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LEG 157 PRELIMINARY REPORT

DRILLING INTO THE CLASTIC APRON OF GRAN CANARIA AND INTO THE MADEIRA ABYSSAL PLAIN

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SCIENTIFIC REPORT

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ABSTRACT

ODP Leg 157 drilled seven sites (Sites 950 through 956) in the Madeira Abyssal Plain and the volcaniclastic apron around Gran Canaria, recovering over 3 km of core, which ranges in age from middle Eocene to Quaternary. Sites 950, 951, and 952, situated in the southwestern, northern, and southeastern parts of the Madeira Abyssal Plain, respectively, reveal a detailed history of organic, calcareous, and volcaniclastic turbidite deposition that began between 11.3 and 15 Ma. The highest rate of turbidite deposition (all types) occurred between 0 and 3 Ma. The input of volcaniclastic turbidites was minimal before 6.5 Ma. Integrated biostratigraphic, lithologic, and logging data show that many individual turbidites can be correlated across the entire plain. A change in the carbonate compensation depth (CCD) is reflected by an increase in calcium carbonate from very low values before about 3 Ma to oscillating high and low values from 0-3 Ma. Pore-water-chemistry data reveal the great importance of bacterially mediated oxidation of organic matter, located principally in organic-rich turbidites, in controlling diagenetic environments. Active sulfate reduction and methanogenesis are documented for the first time in this area. Resulting changes in pore-water chemistry modified carbonate equilibria, causing the precipitation of calcite and dolomite, while the dissolution of biogenic silica and volcanic glasses led to the appearance of new silicate minerals, principally smectites and zeolites.

Four sites (Sites 953 through 956) drilled north and south of Gran Canaria demonstrated that the compositional evolution, growth, and mass wasting of an ocean island is reflected in the sediments of the adjacent volcaniclastic apron. All major volcanic and nonvolcanic phases of Gran Canaria have been recognized in the ages and compositions of sediments, physical properties, and geophysical logs. Sites 953 and 954 were drilled in the basin north of Gran Canaria, whereas Sites 955 and 956 were drilled to the southeast and southwest of the island, respectively. The shield stage is represented at Sites 953, 954, and 956 by a sequence of massive hyaloclastite tuffs and debris flows, breccias and lapillistones, and fine volcanic turbidites. Middle Miocene felsic volcanics overlying the shield stage were recognized at Sites 953, 955, and 956, including the submarine facies of ignimbrite P1, which marks the beginning of explosive volcanism on Gran Canaria at 14.1 Ma. Pliocene Roque Nublo volcanism is represented by a layer of basaltic lapillistone at Sites 953 and 954. Pleistocene volcanic ashes and pumice layers occur in both the northern and southern sites and presumably come from Tenerife. The two southern sites contain both organic-rich sediments and quartz, reflecting a source from the African margin. In contrast,

the two northern sites have little or no organic muds and quartz, indicating that they were mostly protected from African sediment sources by the barrier of the eastern Canary Islands. Major slump deposits in the southern sites also likely come from the African margin. Pore-water-chemistry data show remarkable correlations to sediment composition; Site 953 is dominated by fluid-rock interaction between pore waters, volcanic glasses, and minerals; Site 954 displays large geochemical anomalies associated with levels of carbonated pore waters, possibly related to Holocene volcanic activity on northern Gran Canaria; at Site 955, organic matter, located principally in slumped sediments derived from the Northwest African margin, is driving intense sulfate reduction and methanogenesis at shallow depths, while the deeper sediments contain saline brines, possibly originating from the leaching of African shelf evaporites.

INTRODUCTION

MAP

The Madeira Abyssal Plain (MAP) project was aimed at testing the hypothesis that ocean-basin sedimentation is controlled by sea-level changes that affect the stability of sediments on continental margins, including those on the flanks of volcanic islands. The products of mass-wasting events accumulate on the continental slope and on the abyssal plains, but the abyssal plain is the only place where a complete record can be obtained at one drill site. Seismic evidence suggests that the abyssal plain is a young feature, with the whole 350-m-thick turbidite sequence (20,000 km^3) having been deposited in just a few million years. The drilling on the Madeira Abyssal Plain will also allow mass-balance calculations of sediment transported from the continental margins to the deep sea, including mass balances for volcanogenic sediments derived from Madeira and the Canary Islands. The history of volcanogenic turbidites will be closely tied to the history of the volcanic islands and should provide information on the initiation of hot-spot activity, on phases of increased volcanic activity, and major island-flank collapse events.

The study of early diagenesis in sediments accumulating under non-steady-state conditions will also be advanced by study of these sediment sequences. The concept of a "progressive oxidation front" was first proposed following studies of the MAP turbidites (Wilson et al., 1985, 1986; Thomson et al., 1987). When the turbidite top is in diffusive contact with bottom waters following deposition, several elements redistribute themselves around the oxic/postoxic (or suboxic) boundary at the front. This results in layers of metal concentrations, with some metals persisting long after conditions have become reducing, and some metals disappearing quickly. We need to know more about the long-term persistence of these signatures to aid in interpreting paleo-redox conditions. The presence of multiple fronts will allow successively older signatures to be examined. The diagenesis and maturation of organic matter can also be examined in the turbidites, as well as in the clastic apron sites, by techniques such as Rock-Eval pyrolysis.

VICAP

The aim of VICAP (Volcanic Island Clastic Apron Project) was to study the physical and chemical evolution of the confined system "asthenosphere-lithosphere-seamount-volcanic island-peripheral sedimentary basin" by drilling into the proximal, medial, and distal facies of the volcaniclastic apron around Gran Canaria, one of the best studied volcanic islands.The volcaniclastic apron consists of the seismically "chaotic" flank facies with velocities around 3.4-4 km/s, and the basin facies characterized by widespread reflectors that represent volcaniclastic sediments interfingering with biogenic and continent-derived clastic material. The basin facies contains large amounts of material representing the evolution of the entire complex island volcano; most importantly, it includes material from the inaccessible submarine stage, representing >90%, by volume, of the volcanic edifice.

Gran Canaria is unusually well exposed and well studied. The island has been volcanically active intermittently throughout the past 15 m.y. Igneous rocks, both mafic and evolved, show a large spectrum in chemical and mineralogical composition. Gran Canaria has experienced several stages of extreme magma differentiation, unique among volcanic islands, generating both frequent explosive rhyolitic, trachytic, and phonolitic fallout ashes and many ash-flow deposits. The distinct composition of individual ash flows, as well as other volcanic rocks, throughout the island's evolution will greatly facilitate stratigraphic subdivision of the cores. The evolved rocks contain significant amounts of K-rich mineral phases (feldspar and mica), a prerequisite for high-resolution age studies. A major element of the program will be high-precision, single-crystal $^{40}Ar/^{39}Ar$ age dating with the aim of monitoring the island and basin evolution in time slices as short as 100,000 years.

The combined VICAP-MAP project focuses on the development of the Canary Basin in terms of the history of volcanic activity in the Canary hot spot, the detailed evolution of large volcanic oceanic islands, the growth of peripheral sedimentary basins (volcanic aprons), and the filling of the distal Madeira Abyssal Plain (Figure 1a).

RESULTS

Site 950

Site 950 is located in the western part of the Madeira Abyssal Plain at 31°9.01'N, 25°36.00'W, at a water depth of 5437.8 m in the Cruiser Fracture Zone Valley (Figure 1b). Seismic profiles for the area show two major units: an upper unit showing relatively high-amplitude parallel reflectors that onlap onto basement highs, and a lower unit that partly onlaps and partly drapes the basement highs. The upper unit can be subdivided into three subunits by relatively strong reflectors at 180 ms and 240 ms. Reflectors within the lower two subunits are weaker than in the upper subunit. This seismic pattern is typical for the whole abyssal plain and is interpreted as pelagic drape over basement, with the deeper draped sequences being later infilled by rapidly accumulated turbidites. The primary objective of this site was to determine the nature of the turbidite fill and distinguish discrete sources for the various compositional groups of sediment flows. When combined with information from the other two sites, and the extensive seismic coverage on the abyssal plain, these data will facilitate estimations of the volumes of sediment eroded and redeposited within the Canary Basin through time. Secondary objectives include (1) estimation of the volumes and timing of volcaniclastic sediment flows from the Canaries, and (2) monitoring the history of the CCD in one of the deepest areas drilled in the North Atlantic.

A single hole was cored at Site 950, and a total of 17 APC cores (0-154.4 mbsf) and 24 XCB cores (154.4-381.3 mbsf) were retrieved with average recovery rates of 100.5% and 81.1%, respectively. The hole was logged with the seismic stratigraphy, lithoporosity, geochemical, and formation microscanner (FMS) tools.

The sedimentary sequence at Site 950 comprises four lithologic units (Figure 2).

Unit 1 (0-314 mbsf) consists of Pleistocene to middle Miocene (0-13.6 Ma), thick, clayey, nannofossil mixed sediment and nannofossil clay turbidites, interbedded with pelagic nannofossil oozes, mixed sediments, and clays. Below 150 mbsf, the pelagic interbeds are all clays. There are three primary types of turbidites: volcaniclastic from the volcanic islands within the basin, organic-rich from the Northwest African margin, and calcareous from seamounts to the west of the plain. All three types are found throughout Unit I. The volcaniclastic and organic-rich turbidites are fine grained and have only sporadic silty bases, indicating their distal nature. Such flows are unlikely to erode the underlying sediments. Some of the calcareous turbidites have bases consisting of foraminifer sand, but even these show few signs of having eroded the underlying beds. A remarkable feature is the regular, but rare, deposition of the turbidites, with a few centimeters to decimeters of pelagic sediment lying between successive flows. Only rarely do two turbidites lie adjacent to each other.

Unit II (314-332 mbsf) consists of massive calcarenite of middle Miocene age (13.6-15 Ma). Core recovery in this interval was poor, but the logging data clearly show three calcarenite units with turbidites between each unit. The calcarenite consists of coarse, shallow-water carbonate clasts with shallow-water benthic foraminifers such as *Amphistegina*, and some mafic and felsic glass shards. The composition of this unit strongly suggests that it was derived from local sources such as the Cruiser/Hyeres/Great Meteor seamount complex to the west.

Unit III (332-370 mbsf) consists of dominantly red pelagic clays with thin interbeds of clayey, nannofossil mixed sediment and zeolitized volcanic-ash bands. Nannofossils from within the turbidites suggest that this unit ranges in age from middle Miocene to middle Eocene (15 to 47 Ma).

Unit IV (370-381 mbsf) consists of two depositional units of dark volcaniclastic siltstone and sandstone separated by clay. The volcanic-ash bands and volcaniclastic flows are all interpreted to have been derived from the Cruiser/Hyeres/Great Meteor seamount complex.

Paleomagnetic stratigraphy gave usable datum levels from C1n to C2An.2, based on measurements in the pelagic interbeds between turbidites. Planktonic foraminifers also provided useful biostratigraphic data from the pelagic interbeds in the upper part of the hole (0-140 mbsf), below which they were preserved only in the bases of calcareous turbidites. Nannofossils, however, were found consistently in pelagic interbeds from 0 to 200 mbsf (0-5.8 Ma) and intermittently to 273 mbsf (11.5 Ma). Below this, stratigraphy is based on first-occurrence data from turbidites and also deduced from extrapolation of the accumulation rates of the pelagic units.

The major change in the accumulation rate of the pelagic interbeds from 1.5 m/m.y. to 5.6 m/m.y. occurs at 2.6 Ma, coinciding with the change from clays to alternating clays, marls, and oozes. This is also coincident with the onset of major Northern Hemisphere glaciation and associated deepening of the CCD, which placed this site above the CCD. The overall sediment-accumulation rate for Unit I, which is dominated by the deposition of turbidites, averages 42 m/m.y. from 0-3 Ma, 28 m/m.y. from 3-6.5 Ma, and 21 m/m.y. between 11 and 13.6 Ma. The interval from 6.5 to 11 Ma appears to have a lower accumulation rate of 9 m/m.y. The lower part of the hole, dominated by red clay deposition (Unit III), has a very low accumulation rate of 1 m/my.

Carbonate, organic carbon, and sulfur data from both pelagic sediments and turbidites display significant stratigraphic variation to facilitate the subdivision of the sequence. Organic-rich turbidites, containing up to 2% C_{org}, occur throughout the sequence but contain less carbonate and higher sulfur in the lowest beds, reflecting both environmental changes in their source area and a longer diagenetic history. Carbon/nitrogen ratios indicate that marine organic matter dominates in most beds.

An excellent suite of pore-water geochemical results was obtained from Site 950. Sulfate and ammonia data demonstrate that sulfate reduction is occurring principally in the deeper parts of the sequence, below 130 mbsf. No evidence of methanogenesis is recorded in the sequence. Calcium and magnesium results suggest that precipitation of carbonate is occurring above, and within, the sulfate-reducing zone. Silica, potassium, and other pore-water data demonstrate that biogenic silica is being dissolved in the upper parts of the sequence, while diagenesis in the deeper section is related to clay-mineral and zeolite formation.

A total of four Schlumberger tool strings were run at Hole 950A: the seismic stratigraphy, lithoporosity, geochemical, and FMS tool combinations. The coverage of the hole with all tool strings was good and the data quality appear high, with some excellent correlation to physical property measurements on core. The thick sequence of interbedded turbidites is well defined by the geochemical logs, which respond to the varying clay and carbonate composition. The transition, lower down in the hole, to a more clay-rich, carbonate-poor sequence is well characterized by the chemical logs and correlates to biostratigraphic data, which indicates a decrease in the rate of sediment deposition. Beneath this unit, in an area of poor recovery, the physical and chemical logs clearly delineate the presence of three calcarenite units, the thickest of which is 10.5 m, of which only 1.1 m in total was recovered in the cores. Multisensor track (MST) velocities measured in the laboratory closely followed the same trends as those estimated by logging, but were approximately 100 m/s lower.

A combination of the downhole sonic-log data with the MST velocities measured on the APC cores (0-150 m) provided a complete velocity profile down to 340 mbsf. Based on this, a twt (two-way traveltime)-depth relation was established that will enable a precise correlation between seismic profiles and lithologic/stratigraphic observations in the cores. The base of seismic unit A correlates with the surface of the red clay sequence at about 330 mbsf. The internal subunits in unit A probably mainly reflect large-scale changes in turbidite thickness and lithology. In unit B, the upper, parallel reflectors seem to represent the red clay, and the chaotic interval below seems to image the turbidites encountered in the cores below 366 mbsf.

The excellent core recovery and downhole logs from this site will facilitate later correlations to the other two sites drilled on the plain and to the wide seismic coverage across the whole plain. Although the biostratigraphy was poor in the deeper parts of the hole, owing to preservation problems, enough datum levels were established to interpret the sequence. Preliminary results show that major turbidite deposition from the Northwest African margin and Canary Islands began at about 15 Ma, with an increase in the volume of eroded sediment at about 3 Ma. The Cruiser/Hyeres/Great Meteor seamount chain appears to have been volcanically active from at least 47 to 15 Ma.

Site 951

Site 951 is located in the northeastern part of the Madeira Abyssal Plain at 32°1.89'N, 24°52.23'W, at a water depth of 5449.4 m in the Charis Fracture Zone Valley. Seismic profiles for the area show the same major units as at Site 950: an upper unit showing relatively high-amplitude parallel reflectors that onlap onto basement highs, and a lower unit that drapes the basement highs. A third unit is present in the deepest part of the fracture zone, showing reflectors with low coherency. The upper unit can be subdivided into three subunits by relatively strong reflectors at 180 and 235 ms. Reflectors within the lower two subunits are weaker than in the upper subunit. This seismic pattern is interpreted as pelagic drape over basement, with the deeper draped sequences having been later infilled by rapidly accumulating turbidites.

In combination with the other two abyssal plain sites, the primary objective of this site was to determine the nature of the turbidite fill, and to distinguish discrete sources for the various compositional groups of sediment flows. Our objective is to correlate individual turbidite units between the three sites and tie them to the downhole-log data and, thereby, to the extensive seismic-profile network on the abyssal plain. This will enable mapping of individual flows or groups of flows, calculations of their volumes, and, in combination with the stratigraphic data, estimates of the amount of sediment contributed from each source since the inception of the plain. A secondary objective at all three sites involves determination of the long-term effects of sediment burial and diagenesis in a sequence of mixed volcanic, organic-rich, and organic-poor sediments.

Hole 951A was cored to 255.6 mbsf, and a total of 13 APC cores (0-118.8 mbsf) and 15 XCB cores (118.8-255.6 mbsf) were retrieved, with average recovery rates of 98.6% and 97.5%, respectively. The hole was prematurely aborted when the XCB barrel became jammed inside the drill pipe. Hole 951B was washed to 255 mbsf, and coring continued with the XCB barrel to 351.6 mbsf, recovering 10 cores with 87.6% average recovery rate.

The sedimentary sequence at Site 951 comprises only one lithologic unit, which is comparable to Unit I at Site 950.

> Unit I (0-351.6 mbsf) consists of Pleistocene to middle Miocene (0-ca. 13 Ma), thick, clayey, nannofossil mixed sediment and nannofossil clay turbidites, interbedded with pelagic nannofossil oozes, mixed sediments, and clays. The unit has been subdivided into two subunits (IA and IB), based on the proportion of calcium carbonate in the pelagic interbeds. Below 123 mbsf (Subunit 1B), the pelagic interbeds are all clays. The three primary types of turbidites seen at Site 950 are again present: volcaniclastic from the volcanic islands within the basin, organic-rich from the Northwest African margin, and calcareous from seamounts to the

west of the plain. All three types are found throughout Unit I, but the occurrence of volcaniclastic turbidites is limited below 250 mbsf. Turbidites between 250 and 351.6 mbsf are dominated by the organic-rich type and show increasing amounts of siliceous microfossils downward. At Site 951, all three groups of turbidites are fine grained and have only sporadic silty bases, indicating the distal nature of each group. Again, individual flows are separated by a few centimeters to decimeters of pelagic sediment, indicating regular, but infrequent, deposition.

Preliminary AMS measurements yielded a sedimentary-bedding-plane-dominated fabric with sufficiently dissimilar maximum and intermediate susceptibility magnitudes that it should eventually be possible to establish flow directions within the various sedimentary units.

A magnetostratigraphy for the APC cores from this site yielded a sequence of reversal boundaries from C1n to C2An.2, similar to those found at Site 950. Planktonic foraminifers provided useful biostratigraphic data from the pelagic interbeds in the upper part of the hole (0-80 mbsf), below which they were preserved only in a few turbidite bases. Nannofossils, however, were found consistently in pelagic interbeds from 0 to 218 mbsf (0-6.5 Ma). Below this, turbidites were sampled to the base of each hole, but no FO's (first occurrences) were encountered. The deepest sediment examined at 351.13 mbsf contained *Reticulofenestra pseudoumbilicus*, suggesting an age for the base of Hole 951B of less than 13.1 Ma.

Sediment-accumulation rates for the pelagic interbeds average 4.4 m/m.y. from 0 to 2.6 Ma and 2.0 m/m.y. between 2.6 and 6.5 Ma. This change at 2.6 Ma is again caused by a deepening of the CCD at this time, allowing some calcium carbonate to be preserved through the late Pliocene and Pleistocene. The thickness of pelagic layers at Site 951 is 11.39 m, compared to 14.6 m at Site 950. The reasons for this difference are not clear. The total sediment sequence has an accumulation rate of 33.8 m/m.y. from 0 to 6.5 Ma. Below this, the absence of stratigraphic data precludes estimates of accumulation rates. Further studies are expected to provide some data for this interval.

As at Site 950, carbonate, organic carbon, and sulfur data from both pelagic sediments and turbidites display major stratigraphic variation that facilitates the subdivision of the sequence. The data confirm that essentially synchronous regional changes in carbonate preservation occurred on the abyssal plain and in turbidite provenance areas during the late Miocene and the late Pliocene. The upper 250 m at Sites 950 and 951 may be correlated with a high degree of confidence. At both sites, organic-rich turbidites contain up to 2% C_{org}, but display less carbonate and higher sulfur below 220 mbsf. Carbon/nitrogen ratios again indicate that marine organic matter dominates in most beds.

A comprehensive suite of pore-water geochemical results was obtained from Site 951. Sulfate and ammonia data demonstrate that sulfate reduction is occurring principally in the deeper parts of the sequence, below 150 mbsf. No evidence of significant methanogenesis is recorded in the sequence. Calcium and magnesium results suggest that precipitation of carbonate is occurring above, and within, the sulfate-reducing zone. Silica, potassium, and other pore-water data demonstrate that biogenic silica is being dissolved in the upper parts of the sequence, while diagenesis in the deeper section is related to clay-mineral and zeolite formation. High pore-water silica and alkalinities below 250 mbsf coincide with an interval of organic-rich turbidites, yielding diatoms and radiolarians that were not represented at Site 950. This emphasizes the role that lithology may play in controlling the distribution of pore-water species.

The physical properties from Site 951 show a close relationship to the lithologic units, with high magnetic susceptibilities correlating with volcaniclastic turbidites. The downcore increase of GRAPE density, thermal conductivity, compressional velocity, bulk density, and shear strength, as well as the downcore decrease of water content and porosity with depth, all suggest that the dominant process within the upper 200 mbsf is gravitational compaction. In contrast, grain density, a parameter normally characterized by a small variation and no general depth trend, shows downcore variations that may result from changes in the chemical, or mineralogical, composition of the sediment.

Site 951 was not logged, but by comparison to the logging results at Site 950, the base of the upper seismic unit should have been at about 320 mbsf. This depth did not represent the base of the turbidite sequence, but a distinctive green to white turbidite, with a coarse sandy base, is present from 316.5 to 320.1 mbsf. The basal 2.4 m of this core (Core 157-951B-7X) was not recovered, but it could have consisted of similar sandy material. No other distinctive units were found above, or below, this turbidite.

The excellent core recovery at Site 951 will enable cross-correlation of individual turbidite units with the other two abyssal-plain sites. Preliminary correlations can already be made between the thicker and more distinctive units. These correlations, and the similar accumulation rates for Sites 950 and 951, indicate that there are few variations in thickness of individual beds between the two sites, even though they are over 59 nmi apart. This, with the aid of seismic profiles, will greatly assist mapping of individual units across the whole plain. The sequence of organic-rich turbidites with high siliceous contents, encountered near the base of Site 951, however, may not correlate at all between the two sites. At present, it is not certain whether these turbidites are equivalent in time to the lower organic-rich turbidites at Site 950, or whether they are older. Improved biostratigraphy should solve this problem.

Site 952

Site 952 is located in the southeastern part of the Madeira Abyssal Plain at 30°47.45'N, 24°30.57'W, at a water depth of 5431.8 m in the Cruiser Fracture Zone Valley. Seismic profiles for the area show the same major units as at Sites 950 and 951: an upper unit (0-450 ms) showing relatively high-amplitude parallel reflectors, and a lower unit that drapes the basement highs. The upper unit can be subdivided into three subunits by relatively strong reflectors at 160 and 245 ms. Reflectors within the lower two subunits are weaker than in the upper subunit. This seismic pattern is interpreted as pelagic drape over basement, with the deeper draped sequences having been later infilled by rapidly accumulating turbidites.

In combination with the other two abyssal-plain sites, the primary objective of this site was to determine the nature of the turbidite fill, and to distinguish discrete sources for the various compositional groups of sediment flows. Our objective is to correlate individual turbidite units between the three sites, tie them to the downhole-log data, and, thereby, to the extensive seismic-profile network on the abyssal plain. This will enable mapping of individual flows, or groups of flows, calculations of their volumes, and, in combination with the stratigraphic data, estimates of the amount of sediment contributed from each source since the inception of the plain. A secondary objective at all three sites involves determination of the long-term effects of sediment burial and diagenesis in a sequence of mixed, volcanic, organic-rich, and organic-poor sediments.

Hole 952 was cored to 425.9 mbsf, and a total of 15 APC cores (0-142.8 mbsf) and 30 XCB cores (142.8-425.9 mbsf) were retrieved with average recovery rates of 100.6% and 95.9%, respectively. The hole was logged with the quad-combo tool between 76-295 mbsf.

The sedimentary sequence at Site 952 comprises only one lithologic unit, which is comparable to Unit I at Sites 950 and 951.

Unit I (0-425.9 mbsf) consists of Pleistocene to middle Miocene (0-ca. 13 Ma), thick, clayey, nannofossil mixed sediment and nannofossil clay turbidites, interbedded with pelagic nannofossil oozes, mixed sediments, and clays. The unit has been subdivided into two subunits (IA and IB), based on the proportion of calcium carbonate in the pelagic interbeds. Below 100 mbsf (Subunit IB), the pelagic interbeds are all clays. The three primary types of turbidites seen at Sites 950 and 951 are again present: volcaniclastic from the volcanic islands within the basin, organic-rich from the Northwest African margin, and calcareous from seamounts to the west of the plain. Above 243 mbsf, all three turbidite types are well represented but, below this depth, the turbidites become much thinner with less common volcaniclastic and calcareous units. The organic-rich turbidites below about 225 mbsf contain siliceous microfossils (diatoms and sponge spicules), and are separated by very thin, or absent, pelagic layers, suggesting frequent input of flows. The siliceous components were identified in the deeper turbidites at Site 951 but were not present at Site 950.

Several thick-bedded sands occur between 380 and 405.5 mbsf, grading up into thick turbidite muds. These contain a mixed assemblage of volcanic and continental minerals, suggesting an origin from the east. A distinctive gray to white turbidite, with a thick calcareous sand at its base, occurs from 373.7 to 377.6 mbsf at Site 952 and appears identical to a unit between 318.5 and 320 mbsf at Site 951. The thick and sandy turbidites between 373.7 and 389 mbsf appear to correlate with the base of seismic unit A.

Magnetostratigraphic determinations gave a reversal sequence from C1n to C2r in the pelagic units between the turbidites. This was the same length of record as in the previous two sites and correlates with the interval of thicker, pelagic intervals, which was caused by the better preservation of calcium carbonate since 2.6 Ma due to a deepening of the CCD at this time. Planktonic foraminifers provide useful biostratigraphic data from the well-preserved carbonates in the upper 75 m of Hole 952, but nannofossils were found in pelagic layers to 266 mbsf. Below this, turbidites were sampled to the base of the hole, and the FO of *Discoaster kugleri* was found at 342.8 mbsf, indicating an age of about 12.2 Ma. The deepest sediment examined, at 415.35 mbsf, contains *Reticulofenestra pseudoumbilicus*, suggesting an age for this level (near the base of the hole) of less than 13.1 Ma (Figure 3).

Sediment-accumulation rates for the pelagic interbeds average 4.3 m/m.y. from 0 to 2.6 Ma and 1.3 m/m.y. from 2.6 to 5.04 Ma. The rate from 0 to 2.6 Ma is almost identical to that at Site 951, but less than the 5.6 m/m.y. recorded at Site 950. The rate between 2.6 and 5.04 Ma is slightly lower than at Site 950 (1.5 m/m.y.) and considerably less than at Site 951 (2.0 m/m.y.). The total sediment sequence has an accumulation rate of 31.1 m/m.y. from 0 to 5.56 Ma and probably a similar rate beyond 5.56 Ma, although, in this interval, the estimate is poorly constrained. This rate is similar to those at Sites 950 and 951 for the interval 0-6.5 Ma. At Site 950, from 6.5 to 13.5 Ma, rates varied from 9 to 21 m/m.y. This may indicate that the deeper turbidite sequence is different between Sites 950 and 952, and indeed these deeper sediments show many more thin turbidites at Site 952.

Geochemical data obtained at Site 952 correspond closely to those already described at Sites 950 and 951. Significant differences relate to sulfate-reduction-controlled profiles of pore-water sulfate, ammonia, and alkalinity, which are more strongly developed at Site 952, indicating increased rates of sulfate reduction.

Site 952 is the only one of the Madeira Abyssal Plain sites to yield significant quantities of headspace methane, with over 30,000 ppm being recorded below 400 mbsf, together with significant ethane and increasing C_1/C_2 ratios. These data provide evidence of diagenetic methanogenesis below the cored interval, probably within a continuation of the thinly bedded, organic-rich turbidites, which occur at the base of Hole 952A. The anomalously high rates (for a deep-water, open-ocean site) of bacterially mediated diagenesis occurring in MAP sediments are a consequence of the high organic-matter content (typically about 2% C_{org}) of the buried turbidite sequence.

Physical properties data from Site 952 revealed a similar pattern to that observed at Sites 950 and 951. P-wave velocities correlate well with the gamma-ray porosity and are anti-correlated with the magnetic susceptibility. Peaks in the magnetic susceptibility are related to negative kicks in velocity, both due to the volcanic turbidites interspersed within the sequence. Cross-plots of these measurements, at common depths below seafloor, may provide a means to discriminate different lithologies and recognize intermediate mixtures of independent components. Index properties data show a distinctive change in the average porosity below about 370 m, due to the introduction of coarser sands and occasional debris flows below this level. This change in density supports the inference that Hole 952A penetrated the prominent reflector seen in the site-survey data.

Despite difficult logging conditions, downhole logs were successfully recorded with the quad-combo tool string down to about 290 mbsf. The logs appear to be of good quality and characterize the thick sequence of interbedded turbidites, with the natural gamma-ray logs delineating the varying clay and carbonate composition of the turbidites. Comparison of the downhole-logging data from Sites 950 and 952 shows an excellent correlation, providing an unequivocal means of high-resolution depth correlation, and hence sedimentation-rate variations between the two sites.

The age of the widespread reflector at the base of the main turbidite sequence, again, approximates 13 Ma and is represented at Site 952 by the series of thick sands and breccia beds. Below this, however, the fracture zone valley appears to be filled with thin, green, organic-rich turbidites. The reflector may, therefore, indicate a change from input of small turbidity flows to larger flows that rapidly filled the deeps in the seafloor and spread to form the broad abyssal plain we see today. Numerous turbidite units can be correlated between all three sites (Figure 4), and, using the seismic network, will be mappable across the whole abyssal plain. This will enable estimates of their volumes and, ultimately, calculations of volumes of sediment added to the plain from each of the main sources through the last 15 m.y.

<u>Site 953</u>

Site 953, the first of four sites to be drilled into a volcanic apron, is located 45 km northeast of Gran Canaria, 100 km west of Fuerteventura, and 100 km east of Tenerife, at a water depth of 3577.8 m (Figure 5).

As no structural or other complications were indicated on the high-resolution, pre-site survey data, no additional reflection seismic data were acquired on our approach to Site 953. The pre-site survey profiles show a sequence, about 1 s in thickness, with an almost parallel layering and with a gentle dip (about 1°) north.

The objective in drilling Site 953 was to study the evolution of the complex, ca. 15-m.y.-long history of Gran Canaria, as reflected in the volcaniclastic sediment deposited in the sedimentary basin north of the island.

Drilling at Site 953 penetrated a practically complete Quaternary to lower Miocene 1159-m-thick section, based on calcareous nannofossil and planktonic foraminifer biostratigraphies. These nonvolcanic and volcaniclastic sediments were divided into seven major units and three subunits, corresponding closely to the lithostratigraphic subdivision of the volcanic rocks on Gran Canaria (Figure 6).

Unit I (0-197 mbsf) is Holocene to late Pliocene (0-3 Ma), and consists dominantly of pelagic clayey, nannofossil ooze and graded nannofossil clay-silt, with lesser amounts of foraminifer sands, lithic crystal sands, and silts. The remarkable coarse beach sands, rich in neritic biogenic material, recovered in the upper 100 m are interpreted as turbidites possibly related to glacially controlled changes in sea level. The minor, thin fallout tephra layers at this site were probably erupted in Tenerife and may represent the outer part of larger fallout fans.

Unit II (197-264 mbsf) is late to early Pliocene (3-4.3 Ma), and consists of clayey nannofossil ooze with foraminifers and graded nannofossil clay-silt, foraminifer lithic silts and sands, and basaltic lapillistones. This unit coincides closely in time and mineralogical composition with sands of the Roque Nublo volcanic phase on Gran Canaria. It is also a period of high sedimentation rates.

Because the evolution of Gran Canaria shows one major, and several minor, hiati with no volcanic activity, one of the objectives was to characterize the major late Miocene erosional period.

Unit III (264-398 mbsf) is early Pliocene to late Miocene (4.3-8.3 Ma), and coincides with the major hiatus in volcanic activity on Gran Canaria. The sediments of this unit contrast in many physical and chemical properties from the intervals that correspond to volcanically active periods. The recovered sediments are dominantly gray to brownish-gray, clayey nannofossil ooze; coarse volcaniclastic material is almost absent.

Unit IV (398-850 mbsf) is late to middle Miocene (8.3-14 Ma), and was subdivided into three subunits, based on the number and composition of volcaniclastic mass-flow deposits. Subunit IVA (398-504 mbsf) consists of interbedded, nannofossil mixed sedimentary rock, nannofossil chalk, slump deposits, graded green nannofossil clay-siltstones, foraminifer sandstones, and green lithic-crystal sandstones and siltstones. Rock fragments in the volcaniclastic sediments are characteristically pieces of trachyphonolitic lava flows and eroded ignimbrites. Subunit IVB (504-754 mbsf), coinciding with the middle and early Fataga phases, shows a marked increase in abundance and thickness of volcaniclastic sandstones and some pumiceous units that could represent the distal, submarine equivalent of some large ash flows. Subunit IVC (754-850 m) consists of nannofossil mixed sedimentary rock, crystal vitric siltstones and sandstones, vitric tuffs and lapillistones, and slump deposits. An influx of volcaniclastic material in this unit is correlated to the Mogan phase on Gran Canaria (13.4-14.0 Ma), which was dominated by major ash-flow eruptions. Most striking are pumice-rich massive units, tentatively correlated to ash flows entering the seas, and thick tuffs consisting entirely of glass shards. A notable discovery at this site was the marine facies of cooling unit P1, a 14-Ma ignimbrite that forms the most important stratigraphic marker on the island and separates the basaltic shield from the overlying felsic volcanics.

A major goal of Site 953 was to drill through the feather edge of the shield volcano, which was expected to be composed of basaltic debris flows due to the low slopes of the flanks (apparent in the seismic records) and the large distance from the island. The deepest target reflectors, assumed to image the distant, very thin flank of Gran Canaria, are found at, and below, 900 ms twt.

This thin, outermost flank of the shield volcano is now believed, based on both drilling and more detailed interpretation of the seismic reflectors, to be represented by Unit VI. But the sediments representing the subaerial part of the shield are believed to begin with Unit V.

Unit V (850-889 mbsf) is middle Miocene (10.4-ca. 13 Ma), and consists of nannofossil mixed sedimentary rock, nannofossil claystone, claystone, lithic crystal siltstones and sandstones, and basaltic lapillistone. Hundreds of small turbidite units of volcanic sand

and silt, many only a few centimeters thick, occur in the interval from Section 157-953C-70R-3 to at least Section 157-953C-75R-1. These turbidites apparently record the growth of the subaerial shield prior to flooding and sealing of the shield volcano by the Mogan ash flows. They occur above the main reflector, which, prior to drilling, was interpreted as the thin submarine flank of Gran Canaria.

Unit VI (889-969 mbsf) is middle Miocene. Volcaniclastic rocks between Cores 157-953C-76R and -83R are more complex and variable. They consist largely of basaltic sandstone, lapillistone, and breccia, interbedded with minor calcareous claystone and nannofossil mixed sediments. Recovery in this interval was extremely low, probably because of the abundance of coarse mixed breccias, containing both shallow-submarine and subaerially derived basaltic material. The sequence reflects the change from subaerial to emergent and shallow submarine volcanism.

The only major fossil-bearing pelagic interval (Sections 157-953C- 83R-1R to -2R) encountered between 850 and 1158.7 mbsf separates Unit VI from Unit VII.

Unit VII (969-1158.7 mbsf) is early Miocene, and consists almost entirely of green hyaloclastite tuffs, lapillistones, and breccias, which are interpreted as debris-flow deposits, from 10 to 50 m thick. They consist of moderately to highly vesiculated shards and contain 30%-70% (by volume) of basaltic fragments, including oxidized scoria. Most basalt clasts have quench textures, which probably represent true submarine basalts. Clinopyroxene, commonly in clots, dominates throughout, and some units are almost picritic, with strongly altered and rarely fresh olivine. Fresh olivine occurs in some basalt clasts. A 0.5-cm-thick, nannofossil-bearing chalk occurs in the lowermost core (Core 157-953C-103R) and indicates an age of 15.8 to 17.4 Ma. Unit VII may be older than Gran Canaria because it is separated from Unit VI, both seismically and by the only thick nonvolcanic sediment bed in the lower 300 m of the hole, and because they differ lithologically.

Major and trace element abundances clearly distinguish between mafic and evolved rocks, and between the Miocene and Pliocene rock suites. More subtle differences between Mogan peralkaline trachytes and low-silica rhyolites and early and late Fataga can be clearly recognized. Major changes in sediment (phenocryst) mineralogy throughout the hole reflect known, and dated, changes on land.

A reliable magnetostratigraphy was determined to a depth of 800 m (approximately 14 Ma) but not in the thick underlying hyaloclastites. The intensity of magnetization and susceptibility records varies as a function of depth; these records appear to correlate with volcanic input, so they may eventually serve as useful proxies for volcanic input.

An accumulation rate, based on an integrated bio- and magnetostratigraphy sedimentation-rate curve, reflects the major contrast between volcanically active phases (shield, Mogan, Fataga, Roque Nublo, and post-Roque Nublo) and nonvolcanic periods, chiefly the time between approximately 8 and 5 Ma. Accumulation rates are as high as 112 m/m.y. during Mogan and early Fataga time, possibly 182 m/m.y. during accumulation of the basal hyaloclastite debris flows, and only 18 m/m.y. during the central part of the volcanic hiatus between 6.2 and 8.2 Ma (360-390 mbsf).

This volcanic hiatus is also reflected in grain- and bulk-density data. In Unit III, which corresponds to the 5-m.y-long nonvolcanic phase, the densities are remarkably constant, contrasting with major variations in sediment densities in other intervals, which correspond to volcanically active periods.

The pore-water chemistry at Site 953 displays some of the most marked changes documented in the deep ocean and can be correlated with major chemical changes in the source rocks as well. Calcium and strontium are being liberated to pore waters in the upper few hundred meters. High sulfate concentrations at about 500 mbsf are attributed to the dissolution of sulfur-rich volcanic glasses. High salinities, chlorinities, and alkali metal concentrations between 400 and 850 mbsf, combined with the precipitation of phillipsite, smectites, and analcime indicate intense alteration of pyroclastic material. Alteration processes in the thick basaltic hyaloclastites below 890 mbsf act as a major source of pore-water Ca, Sr, and possibly K, and provide a sink for most other pore-water constituents. Natrolite and other zeolites are being precipitated in vesicles, vugs, and veins in this interval. Variation in pore-water geochemistry is controlled principally by dissolution of volcanic glasses and the precipitation of smectites and zeolites.

Despite poor hole conditions, the quad-combo tool string (sonic velocity, bulk density, resistivity, neutron porosity, and natural gamma ray) was successfully deployed open-hole from 980 to 375 mbsf. The quality of the geophysical logs appears to be good. The components of K, U, and Th derived from the total natural gamma-ray log are particularly diagnostic. The increase of K, U, and Th downhole (~400 mbsf) relates to the increase in supply of volcaniclastics from the Fataga phase, relative to the volcanic hiatus above. The preceding Mogan volcanic phase (~750-840 mbsf) is well distinguished by high U and Th values, relating to highly evolved rhyolitic pumice flows within this unit. Beneath this, the transition to the basaltic Gran Canaria shield phase (~840 mbsf) is delineated by a dramatic decrease in the Th log from the natural gamma-ray tool. The density, resistivity, and sonic velocity logs show an increasing lithification trend with depth through the Fataga phase and show less indurated lithologies with a higher degree of variance in the Mogan phase (750-840 mbsf). The transition downward into the shield phase (~840 mbsf) is characterized by a sharp increase in density, sonic velocity, and resistivity.

One of our objectives was to compare the predicted depth and stratigraphic correlation of reflectors obtained during the pre-cruise surveys. Sonic log data from 361 to 963 mbsf show that discrete velocity measurements from the cores are systematically too high in the deepest part of the hole, where sonic-log velocities approximately fit the minimum values from the cores. The discrepancy is most likely due to the sampling, which tends to favor the more solid parts of the sediment sequence. Based on the sonic data, a new twt/depth relation has been constructed, and a good correlation was found with the lithostratigraphic and volcanic-event interpretations of the cored section. For example, the Mogan phase is seen as a characteristic band of concordant reflectors. The top of the Fataga phase seems to be represented by a high-amplitude reflector, apparently well suited for regional mapping. The same is the case for the Roque Nublo phase, which appears as a narrow band of high-amplitude reflectors. A synthetic seismic profile, calculated from the sonic log, seems to provide a precise correlation between cores and the seismic profiles.

All available data indicate that most volcaniclastic material was supplied to Site 953 from Gran Canaria. Notable exceptions include Pleistocene tephra layers, presumably from Tenerife and the lower part of the basal hyaloclastites (Unit VII), which may have been supplied from islands to the east. Interestingly, the amount of quartz in the coarse fraction is very small, in contrast to nearby DSDP Site 397 (Leg 47A). Stained quartz at Site 397 was interpreted to be of eolian origin. The near-absence of quartz at Site 953 suggests that quartz found at Site 397 may have been transported by bottom currents rather than by wind. Site 953 is sheltered from Africa by the barrier of the older eastern Canary Islands. The only influx of sediments from Africa to Site 953 may be the green, slightly organic-rich turbidites in Subunits IVB and IVC, which also contain some quartz at their bases. The channel between Gran Canaria and Fuerteventura may have been much shallower at that time, allowing minor sediment mass flows to enter the sedimentary basin north of Gran Canaria.

In summary, the marine record at Site 953 shows an excellent first-order correlation to the geological history of Gran Canaria. All major volcanic and nonvolcanic phases on this island are reflected in the ages, types, and compositions of sediments, physical properties, and downhole logs. The lithostratigraphy has been controlled almost entirely by the mid-Miocene to recent subaerial and submarine volcanism of the island. The changes from submarine through emergent and subaerial shield and subsequent ash-flow eruptions are especially well reflected in the sediments. Fundamental changes in composition of the dominant magma types, in the type of volcanic activity, and in the duration and volume of volcanic/magmatic phases as they evolved on land, could be inferred from the marine record.

Site 954

Site 954, the second of four sites to be drilled into a volcanic apron, is located 45 km northeast of Gran Canaria, 100 km west of Fuerteventura, and 100 km east of Tenerife at a water depth of 3485 mbsl (Figure 5).

Although no structural or other complications were indicated on the high-resolution, pre-site-survey data, additional reflection seismic data were acquired on our approach to Site 954. This was because an investigation of Admiralty Chart 1869 revealed the presence of an underwater cable within a half mile of the proposed location. This short seismic survey repositioned the site approximately 1.3 nmi east of the original prospectus site. The pre-site-survey profiles show a sequence, about 0.4 s in thickness, with an almost parallel layering, overlying an acoustic reflector dipping to the north.

The objective in drilling Site 954 was to study the evolution of Gran Canaria as reflected in the amount, composition, and type of proximal volcaniclastic sediment deposited in the sedimentary basin north of the island, close to an area of young volcanism, and to drill into acoustic basement assumed to represent the flank of the island.

Drilling at Site 954 recovered a 446-m-thick succession of middle Miocene to Holocene sediments, consisting dominantly of fine-grained sediments interbedded with coarser bioclastic and volcaniclastic material (Figure 7). The sequence is interrupted by at least four, possibly slump-related, hiatuses; at about 80 mbsf in the lower Pleistocene to upper Pliocene at about 1 to 1.9 Ma; at about 235 mbsf in the lower Pliocene from roughly 4.4 to 5.3 Ma; at 373 mbsf in the upper Miocene from roughly 8.8 to 9.4 Ma; and between the lowermost sediments and the top of the basal basalt breccia unit. The preservation and abundance of calcareous nannofossils are generally good throughout the hole, but planktonic foraminifers, in contrast, are poorly preserved below about 280 mbsf, except in the basalt breccia, where they are well preserved in the lithified matrix.

A preliminary, but not continuous, magnetostratigraphy consistent with the biostratigraphy was determined to a depth of ca. 400 mbsf (approximately 11 Ma), but not in the underlying basalt breccia.

The sediments were divided into four major units.

Unit I (0-177 mbsf) is Holocene to late Pliocene (0-3 Ma), and consists of dominantly clayey nannofossil ooze with foraminifers, graded clayey nannofossil mixed sediment, and calcareous sand with lithics. Minor interbeds of crystal lithic sand, pumice sand, and vitric ash layers occur throughout the upper part of Unit I. The remarkable beach sands, rich in neritic biogenic material and coarse volcanic clasts, recovered in the upper 100 m, are even more coarse grained than similar sands recovered at Site 953. They are interpreted as turbidites, the emplacement of which was possibly related to glacially controlled changes in sea level. The minor, thin fallout tephra layers at this site, which probably erupted in Tenerife, are also coarser grained than at Site 953, and pumice is more abundant. The tephra layers have not yet been correlated between the two sites. Recovery was excellent in the upper part of the hole (APC coring) but poor from 80 to 175 m.

Unit II (177-179 mbsf) is a 2-m-thick, upper Pliocene dark greenish-gray lapillistone containing abundant mafic volcanic clasts. The lapillistone unit is overlain by a dolomitized siltstone, and dolomitization occurs sporadically throughout the lower part of the underlying unit. The lapillistone is similar to lapillistones of roughly similar age in Unit II of Site 953, and closely coincides, in time and mineralogical and chemical composition, with the Roque Nublo volcanic phase on Gran Canaria.

Unit III (179-408 mbsf) is early Pliocene to late Miocene (4.3-11 Ma). Recovery was poor again in the upper ca. 90 m of this unit, which consists dominantly of gray to brownish-gray, thick nannofossil chalk and clayey nannofossil mixed sedimentary rock with minor crystal lithic sandstone, and siltstone interbeds. Coarse volcaniclastic material, not unexpectedly, is almost absent in this interval, which approximately coincides with the major hiatus in volcanism on Gran Canaria. The base of the sediments in Unit III is assigned to calcareous nannofossil Zone CN6/7, and is dated at approximately 9.4-10.8 Ma.

Unit IV (408-446 mbsf) represents acoustic basement, which consists of a thick breccia with basalt clasts, minor green hyaloclastite tuffs, lapillistones, and a matrix of calcareous sediments and clay. The breccia is dated at approximately 15-14 Ma, based on thin-section examination, which identified *Orbulina universa* (age no older than Zone M7). Basalt clasts, which represent both subaerial and shallow submarine eruptions, as indicated by rinds of vesicular pillows, are interpreted to represent the emergent stage of the shield volcano. The mineralogical and chemical composition of basalt clasts and volcaniclastic rocks allows us to clearly distinguish the shield and the younger phases and is consistent with the chemical composition of the subaerial shield basalts from Gran Canaria (Schmincke, 1982).

Volcaniclastic rocks representing most of the Fataga and Mogan phases of dominantly explosive volcanism on Gran Canaria (10-14.0 Ma) are completely missing. It is not clear whether the basalt breccia is much thicker than drilled, and if it rests entirely on submarine rocks or represents a slide block that has overridden the Fataga and Mogan sediments.

Extreme pore-water compositions occur immediately above and below the lapillistone of Unit II at 180 mbsf, and below 400 mbsf, in the boundary interval between nannofossil chalk of Unit III and the underlying basaltic breccia of Unit IV. Large increases in alkalinity, salinity, sodium, lithium, silica, magnesium and calcium, and low chlorinity are associated with CO_2-charged effervescent pore waters. Alkalinities of up to 120 mmol/L are recorded, with more than 250 µmol/L Li and

1500 µmol/L Si. These characteristics are tentatively attributed to alteration of glasses and the introduction of CO_2-charged fluids associated with Holocene volcanic activity in northern Gran Canaria. The proximity of the site to an area of young volcanism is also reflected in the high geothermal gradient (52.7°C/km) and the heat flow (52.7 mW/m^2) at average conductivities of 1.0 W/m·K. Dolomitization is widespread below Core 157-954B-11R.

Seismic and lithostratigraphic correlation between Sites 953 and 954 is good to excellent, despite poor recovery from holes at Site 954. Significant volcaniclastic material, supplied to the site from other islands, appears to be restricted to late Pliocene and Pleistocene fallout tephra layers, presumably from Tenerife.

An accumulation rate, based on an integrated bio- and magnetostratigraphy sedimentation-rate curve, which is reasonably constrained above ca. 370 mbsf, reflects the major contrast between volcanically active phases (Roque Nublo and post-Roque Nublo) and nonvolcanic periods, chiefly the time between approximately 8 and 5 Ma. Accumulation rates are as high as 75 m/m.y. from 0 to 80 mbsf, possibly a combination of high pelagic background sedimentation, coupled with periodic influx of thick, coarse-grained "beach sands," and relatively high ash and pumice input from Tenerife. Rates fall to ca. 59 m/m.y. from 80 to 235 mbsf, which includes the phase of Roque Nublo volcanism, and are only 40 m/m.y. during the central part of the volcanic hiatus between 5 and 9 Ma (235-370 mbsf). Accumulation rates were probably much higher during accumulation of the basal breccia flows.

The amount of quartz in the coarse fraction is negligible, as in sediments at Site 953, contrasting with the high abundance of quartz in the sediments of DSDP Site 397 (Leg 47A). The near-absence of quartz and of organic-rich sediments at Site 954 indicates that the basin north of Gran Canaria was largely cut off from turbidity currents and slumps originating at the African continental margin, because of the barrier of the older eastern Canary Islands and the high submarine ridge between Gran Canaria and Fuerteventura.

In summary, the geologic evolution of Gran Canaria is well reflected in the sediments cored at Site 954, but not as fully as at Site 953 because of poor recovery between 80 and 270 mbsf and the ca.-4-m.y. hiatus between the lowermost, marly sediments and the basement basalt breccia. The chemical and mineralogical composition of basaltic clasts indicates that the breccia represents the shield and most likely forms a cover above the true submarine seamount stage of the island. The continuing volcanic activity on Gran Canaria, as on almost all Canary Islands, which is documented on land by a string of scoria cones and lava flows approximately 3000 years old (Schmincke, 1982), is dramatically reflected in the high heat flow and in the CO_2-charged pore waters at 180 mbsf and above the basal breccia, which most likely reflect the degassing of mafic magma at depth. The extreme compositions of these pore waters suggest strong leaching of the volcaniclastic units by these fluids.

Site 955

Site 955, the third of four sites to be drilled into the volcanic apron peripheral to Gran Canaria, is located in the southern Canary Channel, 55 km southeast of Gran Canaria, 110 km southwest of Fuerteventura, and 125 km west of the African continental margin on the southeastern volcanic apron of Gran Canaria (Figure 5). The site is on line with DSDP Sites 397 and 369, 50 and 100 km southeast of Site 955, respectively. The site is separated from Site 953, in the northern basin, by the submarine ridge separating Fuerteventura and Gran Canaria; this ridge has a maximum water depth of ca. 1550 m. The drill site is in a fairly flat area at a water depth of ca. 2860 m. Although no structural or other complications were indicated on the high-resolution pre-site-survey data, additional reflection seismic data were acquired on our approach to Site 955.

Site 955 is the first of two sites drilled in the southern volcanic apron of Gran Canaria, which is open to sediment influx from the African continental margin. One of the objectives is to compare and correlate the volcaniclastic sediments south of Gran Canaria with those drilled in the northern basin. Because post-Miocene volcanic activity has been absent in the south of the island, the influx of volcaniclastics in the upper part of the sediment column (younger than ca. 10 Ma) is probably small. The major events include large explosive eruptions, which resulted in widespread ash flows and ash falls during Mogan and Fataga volcanism, roughly between 14 and 10 Ma.

The sedimentary succession at Site 955 was drilled with excellent recovery of ca. 85%. the succession is 599 m thick, and consists dominantly of fine-grained, hemipelagic sediments interbedded in the lower part with coarse-grained volcaniclastic and siliciclastic material, ranging in age from latest Quaternary to late early Miocene-early middle Miocene (Figure 8). The sequence at Site 955 differs from that found at Sites 953 and 954 in that the lithostratigraphy has been influenced significantly by the Northwest African continental margin, resulting in the larger amount of (1) siliciclastic material, (2) clay, as reflected also in the generally lower $CaCO_3$ concentrations of the sediment, (3) organic material, and (4) the greater abundance of slumps. Volcaniclastic material, chiefly Miocene fallout and ignimbrites from the Canary Islands, is abundant in the lower part of the sequence.

Unit I (0-207 mbsf) is composed dominantly of clayey nannofossil mixed sediment interbedded with quartz-rich silt and sand, and minor ash layers, and has been strongly affected by slumping. Several discrete packages of, presumably, slumped sediment were identified in the interval from 102 to 240 mbsf. All the sediment within each of these packages belongs to the same nannofossil zone or consecutive zones, within the limits of zonal resolution. Some zones are missing between these packages, and younger zones are present beneath older ones. The sediment-accumulation rate, for the surface to 102 mbsf (0-1.6 Ma), is about 67 m/m.y. At least one interval in the upper Pliocene appears to contain an allochthonous block of lower Pliocene sediment. Below approximately 160 mbsf, a more typical biostratigraphic sequence is encountered.

Units II (207-273 mbsf) and III (273-374 mbsf), the middle part of the sequence, are composed of clayey nannofossil mixed sediment and nannofossil clay with minor interbedded silt and sand. No slump dislocation was found below 240 mbsf. Sediment-accumulation rates (18 m/m.y.) are reasonably well constrained for the interval below 240 mbsf to about 285 mbsf (4.63-6.8 Ma) in Unit II, possibly reflecting the later part of the hiatus in volcanic activity on Gran Canaria. For Unit III (6.8-8.8 Ma), the accumulation rate is about 42 m/m.y. This probably reflects the earlier part of the volcanic hiatus on Gran Canaria. A hiatus appears to be present at about 370 mbsf, spanning about 0.6 m.y. between 8.8 and 9.4 Ma. A hiatus occurs in the same interval at Site 954, suggesting the possibility of a regional event.

Unit IV (Subunits IVA and B; 374-567 mbsf), the bottom part of the sequence, has numerous interbedded volcaniclastic deposits that can be correlated with Miocene Fataga and Mogan group volcanism on Gran Canaria. Zeolitized tuffs are common in Subunit IVA (Fataga), whereas abundant fresh glass occurs in Subunit IVB (Mogan); similar relationships were found at Site 953. Several compositionally distinct and dated individual ignimbrites studied on land have been recognized in the volcaniclastic-rich lower part of the hole (374-567 mbsf), specifically P1 (14 Ma), an ignimbrite that was recognized at 845 mbsf at Site 953, ca. 160 km to the north of Site 955, and ignimbrites A and X (Schmincke, 1993).

Unit V (567-599 mbsf) marks a return to hemipelagic sedimentation with thin, interbedded siliciclastic sediments and minor basaltic clasts that were probably derived from subaerial erosion of the shield of Gran Canaria.

The sediment-accumulation rate is about 60 m/m.y. for the interval from 370 to about 445 mbsf (9.4-10.8 Ma) in Subunit IVA. This high rate is probably related to the later part of the Fataga phase of volcanism on Gran Canaria. The microfossil age at 595 mbsf is 15.8 Ma, with the volcaniclastic layers suggesting an age of about 14.5 Ma by extrapolation. The younger ages suggested by the volcaniclastic layers give an accumulation rate of about 50 m/m.y. The discrepancies between the microfossil ages and radiometric ages, suggested by correlation with Gran Canaria, may reflect the generally poor correlation of microfossil datum levels to the absolute time scale for the early and middle Miocene, lithostratigraphic miscorrelations between this site and Gran Canaria, or microfossil reworking.

Two hiatuses interrupt the sequence: one from the lower Pleistocene to upper Pliocene between 102.81 and 103.1 mbsf (representing at least 1.6 to 2.37 Ma), and one in the upper Miocene between 364.0 and 373.6 mbsf (representing about 8.8 to 9.4 Ma). Hiatuses of similar age occurred at Site 954 on the north flank of Gran Canaria.

Changes in pore-water composition are driven by the bacterially mediated oxidation of organic matter from organic-rich sediments, precipitation of dolomite, dissolution of biogenic silica, and diagenetic reactions in the siliciclastic fraction, particularly the appearance of smectites and zeolites that form at the expense of volcanic glass.

Sulfate-depletion, ammonia-production gradients are the steepest at Site 955 and reach the most extreme values of any site drilled during Leg 157, indicating that sulfate-reduction rates are greatest in this area. High methane contents and constant methane/ethane ratios characterize all sediments below the top of the sulfate-reduction zone. Silica concentrations reach moderate values in the upper 120 m, where biogenic silica is undergoing active dissolution.

Salinity and chloride contents approach twice sea-water concentrations near the base of the hole. Such high values are difficult to explain by normal diagenetic processes, and may indicate the advection of brines derived from leaching of evaporites on the Northwest African continental margin.

Pore waters display progressive calcium enrichment and, generally, magnesium depletion with depth, in response to precipitation of dolomite combined with alteration processes affecting the volcanogenic fraction. Salinity and chloride contents approach twice sea-water concentrations near the base of the hole. Such high values are difficult to explain by normal diagenetic processes and may indicate the advection of brines derived from leaching of evaporites on the Northwest African continental margin. A temporary reversal in the magnesium trend at intermediate depths may relate to brine influx.

At 71 mbsf, headspace samples of methane gas increased from background levels to between 1034 and 54,965 ppm throughout the hole. C_1/C_2 ratios were mostly fairly constant between 3000 and 5000, indicating a biogenic origin of the gas, which is also supported by vacutainer samples. Organic carbon showed values between 0.5% and 2.6% C_{org} in the upper part of the hole, with a maximum of 4.77% C_{org} at 164 mbsf, while the deeper part of the hole showed fairly constant lower values of C, N, and S.

Below about 80 mbsf, cracks and fractures caused by expansion of gas, which disrupted the fabric of the core, made it impossible to determine compressional-wave velocities either with the MST, the penetration transducers, or the Hamilton Frame instrument.

A complete suite of three logging strings was successfully run at Hole 955A. The quad combo, geochemical, and FMS logs recorded data from the base of hole (599 mbsf) to the end of pipe (72 mbsf). The quality of the recorded logs appears to be good, enabling detailed characterization of this Miocene to Holocene sequence of pelagic, turbidite, and volcaniclastic material. The geochemical logs are diagnostic indicators for the amount and affinity of volcaniclastic material. An increase in the Th log (~500 mbsf) delineates the more geochemically evolved volcaniclastics correlated to the Gran Canaria Mogan stage of volcanism. The downward transition into the shield phase of volcanism (~570 mbsf) is marked by a significant decrease in Th, indicating the more mafic nature of the sediments. Geochemical logs indicate significant concentrations of carbonate above 217 mbsf, and these abrupt variations in carbonate may delineate thick, contiguous slump blocks from the African margin to the east. High-resolution microresistivity images from the FMS show current bedding in sand units and delineate ash layers as thin as 1 cm. The images will augment core-based studies of ash abundance and thickness in the zones of poor recovery, and will also enable unequivocal correlation between core and logging depths. Oriented images from the FMS provide dip and strike information about the beds and should provide information on the tectonic evolution of this site.

Together with velocity data from the MST, a complete velocity function from seafloor to 575 mbsf was obtained from the sonic logs, allowing a precise transformation of two-way traveltime to depths. The depths of the seismic units at Site 955 were calculated as follows: unit A, 0-140 mbsf; unit B, 140-170 mbsf; unit C, 170-270 mbsf; unit D, 270-420 mbsf; and unit E, 420-525 mbsf.

There is generally good agreement between the stratigraphic and lithologic interpretations of the cores and the depositional architecture as derived from the seismic profile. Two major sequences can be discerned in the seismic profile, an upper one comprising units A-C, and a lower comprising units D and E. The upper sequence, characterized by basinward-thickening units and pronounced lateral change in seismic facies, corresponds to the Plio-Pleistocene deposits in lithostratigraphic Units I and II. The lower sequence, which thins basinward, corresponds to middle-late Miocene lithologic Units III and IV. The transition from seismic unit D to E seems to mark the middle-late Miocene boundary. The acoustic basement, i.e., the base of unit E at 515 mbsf, corresponds to the top of the lower volcanic sands (lithologic Subunit IVB), tentatively correlated to the Mogan Formation on the island.

Four ADARA temperature measurements, taken between 27 and 113 mbsf, gave a geothermal gradient of 39.99°C/km. Thermal conductivity downhole had an average value of approximately 1.15 W/m·K, resulting in a heat flow value of 45.99 mW/m^2. These values are high for a continental-margin setting and most likely reflect the Canary Islands hot spot.

Site 956

Site 956 is located in the southern Canary Channel, 60 km southwest of Gran Canaria, 65 km southeast of southern Tenerife, and ca. 200 km west of the African continental margin (Figure 5).

Unlike the two northern sites, this location is not shielded from sediment influx from the African continental margin. Site 956 is the second of two sites drilled in the southern volcanic apron of Gran Canaria.

The major events that were studied include the large explosive eruptions that resulted in widespread ash flows and ash falls during Mogan and Fataga volcanism, the basaltic shield phase, and Pleistocene tephra layers from Tenerife. The influx of volcaniclastics in the upper part of the sediment column (younger than ca. 10 Ma) was expected to be small, because post-Miocene volcanic activity is absent in the south of the island. Larger thicknesses of volcaniclastic sediments from Tenerife were expected, however, because of the greater proximity to this island and presumed paleowind directions comparable to the present.

The sedimentary succession drilled at Site 956 is 704 m thick and consists dominantly of fine-grained, hemipelagic sediments with interbeds, in the uppermost and lower part, of coarse-grained volcaniclastic and, in the middle part, of siliciclastic material (Figure 9). Ages range from latest Quaternary to middle Miocene. The supply of volcaniclastic material, by sediment gravity flows and fallout from both Gran Canaria and Tenerife, has played a fundamental role in determining the lithostratigraphy of Site 956. The sedimentary succession has therefore been subdivided into five lithostratigraphic units based chiefly on the abundance and composition of volcaniclastic deposits, which correspond broadly in time and composition to the magmatic phases of Gran Canaria and Pleistocene Tenerife.

Unit I (0-158 mbsf) consists mostly of nannofossil mixed sediment with foraminifers, and thick, interbedded coarse debris flows, typically rich in pumice, which were most likely derived from Tenerife. Their initiation may be related to sea-level changes caused by Pleistocene glacial-interglacial cycles. Tephra fallout layers of similar age and mineralogy have also been found at all other sites and at DSDP Site 397, southeast of the island of Gran Canaria. Slump deposits are common in this unit.

Unit II (158-195 mbsf) had poor recovery, but the angular clasts are petrographically identical to Miocene shield basalts and to trachyphonolitic ignimbrites from Gran Canaria. Much of the unit may represent slump debris from the collapsed flank of Gran Canaria.

Unit III (195-370 mbsf) is 175 m thick, early Pliocene to late Miocene in age, and consists dominantly of nannofossil mixed sediment and clayey nannofossil ooze. The unit is distinguished from Unit II by the lack of coarse-grained material, with only minor interbeds of quartzose and calcareous sand deposits. Slumping is pervasive.

Unit IV (Subunits IVA and IVB, 370-564 mbsf) has numerous, interbedded, volcaniclastic deposits, which can be correlated with Miocene Fataga and Mogan group volcanism on Gran Canaria. Core descriptions and logging data indicate that tuff layers begin to appear in Core 157-956B-23R, where the upper boundary of the Fataga-equivalent sediments (Subunit IVA) was placed. Zeolitized and fresh, vitric tuffs are common in Subunit IVA (Fataga), whereas abundant fresh glass occurs in Subunit IVB (Mogan); similar relationships were found at Sites 953 and 955. The compositionally distinct ignimbrite, P1 (14 Ma), previously recognized at 845 mbsf at Site 953, ca. 170 km to the north of Site 956, and at 560 mbsf at Site 955, 70 km to the east, also occurs at Site 956 at 564 mbsf. Some of the vitric material was reworked and deposited by turbidity currents, whereas at least some may have been associated with the entrance of pyroclastic flows into the sea, with subsequent transformation to water-rich sediment gravity flows. In general, the flux of coarse volcaniclastic material was high during this time, reflecting the voluminous nature of the mid-Miocene Mogan activity.

Unit V (564-704 mbsf), 140 m thick and middle Miocene in age, consists of moderately sorted and graded, massive basaltic breccia and hyaloclastite tuff units, interpreted as debris flows. The breccias contain abundant subrounded to rounded clasts of nonvesicular basalt and red, oxidized, scoriaceous fragments, indicating derivation from subaerial volcanism. Smaller amounts of altered, vesicular hyaloclastite grains also occur, suggesting that hydroclastic eruptions were taking place at this time. The products of both submarine and subaerial volcanism were mixed prior to deposition. Minor hemipelagic interbeds and mixed volcaniclastic and siliciclastic sediments occur in the upper part of the unit, and a foraminifer sand rich in amphibole, zircon, sphene, and minor quartz occurs at 600 m. A huge debris flow, at least 85 m thick, is present in the basal part of the hole.

Sediment-accumulation rates are difficult to calculate for Site 956, except for the upper 50 m of the sequence, because the upper 370 m within Units I, II, and III contain abundant, chaotically disturbed sediments. Discrepancies exist between the microfossil ages and paleomagnetic ages in the lower part of the hole, which should be clarified by onshore single-crystal dating. Very high accumulation rates must be assumed for Unit V (564-704 mbsf), based on biostratigraphic grounds and because most of this sequence is made up of three debris flows.

A complete suite of three logging strings was successfully run at Site 956. The quad-combo, geochemical, and FMS logs recorded data from the base of hole (650 mbsf) to the end of pipe (300 mbsf). The quality of the recorded logs is excellent, enabling detailed characterization of the sequence of pelagic, turbidite, and volcaniclastic material. The changes from shallow submarine, through emergent basaltic, to subaerial shield, and subsequent ash-flow eruptions are especially well reflected in the logs. The components of K, U, and Th, derived from the total natural gamma-ray log, are particularly diagnostic. The transition from the shield to the volcaniclastic sediments, which are correlative to the Mogan Formation, is characterized by sharp increases in density, sonic velocity, and resistivity, as well as an abrupt increase in K, Th, and U. Similarly, the abrupt decrease of K, U, and Th and, to a lesser degree, resistivity, reflects the pronounced decrease in supply of volcaniclastics in the volcanic hiatus above. Even the geochemically similar Mogan and Fataga formations can be distinguished from each other by the patterns of the natural gamma-ray log.

There is generally good agreement between the stratigraphic and lithologic interpretations of the cores and the depositional architecture, as derived from the seismic profile. Two major sequences can be discerned in the seismic profile: an upper one comprising seismic units A-C, and a lower comprising seismic units D and E. The upper sequence, characterized by basinward-thickening units and pronounced lateral change in seismic facies, corresponds to the Plio-Pleistocene deposits in lithostratigraphic Units I and II. The lower sequence, which thins basinward, corresponds to middle-late Miocene lithologic Units III and IV. The transition from seismic unit D to E seems to mark the middle-late Miocene boundary. The acoustic basement, i.e., the base of seismic unit E at 515 mbsf, corresponds to the top of the lower volcanic sands (lithologic Subunit IVB), tentatively correlated to the Mogan Formation on the island.

Four ADARA temperature measurements, taken between 44.1 and 101.1 mbsf, gave a geothermal gradient of 33.51°C/km. Thermal conductivity, downhole, had an average value of approximately 1.11 W/m·K, resulting in a heat-flow value of 37.20 mW/m^2. These values are high for a continental-margin setting and most likely reflect the Canary Islands hot spot.

In summary, the basaltic shield stage of Gran Canaria was penetrated by 140 m and found to consist basically of three debris flows. These do not represent the true submarine stage below the volatile fragmentation depth, but must have formed while the island was already emerged. Seismic data, acquired during the approach to the site, imply that volcaniclastic sediments related to the shield stage extend to much greater depth.

A very thick sequence of vitric tuffs is interpreted to reflect both primary and reworked ash-flow eruptions during the origin of both the Mogan and Fataga formations. The compositionally distinct ignimbrite P1 (14.1 Ma) was recognized at the base of the vitric-tuff-rich, lower part of the hole, as at Sites 953 and 955. Significant volcaniclastic material, supplied to the site from other islands, appears to be restricted to Pleistocene turbidite, grain-flow, and fallout-tephra layers, presumably from Tenerife; much will be learned from this material about composition, repose periods, and magnitude of explosive volcanism of Pico de Teide.

The sedimentary succession recovered at Site 956 bears many similarities to that at Site 953. In contrast to Site 953, however, Site 956 in the southern basin also received siliciclastic material and clay from the African continental margin, as is also reflected in the generally lower $CaCO_3$ concentrations of the sediment. The greater abundance of slumps in the upper ca. 380 m at Site 956 may reflect wholesale sediment-packet sliding, but to a much lesser degree than at Site 955.

CONCLUSIONS

Leg 157 of the Ocean Drilling Program had two distinct goals: to study the evolution of an oceanic island from sediments in the volcanic apron and to study the history of sediment mass wasting in a deep-sea basin by drilling abyssal-plain turbidites. The abyssal plain receives sediment flows from the Northwest African continental margin and the Canary Islands, thus linking the two research programs.

Madeira Abyssal Plain

The excellent core recovery at all three sites in the Madeira Abyssal Plain will facilitate shore-based mapping of individual turbidites across the whole abyssal plain, aided by downhole-logging data and an extensive network of seismic profiles.

We found that the early infilling of the abyssal plain took place in the deeper parts of the fracture zone valleys (Sites 951 and 952) by relatively small flows derived from the Northwest African margin. The widespread flooding of turbidites, and hence increased erosion within the Canary Basin, began between 11.3 and 15 Ma with a series of large turbidites with thick sandy bases, again from the Northwest African margin. The input of volcaniclastic turbidites from the Canaries or Madeira increased dramatically at 6.5 Ma and has remained high since this time.

Turbidite deposition continued from the inception of the abyssal plain to the present day with major flows involving tens to hundreds of cubic kilometers of sediment occurring every few tens of thousands of years. The pelagic interbeds between turbidites record dramatic changes in the position of the CCD through the last 3 m.y., related to Northern Hemisphere glaciations and associated changes in ocean circulation. These sediments will provide a high-resolution stratigraphy to determine the relationship of turbidite input to sea-level change throughout this interval.

Gran Canaria Volcanic Apron

Four sites (Sites 953 through 956) drilled north and south of Gran Canaria penetrated a total of almost 3000 m and have demonstrated that the compositional evolution, growth, and mass wasting of the island is reflected in the sediments of the adjacent volcaniclastic apron. All major volcanic and nonvolcanic phases of Gran Canaria have been recognized in the ages and compositions of sediments, physical properties, and geophysical logs.

The highest rate of volcaniclastic deposition corresponds to the mid-Miocene basaltic shield stage of Gran Canaria. Initial phases included deposition of thick, graded hyaloclastite tuffs and debris flows, some containing large clasts of subaerial basalts (the thickest single depositional unit exceeding 80 m), which are possibly associated with large slump events. These are overlain by 40 m of breccias and lapillistones, which record the transition from shallow submarine to subaerial conditions. Establishment of the subaerial shield is reflected in numerous thin fine-grained turbidites (40 m thick at Site 953).

On land, the shield basalts are covered by > 200 m of peralkaline rhyolitic ignimbrites and minor lavas (Mogan Formation, ca. 14.1-13.4 Ma), which in turn are overlain by >500 m of trachyphonolitic ignimbrites and lava flows (Fataga Formation, 13.4-9.5 Ma). Different facies of volcaniclastic sediments, which can be correlated to both of these volcanic phases, occur at Sites 953, 955, and 956 and range in thickness from 54 to 50 m (Mogan) and 120 to 250 m (Fataga). At three sites, up to 170 km apart, we recognized the marine facies of cooling unit P1, a 14.1-Ma ignimbrite that forms an important stratigraphic marker on Gran Canaria, separating the basaltic shield from the felsic volcanics. Abundant fresh glass, some possibly generated by quenching of dense hot-ash flows upon entry into the sea, will be used to help geochemically correlate most of the 15 Mogan cooling units to volcaniclastic turbidites. This will contribute to a better understanding of the processes that occur during the passage of hot ash flows into water. Abundant alkali feldspars will be used for a detailed single-crystal dating that will aid high-resolution correlation with biostratigraphic and paleomagnetic data, which are particularly continuous at Site 953.

An important volcanic hiatus on Gran Canaria between 4.5 and 9.5 Ma corresponds to a period of very low volcaniclastic input to surrounding basins. Erosion of the island, apart from episodic flank collapses, does not appear to contribute large volumes of coarse material to the apron during this hiatus. A significant flux of coarse volcaniclastic sediment to the deep sea occurs only during, and immediately after, periods of active volcanism.

Unusually high alkalinity in the absence of significant organic-matter diagenesis, combined with high magnesium and lithium contents, was observed at Site 954. These CO_2-charged, effervescent pore waters are presumably due to the proximity of Holocene volcanism in northern Gran Canaria, which is also reflected in the highest geothermal gradient (52.7°C/km) measured at any of the sites.

In summary, the evolution of the volcanic apron of Gran Canaria and its detailed correlation with the land record can serve as a model that will improve assessment of the significance of volcaniclastic facies in ancient rock successions, their relationship to the tempo of volcanic activity, and the past volcanic, petrologic, and plate-tectonic environments of sedimentary basins adjacent to volcanic source regions. Drilling, in combination with the high-resolution seismic data and the land record, will allow more realistic calculations of magma-production rates and thus mantle dynamics in hot-spot regions. The great thickness of hyaloclastites and debris flows at the base of the two deepest holes supports the conclusion, based on dating the shield basalts, that the eruptive rate was very high.

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FIGURE CAPTIONS

Figure 1a. Bathymetric map showing the location of the Madeira Abyssal Plain and the Canary Islands. Bathymetry in thousands of meters. Shaded region represents the area of flat ponded sediments.

Figure 1b. Bathymetric map of the Madeira Abyssal Plain, showing the location of Sites 950, 951, and 952. Bathymetry in meters.

Figure 2. Summary diagram of Site 950, showing lithology, lithologic units, age, pelagic calcium carbonate content, pore-water chemistry (SO_4, NH_4, alkalinity), and logging data (Ca/[Ca+Si+Fe] ratio and spectral gamma).

Figure 3. Summary of biostratigraphic zonations and ages of Sites 950, 951, and 952.

Figure 4. Example of turbidite correlation between all three MAP sites.

Figure 5. Map showing locations of Sites 953 through 956, in relation to the islands of Gran Canaria, Tenerife, and Fuerteventura.

Figure 6. Summary diagram of Site 953, showing lithology, units, age, relationship to Gran Canaria volcanic history, and pore-water chemistry (SO_4, NH_4, Ca, K, SiO_2).

Figure 7. Summary of Site 954, showing lithology, units, age, percentage of sand units/core, relationship to Gran Canaria volcanic history, and pore-water chemistry (alkalinity and lithium).

Figure 8. Summary of Site 955, showing lithology, units, age, relationship to Gran Canaria volcanic history, percentage of sand units/core, and pore-water chemistry (Cl, SO_4, NH_4).

Figure 9. Summary of Site 956, showing lithology, units, age, and relationship to Gran Canaria volcanic history.

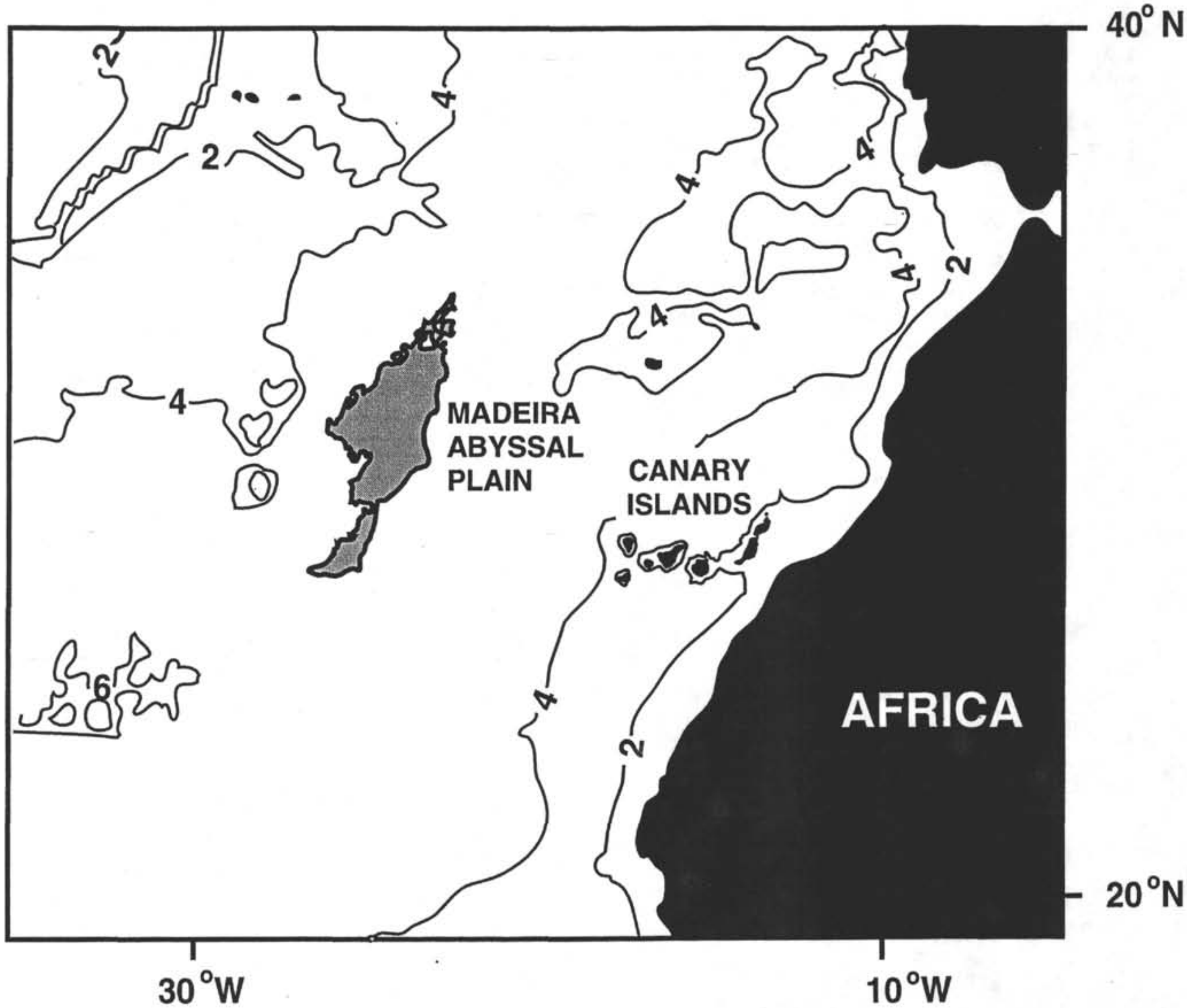

40° N
20°N
30°W
10°W
MADEIRA
ABYSSAL
PLAIN
CANARY
ISLANDS
AFRICA
2
4
6

Figure 1a

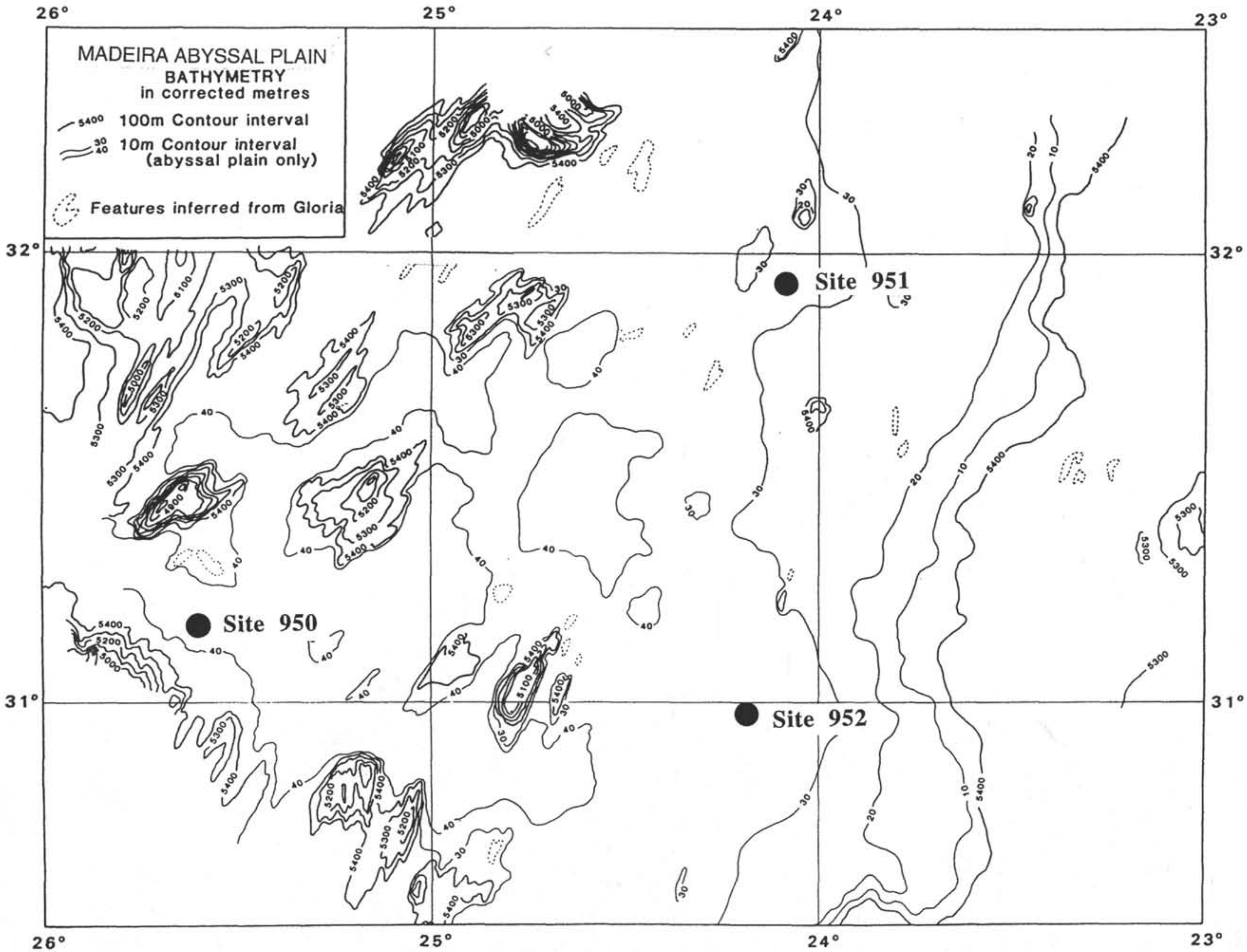

MADEIRA ABYSSAL PLAIN
BATHYMETRY
in corrected metres
100m Contour interval
10m Contour interval
(abyssal plain only)
Features inferred from Gloria
26°
25°
24°
23°
32°
31°
Site 950
Site 951
Site 952

Figure 1b

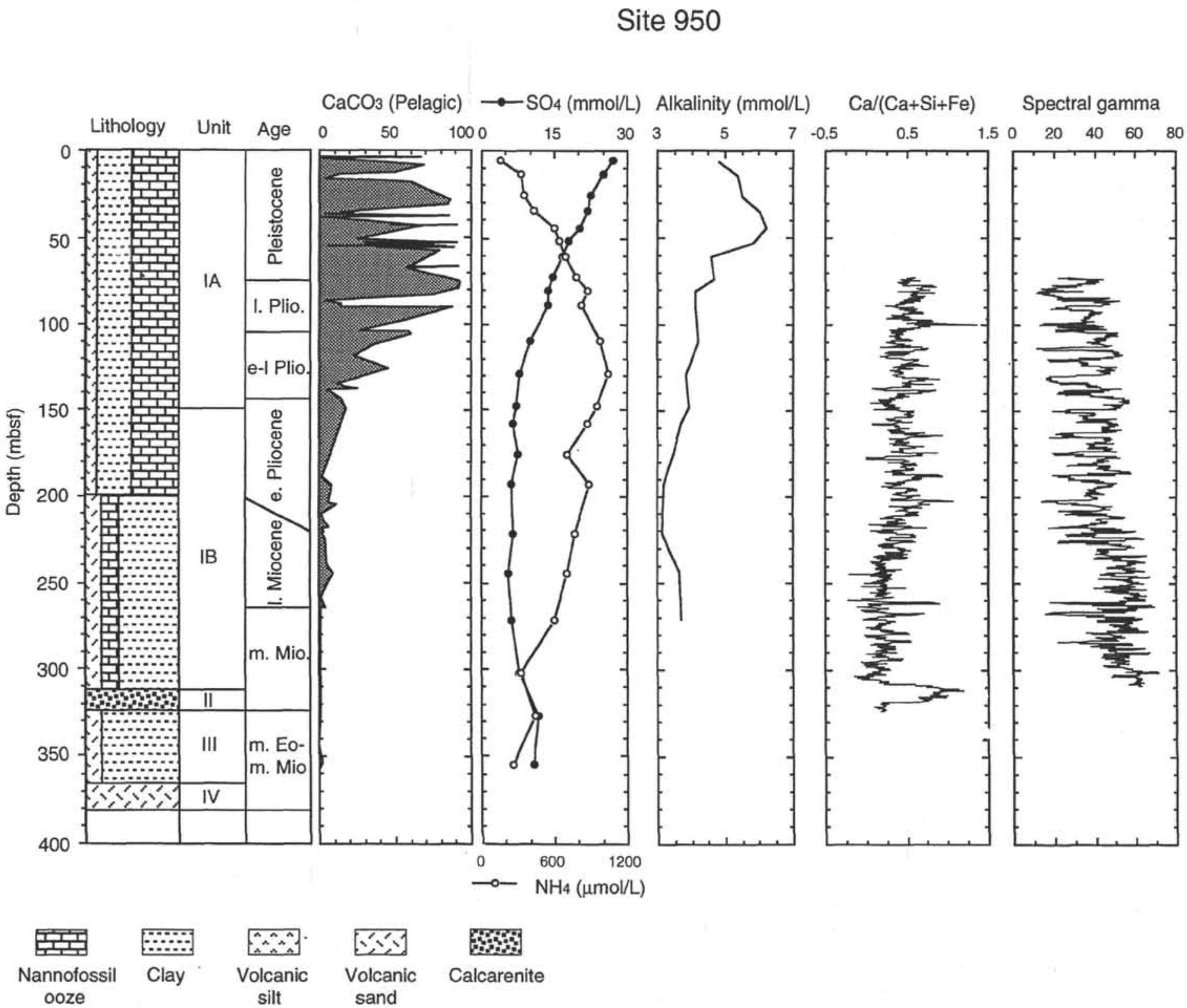

Site 950
Lithology
Unit
Age
CaCO3 (Pelagic)
SO4 (mmol/L)
Alkalinity (mmol/L)
Ca/(Ca+Si+Fe)
Spectral gamma
Depth (mbsf)
IA
IB
II
III
IV
Pleistocene
l. Plio.
e-l Plio.
e. Pliocene
l. Miocene
m. Mio.
m. Eo-
m. Mio
NH4 (µmol/L)
Nannofossil
ooze
Clay
Volcanic
silt
Volcanic
sand
Calcarenite

Figure 2

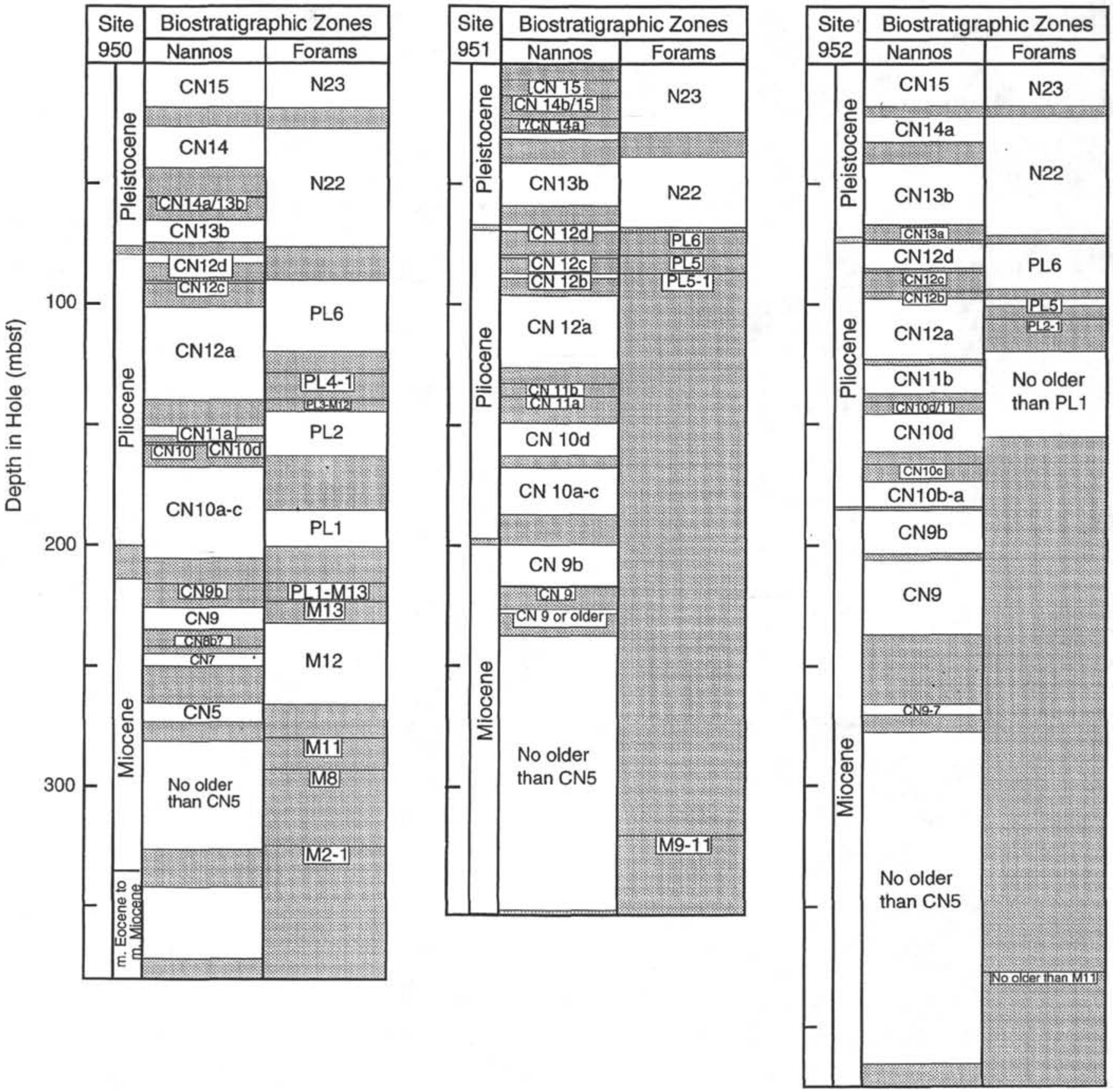

Site 950
Biostratigraphic Zones
Nannos
Forams
Site 951
Site 952
Depth in Hole (mbsf)
100
200
300
Pleistocene
Pliocene
Miocene
m. Eocene to m. Miocene
CN15
CN14
CN14a/13b
CN13b
CN12d
CN12c
CN12a
CN11a
CN10
CN10d
CN10a-c
CN9b
CN9
CN8b?
CN7
CN5
No older than CN5
N23
N22
PL6
PL4-1
PL3-M12
PL2
PL1
PL1-M13
M13
M12
M11
M8
M2-1
CN 15
CN 14b/15
?CN 14a
CN 12d
CN 12c
CN 12b
CN 12a
CN 11b
CN 11a
CN 10d
CN 10a-c
CN 9b
CN 9
CN 9 or older
PL5
PL5-1
M9-11
CN14a
CN13a
CN12b
CN11b
CN10d/11
CN10c
CN10b-a
CN9-7
PL2-1
No older than PL1
No older than M11

Figure 3

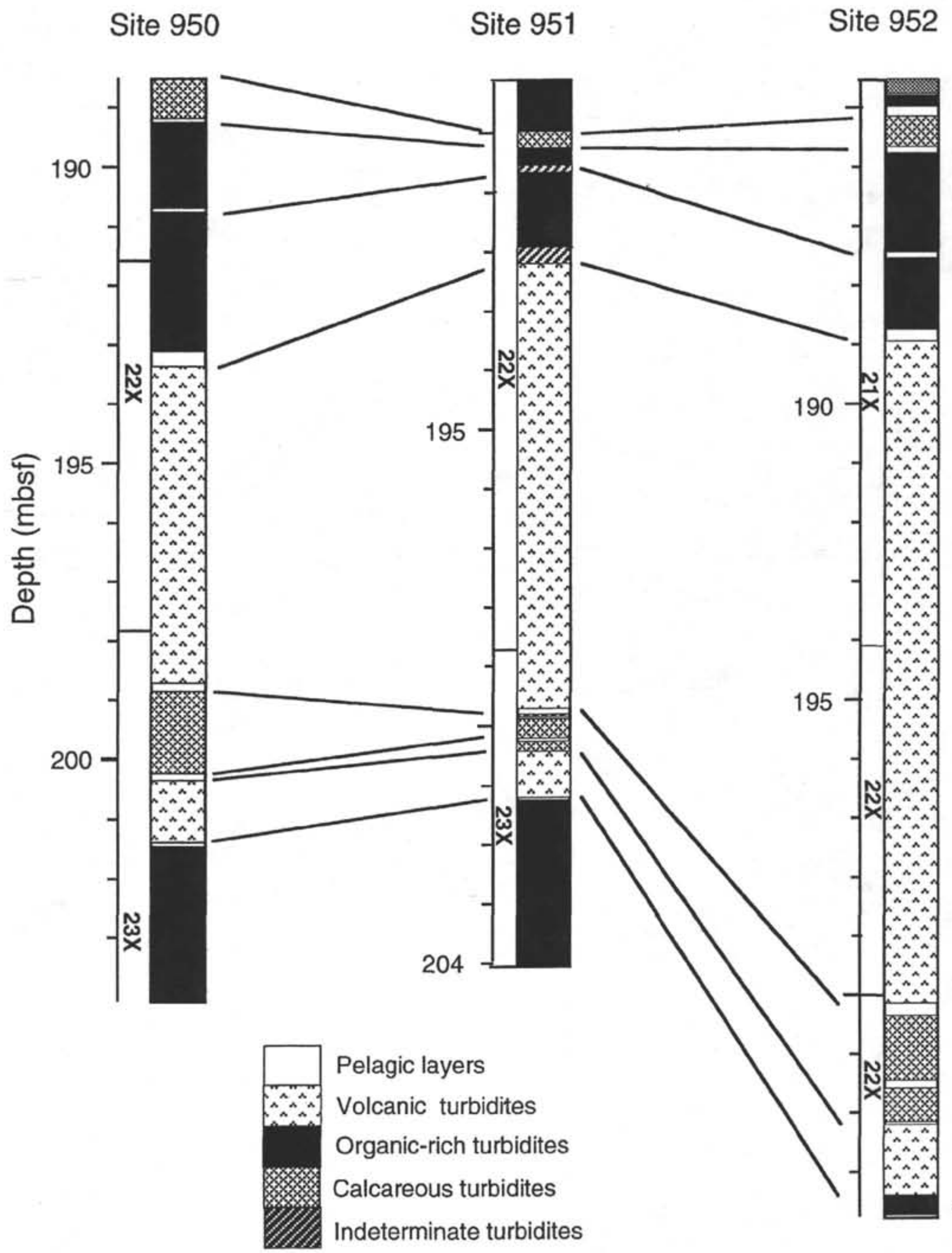

Site 950
Site 951
Site 952
Depth (mbsf)
190
195
200
22X
23X
195
204
22X
23X
190
195
21X
22X
22X
Pelagic layers
Volcanic turbidites
Organic-rich turbidites
Calcareous turbidites
Indeterminate turbidites

Figure 4

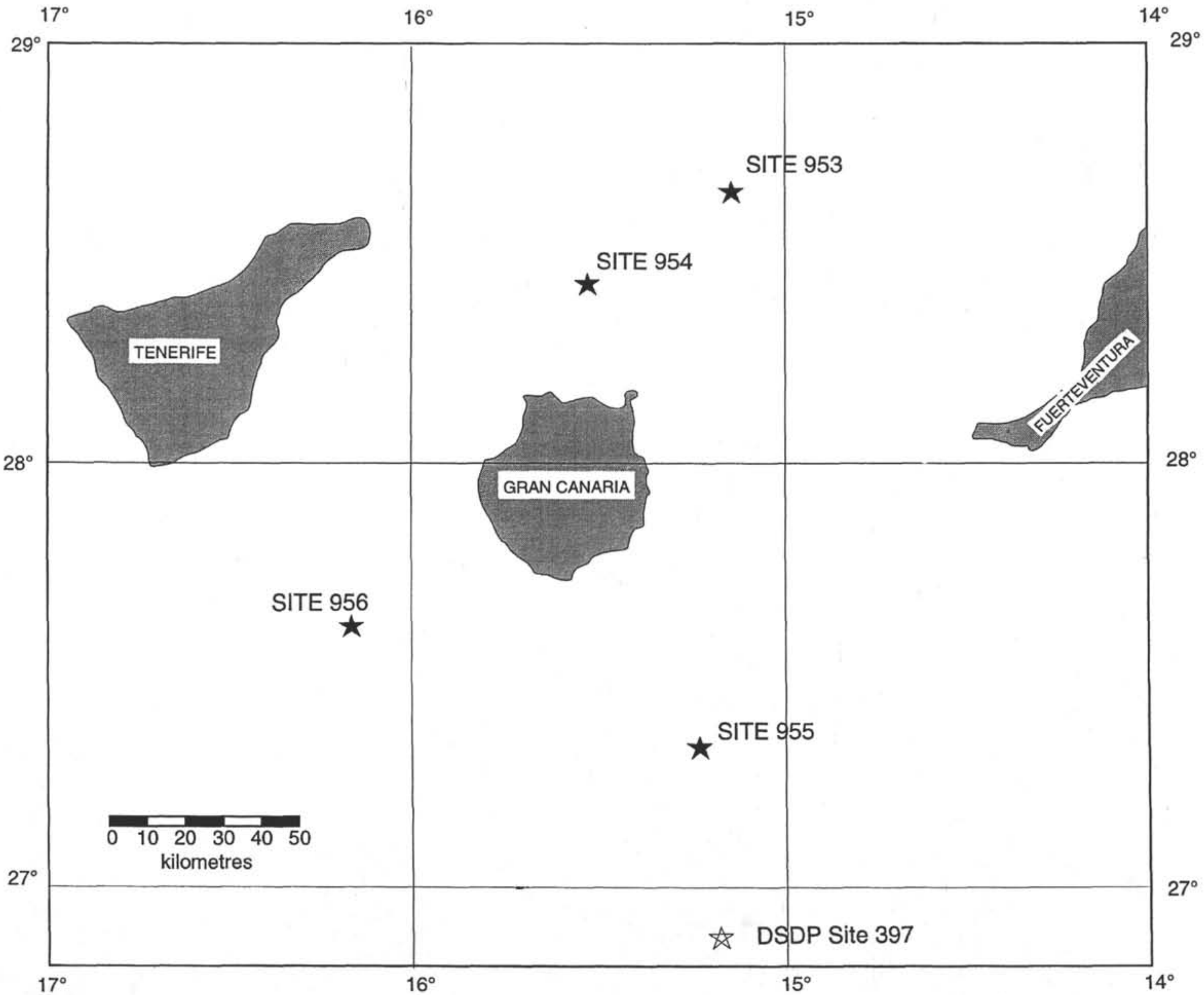
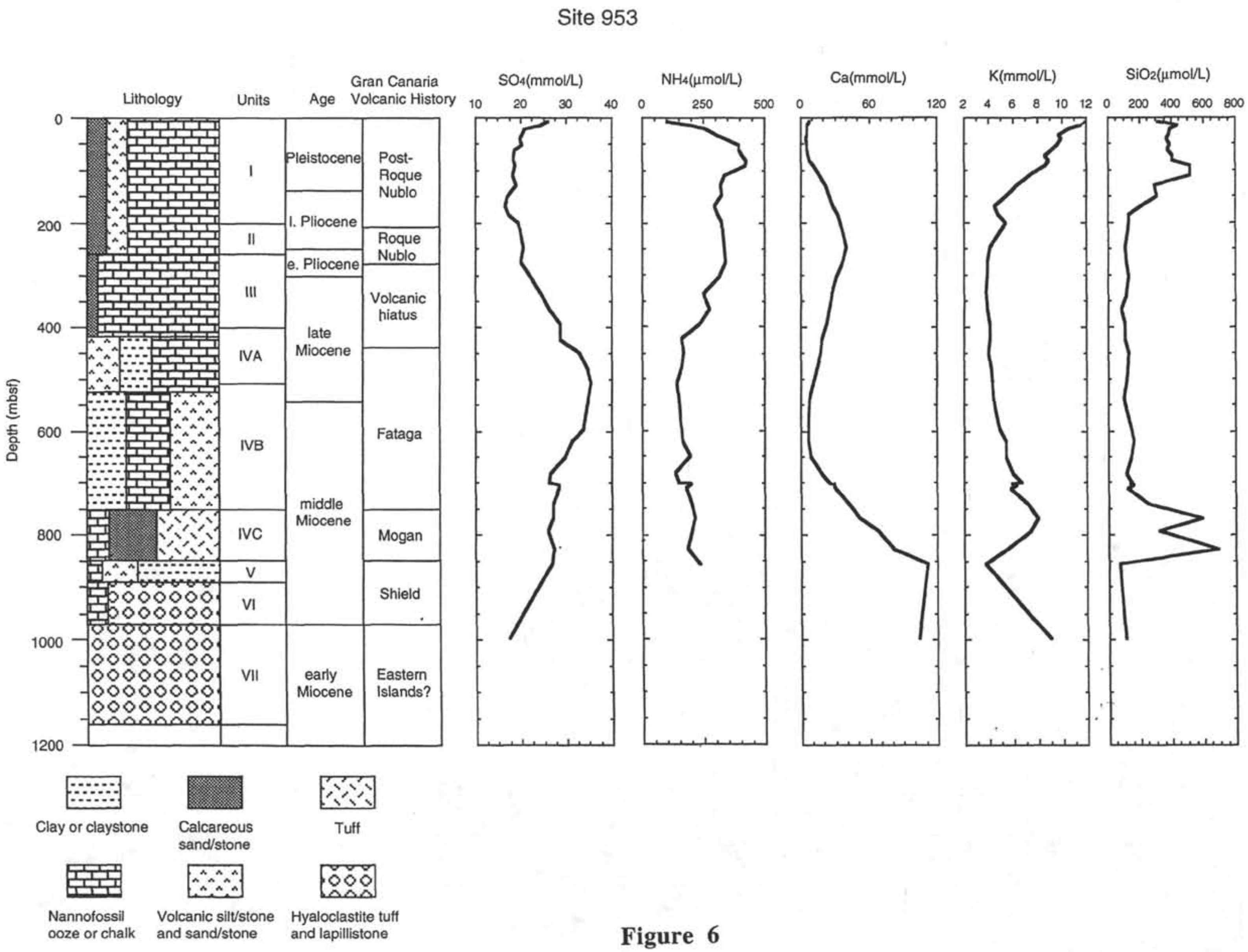

17°
16°
15°
14°
29°
29°
SITE 953
SITE 954
TENERIFE
FUERTEVENTURA
GRAN CANARIA
28°
28°
SITE 956
SITE 955
0 10 20 30 40 50
kilometres
27°
27°
DSDP Site 397
17°
16°
15°
14°

Figure 5



Site 953
Lithology
Units
Age
Gran Canaria Volcanic History
SO4(mmol/L)
NH4(µmol/L)
Ca(mmol/L)
K(mmol/L)
SiO2(µmol/L)
Depth (mbsf)
I
II
III
IVA
IVB
IVC
V
VI
VII
Pleistocene
l. Pliocene
e. Pliocene
late Miocene
middle Miocene
early Miocene
Post-Roque Nublo
Roque Nublo
Volcanic hiatus
Fataga
Mogan
Shield
Eastern Islands?
Clay or claystone
Calcareous sand/stone
Tuff
Nannofossil ooze or chalk
Volcanic silt/stone and sand/stone
Hyaloclastite tuff and lapillistone

Figure 6

Site 954

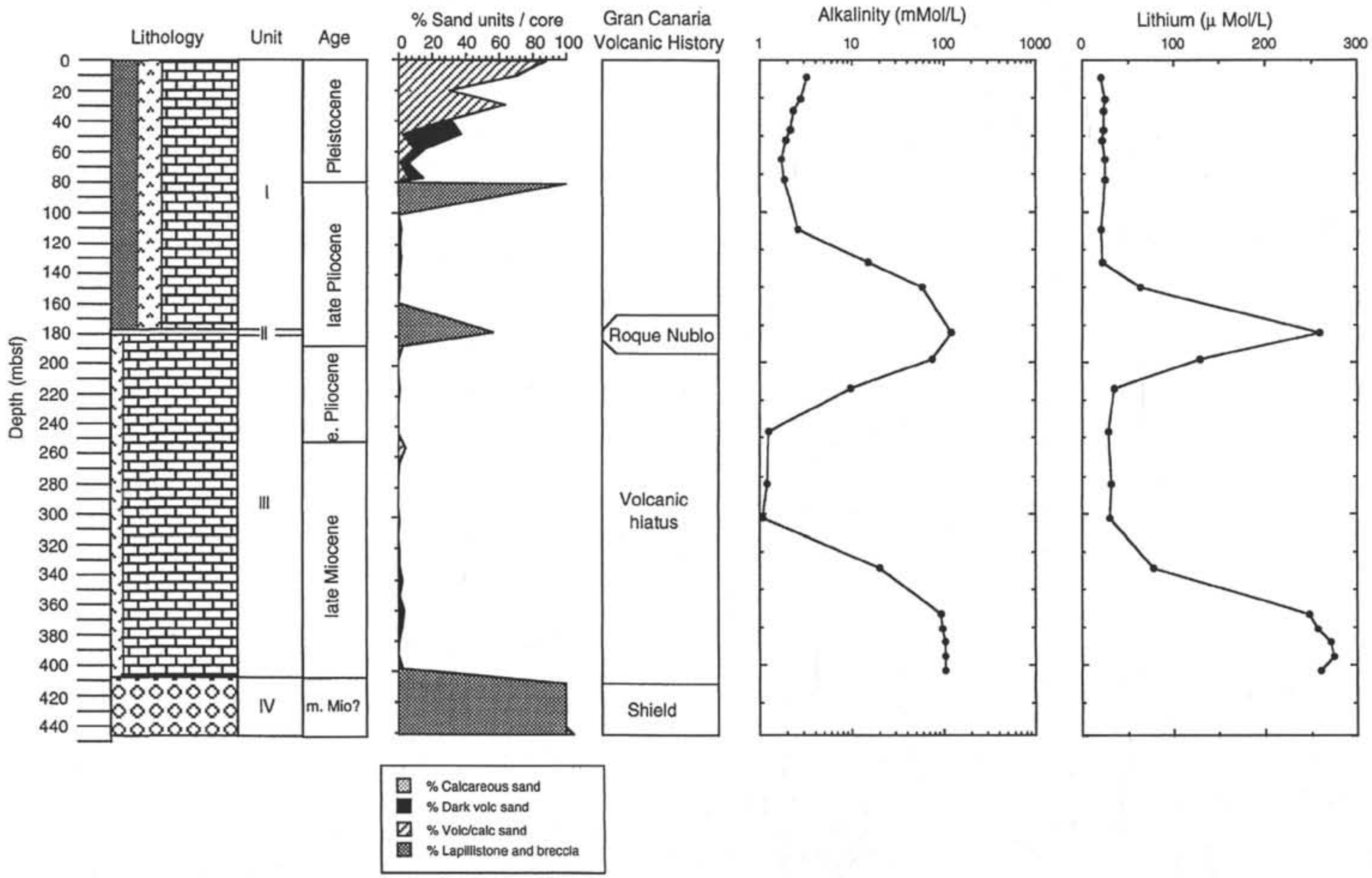


Figure 7

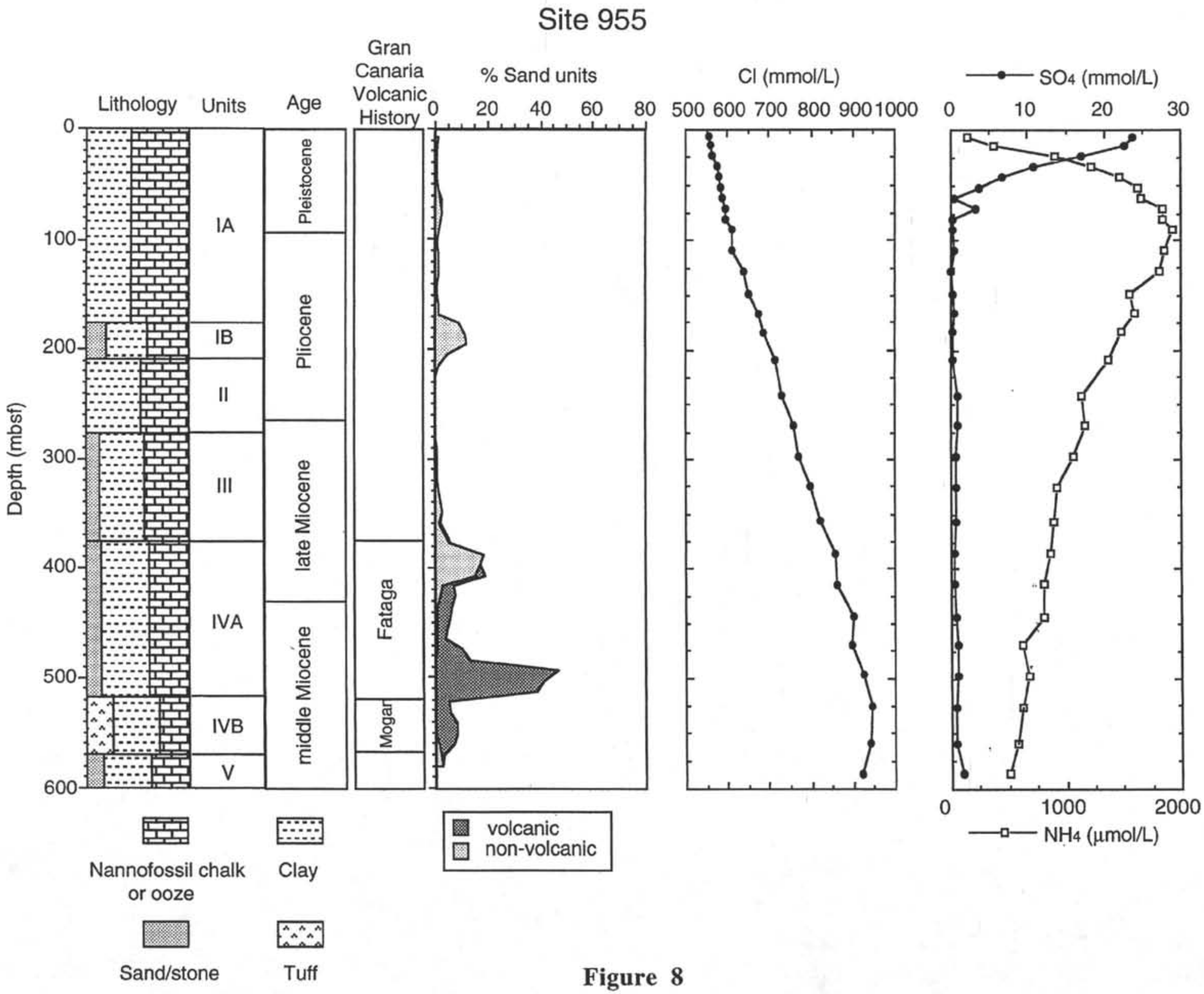

Site 955
Lithology
Units
Age
Gran Canaria Volcanic History
% Sand units
Cl (mmol/L)
SO4 (mmol/L)
NH4 (µmol/L)
Depth (mbsf)
IA
IB
II
III
IVA
IVB
V
Pleistocene
Pliocene
late Miocene
middle Miocene
Fataga
Mogan
volcanic
non-volcanic
Nannofossil chalk or ooze
Clay
Sand/stone
Tuff

Figure 8

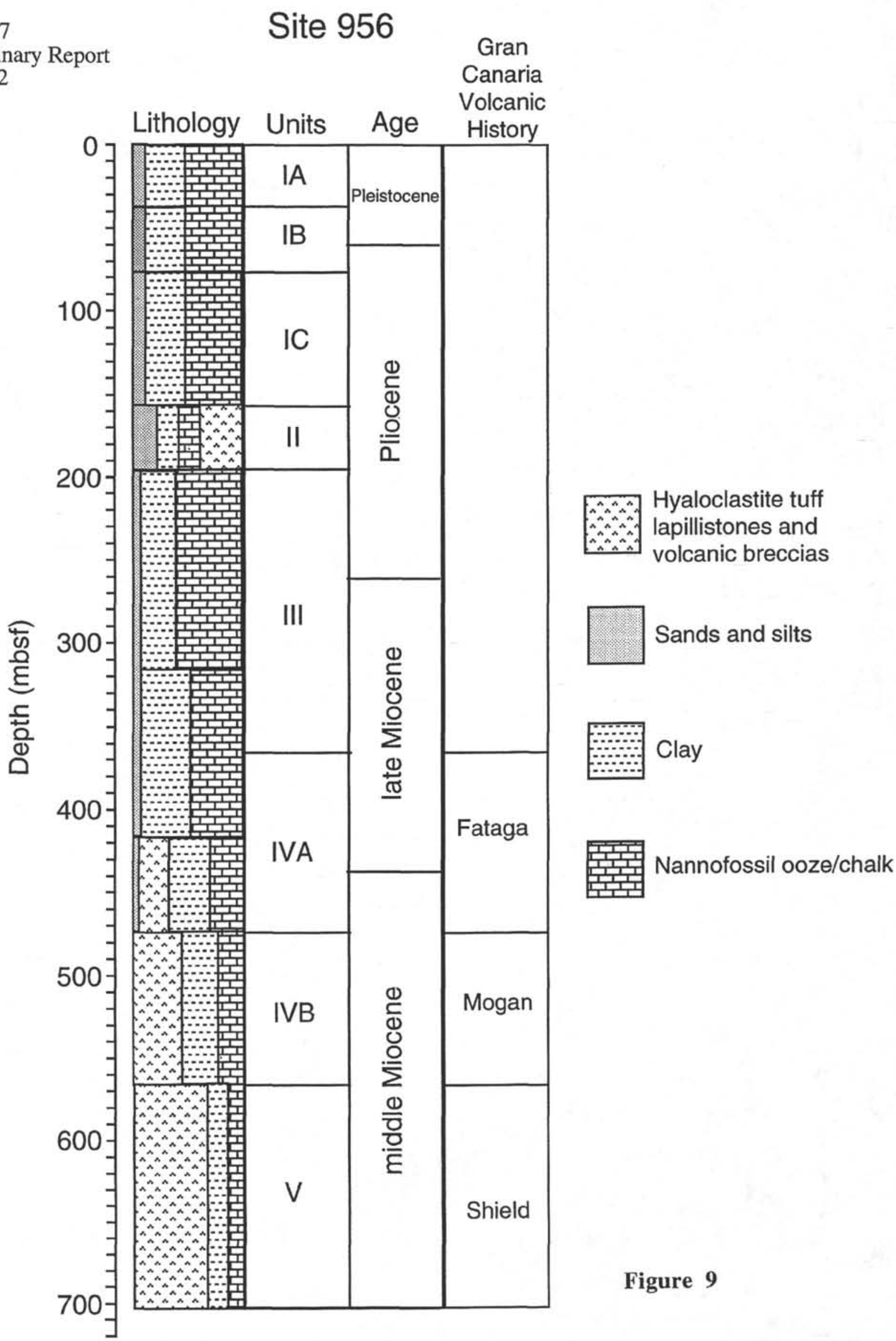

Site 956
Lithology
Units
Age
Gran Canaria Volcanic History
Depth (mbsf)
0
100
200
300
400
500
600
700
IA
IB
IC
II
III
IVA
IVB
V
Pleistocene
Pliocene
late Miocene
middle Miocene
Fataga
Mogan
Shield
Hyaloclastite tuff lapillistones and volcanic breccias
Sands and silts
Clay
Nannofossil ooze/chalk

Figure 9

OPERATIONS REPORT

The ODP Operations and Engineering personnel on board *JOIDES Resolution* for Leg 157 were:

Operations Superintendent: Ron Grout

Schlumberger Engineer: Steven Kittredge

PORT CALL IN BRIDGETOWN, BARBADOS

Leg 157 began with the first mooring line at Bridgetown Harbor, Barbados, at 1000 hr, 24 July 1994 (all times reported as local).

The port call entailed a heavy logistical workload with the loading of hardware which had been offloaded and stored in Barbados prior to Leg 156. From storage in Barbados, we picked up two hard-rock guide bases (HRB) and various running tools. Additional hardware, loaded from College Station, were one reentry cone (Russian manufacture), two new nonmagnetic drill collars, and two tapered drill collars that will replace the $7^1/_4$-in. drill collar in the BHA. Sepiolite, barite, and cement were also loaded.

The standard on- and off-going freight shipments were handled, and crew changes were made. Fresh water tanks were filled, and approximately 1322 metric tons of marine gasoil were loaded. The replacement of the forward core-winch bearing could not be completed during the port call because a grease seal was not included in the shipment of replacement parts. Because the forward winch contained only 5550 m, it was not going to be used during operations at the MAP sites. Arrangements were made to transport the grease seal to the ship when the vessel reached the VICAP area during the last half of the leg. The core winch was not reassembled.

A diver survey of the stern tubes and skeg thrusters was made to see if any hydrophone cable was fouled in the propellers as a result of a hydrophone being cut during Leg 156 VSP operations. The survey did not show any foreign material in, or damage to, the skeg or main propellers.

At 1800 hr, 27 July, the last line was away, and *JOIDES Resolution* departed for proposed site MAP-1.

BRIDGETOWN TO SITE 950
(Proposed site MAP-1)

At 1813 hr, 27 July, a flashover occurred in propulsion motor P15A on the starboard shaft. This happened almost immediately after putting the motor in service and resulted in an immediate shut-down of the starboard shaft. After a quick inspection indicated that a brush holder ring had burnt, the starboard shaft was operated with only four motors on line. During routine maintenance in port, a very low insulation resistance was discovered in the armature circuit of P13B, which necessitated the disabling of this motor.

At 1824 hr, 27 July, the breaker for starboard propulsion motor P13A tripped off-line. On resetting the breaker, the electrician noticed a malfunction in the Thyrig bay assigned to this motor and immediately shut down the power to this unit. The vessel proceeded with only three on-line motors driving the starboard shaft. P13A was back on line at 0543 hr, 28 July, after the electrician replaced two blown fuses.

The electricians installed a temporary jumper cable from P13B to the Thyrig bay and had this motor in operation by 1600 hr, 30 July. At the same time, ocean swells calmed, so the average speed of *JOIDES Resolution* increased from 9.3 to 9.7 kt and continued to build during the voyage to the MAP area. On 2 August, the port shaft had to be shut down for 30 min while a high-pressure oil leak was repaired on the port gearbox.

Throughout the rest of the transit, the vessel's speed continued to increase and, by the time the air guns were deployed at proposed site MAP-1, the average speed for the transit had improved to 10.2 kt. The clock was advanced 3 hr during the transit.

SITE 950
(Proposed site MAP-1)

At 1645 hr, 5 August, *JOIDES Resolution* slowed to 6 kt, after a 9-day transit from Barbados, and the seismic gear was deployed as the vessel approached the Site 950 survey area from the southwest. After a 2-hr survey, the gear was retrieved and the vessel returned to the site. A beacon was deployed at 2000 hr, 5 August.

A standard short-drill-collar, APC/XCB bottom-hole assembly (BHA), comprising a nonmagnetic drill collar (NMDC) and a drag-type $10^1/_8$-in. PDC bit, was assembled to begin the pipe trip. The BHA was complete with a new tapered drill collar in place of the $7^1/_4$-in. drill collar and assorted subs. The initial running in the hole was lengthened because of the standard practice of measuring and passing a drift through the drill string on the initial pipe trip of an ODP leg.

The water depth was determined to be 5437.8 mbsl (drill-pipe measurement, DPM) with Core 157-950A-1H, and the core recovered 8.9 m of clayey nannofossil mixed sediment. APC coring advanced to 154.4 mbsf (Core 157-950A-17H). The kelly hose ruptured while pressuring up to fire the last APC core, Core 157-950A-17H, and the core achieved only 3 m penetration in the hard, sticky clays. After replacing the kelly hose, coring resumed with the XCB system and advanced to 381.3 mbsf (Cores 157-950A-18X to -41X), where contact with volcanic sandstone reduced the rate of penetration (ROP) to a very slow 4 m/hr. This was considered XCB refusal and the end of the hole. The hole was then prepared for logging by a flush of sepiolite mud and a wiper trip.

The initial log was the seismic stratigraphic combo, which logged down, and up, the hole from 363.4 mbsf. The second was the litho-porosity combo, which logged up from 359 mbsf. The third was a geochemical combo, which logged the hole from 324 mbsf. Finally, the FMS was logged up from 314 mbsf. Coverage of the open-hole section was very good, with the first two strings encountering only a minimal amount of hole fill (approximately 16 m). The geochemical and FMS strings lost the bottom 50 m of the hole. The hole deviation was a maximum of 3° at 276 mbsf.

After rigging down the logging tools and pulling pipe, *JOIDES Resolution* was under way to proposed site MAP-4 by 2330 hr, 10 August.

TRANSIT TO SITE 951
(Proposed site MAP-4)

As soon as the main propulsion was commanded ahead, the drive coupling between propulsion motors P13A and P15A disintegrated, scattering metal fragments, which caused damage to motor P13A. The vessel was cautiously under way with only two of the six propulsion motors on the starboard shaft by 0040 hr, 11 August.

The 59-nmi transit to proposed site MAP-4 was made at an average speed of only 9.0 kt, due to the reduced shaft horsepower. At 0615 hr, 11 August, the seismic gear was deployed, and a short survey was conducted over the site. The gear was retrieved, and the hydrophones and thrusters were lowered as the vessel was moved on location, according to GPS coordinates. The beacon was deployed after reaching the desired position.

SITE 951

Hole 951A

The standard, short-collar APC/XCB BHA used on the previous site was made up, without the lockable float valve (LFV), and run to 5443 mbrf. Based upon a PDR depth of 5449.4 m, the first piston core was shot at 5443 mbrf and recovered 4.9 m of nannofossil ooze. This established the mud-line depth for this hole at 5436.8 mbsl.

APC coring advanced to 118.8 mbsf and recovered 117.2 m (98.6% recovery). The last two piston core liners (Cores 157-951A-12H and -13H) were twisted and crushed, indicating that the liners were exposed to extreme suction while being extracted from the sticky clay of the formation. We decided to continue coring with the XCB assembly. Cores 157-951A-3H to -13H were oriented.

Coring continued with the XCB assembly and gave excellent results. The hole was prematurely aborted when the XCB core barrel became jammed inside the drill pipe, 366 m below the rig floor. The barrel was being retrieved after successfully cutting Core 157-951A-28X, and was nearly home when the assistant driller noticed that the wire had "cross-wrapped" on the drum. The reaction was to immediately stop and reverse the direction of the winch. The reaction was sudden enough to cause the core barrel inertia to carry the barrel into the sinker bars. The net effect was to part the shear pin and, at the same time, jam the barrel in the pipe at approximately 366 mbrf.

After spending 1.5 hr in a vain attempt to free the barrel, the top drive was set back and the pipe was pulled up enough so that the joint with the core barrel could be laid down. Because the length of the pullout exceeded the depth of Hole 951A, the hole was terminated when the bit cleared the mud line at 1140 hr, 13 August. Coring with the XCB penetrated 137.8 m, with 134.3 m recovered (97.5%). The total recovery on the hole was 251.5 m or 98.0% of the cored interval.

To prevent a recurrence of this incident, a policy was introduced that the core winch operator has to bring the core winch to a complete stop before reversing the direction the next time that a cross-wrap is observed. This action should prevent the core barrel from impacting the sinker bars.

Hole 951B

After the bit cleared the mud line at 1140 hr, 1.5 hr was spent with the routine task of cutting and slipping 115 ft of drilling line. While this operation was under way, the vessel was offset 10 m south of Hole 951A. At 1450 hr, 13 August, Hole 951B was spudded and drilled ahead to 255 mbsf. After drilling down at an average ROP of 85.0 m/hr, the wash barrel was retrieved and a core barrel dropped at 2215 hr, 13 August. XCB coring resumed on Site 951 and continued to 351.6 mbsf. A total of 10 cores were obtained with 87.6% recovery after penetrating 96.6 m.

TRANSIT TO SITE 952
(Proposed site MAP-3)

The 69-nmi voyage to Site 952 was made at an average speed of 10.3 kt. At 0815 hr, 15 August, the vessel slowed to 6.5 kt and conducted a short survey over the area. By 1100 hr, the survey had been completed and the beacon dropped on location at 1101 hr, 15 August.

SITE 952

Hole 952A

The standard, short-collar APC/XCB BHA used on the previous sites was made up with the LFV for logging. Core 157-952A-1H recovered 9.82 m of nannofossil ooze and established the mud line at 5431.8 mbsl. APC coring advanced to 142.8 mbsf (Core 157-952A-15H) and recovered 143.7 m (100.6% recovery). Coring continued with the XCB assembly but, after Core 157-952A-15H, did not extend to full stroke. Cores 157-952A-3H to -15H were oriented. Coring with the XCB system advanced to total depth (TD) at 425.9 mbsf with excellent recovery (95.9%). The total recovery for the hole was 97.5%. Because all the subsequent sites of the leg are in shallower water, the coring line was coated with a preservative from 5868 to 3500 m while retrieving Core 157-952A-45X.

At 1430 hr, 18 August, the hole was flushed with 30 bbl of sepiolite mud. The first wiper trip found 18 m of fill at the bottom of the hole. The hole was washed and reamed to 425.9 mbsf (TD). Another treatment of mud followed, and the pipe was then pulled up to logging depth (92 mbsf).

At 2230 hr, 18 August, the logging equipment was rigged up, and the quad-combo tool assembled. Despite encountering difficult hole conditions, downhole logs were successfully recorded with the quad-combo tool string down to approximately 290 mbsf. The quad-combo tool string, comprising natural gamma-ray (NGT), sonic (LSS), neutron porosity (CNT), density (HLDT), and induction (DIT), was deployed on three separate occasions, with drill pipe set at different levels, in an attempt to pass obstructions in the borehole. The initial deployment reached a depth of 202 mbsf, and data were recorded from here to the end of pipe at 76 mbsf. The tool string was then removed from the hole and the pipe reset below the obstruction, at 207 mbsf, and the tool was redeployed. A secondary obstruction was encountered at 293 mbsf, and data were recorded from this depth to 179 mbsf. The tool string was removed from the hole for a second time, and the hole flushed with 50 bbl of sepiolite in an attempt to log the bottom section of the hole. The pipe was reset at 304 mbsf and the tool string redeployed, but no significant progress could be made down into open hole from the end of the drill string. Logging operations were then terminated, owing to time constraints.

After the logging equipment was rigged down, the drill pipe was started out of the hole at 2400 hr, 19 August. Concurrent with the pulling of the pipe, the beacon was recalled, recovered, and on deck at 0420 hr, 20 August. The drilling equipment was secured and the thrusters and hydrophones retracted by 1100 hr, 20 August, as the vessel began the transit to the VICAP area.

TRANSIT TO SITE 953
(Proposed site VICAP-1A)

JOIDES Resolution covered the 506-nmi transit to Site 953 at an average speed of 11.2 kt. The vessel approached the position on a southerly heading and slowed as it neared the beacon drop point. The thrusters and hydrophones were deployed as the vessel was offset to the GPS coordinates of the site. At 1053 hr, 22 August, the beacon was deployed on site.

Hole 953A

An APC/XCB BHA was made up, and Core 157-953A-1H established the mud-line depth at 3577.8 mbsl. APC coring proceeded routinely to 188.1 mbsf (Cores 157-953A-1H to -20H).
Core 157-953A-21H failed to achieve full stroke. The core barrel was drilled over, and then pulled out with 175 kips. Only half the core barrel was retrieved, leaving the other half stuck in the hole.

The hole was terminated, and the pipe was pulled out of the hole, with the bit clearing the mud line at 1355 hr, 23 August. Cores 157-953A-3H to -16H were oriented. Recovery was 102.6% of the cored interval of 192.6 m.

Hole 953B

The vessel was offset 20 m south of the first hole; Hole 953B was spudded and drilled ahead without a wash barrel to 188.1 m, and then XCB coring began. It was not possible to retrieve the first core barrel with wireline overpulls as high as 12.5 kips. Repeated attempts at freeing the barrel with the wireline jars also proved fruitless. The pipe was pulled out of the hole, ending Hole 953B. Investigation of the stuck core barrel showed that the POLYPAK material in the bit seal had apparently squashed on the landing of the XCB core barrel and jammed the POLYPAK material between the inner barrel spacer sub and the hard edge of the bit seal. When the bit cleared the mud line at 2309 hr, 23 August, operations had to be suspended for 1.5 hr while 115 ft of drilling line was cut and slipped.

Hole 953C

The vessel was offset 20 m east of Hole 953B, and an RCB BHA was run in and spudded Hole 953C at 1525 hr, 24 August. The hole was drilled ahead with a wash barrel to a depth of 187 mbsf. RCB coring advanced rapidly through the upper part of the hole, which was composed of hard and soft interlayers of calcareous claystone and nannofossil mixed sediments. Recovery typically was below 50%. As the formation became more indurated with depth, recovery improved. Coring was concluded at 0915 hr, 2 September, after coring a total of 972 m (1159 m TD) with a recovery of 57.2%. The rate of coring averaged 11.3 m/hr for the entire hole. There were no hole problems noted during coring operations. Regular preventive sweeps of sepiolite (30 bbl) were circulated. The chisel deplugger was deployed twice to unplug the bit after coring Core 157-953C-88R (1014 to 1017 mbsf). Methane was detected in trace amounts (maximum of 34 ppm) with no heavier hydrocarbons detected. A drift survey at 870 mbsf found the hole angle to be 4°.

Because of the extreme depth of the hole, an extensive wiper trip and hole-conditioning exercise was performed, with three 50-bbl flushes of sepiolite and several washes to clear the bottom of fill. A tight spot at 598 mbsf required extra washing and reaming. The bit was released, and the pipe was pulled up to logging depth. The bottom of the pipe was positioned at 372 mbsf. The first log was the quad combo (natural gamma-ray, sonic, neutron porosity, density, induction, and Lamont Temperature Logging Tool), which logged down from 372 to 975 mbsf. An uplog was then recorded from 975 mbsf to the mud line (372 m inside pipe) during which 4000 to 5000 lb of overpull was encountered between 975 and 911 mbsf and 535 and 499 mbsf. Having completed the uplog, the quad was run into the hole for a repeat section, but downward progress was stopped by an obstruction at 477 mbsf, and the tool was pulled out of the hole. The logging equipment was rigged down, and the pipe was run in the hole to clear bridges at 535 mbsf and deeper. While attempting to work past 533 mbsf, the pipe became stuck. During the attempts to free the drill string, the hole packed off, and circulation, rotation, and vertical movement were lost. Efforts at freeing the pipe were fruitless, so the pipe was severed with explosives at the first joint of 5-in. pipe above the BHA. The drill string was pulled out of the hole, and the rig floor was secured by 1000 hr, 4 September, and *JOIDES Resolution* was under way to the next site at full speed.

TRANSIT TO SITE 954
(Proposed site VICAP-2A)

The 21-nmi transit to the survey point was covered at an average speed of 11.7 kt. The initial plan was to transit to the location and drop a beacon on GPS coordinates. However, an investigation of Admiralty Chart 1869 revealed the presence of an underwater cable within a half mile of the proposed location. This necessitated a short seismic survey, which repositioned the site approximately 1.3 nmi east of the original proposed site. The beacon was deployed at 1341 hr, 4 September.

SITE 954

Hole 954A

An APC/XCB BHA was made up. Core 157-954A-1H established the mud-line depth at 3485.2 mbsl. APC coring advanced to 79.2 m, which was considered APC refusal when Core 157-954A-11H only partially stroked. The APC system recovered 101% of the interval cored. The cores were oriented, starting with Core 157-954A-4H. Heat-flow measurements were carried out on Core 157-954A-5H and -8H. XCB coring began at 79.2 mbsf but was given up when Core 157-954A-11X and -12X recovered coarse basaltic breccia with a low ROP of 4 m/hr. In addition, the PDC cutting structure was not well matched to the very coarse gravel. The bit was tripped to the surface to change to the RCB system. At 2013 hr, 5 September, the bit cleared the rotary table, ending Hole 954A. The vessel was offset 20 m south.

Hole 954B

An RCB BHA was made up, and Hole 954B was spudded and drilled to 80.2 mbsf. The wash barrel was retrieved, and the first rotary core barrel was dropped. RCB coring advanced quickly through what turned out to be a shallow zone (approximately 2 m thick) of basalt breccia, which had thwarted the XCB. For the next 100 m, recovery was very low because the formation was very soft. Recovery improved with depth as the formation became more indurated. Total penetration was 446.0 mbsf (cored interval of 365.8 m) with 45.5% recovery.

At 1430 hr, 8 September, coring operations were terminated and the hole swept with a 25-bbl sepiolite flush. The pipe began to be pulled up for logging. At 1522 hr, 8 September, the bit had reached 379 mbsf and was being pulled up with 25 kips, when a sudden jolt was felt. The driller noticed that the string weight had dropped by 67 kips. With the obvious loss of a significant amount of hardware, logging was canceled and the pipe pulled out of the hole. At 2013 hr, 8 September, the bottom of the drill string cleared the rig floor. Inspection of the recovered drill pipe indicated that a pin failure at the last-engaged thread on a 5-in. tool joint had resulted in the loss of the total BHA, including drilling jars, and 46 joints of 5-in. drill pipe. Initial analysis suggests fatigue failure. The remaining tool joint will be sent to shore for further analysis.

After the drill pipe was pulled, and the hydrophones and thrusters were secured, the vessel departed for proposed site VICAP-4 at 2030 hr, 8 September.

TRANSIT TO SITE 955
(Proposed site VICAP-4)

The 64-nmi transit from Site 954 to Site 955 was accomplished in 6 hr. During the short cruise, the vessel passed within 4 nmi of the city of Las Palmas on Grand Canary Island. At 0230 hr, 9 September, the vessel slowed to 6 kt and the seismic gear was deployed as the vessel approached the survey area. After a 2-hr survey, the gear was retrieved and the vessel returned to the site. A beacon was deployed at 0531 hr, 9 September.

SITE 955

Hole 955A

An APC/XCB BHA was made up and Core 157-955A-1H was shot, establishing the mud-line depth at 2854.2 mbsl. Cores 157-955A-1H to -18H advanced to 168.9 mbsf, and recovered 177.1 m (104.9% recovery). The cores were oriented starting with Core 157-955A-3H. Heat-flow measurements were made on Cores 157-955A-3H, -6H, -9H, and -12H. The last piston core (Core 157-955A-18H) did not stroke out fully, and it was decided to continue with the XCB system. XCB coring deepened the hole to 599.4 mbsf with 82.9% recovery. Total recovery for the hole was 89.1%. During coring, many of the cores were charged with gas, requiring the drilling of small holes to relieve pressure and prevent sediment from expanding out the ends of the core liner. Headspace analysis measured methane as high as 36,000 ppm (8 ppm ethane at 158 mbsf). The ratio of methane to ethane stayed in the range of 3000-4000. No heavier hydrocarbons were detected. Coring conditions were excellent, with no abnormal pressure or torque problems.

At 1645 hr, 12 September, coring was terminated at a depth of 599.4 mbsf, having achieved all objectives for this site. The hole was swept with a 50-bbl sepiolite flush, and a wiper trip was conducted, with no drag registered. At the bottom of the hole, 12 m of soft fill was quickly washed and reamed to bottom (599.4 mbsf). The bit was pulled up to the logging depth of 103 mbsf.

A complete suite of three logging strings was successfully run in Hole 955A. The quad combo was deployed first and recorded data from 599 to 460 mbsf and a main pass from 599 to 72 mbsf. The geochemical log recorded data from 599 mbsf to the mud line and a repeat section from 599 to 465 mbsf. The FMS tool string recorded two full passes from 599 to 85 mbsf and a third repeat pass from 599 to 390 mbsf. The dip angle of the hole was measured from 2° to 5°.

At 2330 hr, 13 September, the logging equipment was rigged down. The pipe was pulled out of the hole, with the bit clearing the seafloor at 2350 hr, and was on deck at 0455 hr, 14 September. The vessel was under way for the next location by 0515 hr, 14 September.

TRANSIT TO SITE 956
(Proposed site VICAP-7)

The vessel covered the 49 nmi to the survey area at an average speed of 10.4 kt. After a 3-hr seismic survey, the vessel returned to the site coordinates. The hydrophones and thrusters were extended as *JOIDES Resolution* was offset to the GPS coordinates of the site. At 1331 hr, 14 September, a beacon was dropped on location. A backup beacon was dropped at 1401 hr, when the initial beacon's anchor line parted. The first beacon was retrieved.

SITE 956

Hole 956A

An APC/XCB BHA was made up, and Core 157-956A-1H established the mud-line depth at 3441.9 mbsl. Hole 956A was APC/XCB cored to XCB refusal at 161.6 mbsf. The APC cored 158.1 m (17 cores) and recovered 158.7 m (100.1% recovery). Cores were oriented starting with Core 157-956A-3H. Heat-flow measurements were conducted while Cores 157-956A-5H, -8H, and -11H were obtained. XCB coring was initiated at 158.1 mbsf, when the formation prevented even a partial stroke of the APC following Core 157-956A-17H. The XCB core barrel was pulled after penetrating 3.5 m in 20 min. The hard clay and lapillistone recovered in the single XCB core, combined with the slow rate of advance, indicated that the RCB should be used to obtain the deeper objectives of the site. The total recovery of the hole was 99.3%. There was a trace of methane (2-3 ppm) in the cores.

Hole 956B

At 1600 hr, 15 September, the bit was pulled out of the hole to change to the RCB system. The vessel was offset 20 m south, and an RCB BHA was made up. Hole 956B was spudded at 0705 hr, 16 September. After washing down to 157.1 mbsf, the wash barrel was retrieved and a new barrel dropped. RCB coring advanced relatively quickly from 157.1 to 590.0 mbsf (Cores 157-956B-1R to -45R), with 54.6% recovery. During this interval, the deplugger had to be dropped after Cores 157-956B-8R and -9R were retrieved with 0% recovery. Preventive mud flushes of 25 bbl of sepiolite were circulated at 512 and 552 mbsf.

After cutting Core 157-956B-45R, the hole began packing off with a loss of circulation and rotation due to the stalling of the top drive. After the driller bled off the pressure and backed off on the torque on the drill string with the top drive, rotation and circulation were immediately regained. The hole was swept with 50 bbl of sepiolite flush, and the core barrel containing Core 157-956B-45R was retrieved.

To ensure a viable hole for the deeper objective of the site, a wiper trip was initiated. Maximum overpull coming out of the hole was at 221 mbsf (20 kips). The drill string was run in to 313 mbsf, where a hard bridge was tagged. The hole was washed and reamed from 302 to 395 mbsf. The drill string was washed down from 395 to 571 mbsf and tagged 19 m of soft fill. The hole was washed and reamed from 571 to 590 mbsf and then swept with a 30-bbl treatment of sepiolite. After the wash barrel was retrieved, RCB coring resumed at 1600 hr, 19 September.

RCB coring continued until shortly after 2400 hr, 20 September, when the depth objective of 703.5 mbsf was reached. After every core, starting with Core 157-956B-48R, 20-bbl sepiolite flushes were pumped. Total recovery for the hole was 54.4% of the cored interval (546.4 m). The gas detected during this hole ranged from 2 to 4 ppm methane.

At 0030 hr, 21 September, the hole was prepared for logging. A wiper trip was begun, and a hard bridge was contacted at 597 mbsf. The hole was washed and reamed from 577 to 704 mbsf (TD), and flushed with 50 bbl of sepiolite. The bit was released at 703 mbsf. The hole was displaced with an 8.8-ppg concentration of sepiolite mud, and the drill pipe was pulled out to the logging depth of 300 mbsf.

Three tool strings, the quad combo, geochemical, and FMS, were successfully logged from the base of the hole to the end of pipe (300 mbsf).

The logging string and the pipe were pulled, the deck was secured, and the ship was under way to Las Palmas by 2012 hr, 22 September. The first line ashore in Las Palmas was at 0630 hr, 23 September, ending Leg 157.

OPERATIONS SUMMARY

Leg 157

Total Days (24 July 1994 - 23 September 1994)	60.6	
Total Days in Port		3.3
Total Days Underway		13.0
Total Days on Site		44.3

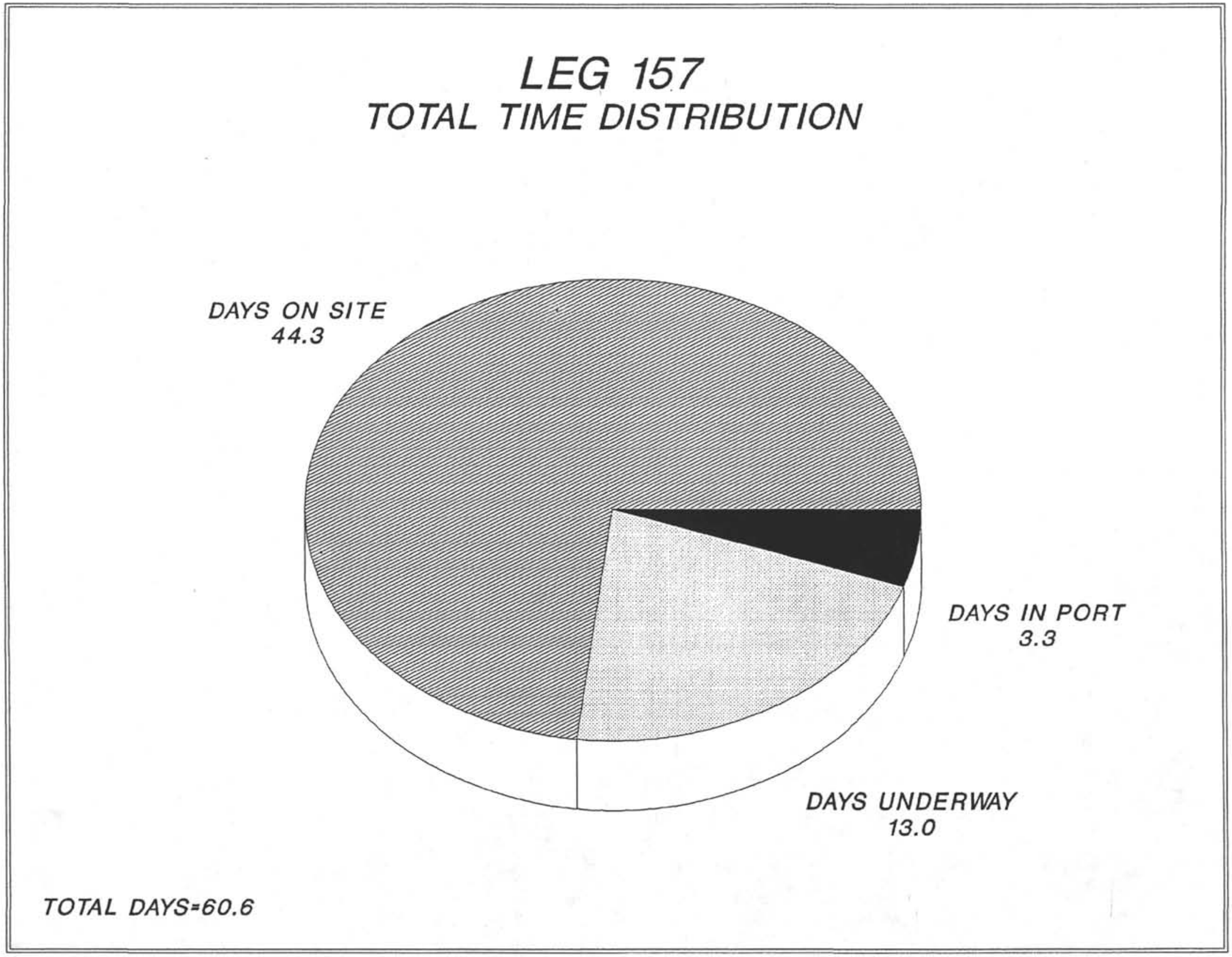
	Days
Stuck Pipe/Downhole Trouble	2.1
Tripping	7.7
Other	0.2
Drilling	1.2
Coring	27.1
Re-Entry	0.0
Logging/Downhole Science	5.8
Fishing and Remedial	0.0
Repair Time (ODP)	0.1
Development Engineering	0.0
Repair Time (Contractor)	0.1
W.O.W.	0.0
Casing and Cementing	0.0

Total Distance Traveled (nmi)	3102.0
Total Miles Transited	3009.0
Average Speed Transit (kt)	10.4
Total Miles Surveyed	93.0
Average Speed Survey (kt)	6.3
Number of Sites	7
Number of Holes	12
Total Interval Cored (m)	4091.3
Total Core Recovery (m)	3089.9
% Core Recovery	75.5
Total Interval Drilled (m)	867.4
Total Penetration (m)	4958.7
Maximum Penetration (m)	1158.7
Maximum Water Depth (m from drilling datum)	5448.6
Minimum Water Depth (m from drilling datum)	2865.4
Reentries	0

SITE SUMMARY

LEG 157

HOLE	LATITUDE	LONGITUDE	WATER DEPTH (mbrf)	WATER DEPTH (mbsl)	NUMBER OF CORES	INTERVAL CORED (meters)	CORE RECOVERED (meters)	PERCENT RECOVERED (%)	DRILLED (meters)	TOTAL PENETRATION (meters)	TIME ON HOLE (hours)	TIME ON SITE (days)
950A	31°09.011'N	25°36.004'W	5448.6	5437.8	41	381.3	339.14	88.9%	0.0	381.3	123.50	5.15
			Site 950 TOTAL:		**41**	**381.3**	**339.14**	**88.9%**	**0.0**	**381.3**	**123.5**	**5.15**
951B	32°1.896'N	24°52.232'W	5447.7	5436.8	28	256.6	251.52	98.0%	0.0	256.6	50.82	2.12
951B	32°1.895'N	24°52.236'W	5447.7	5436.8	10	96.6	84.62	87.6%	255.0	351.6	38.33	1.60
			Site 951 TOTAL:		**38**	**353.2**	**336.14**	**95.2%**	**255.0**	**608.2**	**89.2**	**3.71**
952A	30°47.449'N	24°30.574'W	5442.7	5431.8	45	425.9	415.18	97.5%	0.0	425.9	120.00	5.00
			Site 952 TOTAL:		**45**	**425.9**	**415.18**	**97.5%**	**0.0**	**425.9**	**120.0**	**5.00**
			MAP TOTAL:		**124**	**1160.4**	**1090.46**	**94.0%**	**255.0**	**1415.4**	**332.7**	**13.86**
953A	28°39.023'N	15°08.681'W	3588.9	3577.8	21	192.6	197.69	102.6%	0.0	192.6	27.17	1.13
953B	28°39.015'N	15°08.680'W	3588.9	3577.8	1	9.6	7.46	77.7%	188.1	197.7	17.50	0.73
953C	28°39.014'N	15°08.671'W	3588.9	3577.8	103	971.7	556.24	57.2%	187.0	1158.7	266.58	11.11
			Site 953 TOTAL:		**125**	**1173.9**	**761.39**	**64.9%**	**375.1**	**1549.0**	**311.3**	**12.97**
954A	28°26.197'N	15°31.928'W	3496.5	3485.2	12	83.8	80.50	96.1%	0.0	83.8	30.53	1.27
954B	28°26.191'N	15°31.921'W	3496.5	3485.2	39	365.8	165.56	45.3%	80.2	446.0	72.28	3.01
			Site 954 TOTAL:		**51**	**449.6**	**246.06**	**54.7%**	**80.2**	**529.8**	**102.8**	**4.28**
955A	27°19.546'N	15°13.847'W	2865.4	2854.2	63	599.4	534.08	89.1%	0.0	599.4	119.68	4.99
			Site 955 TOTAL:		**63**	**599.4**	**534.08**	**89.1%**	**0.0**	**599.4**	**119.7**	**4.99**
956A	27°36.905'N	16°09.779'W	3453.4	3441.9	18	161.6	160.48	99.3%	0.0	161.6	33.67	1.40
956B	27°36.895'N	16°09.797'W	3453.4	3441.9	57	546.4	297.40	54.4%	157.1	703.5	165.03	6.88
			Site 956 TOTAL:		**75**	**708.0**	**457.88**	**64.7%**	**157.1**	**865.1**	**198.7**	**8.28**
			VICAP TOTAL:		**314**	**2930.9**	**1999.41**	**68.2%**	**612.4**	**3543.3**	**732.4**	**30.52**
			LEG TOTAL:		**438**	**4091.3**	**3089.87**	**75.5%**	**867.4**	**4958.7**	**1065.1**	**44.38**


LEG 157
TOTAL TIME DISTRIBUTION
DAYS ON SITE
44.3
DAYS IN PORT
3.3
DAYS UNDERWAY
13.0
TOTAL DAYS=60.6

TECHNICAL REPORT

The following ODP Technical and Logistics personnel were aboard *JOIDES Resolution* for Leg 157 of the Ocean Drilling Program:

Laboratory Officer, Marine Laboratory Specialist/Physical Properties:	Bill Mills
Assistant Laboratory Officer, Marine Laboratory Specialist/X-ray, Fantail:	"Kuro" Kuroki
Marine Laboratory Specialist/Curatorial Representative:	Erinn McCarty
Marine Computer Specialist/System Manager:	Cesar Flores
Marine Computer Specialist/System Manager:	Matt Mefferd
Marine Laboratory Specialist/Yeoperson:	Jo Ribbens
Marine Laboratory Specialist/Chemistry:	Anne Pimmel
Marine Laboratory Specialist/Chemistry:	Robert Kemp
Marine Laboratory Specialist/Core Laboratory:	Suzanne Floyd
Marine Laboratory Specialist/Core Laboratory:	Uta Rodehorst
Marine Laboratory Specialist/Paleomagnetics:	Margaret Hastedt
Marine Laboratory Specialist/Photography, Microscopes:	Randy Ball
Marine Laboratory Specialist/Storekeeper, Thin Sections, Downhole Measurements:	Tim Bronk
Marine Laboratory Specialist/Downhole Measurements, Paleontology, X-ray:	Jaque Ledbetter
Marine Laboratory Specialist/Underway:	Monty Lawyer
Marine Electronics Specialist:	Bill Stevens
Marine Electronics Specialist:	Mark Watson

INTRODUCTION

JOIDES Resolution departed Bridgetown, Barbados, on 27 July 1994 with a crew of 107 (46 scientists and technicians). Leg 157 ended in Las Palmas, Canary Islands, on 23 September 1994 for a total of 59 days at sea. At our last site, two engineers from Parvus (DCS subcontractors) joined the ship to study our drilling operations.

PORT CALL ACTIVITIES

On 24 July, *JOIDES Resolution* docked in Bridgetown, Barbados, ending Leg 156. On the same morning, the Leg 157 crew arrived and began cross-over.

In addition to our normal freight-handling activities, all technicians, from both legs, attended a radiation safety course conducted by Keith Carsten (TAMU Radiation Safety Office). Cores from Leg 156 were kept on board and were to have been shipped to Bremen from Las Palmas.

On the evening of 27 July, we departed Barbados to begin the Leg 157 operations but immediately had electrical problems with the propulsion motors. Two motors flashed over, and a third had a short. This left us with three motors on the starboard shaft and six on the port shaft. One of the motors was soon repaired and back on line. The combination of strong headwinds and diminished propulsion kept our cruising speed below 10 kt. The lower speed delayed our arrival at the first MAP site until 5 August.

UNDERWAY ACTIVITIES

Technicians routinely collected bathymetric, magnetic, and navigational data on all transits. Brief seismic surveys were conducted at most sites with just one 80-in.^{3} water gun. The new seismic data-acquisition system worked very well.

LABORATORY ACTIVITIES

The Core Laboratory activities were routine, except for a special high-resolution pore-water study at several sites. At the VICAP sites, the Chemistry, Thin Section, and X-ray laboratories work load was very heavy. In addition to our normal operations, Marine Specialists were trained in the Underway Geophysics, X-ray, Chemistry, and Downhole Measurement laboratories. Two additional student technicians were staffed to fill vacant Marine Specialist slots. Their help in the labs was greatly appreciated.

Upgrades to Equipment

Both the MST and VSR systems in the Physical Properties Laboratory were upgraded during the leg. Technicians replaced the MST chain and gears, with a 3/8-in., kevlar-reenforced timing belt and sprockets, and fitted the MST's P-wave transducers with pneumatic actuators. The actuators are used to keep the P-wave transducers retracted until the core's top-end cap has passed. Controlling the actuators are sensors that determine the core's position and direction of travel. These same sensors are also used to control the drip-wetting system, eliminating the need for someone to stand and spray the core with water. These improvements, along with other modifications since Leg 154, have eliminated all track errors on the MST and improved the quality of the P-wave data.

The VSR upgrades involved both new software and hardware. The new software, which was developed on this leg, integrates the velocity, strength, and resistivity data acquisition with the VSR track functions. The hardware upgrades involved replacing the Digital Sonic Velocity and Vane Shear jack-screw stands with pneumatic linear slides. The new stands provide for easier handling and consistent insertion depth of instrument probes.

The paleontological database FossiList was introduced on this leg for beta testing, and the initial response from the science party was positive. The software will undergo further development before its final release.

Three new HP 4M-plus laser printers were installed as well as five Quadra 840AV's.

Special Projects

In anticipation of dry-dock work over the gymnasium, the lockers were relocated. The initial removal of a few floor tiles to accommodate locker relocation soon evolved into a major cleaning project. The floor tiles were taken to the catwalk and cleaned. They are now stored on the upper 'tween deck and will be reinstalled after dry dock. Also, gymnasium equipment, and the floor underneath the tiles, were scrubbed and cleaned.

Other projects included (1) a complete overhaul of the core splitter, (2) extension of the Batcave decking, (3) reorganization of the computer machine room, and (4) cleaning of the carpet floor tiles in the Computer User Room.

LEG 157 SAMPLING AND ANALYSIS TOTALS
(estimates only)

SAMPLES	
Total number:	16,600
PHYSICAL PROPERTIES LABORATORY	
MST (including Susceptibility, GRAPE, P-wave, and Natural Gamma) (m scanned):	3,353
Index properties:	4,800
Velocity:	2,100
Strength:	500
Thermal conductivity:	257
DOWNHOLE TOOLS LABORATORY	
In situ temperature:	8
THIN SECTION LABORATORY	
Thin sections:	90
CHEMISTRY	
Carbon-carbonate:	1,480
CNS:	700
Interstitial water analysis:	190
Headspace (GC):	360
Rock Eval:	60
X-RAY LABORATORY	
XRD:	200
XRF:	77
PALEOMAGNETICS LABORATORY	
Discrete:	60
Cryomagnetometer (m scanned):	2,700
UNDERWAY GEOPHYSICS	
Magnetics and bathymetrics (nmi):	3,100
Seismics (nmi):	36