysis.

Compositions and concentrations of hydrocarbons and other gases were monitored in the sediments, generally once per core. Two different gas chromatographic (GC) systems were available for this: (1) Hach-Carle AGC Series 100 (Model 211), referred to as HC; and (2) Hewlett-Packard 5890A, Natural Gas Analyzer, modified by John Booker and Company, Austin, Texas, and referred to as NGA. The HC instrument is designed to measure accurately and rapidly the concentrations of methane (C1), ethane (C2), and propane (C3) in about 7 min. Ethylene $(C_{2=})$ is resolved from ethane and can also be quantified. The NGA instrument is equipped with both thermal conductivity (TCD) and flame ionization (FID) detectors. Three GC columns used sequentially provide a rapid partitioning and measurement of N₂, O₂, CO₂, H₂S, and C₁ to C₇ hydrocarbons. During Leg 157, only the HC instrument was used at most sites, as no higher hydrocarbons than ethane were indicated. The NGA instrument was used only at Site 955 for vacutainer analysis of gas pockets.

Organic Matter

Organic Carbon

The TOC of the sediment was calculated by the difference between carbonate carbon, determined with the Coulometrics Model 5030 Carbonate Carbon Apparatus, and the total carbon value, determined by the Carlo Erba Model NA 1500 CNS Analyzer. A description of the Coulometrics instrument and procedure can be found in the "Inorganic Geochemistry" section (this chapter).

Organic Matter Type (Pyrolysis Methods)

Two pyrolysis systems were available on Leg 157 to evaluate the quality and quantity of organic matter. The standard system is the Delsi-Nermag Rock-Eval II, plus TOC. A newer system is the Geofina Hydrocarbon Meter (GHM). Both systems use a whole-rock pyrolysis technique to identify the type and maturity of organics and to detect petroleum potential and oil shows in sediments, as described by Espitalié et al. (1985a, 1985b, 1986). For details of operation, see the "Explanatory Notes" of the Leg 156 *Initial Reports* (in press). Only the Rock-Eval instrument was used on Leg 157.

PHYSICAL PROPERTIES

Introduction

The objectives of the physical properties measurements program of Leg 157 include the following: (1) to provide a high resolution data set of the physical signals recorded in the sediments, and (2) to determine the effect of sedimentologic and textural changes (i.e., turbiditic vs. volcaniclastic vs. pelagic sediment vs. carbonate and organic carbon content) on the sediment physical properties. The measured properties also provide a means of comparison with and verification of downhole logging results, and constraints on the interpretation of seismic reflection and other geophysical data.

Nondestructive high-resolution measurements of whole-round core sections were obtained from the MST, including a gamma-ray attenuation porosity evaluator (GRAPE) for estimating wet-bulk density, a compressional-wave (*P*-wave) core logger (PWL), a magnetic susceptibility meter, and a multichannel natural gamma spectrometer. Thermal conductivity measurements were performed at discrete intervals in unlithified whole-round sections using a full-space needle probe method.

In unlithified sediment, measurements from the working half of the core included vane shear strength and *P*-wave velocity. In the more lithified sediments, thermal conductivity was measured using a half-space needle probe method, *P*-wave velocities were determined from cut pieces of the sediments, and strength was measured using a handheld penetrometer. Throughout the core, index properties (water content, wet- and dry-bulk density, grain density, porosity, and void ratio) were determined from discrete samples. The samples were chosen to be representative of relatively undisturbed material in the core. Some of the dried samples were also used for organic and inorganic geochemical analyses (see "Geochemistry," this chapter), as well as shore-based analysis of grain size and texture.

Multi-Sensor Track

The MST sampling rate was typically one measurement every 0.5 to 2.5 cm for GRAPE, 3 to 5 cm for magnetic susceptibility, 30 to 50 cm for natural gamma, and 1.5 to 3 cm for *P*-wave velocity. For details on the MST sensors see the "Explanatory Notes" of the Leg 156 *Initial Reports* (Shipboard Scientific Party, in press).

Thermal Conductivity

Standard shipboard ODP thermal conductivity measurements were made following procedures outlined in the "Explanatory Notes" of the Leg 135 *Initial Reports* (Shipboard Scientific Party, 1992).

Shear Strength Measurements

The undrained shear strength (S_u) of soft cohesive sediments was measured with the Wyckham-Farrance motorized vane shear device following the procedures of Boyce (1976). In more lithified sediments a Soil Test CL-700 handheld penetrometer was used. Measurements were performed on an average rate of one per core section until the depth in which the instrument limits were met.

In sediments where progressive cracking occurs prior to failure, or where undrained shear strengths were anticipated to exceed the capability of the motorized vane shear, measurements were made using the handheld pocket penetrometer. The penetrometer provides an estimate of the unconfined compressive strength, qu, which for fine grained sediments approximates to $2 \times S_u$ (Lee, 1985). Measurable values with this device range from 0.5 to 4.5 kg/cm². Conversion from unconfined strength to undrained strength requires multiplying the penetrometer readings by 98.067 kPa · cm3/kg and then dividing by 2, generating a range of strength measurements from 25 to 221 kPa. The penetrometer test is sensitive to the rate of penetration of the probe, which may lead to errors in measuring strength from different operators. This may account for some of the scatter in the data, although core disturbance is another possibility. For a full discussion on the vane shear and penetrometer instruments see "Explanatory Notes" chapter, Leg 156 (Shipboard Scientific Party, in press).

P-wave Velocity

In addition to the MST measurements, P-wave velocity was determined using two different measurement systems, depending on the degree of sediment lithification. Traveltimes were measured in poorly consolidated sediment by a Dalhousie University/Bedford Institute of Oceanography Digital Sound Velocimeter (DSV) (Mayer et al., 1987; Courtney and Mayer, 1993). Velocity calculation is based on the measurement of the traveltime of an impulsive acoustic signal traveling between a pair of piezoelectric transducers inserted in the split sediment cores. The transducer pair, mounted with a fixed separation (approximately 7.0 cm), is positioned parallel to the core axis. The signal used is a 0.1 µs square wave with a period of 0.2 ms. The received signal was stacked on the rise of the source impulse, resulting in decreased noise and improved detection of the first arrival. The first arrivals were handpicked and the DSV software calculated sediment velocity. Temperature of the unlithified sediments was measured with a digital thermometer probe so that corrections for in-situ temperature could be made.

When the material became too consolidated to insert the DSV transducers, measurements were made through the core-barrel liner with the Hamilton Frame system. Typically there is a gap of about 50 m where the sediment is too consolidated to accommodate the insertion transducers without splitting, but it is not sufficiently stiff to utilize the Hamilton Frame. The velocity estimate is based on the traveltime between two contact transducers. One transducer is placed on the cut surface of the core; the other is directly beneath, in contact with the core-barrel liner. Sample thickness is usually measured by a vertical offset gauge. Occasional failure of this device necessitates the use of a handheld caliper. Measurements were made perpendicular to the axis of the core. Fresh water was used to improve the acoustic contact between the sample and the transducers. The source signal for the Hamilton Frame, stacking, and identification of the first arrival is identical as for the insertion transducers described above. Velocities reported here are raw uncorrected values. For a complete description of the DSV and Hamilton Frame, refer to the "Explanatory Notes" of the Leg 156 Initial Reports (Shipboard Scientific Party, in press).

Index Properties

Sampling for discrete measurements of physical properties aimed to represent the whole core, in zones with the least amount of disturbance. Cross-correlation of results was intended; thus measurements were made on adjacent samples of similar lithology. Index properties (water content, wet- and dry-bulk density, grain density, porosity, and void ratio) were determined from typically one sample per section throughout the hole. Samples were taken from layers of different lithologies.

Index properties were calculated from measurements of the wetand dry-weight and volume of sediment and rock samples (approximately 10–12 cm³). Values were calculated using two different methods (different sets of equations) to intercompare results. For each sample, Method "B" utilizes the "wet" or bulk-sample volume measurement in the pycnometer to calculate the other values. Method "C" utilizes a "dry" volume measurement in calculating the other index properties; the dry volume is corrected for the weight of salt in each sample, calculated from the volume of pore fluid and assuming a constant pore fluid salinity and salt density. Method C is observed to produce the most consistent grain densities. The dry volume includes a correction for salt assuming an interstitial pore-water salinity of 35% (Boyce, 1976). This correction was applied to grain density and porosity computations (Hamilton, 1971; Boyce, 1976), but not to bulk density.

Materials were placed in precalibrated aluminum containers prior to weight and volume measurements. Sample weights were determined aboard ship to a precision of ± 0.005 g using a Scitech electronic balance and a specially designed statistical routine using LabView software. The individual weights were determined with a confidence level of 99.5%; weight was determined from *n* discrete weighings to the point where the error was equal to or less than 0.005 g. The weight was averaged from two successive determinations. Volumes were determined using a helium-displacement Quantachrome Penta-Pycnometer. The pycnometer measures the volume of each sample to an approximate precision of +0.02 cm³. Two determinations were made and averaged. Dry-weight and volume measurements were performed after the samples were oven-dried at 110°C for 24 hr and allowed to cool in a desiccator. See "Explanatory Notes" of the Leg 151 *Initial Reports* (Shipboard Scientific Party, 1995) for the calculation procedures used to determine index properties.

DOWNHOLE MEASUREMENTS

Introduction

The Lamont-Doherty Earth Observatory Borehole Research Group (LDEO BRG), in conjunction with Schlumberger Well Logging Services, provides the geophysical well logging aboard the *JOIDES Resolution*. Designed for use in hydrocarbon exploration, the logging tools have been adapted to meet ODP requirements; this adaptation consists primarily of reducing tool diameter to allow insertion into the 3.8 in. drill-string bore.

Downhole logs characterize the geophysical, geochemical, and structural properties of a drilled sequence. Log data offer advantages over core-based analyses in that they are collected rapidly and represent continuous, in-situ measurements of the formation that are unaffected by the vagaries of core recovery and disturbance. Combined core-log research efforts can potentially integrate the ground-truth information provided by detailed core analyses with continuous and multivariate log data, resulting in continuous and quantitative records of sediment lithological variation.

After coring is completed, the hole is flushed of debris and a combination of sensors are lowered downhole on a seven-conductor cable. A wireline heave motion compensator is employed during rough seas to minimize the effect of ship heave on tool position in the borehole. The sensors continuously monitor geophysical, geochemical, or structural properties of the formation, which are recorded typically at 15 cm increments by the Schlumberger MAXIS 500, or Cyber Service Unit (CSU) computers. The interval of investigation and vertical resolutions is sensor-dependent, but it is typically between 50 and 100 cm (Table 7).

Logging Tool Strings

Four different Schlumberger tool strings were used on Leg 157: (1) a seismic stratigraphic tool string, (2) a lithoporosity tool string, (3) the Formation MicroScanner (FMS), and (4) the geochemical tool string. Figures 6 and 7 show schematic diagrams of these tool strings.

The seismic stratigraphic and lithoporosity strings frequently are combined to form the Quad combination tool string. The 33 m total length of this tool string makes it difficult or impractical to run in shallow holes. Splitting the Quad combination into two separate strings (1 and 2 above) also improves the quality of the sonic and neutron porosity logs. The sonic tool in the seismic stratigraphic tool string requires a centralizer for optimum performance, while the neutron porosity and density tools in the lithoporosity tool string perform best when eccentralized in the borehole. The Lamont-Doherty temperature tool was attached to the base of each tool string to monitor borehole temperature variations. The natural gamma-ray spectrometry tool (NGT) is placed at the top of all tool strings to facilitate correlation between logging runs at each logged hole.

Tool	Vertical resolution	Depth of investigation		
DIT				
ILD deep resistivity	200 cm, 88 cm, 59 cm	1.5 m		
ILM medium resistivity	150 cm, 88 cm, 59 cm	76 cm		
SFL shallow focused	59 cm	38 cm		
NGT	46 cm	Variable 15-30 cm		
HLDT		Variable 15-60 cm		
Density, photo-electric effect	49 cm (6 in, sampling)			
	35 cm (2 in, sampling)			
	20 cm Alpha processing			
	30 cm Alpha processing (2 in.)			
SDT-C/array	30 cm special processing 15 cm	Variable 10 60 cm		
GST	75–130 cm	Variable 12–20		
AACT	25 cm	Variable 12–20		
CNT-G	55 cm (6 in, sample)	Variable and porosity dependent (15-60 cm)		
	33 cm Alpha processing (6 in sampling)			
	25.4 cm Alpha processing (2 in, sampling)			
FMS	6 mm	5–25 cm		
Lamont temperature tool	a) fast-response (1 s time constant;	o no chi		
	1 reading/s)			
	b) slow-response, high-accuracy reading			
	(10 s time constant: 1 reading/10 s)			

Table 7. Approximate vertical resolution of logging tools used on Leg 157.

Notes: Standard sampling is at 15 cm (6 in.) intervals. High resolution sampling is at 5.5 (2 in.) intervals. Alpha processing is a special high resolution processing routine. Depth of investigation is formation and environment specific; these depths are only rough estimates/ranges.



Figure 6. Diagram showing the conventional logging tool strings used on Leg 157 (not drawn to scale).

A brief description of the logging tools used during Leg 157 appears below. Additional information may be found on the accompanying CD-ROM (back pocket, this volume), which contains all of the logging data collected on Leg 157. The detailed principles of operation of the various logging sensors can be found in Ellis (1987), Schlumberger (1989), Serra (1984), and Timur and Toksöz (1985).

Electrical Resistivity: Dual Induction Tool (DIT)

The DIT provides three different measurements of electrical resistivity, each with a different depth of investigation in the formation. Two induction devices (deep and medium resistivity) transmit highfrequency alternating currents (AC) through transmitter coils, creating magnetic fields that induce secondary (Foucault) currents in the formation. These ground-loop currents produce new inductive sig-

Figure 7. Schematic drawing of the Schlumberger geochemical logging tool string used in the Ocean Drilling Program.

nals, proportional to the conductivity of the formation, which are measured by the receiving coils. The measured conductivities are then converted to resistivity. A third device, a spherically focused resistivity instrument that gives higher vertical resolution, measures the current necessary to maintain a constant voltage drop across a fixed interval.

Water content and salinity are the most significant factors controlling the electrical resistivity of rocks. To a first order, resistivity is related to the inverse square of porosity (Archie, 1942). Other factors also influencing resistivity include the concentration of hydrous and metallic minerals and the abundance and geometry (tortuosity) of interconnected pore spaces.

High-temperature Lithodensity Tool (HLDT)

The high-temperature lithodensity tool (HLDT) utilizes a ¹³⁷Ce source of 0.66 MeV gamma-rays to measure formation bulk density. The source is mounted in the tool body and an eccentralizing arm presses it and a pair of detectors against the borehole wall. Determination of density is based on the theory of Compton scattering of gamma rays within the formation, which is a function of electron density. The electron density is converted to bulk density on the assumption that most rock-forming elements have atomic weights that are twice their atomic numbers. In addition, the lithodensity tool records a photoelectric effect index. Photoelectric absorption occurs in the energy window below 150 MeV and is principally dependent upon the energy of the incident gamma ray and the atomic cross-section. The measurement is independent of porosity and therefore can be used as a matrix lithology indicator. The density and photoelectric effect measurements require adequate contact between the sensor and borehole wall; the tool measures the "standoff"; corrections can be made for excessive borehole roughness. The intrinsic vertical resolution of the tool is approximately 0.4 m.

Digital Sonic Tool (SDT)

The digital sonic tool (SDT) records the time required for sound to travel along the borehole wall from one of two acoustic transmitters to two receivers over source-receiver distances of 8, 10, and 12 ft (2.4, 3.0, and 3.6 m). First arrivals for the individual source-receiver paths are used to calculate sonic velocities; four velocity values are measured at each depth, along four possible paths. Only compressional-wave velocities are determined aboard ship, but the full sonic waveforms are recorded for post-cruise processing to determine shear wave and Stonely wave velocities. The vertical resolution of the tool is ~2 ft (0.61 m). Logs can be corrected for cycle skipping (where the receiver misses the first arrival and responds to that of the second signal) using the four-fold measurement redundancy. Compressional-wave velocity is controlled primarily by porosity and lithification; decreases in porosity and increases in consolidation and lithification typically result in velocity increases with depth in a sedimentary deposit.

Dual Porosity Compensated Neutron Tool (CNT-G)

The CNT-G consists of a AmBe neutron source and a set of two neutron detectors designed to measure neutrons of two different energies (thermal and epithermal neutrons). The radioactive source emits high energy neutrons (4 MeV) into the formation, which are scattered and slowed by collisions with other nuclei. When the neutrons reach a low energy level (0.025 MeV), they are captured and absorbed by atomic nuclei such as H, Cl, Si, and B. Because neutrons have an atomic mass similar to that of hydrogen, most neutron slowing is caused by collisions with hydrogen, almost all of which resides in water molecules. Therefore, a change in the number of neutrons detected at a receiver can be related to porosity. As water is present both in pores and as bound water (e.g., in clay minerals), porosities measured in the presence of hydrous minerals are often overestimates of true porosity. This can be alleviated by comparing epithermal and thermal neutron porosities (Ellis, 1987). The accuracy of neutron porosity may be adversely affected by variations in hole size that result in an increased H flux from seawater drill fluid.

Formation MicroScanner (FMS)

The FMS tool produces high-resolution microresistivity images of the borehole wall that can be used for detailed sedimentological or structural interpretations. The tool consists of sixteen electrodes, or "buttons," on each of four orthogonal pads. These four pads are pressed against the borehole wall. Pad electrodes are spaced about 2.5 mm apart and are arranged in two diagonally offset rows of eight electrodes each (Fig. 6). A focused electrical current flows between buttons and is recorded as a series of curves that reflect the microresistivity variations of the formation. Processing converts the measurements into spatially oriented images of the borehole wall using information from the General Purpose Inclinometer Tool (GPIT). Further processing can provide oriented measurements of strike and dip of planar features. The vertical resolution of the FMS is about 6 mm. Coverage is restricted to about 22% of the borehole wall for each pass of the tool. Use of the FMS is restricted to hole diameters less than 37 cm. Thus, no useful information can be obtained from washed-out hole sections.

FMS images may be used in the detailed correlation of core-logging depths, in the orientation of cores, mapping of fractures, faults, foliations and formation structures, as well as for determining strikes and dips of bedding (Serra, 1989). By imaging the directions of borehole breakouts, the FMS can also provide information on the orientation of the in-situ stress field. In an isotropic, linearly elastic rock subjected to an anisotropic stress field, breakouts form in the direction of the least principal horizontal stress. Bell and Gough (1979) and Zoback et al. (1987) demonstrated that the stress orientations deduced from such rock breakouts are consistent with other independent stress indicators. The FMS also uses a triaxial magnetometer and accelerometer in the GPIT cartridge, primarily for tool orientation, but they are very useful in giving the hole azimuth and deviation from vertical, often enabling the orientation of core material.

Geochemical Tool String (GLT)

The geochemical logging tool string (GLT) consists of four separate logging tools: the natural gamma-ray spectrometry tool (NGT), the compensated neutron tool (CNT), the aluminum activation clay tool (AACT), and the gamma-ray spectrometry tool (GST). (GLT, NGT, CNT, AACT, and the GST are trademarks of Schlumberger.) A schematic drawing of the GLT, which was run in Holes 950A, 955A, and 956B on Leg 157, is shown in Figure 7. These four tools use three separate modes of gamma-ray spectroscopy for a comprehensive elemental analysis of the formation. The NGT is located at the top of the tool string so that it can measure the naturally occurring radionuclides, thorium (Th), uranium (U), and potassium (K), before the formation is irradiated by the nuclear sources contained in the lower tools (Fig. 7). The CNT, located below the NGT, carries a californium (252Cf) neutron source to activate the Al atoms in the formation. The AACT, a modified NGT, is located below the ²⁵²Cf source, measuring the activated gamma rays in the formation. By combining the AACT measurement with the previous NGT measurement, the background radiation is subtracted out and a reading of formation Al is obtained (Scott and Smith, 1973). The gamma-ray spectrometry tool, at the base of the string, carries a pulsed neutron generator to induce prompt-capture gamma-ray reactions in the borehole and formation and an NaI(TI) scintillation detector to measure the energy spectrum of gamma rays generated by the prompt neutron capture reactions. As each of the elements in the formation is characterized by a unique spectral signature, it is possible to derive the contribution (or yield) of each of the major elements silicon (Si), iron (Fe), calcium (Ca), titanium (Ti), sulfur (S), gadolinium (Gd), and potassium (K) from the measured spectrum and, in turn, to estimate the relative abundance of each in the formation when combined with the elemental concentrations from the NGT and AACT (Hertzog et al., 1989). The GST also measures the hydrogen (H) and chlorine (Cl) in the borehole and formation, although these elements are not used for determining the rock geochemistry.

The only major rock-forming elements not measured by the geochemical tool string are magnesium (Mg) and sodium (Na); the neutron-capture cross sections of these elements are too small relative to their typical abundances for the GLT to detect. A rough estimate of Mg + Na can be made in some instances by using the photoelectric factor (PEF), measured by the lithodensity tool (Hert-

zog et al., 1989). This calculation was not implemented on the geochemical data from Leg 157 as the (Mg + Na) component was generally below the detection resolution of this technique (Pratson et al., 1993).

Lamont Temperature Tool (TLT)

The TLT is a self-contained temperature recording tool that can be attached to any Schlumberger tool string. Data from two thermistors and a pressure transducer are collected at a predetermined rate of one sample every 0.5–5.0 s and stored within the tool. Following the logging run, data are transferred from the tool to a shipboard computer for analysis. A fast-response, lower accuracy thermistor is able to detect sudden temperature excursions caused by fluid flow from the formation. A slow-response, higher accuracy thermistor can be used to estimate borehole fluid temperature. If the history of drill-fluid circulation in the hole and at least two temperature logs are available (Jaeger, 1961) the post-drilling equilibrium geotherm can be estimated. Conversion to depth is based on pressure recordings from the pressure transducer and from the Schlumberger unit elapsed time (ETIM) records.

Log Data Quality

Log data quality may be seriously degraded by rapid changes in the hole diameter and in sections where the borehole diameter greatly increases or is washed out. The resulting increase in the fluid volume between the formation and the logging tool can impair data quality. Deep investigation devices such as resistivity and velocity tools are least sensitive to such borehole effects. Nuclear measurements (density, neutron porosity, and both natural and induced spectral gamma ray) are more sensitive because of their shallower depth of investigation and the effect of increased drill-fluid volume on neutron and gamma-ray attenuation. Corrections can be applied to the original data in order to reduce these effects. Very large washouts, however, cannot be corrected for.

By use of the NGT on each string, data can be depth correlated between logging runs. Logs from different tool strings may still, however, have minor depth mismatches caused by either cable stretch or ship heave during recording. Small errors in depth matching can impair the multilog analyses in zones of rapidly varying lithology. Ship heave is minimized by a hydraulic wireline heave compensator designed to adjust for rig motion during logging operations. Precise depth matching of logs with cores is difficult in zones where core recovery is low because of the inherent ambiguity of placing the recovered section within the cored interval.

Synthetic Seismograms

Synthetic seismograms are generated from an impedance log. The interval transit time log (from the SDT tool) and density log (from the HLDT tool) are used to generate an impedance log (Gal'perin, 1974). The impedance vs. depth logs are then converted to impedance vs. 2-way traveltime and convolved with a digitized wavelet acquired from the pre-cruise site survey seismic source. The dominant frequency of the wavelet is about 100 Hz. The vertical resolution of a 100-Hz wavelet is about 5–10 m (depending on interval velocity), so reflectors cannot generally be attributed to smaller scale lithologic horizons (less than 10 m).

Shore-based Processing of Logging Data

Processing of Conventional Logging Data

Additional log processing and display have been performed at each of the five sites by the Borehole Research Group (BRG) at LDEO, IMT, and Leicester University, using Schlumberger "Logos" software and additional programs developed by members of the BRG. Displays of most of these processed data appear with accompanying text at the end of the appropriate site chapters in this volume. Files of all processed logs (including FMS, dipmeter, BRG temperature, high resolution density and neutron data), sonic waveforms, and explanatory text are included on the CD-ROM accompanying this volume (back pocket); a directory of the contents of the disk appears in this volume's table of contents.

Shore-based processing of conventional logging data from each hole includes (1) depth adjustments of all logs to a common measurement below the sea floor, (2) corrections specific to certain tools, and (3) quality control and rejection of unrealistic values.

The depth shifting procedure is based on an interactive, graphical depth-match program that allows the processor to visually correlate logs and define appropriate shifts. The reference log and the log to be adjusted in depth are displayed side-by-side on a screen, and vectors connect the two at positions chosen by the user. The total gamma ray curve (SGR) from the NGT tool run on each logging string was used in most cases to correlate the logging runs. In general, the reference curve is chosen on the basis of constant, low cable tension and high cable speed (tools run at faster speeds are less likely to stick and are less susceptible to data degradation caused by ship heave). Other factors, however, such as the length of the logged interval, the presence of drill pipe, and the statistical quality of the collected data (better statistics are obtained at lower logging speeds) are also considered in the selection. A list of the amount of differential depth shifts applied at each hole is available upon request to LDEO BRG.

Specific tool corrections are performed on the gamma ray data to account for changes in borehole size and for the composition of the drilling fluid. Processing techniques unique to the ACT and GST tools of the geochemical string are described in detail below.

In addition to the standard 15.24 cm sampling rate, bulk density and neutron porosity data were recorded at a sampling rate of 2.54 and 5.08 cm respectively. The enhanced bulk density curve is the result of Schlumberger enhanced processing technique performed on the MAXIS system onboard. While in normal processing short-spacing data is smoothed to match the long-spacing one, in enhanced processing this is reversed. In a situation where there is good contact between the HLDT pad and the borehole wall (low density correction) the results are improved, because the short-spacing data have better vertical resolution.

Quality control has been performed by cross-correlation of all logging data. If the data processor concludes that individual log measurements represent unrealistic values, the choices are to either discard the data outright and substitute the null value of "–999.25," or identify a specific depth interval containing suspect values that must be used with caution. The latter are noted in the text that accompanies all processed log displays. Quality control of the acoustic data is based on discarding any of the four independent transit time measurements that were negative or that fell outside a range of reasonable values selected by the processor.

Locally, some intervals of log data appear unreliable (usually because of poor hole conditions) and are not processed. In general, a large (>12 in.) and/or irregular borehole affects most recordings, particularly those that require eccentralization (CNTG, HLDT) and a good contact with the borehole wall. Hole deviation can also degrade the data; the FMS, for example, is not designed to be run in holes that are more than 10° off vertical, as the tool weight might cause the caliper to close.

Processing of Geochemical Data

Geochemical data were processed by James F. Bristow, Lee Ewert, and Peter K. Harvey at the Borehole Research Department of Geology, University of Leicester, United Kingdom.

Data Reduction

The well-log data from the Schlumberger tools are transmitted digitally up a wireline and are recorded and processed on the *JOIDES Resolution* in the Schlumberger Cyber Service Unit (CSU). The results from the CSU are made available as "field logs" for initial, shipboard interpretation. Subsequent reprocessing is necessary to correct the data for the effects of fluids added to the well, logging speed, and drill-pipe interference. Processing of the spectrometry data is required to transform the relative elemental yields into oxide weight fractions.

The processing is performed with a set of log-interpretation programs written by Schlumberger but have been slightly modified to account for the lithologies and hole conditions encountered in ODP holes. The processing steps are summarized below:

Step 1: Reconstruction of relative elemental yields from recorded spectral data. This first processing step compares the measured spectra from the gamma-ray spectrometry tool with a series of 'standard' spectra to determine the relative contribution (or yield) of each element. These 'standards' approximate the spectrum of each element. Using a weighted, least-squares inversion method, the relative elemental yields are calculated at each depth level.

Six elemental standards (Si, Fe, Ca, S, Cl, and H) are used to produce the shipboard yields, but three additional standards (Ti, Gd, and K) can be included in the post-cruise processing to improve the fit of the spectral standards to the measured spectra (Grau and Schweitzer, 1989). The ability to detect an element is principally dependent on the size of its capture cross section and its abundance in the formation. Although Ti, Gd, and K often appear in the formation in very low concentrations, they can make a significant contribution to the measured spectra because they have large neutron-capture cross sections. Gd for example, has a capture cross section of 49,000 barns, whereas that of Si is 0.16 barns (Hertzog et al., 1989). Therefore, including Gd is necessary when calculating the best fit of the standard spectra to the measured spectrum, even though it typical concentration is only a few ppm.

The elemental standards (Si, Ca, Fe, Ti, Gd, K, Cl, and H) were used in the spectral analysis step for Holes 950A, 955A, and 956B. The spectral standard for S was not used in the final analysis because its concentration was below the detection resolution of the tool in these holes; its inclusion in the spectral inversion was found to increase the noise level in the other elemental yields. A linear ten point (5 ft, 1.52 m) moving average was applied to the output elemental yields to increase the signal to noise ratios.

Step 2: Depth-shifting. Geochemical processing involves the integration of data from the different tool strings; consequently, it is important that all the data are depth-correlated to one reference logging run. The NGT, run on each of the logging tool strings, provides a spectral gamma-ray curve with which to correlate each of the logging runs. A reference run is chosen on the bases of constant and low cable tension, and high cable speed (tools run at faster speeds are less likely to stick and are less susceptible to data degradation caused by ship heave) The depth-shifting procedure involves picking a number of reference points based on similar log character and then invoking a program which expands and compresses the matching logging run to fit the reference logging run. The main run of the quad combination tool string was chosen as the reference run for Holes 950A and 956B and the geochemical tool string for Hole 955A.

Step 3: Calculation of total radioactivity and Th, U, and K concentrations. The third processing routine calculates the total natural gamma-ray radiation in the formation, as well as concentrations of Th, U, and K, using the counts in five spectral windows from the NGT (Lock and Hoyer, 1971). This routine resembles shipboard processing; however, the results are improved during post-cruise processing by including corrections for hole-size changes and temperature variations. A Kalman filtering (Ruckebusch, 1983) is used in the CSU processing at sea to minimize the statistical uncertainties in the logs, which can otherwise create erroneous negative values and anti-correlations (especially between Th and U). An alpha filter has been introduced more recently and is now recommended by Schlumberger for shore-based processing. This filter strongly smooths the raw spectral counts but keeps the total gamma-ray curve unsmoothed before calculating out the Th, U, and K. The outputs of this program are K (wet wt%), U (ppm), and Th (ppm), as well as total gamma-ray and computed gamma-ray (total gamma ray minus U contribution). They are displayed as a function of depth in the log summary figures at the end of the relevant site chapter.

Step 4: Calculation of Al concentration. The fourth processing routine (PREACT) calculates the concentration of Al in the formation using recorded gamma-ray data from four energy windows on the AACT. During this step, corrections are made for natural radioactivity, borehole-fluid neutron-capture cross section, formation neutron-capture cross section, formation slowing-down length, and borehole size.

Porosity and density logs are needed as inputs into this routine to convert the wet-weight percentages of K and Al curves to dry-weight percentages. Porosity logs were calculated from the medium duction logs for all three holes using the relationship of Archie (1942); each had a good correlation with available core porosity measurements. The bulk density logs from the quad tool string were used for Holes 950A and 956B, the latter of which was edited to remove extreme low values caused by a rugose borehole. The log density values for Hole 955A showed a very poor correlation in parts with core bulk density measurements (see Site 955), and as a result the interpolated core porosity measurements were used as input into PREACT.

A correction is also made for Si interference with Al; the ²⁵²Cf source activates the Si, producing the aluminum isotope, ²⁸Al, (Hertzog et al., 1989). The program uses the Si yield from the GST to determine the Si background correction. The program outputs dryweight percentages of Al and K which are combined in the next processing step with the GST-derived elemental yields in the oxide closure model.

Step 5: Normalization of elemental yields from the GST to calculate the elemental weight fractions. Relative concentrations of the GST-derived elemental yields can be determined by dividing each elemental yield by a relative spectral sensitivity factor (S_i). This factor is principally related to the thermal neutron-capture cross sections and also to its gamma-ray production and detection probability of each element (Hertzog et al., 1989). The relative elemental concentrations are related to the desired absolute concentrations by a depthdependent normalization factor (F), as defined by the relationship:

$$Wt_i = FY_i/S_i,\tag{1}$$

where Wt_i = absolute elemental concentration, and Y_i = relative elemental yield. The normalization factor is calculated on the basis that the sum of all the elemental weight fractions is unity (100%). The closure model handles the absence of carbon and oxygen, which are not measured by this tool string, with the approximation that each of the measurable elements combines with a known oxide or carbonate. The dry weight percent of Al and K are normalized with the reconstructed elemental yields to the determine the normalization factor at each depth interval from the following equation:

$$F(\Sigma_{i}X_{i}Y_{i}/S_{i}) + X_{K}Wt_{K} + X_{Al}Wt_{Al} = 100,$$
(2)

where X_i = oxide factor (atomic weight of the associated oxide or carbonate of element $i \div$ atomic weight of element i), X_K = oxide factor (atomic weight K₂O ÷ atomic weight of K), Wt_K = dry-weight % of K as determined from the NGT, X_{Al} = oxide factor (atomic weight of Al₂O₃ ÷ atomic weight of Al), and Wt_{Al} = dry-weight % of Al (as determined from the AACT).

Table 8. Oxide factors used in normalizing elements to 100% and converting elements to oxides.

Element	Oxide/carbonate	Conversion factor	
Si	SiO ₂	2.139	
Ca	CaCO ₃	2.497	
Fe	FeO*	1.358	
K	K ₂ O	1.205	
Ti	TiO ₂	1.668	
Al	$Al_2\tilde{O}_3$	1.889	

The value, X_i , accounts for the C and O associated with each element. Table 8 lists the oxide factors used in this calculation for Holes 950A, 955A, and 956B.

Step 6: Calculation of oxide percentages. This routine converts the elemental weight percentages into oxide percentages by multiplying each by its associated oxide factor, as shown in Table 8. The results are displayed as a function of depth in the log summary figures at the end of the relevant site chapter.

Step 7: Calculation of error logs. The statistical uncertainty of each element is calculated for each of the elements measured with the GST and NGT (Grau et al., 1990; Schweitzer et al., 1988). This error is strongly related to the normalization factor, which is calculated at each depth level (Equation 2). The normalization factor is displayed to the right of the logs in the log summary figures at the end of the relevant site chapter. A lower normalization factor represents better counting statistics and therefore higher quality data.

UNDERWAY GEOPHYSICS

Introduction

Underway geophysical data comprising navigation, bathymetry, and 3.5 kHz sub-bottom profiling were acquired en route to and from the drilling sites along tracks shown in Figures 8 and 9. Magnetic data was collected at all transects except for the transect from Site 954 to 955. Reflection seismic profiles were acquired on approach to the MAP sites and some of the VICAP sites as described in the site chapters. The primary purpose of these site survey lines was to secure the identification of the drilling sites by comparing the data with previously acquired seismic data.

Shipboard Underway Geophysical Data

The JOIDES Resolution is equipped to acquire, display, and process magnetic, single-channel seismic reflection, sonobuoy refraction seismic data, as well as sub-bottom profiling data, bathymetric data, and navigation data. Digital logging makes these data available for real-time and post-cruise processing. Navigation data, bathymetric data, sub-bottom profiling data, and magnetic data are routinely edited and corrected by the Geological Data Center (GDC) at the Scripps Institution of Oceanography under contract to ODP. Merged digital data are produced in MGD77 Exchange format and made available, together with microfilm copies of all original analog records, to the ODP Data Bank at the Lamont-Doherty Earth Observatory (Palisades, NY) and to the National Geophysical Data Center (Boulder, CO).

Navigational, bathymetric, magnetic, sub-bottom profiling data, and reflection seismic data were acquired on Leg 157. The following sections briefly describe the equipment, methods, and recording parameters used for acquisition of underway geophysical data aboard the *JOIDES Resolution*.

Navigation

Primary navigation data were acquired by a Magnavox Transit/ GPS Satellite Navigator, Model MX1107GPS, located in the Under-



Figure 8. Leg 157 track line from Barbados to Site 950 with acquisition of 12 kHz bathymetric data, 3.5 kHz sub-bottom profiling data, and proton magnetometer data. The annotation is in UTC.



Figure 9. Leg 157 track lines between Sites 950–956 with acquisition of 12 kHz bathymetric data and 3.5 kHz sub-bottom profiling data. Proton magnetometer data were not acquired on the transect from Site 954 to 955 because of heavy ship traffic. The annotation is in UTC.

way Geophysics Laboratory (Fig. 10). Additional satellite-based navigation systems and a Loran-C system were installed on the bridge. Position coordinates were logged on the Masscomp 561 computer system on disk every 10 min en route and every 1 min during the profiling over the drill sites. Normally the ship's underway speed was 9– 12 kt. During acquisition of the reflection seismic profile the ship's speed was kept at approximately 6 kt.

Magnetism

Measurements of the total intensity of the earth's magnetic field was made by a Geometrics 801 proton magnetometer. The sonde was towed approximately 490 m astern. En route the data were digitally recorded every 30 s and continuously displayed on a graphic recorder. During acquisition of the reflection seismic profile, data were recorded every 12 s; the readings at the shot points were stored on ninetrack tape.

Bathymetry and Sub-bottom Profiling

Bathymetric data were acquired with a 12 kHz system (Raytheon PTR 105B). The sub-bottom profiling data were routinely acquired underway with a 3.5 kHz system (Raytheon PTR105B). Transducers for these systems are mounted in a sonar dome that reduces the noise from turbulent and bubble-filled water at high ship speeds and in rough weather conditions. The sonar dome is mounted under the bottom of the ship, below the bridge (Fig. 10).



Figure 10. Positions of geophysical and navigational elements relative to drill string on the *JOIDES Resolution*.

Data from both systems were displayed on line scan recorders (Raytheon Model 1807 M) with a sweep rate of 1 s. Both systems were operated with a Cesp-III correlator.

Reflection Seismic Profiling

The seismic source used for the seismic profiles at the MAP Sites 950–952 and VICAP Sites 954–956 was an 80 in.³ water gun (Seismic Systems Inc.) operated at a pressure of approximately 2000 psi. The gun was towed approximately 25 m behind the vessel at a monitored depth of approximately 8 m (Fig. 10). Firing rate was 12 s, corresponding to a shotpoint interval of about 35 m. The seismic signals were recorded with a 100-m-long streamer containing 60 hydrophones coupled in series (Teledyne Model 178). The streamer was towed with the center of the active part at about 275 m astern. The depth of the streamer was monitored and was 8–9 m (Fig. 10).

After electronic amplification and band-pass filtering in a Krohn-Hite filter (30–150 Hz) the seismic data were displayed real-time on Raytheon Model 1807M LSR recorders. Data were digitally recorded with a sample rate of 1 ms by means of the Sun-based acquisition system A2D. The data were stored in SEG-Y format on 8 mm tape. The data were processed aboard ship using SIOSEIS software installed on a Sun workstation. The processed data were displayed on a Versatec plotter in scales comparable to the scales of the existing profiles.

IN-SITU TEMPERATURE MEASUREMENTS

Introduction

In-situ temperature measurements are important to Leg 157 objectives because they provide information about mantle upwelling of a "hot spot," maturation of organic matter (see "Organic Geochemistry," this chapter), and increased rates of volcanic glass alteration. Increased alteration rates are reflected in higher temperatures of secondary minerals, as well as in higher dissolution rates of the volcanic glass that can also be seen in the pore waters. Additionally, temperature measurements are used to determine downhole temperature gradient, and when combined with shipboard measurements of thermal conductivity, they provide an estimate of heat flow. Heat flow is of particular geodynamic interest because of the close proximity to active hot spot volcanic islands. These data are based on measurements spanning several hundred meters and form an interesting comparison with existing heat flow measurements from in-situ probes inserted a few meters into the seafloor (Schultheiss and Noel, 1987; Schmincke and Rihm, 1994).

APC Tool (ADARA) Temperature Measurements

The Advanced Piston Core heat flow coring shoe (ADARA) was used to obtain in-situ sediment temperatures during regular pistoncoring operations. The instrument contains an electronics section, composed of three circuit boards and two battery packs, built into a cylindrical frame. These components of the thermal tool fit inside an annular cavity of a special APC coring shoe. Two steel prongs extend from the base of the frame and anchor the electronics in place inside the shoe. Inside one of the two prongs is a platinum resistance-temperature device (RTD) that has been calibrated over a range of -20° to 100°C, with resolution of 0.01°C. The tool used was calibrated at Woods Hole Oceanographic Institution (WHOI) in April 1993. The platinum sensor records temperature measurements during coring. The tool is programmed after it has been inserted into the coring shoe, and repeated deployments can be run without removing the tool or batteries. After programming and starting the test sequence, a crossover subassembly with O-rings seals the cavity containing the electronics.

In operation, the coring shoe is mounted on a core barrel and lowered down the pipe by wireline. The tool is typically held for 5–10 min at the mud line to equilibrate with bottom temperatures, and then lowered to the end of the drill string. Standard APC coring techniques are used, with the core barrel fired out through the drill bit by hydraulic pressure. The tool is then left in place for 10 min instead of being retrieved immediately. This allows the tool to thermally equilibrate with the formation, and it provides a sufficiently long transient record to allow reliable extrapolation of the steady state temperature.

Data Reduction

The data reduction method for the ADARA tool estimates the steady state bottom-hole temperature by forward modeling the recorded transient temperature curve as a function of time. The shape of the transient temperature curve is determined by the response function of the tool and the thermal properties of the bottom-hole sediments (Bullard, 1954; Horai and Von Herzen, 1985). Synthetic curves are constructed based on tool geometry, sampling interval, and the thermal properties of the tools and surrounding sediments. The ADARA tool has a thermal time constant of several minutes under normal conditions and requires that the probe be kept on bottom for at least 10-15 min to allow extrapolation of the temperature curves with confidence. In general, temperature increases immediately following emplacement of the probe, as a result of frictional heating of the probe tip during insertion. The temperature peaks after a short period of time and decreases monotonically thereafter, approaching the steady-state temperature of the sediments at a rate inversely proportional to time.

The theoretical decay curves simulate the instantaneous heating (or cooling) of the sediment following probe penetration, but in practice a finite time is required for the sensors to reach a maximum temperature. As a result, the effective origin time of the thermal pulse is delayed as a function of tool and sediment properties. In addition, the recorders sample temperatures at fixed intervals, leaving the exact



Figure 11. Example of temperature vs. time and curve-fit records in relatively cool sediment (Core 155-930B-8H, 72.2 mbsf). The heat pulse resulting from insertion of the probe is clearly visible.



Figure 12. Data fit in the 1500–2200 s interval of Figure 11 (Core 155-930B-8H, 72.2 mbsf); the modeled temperature curve extrapolates to 5.095°C. Line represents modeled temperatures; open circles represent measured temperatures.

penetration time uncertain. An effective penetration time and an extrapolated temperature are estimated by shifting the time axis of the theoretical thermal decay curves to fit the actual data. Following penetration, temperatures from the first 5-10 measurements (20-50 s) generally do not follow the theoretical curves (Fig. 11), but later parts of the records (for example, at approximately 1500-2200 s) usually match well (Fig. 12). The choice of which data and time shift are used in the matching is partly subjective. However, as much of the actual decay curve as possible is used. Variations in the extrapolated temperatures that result from choosing different time intervals and time shifts can be used to estimate errors associated with the temperatures finally assigned to represent in-situ conditions. Variables in the modeling method include shipboard thermal conductivity measurements of the sediments, tool insertion time, delay time between tool insertion and peak temperature, and the length of the portion of the curve to be fitted.

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