6. SITE 451: EAST EDGE OF THE WEST MARIANA RIDGE

### HOLE 451

**Date occupied:** 7 March 1978  
**Date departed:** 13 March 1978  
**Time on hole (hrs):** 152.5  
**Position:** 18°00.88'N; 143°16.57'E  
**Water depth (sea level; corrected m, echo-sounding):** 2060  
**Water depth (rig floor; corrected m, echo-sounding):** 2070  
**Penetration (m):** 930.5  
**Number of cores:** 102  
**Total length of cored section (m):** 930.5  
**Total core recovered (m):** 280.1  
**Core recovery (%):** 30  
**Oldest sediment cored:**  
- Depth sub-bottom (m): 930.5  
- Nature: Tuffs and volcaniclastic breccias and conglomerates  
- Age: Upper Miocene (NN 10)  
- Measured velocity (km/s): 2.7  
**Basement:** Questionable whether or not arc basement reached

### Principal results:

Site 451, located on the eastern edge of the West Mariana Ridge and drilled to a depth of 930.5 meters, yielded a sequence of biogenic oozes and volcaniclastic sediments. These sediments are divided into the following units: Unit 1, 36 meters of lower Pliocene to Quaternary, grayish brown foraminiferal ooze, grading downward through interbedded grayish brown foraminiferal-nannofossil and yellow and light yellow nannofossil-foraminiferal oozes to a basal light gray nannofossil ooze, with minor ash and pumice increasing in content downward; Unit 2, 29.5 meters of upper Miocene, olive and gray carbonate-rich vitric ash and minor layers of olivine-gray and very dark gray vitric tuff with intervening layers of yellowish brown foraminiferal-nannofossil chalk; Unit 3, 865.0 meters of upper Miocene volcaniclastic sediments broadly divisible into seven sub-units consisting of interbedded, varicolored green, greenish black, dark gray, dark bluish gray to black, fine vitric tuffs, vitric and vitric-lithic tuffs, breccias, and conglomerates. Many of these lithologies are tuffaceous, some bearing nannofossils and some shallow-water shell fragments, including larger foraminifers and corals, all of the upper Miocene. Basaltic clasts in the breccias are highly vesicular and, along with the pyroclastic debris in the sediment, require explosive volcanism of the type associated with island arcs. Andesite cobbles and boulders that contain plagioclase, olivine, two pyroxenes, and opaque mineral phenocrysts are probably of calc-alkaline affinities. Accumulation rates of the lower part of this volcaniclastic sequence were about 400 m/kyr. Either a basaltic boulder or the brecciated upper surface of a lava flow was encountered in the last core.

### Site Setting

**Shipboard Scientific Party**

The age and petrology of the sedimentary and volcanic rocks of the West Mariana Ridge were not well known. Therefore the principal objective of Site 451 was to obtain this knowledge by drilling through the sedimentary veneer into the arc basement; the overall objective was to gain an understanding of the role of remnant arcs in back-arc marginal basin evolution.

The West Mariana Ridge separates the 5-km-deep Parece Vela Basin, an extinct back-arc basin to the west, from the 4-km-deep Mariana Trough, an actively spreading back-arc basin to the east (Fig. 1). The north-south trending ridge itself is generally less than 2 km deep and locally is within only 55 meters of the surface; it is interpreted to be a remnant arc left behind when the active volcanic Mariana arc broke away during back-arc spreading of the Mariana Trough (Karig, 1975). Karig and Glassley (1970) mention the presence of vesicular dacitic lavas and upper Pliocene sandstones and ashes dredged from the West Mariana Ridge at 3- to 4-km depths. They cite the high vesicularity to suggest that a shallow eruption of dacite took place and that the present depth of the dredge site required Quaternary subidence of parts of the West Mariana Ridge. Although the seismic-refraction profiles in the Philippine Sea did not include the West Mariana Ridge proper, a profile through the southern end of the Honshu Ridge, which begins north of the junction of the West Mariana and Mariana Ridges, showed a 3-km-thick section of a 3.3-km/s layer overlying the 4.6- to 5.5-km/s basement. Site surveys indicated that 700 meters of sediment overlies a 3.9-km/s basement layer at Site 451. The location of Site 451 on the eastern edge of the West Mariana Ridge contrasts with the location of Site 448 on the western edge of the Palau-Kyushu Ridge. The extremely deep sediment wedge on the western edge of the West Mariana Ridge and the dearth of sediments in the central part of the ridge make these parts of the ridge undesirable drilling targets.

Preliminary site surveys indicated that the West Mariana Ridge is bounded by a steep scarp facing the...
Mariana Trough (Figs. 2 and 3). The locations of the survey track lines are shown in Figure 4. Numerous volcanic peaks surmount the ridge within the vicinity of the survey. The eastern edge of the ridge also seems to be broken into a series of steps or ledges, some of which have sediment ponds (for example, see the central part of Profile V), perhaps an excellent place to attempt to reach basement. Sonobuoy results (Fig. 5) suggested that about 1 km of sediment (2.0 km/s) overlies a higher-velocity layer (4.2 km/s) that may be volcanic-arc basement. (This is identical to the velocity of Site 448 arc-volcanic rocks.) The 5- to 6-km/s layer found 1.3 to 1.5 km below the 4.2-km/s layer may also represent oceanic basement. Semblance calculations made on the multichannel seismic data, also acquired during the site surveys in the vicinity of Site 451, indicate that approximately 700 meters of sediments overlie a 3.9-km/s basement layer. Murauchi et al. (1968) point out that at
a considerable distance to the north of Site 451 the ridge is built up mainly of material with a 3.5-km/s velocity, based on the one refraction line across the Honshu Ridge. Dredging (locality shown in Figs. 3 and 4) recovered only weathered mafic rocks and sediments from a massive basement-type block that appears to dip gently to the west.

The broad objective of Site 451 was to compare the drilling results of Site 451 with drilling planned for Leg 60 on the active volcanic Mariana arc in order to determine whether the West Mariana Ridge actually is a remnant arc left behind the Mariana Ridge during back-arc spreading to form the Mariana Trough and to ascertain what the detailed evolution of this process includes. For example, the episodic nature of volcanism within the entire Palau-Kyushu-West Mariana-Mariana remnant arc province was to be investigated, with particular attention to variability of magmas and magma sources in space and time. Timing of volcanic and structural events within the West Mariana Ridge was to be related to sedimentary and structural events in the Parece Vela Basin. Of particular interest was the structural and volcanic control of sedimentation on the West Mariana Ridge. The nature of metallogenesis in immature arc-volcaniclastic sediments and the roles of diagenesis and incipient hydrothermal mechanisms in metallogenesis were especially important in conceptualizing ore formation in island arcs.

The specific objective was to drill through 0.7 to 1 km of sediments on the eastern side of the West Mariana Ridge and to penetrate the 3.9- to 4.2-km/s basement.

**OPERATIONS**

The final drilling location of Site 451 is situated about 240 km due east of Site 450. At 1130 Local Time (L), 7 March, approximately 17.5 hours after leaving Site 450, a brief seismic-profile survey was begun; at 1326 L the positioning beacon was dropped and normal site operations were begun (Fig. 6).

An attempt to retrieve a mudline punch core was made when the core bit had been lowered to 2081.5 meters. Although the depth was 11.5 meters below the precision depth recorder (PDR) depth, no weight indication of contact with the seafloor was felt. No sediment was recovered. The procedure was repeated with an additional joint of pipe to 2091 meters; on this attempt 4.2 meters of sediment were recovered and the water depth was set at 2086 meters from the rig floor.

The record of drilling operations is summarized in Table 1. At 38 meters sub-bottom, firm volcaniclastic material was encountered, and there was concern for the bottom-hole assembly (BHA) because the lower bumper
subs were just reaching the seafloor. After a few meters were carefully drilled, somewhat softer material was encountered and the BHA was buried without incident.

Low core recovery from about 55 to 475 meters sub-bottom was attributed to semi-indurated tuff and ash beds; recovery improved as compaction and induration increased with depth.

Minor hole problems occurred at 537 meters and at 641 meters sub-bottom, created by the influx of excessive accumulations of cuttings in the hole. The hole had been kept clean by regular mud flushes in the course of drilling; it was concluded that “avalanches” of cuttings from the seafloor around the hole or from washouts in the upper part of the hole caused these problems. The lower influx (641 m) occurred during attempts to clear a plugged bit. The altered volcaniclastic material encountered showed a tendency to accumulate in a waxy clay-like mass in the core catcher; this caused repeated jamming, which adversely affected core recovery. A similar buildup apparently occurred in the throat and jets of the core bit. The bit deplugger was run and the throat was opened, indicated by mud pump pressure. The next core barrel failed to seat, however, and even more severe plugging resulted from a 3-meter core attempt. Several more wire-line runs were required to clear the bit completely, and a total delay of 7.5 hours resulted.

Normal operations continued until the final operating day of the leg. At a depth of 926.5 meters sub-bottom, core barrel 101 stuck at the bit, and three wire-line runs (two sheared release pins) were required to retrieve it. A small lump of altered basalt was found imbedded in the clay-like material jamming the core catcher.

The penetration rate was much lower on the subsequent core, and it was decided to retrieve the core after 4 meters were cut to maximize basalt recovery. During the cutting of the core, however, the mud pump pressure increased markedly, indicating that the bit was plugging. Core recovery was only 40 cm, some of which was altered basalt. The amount was insufficient to determine whether the basalt was a large clast or part of a flow.

A last-minute attempt was made to clear the bit and cut one additional core. Pump pressure indicated the bit to be almost completely plugged, and the deplugger did not open the throat when it landed at the bit. The overshot was lowered and engaged the deplugger barrel. Sev-

Figure 4. Survey tracks in the vicinity of Site 451 on the West Mariana Ridge (L-DGO Site Survey data). (The heavily drawn east-west lines with Roman numerals correspond to profiles shown in Fig. 2.)
Site 451

Sonobuoys

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Figure 5. Results of the two sonobuoys shot on the West Mariana Ridge (L-DGO Site Survey data). (Significant topographic slopes along the line of these profiles reduce their accuracy.)

Several attempts were made to break through the obstruction by jarring the wire-line jars, but the deplugger became stuck without reducing the pumping pressure. Attempts to dislodge the deplugger resulted in a sheared release pin.

Operating time had run out and prospects for recovering any additional core were low. The drill string was retrieved, concluding drilling operations for Leg 59. On retrieval, the throat of the bit was found to be solidly packed with pulverized clay and rock for its entire length. The apices of all four cones of the bit had been broken off, leaving only the second row of inserts of two of the cones to trim the diameter of the core.

After the drilling equipment had been secured for sea, the vessel got underway for profile surveying at 1940 L, 13 March. On departure to the west to stream gear, the site was crossed on an easterly profile. The profile was continued 35 km to the east, and then a southerly course was set for Apra, Guam.

SEDIMENTARY LITHOLOGY

At Site 451, 930.5 meters of sediments and volcanioclastic rock were drilled and continuously cored. Basalt fragments recovered from the bottom of the hole may represent the upper surface of a lava flow, but otherwise no flows or igneous intrusions were encountered. Recovery was poor in the interval of poorly consolidated sediments from Cores 11 through 23 and 48 through 51.

The upper Miocene to Quaternary sedimentary section consists of two lithologies that contrast sharply in appearance and genesis, separated by a transition zone of intercalated beds of both lithologies with layers that are intermediate in composition. Thus, the sedimentary column is conveniently separable into three lithologic units (Fig. 7).

At the top, Unit 1 (36.0 m thick) consists of lower Pliocene to Quaternary soft biogenous carbonate oozes. The uppermost two meters of Unit 1 are a grayish brown foraminiferal ooze that grades downward into delicately hued alternations of grayish brown foraminiferal-nannofossil ooze and light yellow-brown and yellow nannofossil-foraminiferal ooze (Core 2). The nannofossil-ooze layers become thicker down-core at the expense of the foraminiferal-nannofossil oozes; Cores 3 and 4 and the upper part of Core 5 are exclusively nannofossil-foraminiferal oozes, and the basal 20 cm of Unit 1 are a light gray nannofossil ooze. A single 20-cm thick, very dark gray bed of ash occurs in Core 3, 20 meters above the base of the unit. Pumice and glass fragments, locally brown or black and covered by manganiferous films, are present in Core 1. Glass (trace to 3%), crystal fragments (trace to 2%),
Figure 7. Lithology, age, core recovery, and drilling rate at Site 451. (The drilling rate is included here to show its correlation with lithology and lithologic boundaries. Core recovery is indicated by the solid symbol in the second left column. Lithologic symbols are summarized in the Introduction to this volume. Component percentages derived from smear slides and core descriptions are indicated in the eight columns on the right of the figure.)
Figure 7. (Continued).
Table 1. Coring summary for Hole 451.

<table>
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<tr>
<th>Core No.</th>
<th>Date (March, 1978)</th>
<th>Local Drill Depth (m, top-bottom)</th>
<th>Depth from Drill Floor (m, top-bottom)</th>
<th>Length Recorded (m)</th>
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Table 1. (Continued).

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andfeldspar and heavy minerals (trace to 1%) are very minor constituents.

Unit 2, 29.5 meters thick, consists of upper Miocene, carbonate-rich fine vitric tuff, fine vitric tuff, and

eutrosossil-foraminiferal ooze interbeds. The uppermost interbeds (80 cm thick) are two olive-gray and dark olive-gray ash beds (25 and 40 cm thick), intercalated with a nannofossil-foraminiferal ooze (15 cm thick). Below this intercalated zone are 8.7 meters of light olive-gray carbonate-rich ash layers (each <10 cm thick) interbedded with lithified dark olive-gray vitric tuff layers. In Core 6 the carbonate-rich ash layers increase in thickness to 70 cm, and the tuff layers increase in thickness to 35 cm. This general lithology continues downward to a sub-bottom depth of 65.5 meters, the base of Unit 2.

The contact between Units 2 and 3 was not recovered but can be reasonably placed just below the lowermost beds of Unit 2, where core recovery dropped markedly as a consequence of the poorly consolidated vitric tuffs dominating the Unit 3 beds. Unit 3, 865.0 meters thick, extends from 65.5 meters to 930.5 meters sub-bottom and consists of upper Miocene fine vitric tuffs, vitric tuffs, and volcanioclastic conglomerates and breccias. Figure 7 shows the stratigraphic distribution of these rock types and the seven recognizable sub-units. This thickness may represent more than the complete Unit 3 section at Site 451, inasmuch as it is believed that the poorly recovered bottom 4 meters of the hole, where drilling rate slowed sharply, were drilled in igneous rock.

Only about 6% of the 215.0 meters of Sub-unit 3a were recovered in the coring. The predominant rock type is a black to dark gray vitric tuff, with lesser dark gray, very dark gray, and black fine vitric tuffs. The sediments are composed of about 25% glass and 45% clay alteration products. Calcareous material makes up most of the remainder, notably as burrow fillings in the fine tuffs and as shallow-water foraminifers (see the biostratigraphy section of this site report) and coral fragments in the coarser tuffs. Foraminifers commonly occur concentrated in laminae.

Approximately two-thirds of the 133.0-meter-thick Sub-unit 3b is composed of the same vitric tuff as is Sub-unit 3a, but in 3b there are interbeds with conglomerate and breccia layers 10 to 340 cm thick. Typical clast sizes are 0.5 mm in diameter, although rare clasts up to 3 cm occur. The clast:matrix ratio varies between 2:1 and 4:1; aphanitic and vesicular basalt account for more
than half (rarely up to 90%) of the clasts, which are angular to subrounded. The matrix consists of fine glass and its alteration products. The sub-unit features laminated intervals of fine sand-sized clasts, graded bedding, load casts, and rare penecontemporaneous normal faulting of small displacement (5 mm) and disharmonic, recumbent folding (Fig. 8). Bioturbation of the finer beds occurs and is intense in one 40-cm-thick layer at the top of the sub-unit. Shallow-water foraminifers, coral fragments, and lignite fragments are present in the coarser layers.

Sub-unit 3c, 11.7 meters thick, features a boulder volcaniclastic conglomerate 4.6 meters thick at its top; the boulders are 20 to 30 cm in size within the core and are composed of plagioclase-olivine-phyric basalt and vesicular plagioclase-phyric basalt. This bed progressively becomes finer down-core, becoming a vitric tuff with intercalations of gray carbonate-rich tuff about 10 cm thick. Two other coarse beds, 40 and 70 cm thick, occur near the base of the sub-unit. Approximately half of the recovery from Sub-unit 3c is breccia and conglomerate.

Sub-unit 3d, 49.3 meters thick, is an interval much like Sub-unit 3a, in which poorly recovered vitric tuff predominates. Biogenic carbonate is present in small amounts as pelagic and benthic foraminifers and nannofossils. Some of the beds are black and structureless; others are dark gray and show lamination and cross-bedding.

Sub-unit 3e, 167.4 meters thick, is an intercalated sequence of vitric tuffs, volcaniclastic breccias, and conglomerates much like those of Sub-unit 3b. Again, coarse beds comprise about one-third of the recovered material. The rock is more indurated and the glassy material more altered to clay. Subangular to subrounded clasts of altered basalts and andesites 3 to 4 mm in diameter occur as minor constituents. Clasts and matrix both contain very small amounts of disseminated pyrite. The clast:matrix ratio is about 4:1. Silicified foraminifers were observed in two of the cores; lignite lenses also are present.

Sub-unit 3f, 61.7 meters thick, is another interval dominated by black vitric tuffs and lesser fine vitric tuffs and characterized by poor core recovery. Andesite clasts occur in the coarser sediments of every core in the sub-unit.

Sub-unit 3g, either 222.9 or perhaps more than 226.9 meters thick, consists primarily of greenish black, dark greenish gray, and grayish olive-green coarse volcaniclastic breccias and conglomerates, in part tuffaceous, in layers 20 cm to 5 meters thick. Interbedded with them, in intervals typically about 1 meter thick, are greenish black, grayish black, dark bluish black, and dark gray vitric tuffs.

The depositional history of Site 451 on the West Mariana Ridge is one of rapid accumulation of great thickness of epiclastic volcanic sediments derived from relatively shallow water during the late Miocene. Many of the coarser clasts in Unit-3 sediments display rounding attributable to reworking in near-surface environments of high wave energy, and it is possible that some of these clasts may even have been rounded in a subaerial setting. Reworked shallow-water carbonate tests were also deposited with the Unit-3 sediments, although carbonate contents are strongly masked and diluted by the volcaniclastic components. Because lignite occurs as lenses and fragments isolated at one stratigraphic horizon, and because lignite does not form in marine environments, the lignite within tuffs was not formed in situ but was most probably derived by erosion of nearby volcanic islands.

In the latest Miocene, the supply of volcaniclastic material was reduced enough so that carbonates comprise a significant fraction of the Unit-2 sediments. By the Pliocene, volcanism had ceased altogether, and only carbonate oozes with insignificant ash admixtures were deposited until the present. At no time in the entire period of time recorded by the cored sequence does Site 451 appear to have been below the carbonate compensation depth (CCD).

**BIOSTRATIGRAPHY**

At Site 451, at least 926.5, if not 930.5 meters of sediment were cored. Foraminifer-nannofossil ooze is present in the first five cores, changing to carbonate-
rich vitric ash and vitric tuffs downward. Volcaniclastic rocks occur with increasing frequency down-hole and dominate in the lower part of the hole.

In Cores 1 to 3 (0.0–24.0 m), foraminifers, calcareous nannofossils, and radiolarians are present, indicating an age of late Pliocene to late Quaternary. Diatoms occur only in the lower part of Core 1 and in Core 2 and are associated with rare silicoflagellates. Below Core 3 only calcareous nannoplankton and foraminifers remain, and these are common down to Core 14 (24.0–128.5 m), indicating an age of late Miocene to early Pliocene for this interval. Cores 15 to 19 (128.5–176.0 m) are essentially barren or had no recovery. From Core 20 downward, fossil occurrences are restricted to interbedded biogenic horizons in which poorly preserved upper Miocene nannofossils and the planktonic foraminifer *Orbulina* spp. (middle Miocene or younger) are present. Larger foraminifers are occasionally present from Core 31 downward. Coral fragments were also found (e.g., Core 91). The lowest nannofossil occurrence was noted in Core 85 (765.0–774.5 m), which is situated in the basal part of Zone NN 10 (*Discoaster calcaris* Zone, upper Miocene).

### Calcareous Nannoplankton

In Cores 1 to 3 (0.0–24.0 m), Quaternary to upper-Pliocene calcareous nannoplankton assemblages are present, represented by calcareous nannoplankton Zones NN 21 (*Emiliania huxleyi* Zone) down to NN 16 (*Discoaster surculus* Zone) in successive order, with the exception of Sample 2,CC. Here an NN 21 assemblage was found that obviously represents material caved-in from above. Core 4 and the upper part of Core 5 (24.0–36.5 m) contain the lower Pliocene calcareous nannoplankton Zones NN 12 (*Ceratolithus tricorniculatus* Zone) to NN 15 (*Reticulofenestra pseudoumbilica* Zone), with rather common occurrences of ceratoliths.

The NN 11 assemblage is found in the lower part of Core 5 probably to Core 20 (36.5–185.5 m), although the lower part of this succession is obscured by nonrecovery and barren intervals. In Core 22 and downward to Core 64, several layers contain poorly preserved nannoplankton assemblages, which may belong to Zone NN 10 (*D. calcaris* Zone), because neither *D. quinque-ramus* (first occurrence [FO] = base of Zone NN 11) nor *D. hamatus* (last occurrence [LO] = top of Zone NN 9) were found in the volcaniclastic sediment. In Cores 78 and 80 the basal part of Zone NN 10 was reached, in which *Catinaster calyculus* (long-rayed specimens) is present. Some levels contain only solution-resistant forms inadequate for precise age determination. The preservation of calcareous nannofossils in Cores 3 to 14 is fair; and preservation in the two uppermost cores is good.

### Foraminifers

Moderately well-preserved planktonic foraminifers are common to abundant in core-catcher samples from Cores 1 to 14, with benthic foraminifers common in the upper cores but rare below Core 5. Below Core 14 all foraminifers occur sporadically because the more abundant volcaniclastic sediments often dilute their presence; preservation is generally poor with increased induration of the sediments.

Mixing of foraminiferal faunas of different age in some of the samples from this site is evident (e.g., Sample 1,CC contains a mixture of foraminifers from Zones N.21 to N.23); this makes it difficult to determine the precise age of these samples.

The following upper Miocene to Quaternary planktonic foraminifer zones were recognized: probably N.23 in the upper portion of Core 1; probably N.22 from Sample 1,CC through Core 2, Section 1; N.21 from Core 2, Section 3 to Core 3, Section 5; N.19 from Core 3, Section 7 to Core 5, Section 1; N.17 from Core 6, Section 1 through Core 8, Section 6 (and Core 10, Section 1[ ]).

Rare occurrences of *Candeina* as low as Core 25, Section 1 indicate the presence of Zones N.16/N.17 at least as far down as this. *Orbulina* spp. (middle Miocene or higher) occurs sporadically throughout the lower portion of the sedimentary section.

Reworked larger foraminifers occur sporadically from Core 31 downward. (The following information on these larger foraminifers and associated shallow-water fossils is a personal communication submitted by Dr. J. P. Beckmann, December, 1978.)

Samples from Cores 31, 40, 42, 46, 47, 50, 69, 71, and 72 were available for investigation. Fossil remains that are generally regarded as shallow-water indicators were found in all of these cores except Core 69. The best faunas were recovered from Cores 40, 71 and 72, but even in these cores only *Amphistegina* spp. and *Ammonia* cf. *inaebrutis* (Thalmann) are fairly common. The remaining taxa are represented in individual samples by only a few specimens (or fragments of specimens). Preservation is usually moderate to poor. Many specimens show signs of breakage or wear, and the material is commonly chalky or recrystallized into clear calcite. A thorough taxonomic study has not been attempted, and an open nomenclature is commonly used in the sample list that follows.

The most significant genera of larger foraminifers at Site 451 are *Lepidocyclina*, *Miogypsinoides*, *Miogypsina*, and *Cycloclypeus*. The group *Operculina*-*Operculinella*-*Operculinoides* is also present in most samples, but because of its limited stratigraphic use has not been studied in detail. *Lepidocyclina* is represented in the upper part of the studied interval (mostly Core 40) by *L. cf. rutteni* van der Vlerk, whereas in the lower cores (71 and 72) the species have broader equatorial chambers and resemble *L. japonica* (Yabe). A few fragments probably belonging to *L. ferreroi* Provale were found in Core 71. *Miogypsinoides* also occurs very rarely in Core 71. Two specimens of *Miogypsina* from the top sample (0–9 cm) of Core 71 seem to be close to *M. complanata* (Schlumberger) and are most probably reworked. The genus *Cycloclypeus* is taxonomically in a confused state, which limits its value for biostratigraphy. In this report, a group named *C. cf. eldae/posteidae* (mostly with 7–15 nepionic chambers) is distinguished from a few larger specimens with five or less nepionic chambers, here referred to as *C. cf. carpenteri/guembelianus*, following mainly the work of MacGillavry (1962).

The presence of presumably reworked specimens limits the value of the larger foraminiferal faunas for age determination. According to the recent stratigraphic compilations of Adams (1970), Haak and Postuma (1975), and Coleman (1978), the association of Cores 71 and 72 (with *Lepidocyclina* cf. *japonica*, *L. cf. ferreroi*, and *Miogypsina* sp.) would suggest the middle Miocene (early Tertiary). The younger samples (particularly Core 40) with *L. cf. rutteni* might be slightly younger (early part of the late Miocene, late Tertiary). The original life habitat of the fauna, following the models of Henson (1950) and...
Chaproniere (1975), was probably a fairly shallow shelf (i.e., a forereef shoal). The associated megafossil remains (pelecypod fragments, echinoid spines, some bryozoans) give some further support to this assumption. The rare coral fragments may indicate the vicinity of a reef. The smaller benthic foraminifers (Lenticulina, Buliminia, Asterigerina, and others) in some samples suggest that faunal components of a slightly deeper-water origin may also be present.

The following is a list of larger foraminifers and associated microfossils found in samples from Hole 451. (All listed fossils are rare [one or few specimens], except where otherwise noted. The sections and intervals within each core are indicated.)

**Core 31**
- 1, 24-26 cm: Ammonia sp.
- 1, 38-40 cm: Operculinoides sp.
- 1, 50-56 cm: No distinct shallow-water fossils
- 1, 88-90 cm: Operculinoides sp.

**Core 40**
- 2, 9-12 cm: Ammonia sp., Cyclolypeus sp., Lepidocyclina sp., Operculinoides sp.
- 2, 37-41 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus cf. eidae/posteidae, Lepidocyclina sp., Operculinoides sp.
- 2, 66-70 cm: Ammonia cf. indopacifica, Amphistegina spp. (fairly common), Cyclolypeus cf. eidae/posteidae, Lepidocyclina sp., Operculinoides sp.
- 2, 95-97 cm: Ammonia sp., Amphistegina sp., Cyclolypeus sp.
- 2, 97-99 cm: Ammonia sp., Amphistegina sp., Cyclolypeus cf. eidae/posteidae, Lepidocyclina sp.

**Core 41**
- 2, 115-120 cm: Ammonia sp., Amphistegina sp., Cyclolypeus sp., (Lepidocyclina sp., Operculinoides sp.

**Core 46**
- 3, 3-6 cm: Ammonia sp., Amphistegina sp.
- 3, 10-12 cm: Operculinoides sp.
- 3, 22-24 cm: Amphistegina sp., Operculinoides sp.

**Core 47**
- 1, 86-88 cm: Amphistegina sp., Ammonia sp., Operculinoides sp., (Planorbilina sp.
- 1, 136-138 cm: Ammonia sp., Amphistegina sp., (Buliminia, Asterigerina)

**Core 50**
- Sample 50,CC: Ammonia sp., Amphistegina sp.

**Core 69**
- 1, 34-39 cm: No distinct shallow-water fossils
- 2, 118-120 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (common), Cyclolypeus cf. carpenteri/guembelianus, Lepidocyclina sp., Lepidocyclina cf. japonica, Miogypsinoides cf. complanata, Operculina cf. complanata, Operculina sp., Sphaerogypsina sp., Operculinoides sp.

**Core 71**
- 1, 0-9 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus sp., Lepidocyclina sp.
- 1, 143-150 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus sp., Lepidocyclina sp.
- 3, 113-120 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus sp., Heterostegina sp., Lepidocyclina cf. japonica, Miogypsinoides sp., Operculinoides sp., Planorbilina sp.
- 4, 122-132 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus sp., Lepidocyclina cf. japonica, Miogypsinoides sp., Operculinoides sp.

5, 8-12 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus sp., Heterostegina sp., Lepidocyclina cf. japonica, Operculinoides sp., Planorbilina sp.

5, 93-98 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus cf. eidae/posteidae, Lepidocyclina cf. japonica, Operculina cf. complanata, Operculinoides sp., Sphaerogypsina sp. (Lenticulina)

Echinoid spines, bryozoans, coral fragments.

6, 140-145 cm: Ammonia cf. indopacifica (fairly common), Amphistegina spp. (fairly common), Cyclolypeus spp., Lepidocyclina cf. Scatteri, L. cf. japonica, Miogypsinoides sp., Operculinoides sp., Sphaerogypsina sp. (Lenticulina)

Echinoid spines.

Radiolarians

The core-catcher samples of Cores 1 through 3 contain radiolarians in sufficient numbers to study; in Cores 451-4 and -10, and Sample 14,CC, traces of this group were found, whereas all other cores appear to lack radiolarians.

The assemblage in Sample 451-1,CC, although belonging to the uppermost Pleistocene Buccinospheera invaginata Zone (Nigrini, 1971), is mixed with elements of Pliocene to early Pleistocene and, in addition, contains a few Miocene ostracodans. In Samples 2,CC and 3,CC the few species that are present do not allow a zonation; they do, however, indicate an age range from the late Pliocene to the early Pleistocene for the sediments.

Diatoms and Silicoflagellates

Diatoms occur only in the lower part of Core 1, in Core 2, and in the upper of Core 4. They are associated with rare silicoflagellates, sponge spicules, and endoskeletal dinoflagellates and were probably deposited during the late Pleistocene.
PALEOENVIRONMENT

In general, at Site 451, Cores 1 to 14 (except Cores 11-13, which had no recovery) contain common to abundant, moderately well-preserved calcareous nannofossils and planktonic and benthic foraminifers, suggesting deposition above the CCD. Cores 15 to 19 are either essentially barren, or there was no recovery. Below this level, planktonic foraminifers and nannofossils occur sporadically, possibly because of the dilution effect of the ash; preservation is often poor and seems to be associated with increasing induration of these sediments. Both of these fossil groups, however, were occasionally noted nearly to the bottom of the hole.

Benthic foraminifers are rare compared to the planktonic at Site 451, as is typical for sediments deposited at deep bathyal to abyssal depths above the CCD. The rare specimens that were observed in these samples include Cibicides wuellerstorfi, Bulimina alazanensis, Gyroidina broecki, and other indicators of deep bathyal to abyssal waters.

From Core 31 downward, larger foraminifers occur sporadically. These shallow-water forms are reworked.

ACCUMULATION RATES

The depositional history of the sediments drilled at Site 451 can be broken down into four major phases, each characterized by a distinct average sediment accumulation rate (Fig. 9). The phases are gradational, and their boundaries are obviously influenced by the biostratigraphic data that control the overall curve of Figure 9.

In the first phase of deposition (above the bottom of the hole at 930.5 meters sub-bottom), over a span of only about 1.5 m.y. (until the early late Miocene), about 740 meters of volcanic debris consisting of ashes, tuffs, conglomerates, and breccias accumulated at a rate well over 400 m/m.y. On a fine scale, sedimentary structures such as graded bedding, slump features, channel cuts, and sharp fluctuations in size and lithologic character of clasts require that this deposition must have been episodic. In the early late Miocene, a decrease in the influx of volcaniclastic debris resulted in the second phase, during which depositional rates averaged 35 m/m.y. These rates prevailed until the early Pliocene, when a further decline occurred, during which predominantly biogenic sediments accumulated at about 10 m/m.y. It was finally during the Pleistocene that rates decreased to 5 m/m.y.

ORGANIC GEOCHEMISTRY

No gas shows were observed in the sediments of Site 451. The absence of significant hydrocarbon-gas generation within these sediments suggests that they are probably lean in organic matter.

The organic carbon and nitrogen contents were analyzed by methods discussed in the Introduction (this volume). These results, obtained from carbonate-free sediments, are given in Table 2 and plotted against depth in Figure 10. The erratic values of organic carbon and nitrogen in Unit 1, a foraminifer-nannofossil ooze, cannot be readily explained, although it is perhaps significant that the C:N ratio remains roughly constant throughout Unit 1. The values of organic carbon and nitrogen for the vitric tuffs (Units 2 and 3) are low, resembling those of the same lithologies at Site 450. At one stratigraphic horizon, several brown-black seams
Subsequent shore-based analysis of the separated kerogen gives a much higher organic carbon value (56.18 wt. %) with a higher C:N ratio of 119, confirming that the material is carbonaceous and of terrestrial origin.

Methods used in Rock Eval analyses are presented in the Introduction (this volume). The results of these analyses are summarized in Table 3. Sediments from Units 1, 2, and 3 all have undetectable $S_2$ responses, except for the lignite seams, which have a broad flat $S_2$ peak maximizing at 425°C on the boundary of the oil zone of maturation. The small $S_1$ peak suggests that the sediments consist of mature organic matter. They have a low hydrocarbon potential, characteristic of Type III kerogens of terrestrial original (Tissot and Welte, 1978).

Unfortunately, only about 5 mg of kerogen concentrate were recovered; this amount is insufficient for detailed analysis to obtain further information on the characteristics and origin of this lignite. Attempts to investigate its pyrolysis-GC, the best geochemical tool for dealing with such small amounts of material, were unsuccessful. Its organic-carbon content, C:N ratio, and Rock Eval response all suggest that it is of terrestrial origin. It could represent a distal input to the sedimentary sequence (e.g., by rafting), but a local origin seems more appropriate, because the interbedded tuff contains a locally derived volcanic input. The formation of lignite is thought to occur only in terrestrial or deltaic environments, so that its occurrence nearly 300 meters sub-bottom in a volcaniclastic-breccia sequence seems to indicate the presence of a nearby land mass when the sediment was deposited. The form of the lignite, as oriented lenses within the tuff, suggests that it was deposited by slumping or a similar phenomenon.

The high organic carbon and nitrogen values of some of the nannofossil oozes cannot be attributed to pipeline contamination, because they have no significant $S_2$ response in Rock Eval analysis. One possibility is that their carbonate was incompletely dissolved during sample preparation, although the consistency in their C:N ratios then becomes rather surprising. Misweighing is a further possibility, because these analyses were not duplicated (as were those for Sites 447, 448, and 449). Sputtering in the combustion furnace could also result in anomalously high values.

Table 2. Organic carbon and nitrogen contents (after carbonate dissolution).

<table>
<thead>
<tr>
<th>Lithologic Unit or Sub-unit</th>
<th>Sample (intervals in cm)</th>
<th>Organic Carbon (wt. %)</th>
<th>Nitrogen (wt. %)</th>
<th>C:N (atomic ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-2, 21-24</td>
<td>0.22</td>
<td>0.015</td>
<td>17.2</td>
</tr>
<tr>
<td>1</td>
<td>1-4, 27-28</td>
<td>0.21</td>
<td>0.021</td>
<td>11.7</td>
</tr>
<tr>
<td>1</td>
<td>2-2, 26-28</td>
<td>0.19</td>
<td>0.019</td>
<td>11.7</td>
</tr>
<tr>
<td>1</td>
<td>2-3, 97-98</td>
<td>0.21</td>
<td>0.018</td>
<td>14.3</td>
</tr>
<tr>
<td>1</td>
<td>3-1, 40-41</td>
<td>0.10</td>
<td>0.009</td>
<td>13.0</td>
</tr>
<tr>
<td>1</td>
<td>4-1, 40-41</td>
<td>0.52</td>
<td>0.042</td>
<td>14.5</td>
</tr>
<tr>
<td>1</td>
<td>4-1, 130-131</td>
<td>0.35</td>
<td>0.030</td>
<td>13.7</td>
</tr>
<tr>
<td>1</td>
<td>4-4, 70-71</td>
<td>1.01</td>
<td>0.82</td>
<td>14.4</td>
</tr>
<tr>
<td>1</td>
<td>5-1, 88-99</td>
<td>0.44</td>
<td>0.032</td>
<td>16.1</td>
</tr>
<tr>
<td>2</td>
<td>5-4, 21-22</td>
<td>0.05</td>
<td>0.002</td>
<td>29.3</td>
</tr>
<tr>
<td>2</td>
<td>6-1, 106-107</td>
<td>0.05</td>
<td>0.004</td>
<td>14.6</td>
</tr>
<tr>
<td>2</td>
<td>6-4, 33-34</td>
<td>0.11</td>
<td>0.005</td>
<td>25.7</td>
</tr>
<tr>
<td>3a</td>
<td>14-1, 63-64</td>
<td>0.12</td>
<td>0.009</td>
<td>15.6</td>
</tr>
<tr>
<td>3e</td>
<td>56-3, 5-7</td>
<td>21.46</td>
<td>0.47</td>
<td>119.0</td>
</tr>
</tbody>
</table>

Note: a = Shipboard measurements using two different standards (whole rock).

b = Shore-based measurement on kerogen concentrate.

Figure 10. Results of organic carbon and nitrogen analyses plotted versus sub-bottom depth in meters.

The high organic carbon and nitrogen values of some of the nannofossil oozes cannot be attributed to pipeline contamination, because they have no significant $S_2$ response in Rock Eval analysis. One possibility is that their carbonate was incompletely dissolved during sample preparation, although the consistency in their C:N ratios then becomes rather surprising. Misweighing is a further possibility, because these analyses were not duplicated (as were those for Sites 447, 448, and 449). Sputtering in the combustion furnace could also result in anomalously high values.

Table 3. Qualitative estimate of the relative amount of free hydrocarbons, bound hydrocarbons, and CO$_2$ from kerogen (and carbonate-rich sediments) based upon sizes of $S_1$, $S_2$, and $S_3$ peaks, respectively, from Rock-Eval analyses.

<table>
<thead>
<tr>
<th>Lithologic Unit or Sub-unit</th>
<th>No. of Samples</th>
<th>Freely Soluble Hydrocarbon (S$_1$)</th>
<th>Bound Hydrocarbon (S$_2$)</th>
<th>CO$_2$ from Kerogen (S$_3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3a</td>
<td>1</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3e (lignite)</td>
<td>1</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Note: - = undetectable, + = minor, ++ = moderate relative amounts.
INORGANIC GEOCHEMISTRY OF INTERSTITIAL WATER

Samples for interstitial-water analysis were taken from four cores (451-2-4, 5-3, 14-1, and 34-1) and analyzed according to procedures outlined in the Introduction (this volume). The pH and alkalinity of Core 34, Section 1 could not be determined because its total pore-water content was too low. The data are plotted in Figure 11. The increase in Ca\(^{2+}\) content and parallel decrease in Mg\(^{2+}\) content with depth probably reflects basalt alteration within the vitric tuffs and ashes, as discussed for Sites 450 and 448. The enhanced alkalinity at 38 meters depth (Section 5-3) suggests that there may be a minor zone of sulphate reduction in the sedimentary sequence at that level. The increase in pH with depth indicates that the CO\(_2\) content of the pore water is decreasing and that the samples may therefore be saturated with calcite.

IGNEOUS PETROGRAPHY

Hole 451 was cored continuously to a total depth of 930.5 meters; predominantly volcaniclastic conglomerates and breccias and interbedded tuffs were recovered. Basalt fragments recovered from the bottom 4 meters of the hole, where the drilling rate appreciably slowed, may represent the brecciated upper surface of a lava flow; otherwise no lava flows or igneous intrusions were penetrated.

The volcaniclastic conglomerates and breccias generally contain clasts of devitrified and/or altered pumice, glass, basalts, and andesites. Rare clasts of relatively fresh igneous rock are found throughout the section. These range in size from 1 to 15 cm (average, 5 cm). Twenty of the least-altered clasts were studied in thin section and subdivided according to phenocryst assemblages. The total abundance of phenocrysts and groundmass constituents are given as percentages of the whole rock (e.g., the phenocrysts consist of plagioclase [60%, 0.8 mm] and olivine [40%, 0.4 mm, altered to green smectite]; the groundmass consists of plagioclase [50%, both pyroxenes [20%], opaques [5%], and glass [25%]).

Five petrologic types are recognized:
1) aphyric or sparsely phytic basalt (2 clasts);
2) plagioclase-clinopyroxene-phyric basalt (2 clasts);
3) clinopyroxene-plagioclase-phyric basalt (1 clast);
4) plagioclase-clinopyroxene-magnetite-(olivine)-phyric andesite (6 clasts); and
5) plagioclase-clinopyroxene-orthopyroxene-magnetite-(olivine)-phyric andesite (8 clasts).

Aphyric or sparsely phytic basaltic clasts contain very rare microphenocrysts of plagioclase (0.2-0.3 mm, subhedral) and clinopyroxene (0.3-0.5 mm, subhedral) set in hyalopilitic groundmass consisting of glass (60%) and flow-aligned microcrysts of plagioclase (40%). Microphenocrysts of olivine are found in a few cases as smectite pseudomorphs.

Plagioclase-clinopyroxene-phyric basaltic clasts contain 12% to 45% phenocrysts of plagioclase (80-95%, 0.1-4 mm, sub- to anhedral, glomerophyric, complex twinning and zoning) and scattered phenocrysts of green clinopyroxene (5-20%, 0.3-2 mm, eu- to subhedral, glomerophyric). The groundmass is vitriphic to hyalopilitic and is 25% to 75% crystalline.

The one clinopyroxene-plagioclase-phyric basaltic clast contains 35% phenocrysts of clinopyroxene (60%) and plagioclase (40%) set in a vitriphic groundmass, similar to the second type.

Plagioclase-clinopyroxene-magnetite-(olivine)-phyric andesitic clasts contain 20% to 55% phenocrysts of plagioclase (65-90%, 0.3-5 mm, An\(_{0-60}\), sub- to euhedral, glomerophyric, scattered clinopyroxene (5-20%, 0.1-2 mm, rounded to euhedral, some partially resorbed), scattered magnetite (5-10%, 0.2-0.5 mm, surrounded octahedral), and rare olivine (0-10%, 0.1-2 mm, pseudomorphed by brown and green smectite). The clasts have 45% to 80% groundmass that is typically hyalopilitic, containing glass (40-60%) and flow-banded plagioclase microlites. Many petrographic features of these rocks suggest an andesitic composition (e.g., impoverishment of mafic constituents coupled with a plagioclase-phenocryst core composition of An\(_{50-60}\), pronounced oscillatory zoning, repeated resorption followed by overgrowth, and strongly zoned glass inclusions).

Plagioclase-clinopyroxene-orthopyroxene-magnetite-(olivine)-phyric andesitic clasts are identical to those just described but contain orthopyroxene as an additional phenocryst phase. These orthopyroxene phenocrysts are euhedral (4-10%, 0.2-1 mm, En\(_{90-70}\)) and contain common inclusions of magnetite. Orthopyroxene phenocrysts are sometimes partially or wholly replaced by smectite.

Preliminary comparison of volcanic sequences from Sites 451 and 448 identifies differences between the geologic evolution of the West Mariana and Palau-Kyushu Ridges. First, extensive deposits of late-Mio-
Epidote (?) are fairly common. Pyrite, clasts of rocks containing pyrite, and clasts of the present environment. Apparently this part of the provenance was more extensively altered because clasts of some parts of the sediment provenance unrelated to the low-grade, gradual, pervasive increase in degree of alteration and abundance of alteration is much lower. There are no occurrences at Site 448, except the degree of alteration by pyrite, zeolites, and clays. In a few cases, fine native copper veinlets were observed in a situation similar to the Palau-Kyushu Ridge. The West Mariana Ridge volcanic rocks are more similar to the Miocene volcanic rocks of Guam and Saipan (Larson et al., 1974; Tracey et al., 1964; Schmidt, 1957). In some basaltic andesites and andesites of the West Mariana Ridge, the presence of magnetite as a liquidus phase is noteworthy. This might be indicative of high oxygen and water fugacities in parental magmas characteristic of calc-alkaline volcanism.

The differences in the geologic evolution of the West Mariana and Palau-Kyushu Ridges are in good accordance with the hypothesis that the Parece Vela Basin has formed as a result of inter-arc spreading from the middle Oligocene to the middle Miocene, with the West Mariana Ridge behaving as the active volcanic arc and the Palau-Kyushu Ridge as the remnant arc during that period of spreading.

**METAMORPHIC PETROGRAPHY**

Although no regional metamorphic rocks were observed in the 930.5 meters drilled at Site 451 on the West Mariana Ridge, much of the upper Miocene volcanic debris has been affected by low-grade hydrothermal activity over small stratigraphic intervals, marked by pyrite, zeolites, and clays. In a few cases, fine native copper veinlets were observed in a situation similar to those occurrences at Site 448, except the degree of alteration and abundance of alteration is much lower. There seems to be two types of alteration present: one is a very low-grade, gradual, pervasive increase in degree of alteration down-hole; the other seems to be relatively higher-temperature hydrothermal metamorphism of some parts of the sediment provenance unrelated to the present environment. Apparently this part of the provenance was more extensively altered because clasts of pyrite, clasts of rocks containing pyrite, and clasts of epidote (?) are fairly common.

**PALEOMAGNETISM**

No paleomagnetic samples were collected from Hole 451. The rock units at this site consisted of coarse to fine volcaniclastic rocks, for the most part. We encountered penecontemporaneous faults, folds, and slumps, as well as rigid-body faulting and uniform tilting, which make the hole unsuitable for paleomagnetic study. Rock magnetic studies of volcaniclastic breccias from Hole 448A (similar to those found in this hole) are described in a later chapter on paleomagnetism (Keating, this volume).

**PHYSICAL PROPERTIES**

Physical properties measured on the sediments recovered from Hole 451 include sonic velocity (horizontal and vertical), wet-bulk density, water content, porosity, and acoustic impedance. Methods and procedures are briefly summarized in the Introduction (this volume). Results are listed in Table 4 and are shown graphically in Figure 12.

Sonic velocities were measured on the least-disturbed sections of split cores from Unit 1 and on samples of the consolidated sediments of Units 2 and 3 in both vertical and horizontal directions. Velocities in calcareous oozes and tuffs of Units 1 and 2 range from 1.59 to 1.62 km/s. A significant increase in sonic velocity occurs in the more lithified tuffs and coarser volcaniclastic breccias of Unit 3. Velocities in Unit 3 range from 1.97 to more than 3.1 km/s, with no apparent increase with depth. The scattered values appear to correlate with the alteration lithologies. Although velocity anisotropy appears to be present, vertical velocity is not always lower than horizontal. This presumably reflects the unsorted, unoriented fabric of the coarse detritus. The velocity of one basalt cobble was measured at 4.75 km/s (Core 45, Section 1).

Wet-bulk density, porosity, and water content were measured on samples from Core 14 to the bottom of the hole. Poor core recovery precluded a continuous sequence of measurements between Cores 9 and 30. Core catcher samples from this interval were used, however, to obtain supplemental values. Wet-bulk densities of 1.91 and 1.75 g/cm³ from Cores 14 and 15, respectively, correspond to the uppermost semiconsolidated sediments (vitric tuffs of Sub-unit 3a). Porosity is about 47%, and water content ranges from 24% to 27% for Cores 14 and 15.

The wet-bulk density of the series of alternating coarse and fine volcaniclastic sediment comprising Sub-units 3b to 3g (from 280.5 m sub-bottom to the bottom of the hole) average only slightly higher than those of Sub-unit 3a, ranging from 1.89 to 2.2 g/cm³. In this interval, water contents range from 15.8% to 24.24% and porosity values from about 34% to about 50%. In general, the density of coarse volcanioclastics is higher than that of the tuffs (Table 4). Acoustic impedance in Unit 3 ranges from 4.49 to 7.14 × 10⁶ g/(cm²s), with no pronounced contrast present to indicate a strong reflector.

**GEOPHYSICS**

Site 451 is located on a terrace on the east face of the West Mariana Ridge. The site is located in about 2000 meters of water (Fig. 3), approximately 6 km west of the site originally selected. Because single-channel seismic-reflection data showed no obvious sediment overburden, we approached the site with some misgivings. Dur-
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<th>Continuous GRAPE (section averages)</th>
<th>Special GRAPE (g/cm³)b</th>
<th>Water Content (%)</th>
<th>Porosity (%)</th>
<th>Calculated Grain Density (g/cm³)</th>
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a Basalt average velocity.
b Based on an assumed grain density of 2.75 g/cm³.

ing the approach, no discernible reflectors were observed in the reflection profile recorded on board the Glomar Challenger (Fig. 1). After crossing the objective site, the vessel came about on a reciprocal course, and the beacon was dropped over what appeared to be a “soft” seafloor reflector. We experienced initial concern, however, as to whether a hard basement was present or at the surface and whether or not a sufficient thickness of soft sediment was present to facilitate burying the bottom-hole assembly. Thus, in spudding-in we exercised more than the usual amount of caution.

After a considerable depth had been penetrated in the drilling at Hole 451, the reason for the absence of discernible sub-bottom reflectors became obvious. No sharp contrast in acoustic impedance was encountered down-hole (see the section on Physical Properties, this chapter), which explains the lack of any strong reflector. Furthermore, the laboratory measured velocity of the highly altered basalt encountered at the bottom of Hole 451 at a depth of 926.5 meters sub-bottom is only about 3.6 km/s and thus is in the range of the basement velocities mentioned earlier.

**SUMMARY AND CONCLUSIONS**

Site 451, at 18°00.88'N and 143°16.57'E on the eastern side of the West Mariana Ridge, was drilled with the primary objective of determining the petrologic character of this formerly active volcanic arc as well as the timing of cessation of volcanism, particularly with reference to the age of the spreading of the Mariana Trough and the creation of the active volcanic arc—the Mariana Ridge—east of Site 451 (Fig. 1). Continuous coring at Hole 451 resulted in a total recovery of 280.1 meters out of 930.5 meters drilled. Hole 451 was terminated at 930.5 meters because of severe plugging of the bit and scheduling considerations. Sediments and sedimentary rocks were cored to a depth of 926.5 meters. Below that level, a decrease of drilling rate and recovery of altered basalt pieces suggest that 4.0 meters of basalt was encountered. A total of three major biogenic and volcaniclastic sedimentary units range in age from the late Miocene to the Quaternary. No unit is assigned to the small interval (4.0 m) of basalt at the bottom of the hole, because insufficient basalt was recovered to refute the possibility that the basalt is only a large clast.

The sedimentary section consists of:

**Unit 1** (0.0–36.0 m), lower Pliocene to Quaternary calcareous biogenic oozes consisting of grayish brown foraminifer ooze, grayish brown foraminifer–nannofossil ooze, light yellow nannofossil–foraminifer ooze, and a light gray nannofossil ooze.

**Unit 2** (36.0–65.5 m), upper Miocene to lower Pliocene olive-gray, carbonate-rich vitric ash with minor vitric tuff.

**Unit 3** (65.5–930.5 m), upper Miocene volcaniclastic rocks consisting of seven sub-units:

Sub-unit 3a (65.5–280.5 m), upper Miocene, dark gray to black vitric tuffs, vitric ash, and carbonate-rich vitric ash;

Sub-unit 3b (280.5–413.5 m), upper Miocene, interbedded dark gray vitric tuff and dark gray volcaniclastic breccias and conglomerates containing organic carbonate grains;

Sub-unit 3c (413.5–425.2 m), upper Miocene, dark gray boulder volcaniclastic conglomerate grading to carbonate-rich vitric tuff;

Sub-unit 3d (425.2–474.5 m), upper Miocene, black vitric tuff;

Sub-unit 3e (474.5–641.9 m), upper Miocene, interbedded black and greenish black vitric tuff and volcaniclastic breccias and conglomerates;
Figure 12. Physical properties of sedimentary and igneous rocks from Hole 451 plotted versus sub-bottom depth in meters. (Acoustic impedance is the product of velocity and bulk density. Sonic velocity measurements include horizontal and vertical velocity of sediments and average velocity of basalts. Gravimetric determinations of wet-bulk density are shown. Special 2-minute and continuous GRAPE determinations of wet-bulk density are also shown, based on an assumed grain density of 2.75 g/cm$^3$. Porosity was determined gravimetrically, and grain density was calculated from porosity and bulk density.)
Figure 13. Reflection profile across Site 451 recorded during the approach to the site aboard the Glomar Challenger.

Sub-unit 3f (641.9–703.6 m), upper Miocene, black vitric tuff; and

Sub-unit 3g (703.6–930.5 m), upper Miocene, interbedded greenish black vitric tuff with greenish black volcaniclastic breccias and conglomerates.

The recovery of thick sequences of coarse, massive volcaniclastic sediments at Site 451 provides a unique opportunity to investigate tectonic, volcanic, and sedimentologic interrelationships. The repetitious sequences of coarse angular debris grading upward into fine bioturbated layers represent spasmodic deposition probably controlled by tectonic events, because sedimentologic evidence suggests that this debris was deposited in shallow-water to subaerial conditions and was not controlled by direct pulses of volcanic activity. Fragments of corals, gastropods, and larger foraminifers suggest significant reworking of shallow-water deposits. In addition, lenses of lignite in the tuffs are proof that a nearby vegetated land surface on the West Mariana Ridge existed. Scattered pumiceous layers may record local explosive andesitic volcanic events.

To elaborate on the previous discussion, in the last 4 meters of drilling (926.5–930.5 m), the drilling record shows that we encountered a unit resistant to drilling, which behaved in a manner similar to basalts encountered in previous sites. The drilling rate slowed in the unit from 4 minutes per meter to nearly 12 minutes per meter (Fig. 7). Although no clear evidence exists to determine absolutely that the rock recovered is a flow or sill and not a clast, there is considerable circumstantial evidence that points in this direction: (1) the drilling record; (2) a green clay surrounding the crystalline rock that may be altered glass; (3) small fragments of the crystalline rock that are isolated in a green clay; (4) a 3.9-km/s basement was predicted close to this level, and the altered basalt has a velocity of 3.6 km/s; and finally (5) the unit above consists of coarse volcaniclastic debris, yet no coarse sedimentary debris surrounds the basalt itself. The basalt is extremely altered to green clays and is riddled with disseminated native copper (up to 5% or 10% in small pockets). Whether the basalt is only a boulder in the sedimentary sequence, an isolated intrusive body, or the uppermost section of the volcanic-arc basement, it is aphyric and very highly altered.

Within the volcaniclastic sediments five petrographic groups of volcanic clasts were found:

1) aphyric or sparsely phyric basalt;
2) plagioclase-clinopyroxene-phyric basalt;
3) clinopyroxene-plagioclase-phyric basalt;
4) plagioclase-clinopyroxene-magnetite-(olivine)-phyric andesite; and
5) plagioclase-clinopyroxene-orthopyroxene-magnetite-(olivine)-phyric andesite.

Groups 4 and 5 are most abundant, and their two-pyroxene-plus-magnetite phenocryst assemblage in an andesite definitely suggests a calc-alkalic volcanic suite. This greater abundance of calc-alkalic rocks from the West Mariana Ridge compared to the Palau-Kyushu
Ridge indicates a progression to more calc-alkalic and more siliceous rocks with time toward the active Mariana arc.

Although these sedimentary units consist predominately of volcaniclastic debris, calcareous fossils are present. Nannofossils give no indication of hiatuses; apparently a continuous upper-Miocene to Quaternary sequence exists. Although radiolarians, diatoms, and silicoflagellates, in addition to nannoplankton and foraminifers, are present above Core 3, only calcareous nannoplankton and foraminifers occur below this level. The nannofossil boundary NN 10/NN 11 is the only boundary found below the Pliocene/Miocene boundary (between 176.0 and 195.0 m), and no foraminifer boundaries were observed. However, in the 765.0 to 774.5 meter sub-bottom interval, the nannoplankton assemblage characterizes the base of NN 10 (upper Miocene). Below Core 31 (>282.0 m) larger foraminifers, coral fragments (Fig. 14), and gastropod fragments are present; this evidence suggests that the sediments were originally deposited in shallow waters (less than 100 m) and then were transported into deeper environments. Fragments of lignite within tuffs probably were not formed in situ because of the local occurrence of numerous isolated lenses, typically only 1 cm in diameter. A more likely origin would be the erosion of nearby existing lignite beds in the landmass of the volcanic arc itself.

Accumulation rates were very high—400 m/m.y. during late Miocene volcanic activity, decreasing to 35 m/m.y. during late Miocene and early Pliocene. By late Pliocene, the rate was as low as 5 m/m.y. These changes reflect only cessation of volcanic activity, because the region stayed above the CCD throughout its history.

The most impressive feature of the physical properties data is the relative uniformity of acoustic-impedance values. Without differences in acoustic impedance, no reflecting horizons would be detected; this explains why no obvious transparent sediment over-burden could be seen at Site 451.

The sequence of events at Site 451 from oldest to youngest can be summarized as follow:

1) A volcanic-arc basement (3.5-4.2 km/s, ~1.5 km thick) was constructed (by 11 m.y. ago) on oceanic(?)(?) basement (5-6 km/s).

2) In the next 2 m.y., about 850 meters of volcaniclastic debris accumulated at a rate of about 400 m/m.y. Locally, the arc was emergent.

3) Tilting (up to 25°) and normal faulting in these sediments occurred both penecontemporaneously by soft-sediment deformation and after induration by rigid-body deformation (Fig. 15, A-D).

4) A dramatic decrease in accumulation rate of volcanic ash marked the end of intense West Mariana Arc volcanism (at 9 m.y. ago).

5) Sporadic volcanism continued, however, for another 4 m.y. (9-5 m.y. ago). The source of the ash may have been waning volcanism of the West Mariana Arc, but the timing of initiation of rifting to form the Mariana Trough and of activation of the modern Mariana Arc is not very well known; the source of the ash may have been early volcanism from the Mariana Arc, windblown across the young, narrow Mariana Trough.

6) Only calcareous biogenous sediments accumulated from 5 m.y. ago to present.

Now that both arcs on either side of the basin and the basin itself have been drilled, a strong case for symmetric spreading can be built for the Parece Vela Basin using several lines of evidence: (1) The time of cessation of volcanism on the Palau-Kyushu Ridge, determined by paleontology, dates the probable initiation of the Parece Vela Basin formation by back-arc spreading (22-32 m.y.). (2) The identification of magnetic anomalies (Langseth, Mrozowski, this volume) in the Western Parece Vela Basin also dates the initiation of spreading (this date coincides with the cessation of volcanism). These anomalies give the time of extinction of the Parece Vela spreading system (about 14-18 m.y.). The Parece Vela Rift bisects the basin. (3) The age of the basement under Site 449 (24 m.y.), determined by paleontology, confirms the magnetic-age estimate; more important, all three dates fall close to a straight line on a time-versus-distance plot (Fig. 16); this requires a rather constant spreading rate (~3.0 cm/yr) and makes the strong case for spreading from the Parece Vela Rift to form the western side of the Parece Vela Basin. More circumstantial evidence must be used for the eastern side, because extrusive basement was never reached and the magnetic-anomaly pattern was not identified. (4) Sites 450 and 53 were drilled into intrusive igneous rocks rather than into extrusive basement; the ages of the oldest sediments encountered are approximately 17 and 18 m.y., respectively, and are several million years younger than basement ages predicted from the symmetrical spreading model (Fig. 16). (5) Site 54 was drilled in the eastern Parece Vela Basin closer to the IPOD Trough over a structure that is similar to the intrusive structures at Sites 450 and 53. Although evidence of the intrusive nature of Site 54 is absent (Karig, Ingle,
et al., 1975), it is possible that this site is also intrusive, particularly in light of the intrusions encountered in the northern extension of the Parece Vela Basin—the Shikoku Basin (Klein, Kobayashi, et al., in press)—on Leg 58. (6) The volcanism of the West Mariana Ridge ended intense activity about 11 m.y. ago and sporadic activity about 5 m.y. ago; that is, volcanism (and presumably subduction) continued for at least 8 m.y. after the end of spreading in the Parece Vela Basin. Careful measurement of the dimensions of the Parece Vela Basin (Fig. 17) shows that the eastern side is about 50 km closer to the IPOD Trough than is the western side. Rather than attribute this phenomenon to asymmetrical spreading, a more probable explanation may be that the western side of the West Mariana Ridge had been extended over the oldest marginal-basin crust during construction of the new arc; that is, not only was the arc side of a marginal basin affected by tectonism, off-axis intrusion, and inundation by arc-derived sediments, but it was also the platform upon which the arc grew.
After rifting of the subduction side of the arc away from the remnant portion, a new "rear end" of the arc was rebuilt over the new basin floor.

REFERENCES


Figure 16. Time-versus-distance plot of the Parece Vela Basin along a profile drawn perpendicular to the IPOD Trough at 18°N. (Solid lines on ridges indicate periods that have direct evidence of abundant volcanism, dashed lines are inferred volcanism based on indirect evidence, and dash-dot lines show periods of waning volcanism. The sloping lines indicate periods of back-arc spreading of the Parece Vela Basin—a line based upon geologic evidence and one on magnetic evidence are both drawn. Periods of lack of volcanism or presence of volcanism in the sedimentary record are depicted by braces.)
Figure 17. Seismic-reflection profiles across the Parece Vela Basin (L-DGO Site Survey data) along about the 17°60′ parallel (above) and about the 15°70′ parallel (below).
**SITE 451 HOLE**

**CORED INTERVAL:** 0.0-5.0 m

**FORAMINIFERAL OOZE,** grayish brown (10YR 5/2) passing gradually in Section 3 to **FORAMINIFERAL-NANNOFOSIL OOZE,** light yellowish brown (10YR 6/4). The grayish-brown fragments, and gravel-sized (0.4-1.5 cm) black Mn-coated pumice clasts. These components are absent near the bottom of Section 3 and in the Core-Catcher. The sediment is uniformly soft; drilling moderate in all sections. Pi form is puccineaceous soft; clay intermixed where Mn-coated clay is present. 

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| 碳酸盐炸弹 | 3, 90-91 (61) |

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**Late Pleistocene**

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**FORELL**

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<tr>
<td>N21</td>
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**ARABANAGE/PERMANTANCE**

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<td>PRESERV.</td>
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<thead>
<tr>
<th>SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>METERS</td>
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</tbody>
</table>

**CORED INTERVAL:** 5.0-14.5 m

**NANNOFOSIL-FORAMINIFERAL OOZE,** mainly brownish-gray interior black where Mn-coated clay is present. Or brown intervals. Or the sediment is uniformly soft; drilling moderate in all sections. Pi form is puccineaceous soft; clay intermixed where Mn-coated clay is present.

**SMEAR SLIDE SUMMARY**

<table>
<thead>
<tr>
<th>TEXTURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>Silt</td>
</tr>
<tr>
<td>Clay</td>
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</tbody>
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**GRANULOMETRIC ANALYSIS**

<table>
<thead>
<tr>
<th>颗粒级</th>
<th>2-49 (70.9, 20.5, 8.7)</th>
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**CARBONATE ANALYSIS**

<table>
<thead>
<tr>
<th>碳酸盐</th>
<th>5, 74-75</th>
</tr>
</thead>
</table>
SITE 451 HOLE CORE 3 CORED INTERVAL: 14.5-24.0 m

LITHOLOGIC DESCRIPTION
FORAMINIFERAL NANNOFOSIL OOZE, light yellowish brown, in Sections 1 through upper portion of 6. Grayish brown and very dark gray mottles are layer of volcanic ash in Section 2; one yellowish brown fragments in Sections 2 and 3. From upper part of Section 6 to Core-Catcher the sediment is NANNOFOSIL FORAMINIFERAL OOZE, alternately pale yellow and very pale brown. Sections 1 to 5; light yellowish brown FORAMINIFERAL OOZE in Section 6. Slight grayish brown mottles in Section 1. Some black pumice fragments (<2 cm) covered by "cauliflower" Mn
FORAMINIFERAL-NANNOFOSSIL OOZE, light brownish gray to pale yellow in Sections 1 and upper part of Section 2, turning to gray to light gray in middle Section 2, dark gray in Sections 3 and 4. The sediments are fine-grained, carbonate-rich, with various tones of olive gray and dark gray. Thin layers of volcanic ash and tuff occur in thin layers in the middle and upper parts of Section 3. The sediments are soft except for some thin layers of volcanic ash in Sections 3 and 4; drilling disturbance is slight in Sections 1 and 4, moderate elsewhere.

SMEAR SLIDE SUMMARY

TEXTURE:
- Sand: 20
- Silt: 70
- Clay: 10

TOTAL DETRITAL:
- 14

COMPOSITION:
- Feldspar: 5
- Heavy minerals: 1
- Clay minerals: 10
- Volcanic glass: 69

General color:
- Micronodules: 4
- Zeolites: 1
- Carbonate:
- Foraminifers: 2
- Nannofossils: 5
- Radiolaria: 3
- Fish remains: 1

GRAIN-SIZE:
- 1-71 (22.7, 59.6, 17.7)

CARBONATE/BOMB:
- 1.06-1.07-1.08 (55)

CARBONATE BOMB:
- 1, 2, 17 (17)
**SITE 451 HOLE B**

**CORE 7**

**CORED INTERVAL:** 52.5-62.0 m

---

**SITE 451 HOLE C**

**CORE 8**

**CORED INTERVAL:** 62.0-71.5 m

---

**LITHOLOGIC DESCRIPTION**

**SITE 451 HOLE B**

**CORE 7**

**CORED INTERVAL:** 52.5-62.0 m

**LITHOLOGIC DESCRIPTION**

**SITE 451 HOLE C**

**CORE 8**

**CORED INTERVAL:** 62.0-71.5 m

---

**LITHOLOGIC DESCRIPTION**

**SITE 451 HOLE B**

**CORE 7**

**CORED INTERVAL:** 52.5-62.0 m

---

**LITHOLOGIC DESCRIPTION**

**SITE 451 HOLE C**

**CORE 8**

**CORED INTERVAL:** 62.0-71.5 m

---

**LITHOLOGIC DESCRIPTION**
<table>
<thead>
<tr>
<th>SITE 451</th>
<th>HOLE</th>
<th>CORE</th>
<th>CORED INTERVAL:</th>
<th>LITHOLOGIC DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>125.0-147.5 m</td>
<td>VITRIC TUFF, carbonate-rich, matrix is light gray with 7 mm diameter shards of medium dark gray vitric tuff sparsely to thinly intercalated. 3 to 5 mm diameter shards of white pumice, and minor (~1%) black melt fabric.</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>SMEAR SLIDE SUMMARY (CC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TEXTURE: Sand 9 Silt 66 Clay 30 TOTAL DETRITAL 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>COMPOSITION: Feldspar 9 Heavy minerals 1 Clay minerals 30 Volcanic glass 95 Micronodules 1 Zeolites 1 Recrystallized carb. 1 Foraminifers 2 Nannofossils 50 Fish remains - Other 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Site 451, Core 17, 147.0-152.0 m: NO RECOVERY.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SITE 451</th>
<th>HOLE</th>
<th>CORE</th>
<th>CORED INTERVAL:</th>
<th>LITHOLOGIC DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>152.0-166.5 m</td>
<td>VITRIC TUFF, carbonate-rich, matrix is light gray with 7 mm diameter shards of medium dark gray vitric tuff sparsely to thinly intercalated. 3 to 5 mm diameter shards of white pumice, and minor (~1%) black melt fabric.</td>
</tr>
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<td></td>
<td>SMEAR SLIDE SUMMARY (CC)</td>
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<td></td>
<td></td>
<td></td>
<td>TEXTURE: Sand 9 Silt 66 Clay 30 TOTAL DETRITAL 100</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>COMPOSITION: Feldspar 9 Heavy minerals 1 Clay minerals 30 Volcanic glass 95 Micronodules 1 Zeolites 1 Recrystallized carb. 1 Foraminifers 2 Nannofossils 50 Fish remains - Other 1</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>Site 451, Core 19, 166.5-171.0 m: NO RECOVERY.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SITE 451</th>
<th>HOLE</th>
<th>CORE</th>
<th>CORED INTERVAL:</th>
<th>LITHOLOGIC DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>176.0-195.5 m</td>
<td>VITRIC TUFF, carbonate-rich, matrix is light gray with 7 mm diameter shards of medium dark gray vitric tuff sparsely to thinly intercalated. 3 to 5 mm diameter shards of white pumice, and minor (~1%) black melt fabric.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SMEAR SLIDE SUMMARY (CC)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>TEXTURE: Sand 9 Silt 66 Clay 30 TOTAL DETRITAL 100</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Site 451, Core 21, 195.0-200.0 m: NO RECOVERY.</td>
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</tbody>
</table>
### SITE 451 HOLE SITE 451 HOLE

<table>
<thead>
<tr>
<th>AGE</th>
<th>NANNOS</th>
<th>FISHES</th>
<th>FOSSILS</th>
<th>GRAPHIC</th>
<th>LITHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FINE VITRIC TUFF, greyish black, with 3mm clast of greyish black glassy clay. Aragonite and a few black intercalated light-bluish grey carbonate-rich tuff.</td>
</tr>
</tbody>
</table>

#### SMEAR SLIDE SUMMARY

<table>
<thead>
<tr>
<th>CE-15</th>
<th>CE-10</th>
<th>CE-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Clay</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>Total Detrital</td>
<td>38</td>
<td>7</td>
</tr>
</tbody>
</table>

#### PHYSICAL PROPERTIES

<table>
<thead>
<tr>
<th>Section</th>
<th>Wet Bulk Density</th>
<th>Porosity (%)</th>
<th>Grain Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>3.17</td>
<td>53.5</td>
<td>2.76</td>
</tr>
</tbody>
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#### MEASUREMENTS

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>250.5-259.5 m</td>
<td>259.5-268.5 m</td>
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</tr>
</tbody>
</table>

#### LITHOLOGIC DESCRIPTION

- **General Color**: 2.5Y 2/0
- **Texture**: Fine-Grained Clayey Drilling Breccia

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<td>1-2</td>
<td>3.17</td>
<td>53.5</td>
<td>2.76</td>
</tr>
<tr>
<td>SITE 451 HOLE 29 CORED INTERVAL: 252.5-261.5 m</td>
<td>SITE 451 HOLE 29 CORED INTERVAL: 261.5-271.0 m</td>
<td>SITE 451 HOLE 29 CORED INTERVAL: 271.0-280.5 m</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
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<td></td>
</tr>
<tr>
<td><strong>AGE</strong></td>
<td><strong>BIODST. ZONE</strong></td>
<td><strong>FOSIL CHARACT.</strong></td>
<td><strong>GRAPHIC LITHOLOGY</strong></td>
</tr>
<tr>
<td>5Y3/1</td>
<td>5Y2/1</td>
<td>5Y4/1</td>
<td>Fine vitric tuff, black, generally enriched in foraminifers, thin section 24 cm. The upper 3 cm intensely disturbed by drilling and contain layers of fine vitric tuff in foraminifer-enriched areas and up to 2 mm thick zones of coarse glass. These zones are very dark gray when freshly broken and contain abundant foraminifers, very dark gray; more sparsely bioturbated. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff.</td>
</tr>
<tr>
<td>5Y4/1</td>
<td>5Y2/1</td>
<td>5Y3/1</td>
<td>Fine vitric tuff, black, generally enriched in foraminifers, thin section 24 cm. The upper 3 cm intensely disturbed by drilling and contain layers of fine vitric tuff in foraminifer-enriched areas and up to 2 mm thick zones of coarse glass. These zones are very dark gray when freshly broken and contain abundant foraminifers, very dark gray; more sparsely bioturbated. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff.</td>
</tr>
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<td>5Y3/1</td>
<td>5Y2/1</td>
<td>5Y4/1</td>
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</tbody>
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**SMEAR SLIDE SUMMARY**

<table>
<thead>
<tr>
<th>/books/ oram slide Summary</th>
<th>5Y3/1</th>
<th>5Y2/1</th>
<th>5Y4/1</th>
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</thead>
<tbody>
<tr>
<td><strong>Texture</strong></td>
<td>Sand</td>
<td>Clay minerals</td>
<td>Volcanic glass</td>
</tr>
<tr>
<td><strong>Porosity (%)</strong></td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Nannofossils</strong></td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>FORAMS</strong></td>
<td>5</td>
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<td>5</td>
</tr>
<tr>
<td><strong>RADS</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Compositions</strong></td>
<td>Clay minerals</td>
<td>Volcanic glass</td>
<td>Zeolites</td>
</tr>
<tr>
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<td>VITRIC TUFF, with foraminifers; very dark gray; interbedded very dark gray silt to clay. The sediment is intensely disturbed by drilling and contains a thin layer of siliceous material.</td>
<td>VITRIC TUFF, with foraminifers; very dark gray; interbedded very dark gray silt to clay. The sediment is intensely disturbed by drilling and contains a thin layer of siliceous material.</td>
</tr>
</tbody>
</table>

**PHYSICAL PROPERTIES**

<table>
<thead>
<tr>
<th>Site 1</th>
<th>TOTAL DETERITAL COMPOSITION</th>
<th>5Y3/1</th>
<th>5Y2/1</th>
<th>5Y4/1</th>
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<tbody>
<tr>
<td><strong>Density</strong></td>
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<td>2.21</td>
<td>2.21</td>
<td>2.21</td>
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<tr>
<td><strong>Grain density</strong></td>
<td>2.93</td>
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<td>2.93</td>
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<tr>
<td><strong>SMEAR SLIDE SUMMARY</strong></td>
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<td>5Y2/1</td>
<td>5Y4/1</td>
<td></td>
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<td><strong>Texture</strong></td>
<td>Sand</td>
<td>Clay minerals</td>
<td>Volcanic glass</td>
<td></td>
</tr>
<tr>
<td><strong>Porosity (%)</strong></td>
<td>2</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Nannofossils</strong></td>
<td>10</td>
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<td></td>
</tr>
<tr>
<td><strong>FORAMS</strong></td>
<td>5</td>
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</tr>
<tr>
<td><strong>RADS</strong></td>
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</tr>
<tr>
<td><strong>Compositions</strong></td>
<td>Clay minerals</td>
<td>Volcanic glass</td>
<td>Zeolites</td>
<td></td>
</tr>
</tbody>
</table>

**REMARKS**

- Fine vitric tuff, black, generally enriched in foraminifers, thin section 24 cm. The upper 3 cm intensely disturbed by drilling and contain layers of fine vitric tuff in foraminifer-enriched areas and up to 2 mm thick zones of coarse glass. These zones are very dark gray when freshly broken and contain abundant foraminifers, very dark gray; more sparsely bioturbated. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. The sediment is intensely disturbed by drilling and contains a thin layer of vitric tuff. | VITRIC TUFF, with foraminifers; very dark gray; interbedded very dark gray silt to clay. The sediment is intensely disturbed by drilling and contains a thin layer of siliceous material. | VITRIC TUFF, with foraminifers; very dark gray; interbedded very dark gray silt to clay. The sediment is intensely disturbed by drilling and contains a thin layer of siliceous material. |
LITHOLOGIC DESCRIPTION

VITRIC TUFF, foraminifer-rich at places, dark gray to very dark gray, interbedded with clay. Section 1 contains abundant gray burrows. Parallel laminae are frequent, sometimes enhanced by digitations of plant-laminae. Section 1 contains also a clastic clast fraction. The whole core is hard rock, with slight drilling deformation.

SMEAR SLIDE SUMMARY

TEXTURE:
- Sand
- Silt
- Clay

TOTAL DETRITAL:
- Feldspar
- Micas
- Clay minerals
- Quartz
- Manganese
- Chlorite
- Ammonite fragments
- Foraminiferous
- Nannofossils

CARBONATE:
- 1-122 (0.1, 0.1, 0.1)

CARBONATE BORN:
- 1-129 (1, 1, 1)

PHYSICAL PROPERTIES:
- Wt./v. density 2.14
- Porosity 24%
- Grain density 2.84
SITE 451 HOLE 
CORE 33 CORED INTERVAL: 350.5-359.0 m

<table>
<thead>
<tr>
<th>AGE</th>
<th>NAMENS</th>
<th>FOSSILS</th>
<th>RADIOCARBON</th>
<th>BIOCSTR. CHARACTER</th>
<th>FOSSIL CHARACT.</th>
<th>FISH REMAINS</th>
<th>GRAPHIC LITHOLOGY</th>
<th>LITHOLOGIC DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>5Y 5/1</td>
<td>burrows</td>
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<td>VITRIFIC TUFF, massive, black and very dark gray; graded interval in top 1 cm, from medium sand- to silt-sized. Parallel burrows have gray burrows locally present. This, dark reddish-brown, deformed layers of yellowish sandstone occur in nonscale surface at 50 and 70 cm. The rock is hard, the bedding deformation is minor.</td>
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<td>5Y2/1</td>
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<td>VITRIFIC TUFF, black, grading down to LITHIC and VITRIFIC VOLCANICLASTIC CONGLOMERATE, dark greenish gray. Fragments of basalt, glass, and pumice up to 1.0 cm in diameter, in the Core-Catcher some of them exceed 4 cm.</td>
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<td>5Y 4/1</td>
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<td>SMEAR SLIDE SUMMARY</td>
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<td>Silt 30 69</td>
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<td>Heavy minerals 4 23</td>
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<td>CARBON/CARBONATE: CARBONATE BOMB:</td>
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<td>2-19 (0.1, 0.0, 0.1)</td>
</tr>
</tbody>
</table>

SITE 451 HOLE 
CORE 34 CORED INTERVAL: 390.5-398.0 m

<table>
<thead>
<tr>
<th>AGE</th>
<th>NAMENS</th>
<th>FOSSILS</th>
<th>RADIOCARBON</th>
<th>BIOCSTR. CHARACTER</th>
<th>FOSSIL CHARACT.</th>
<th>FISH REMAINS</th>
<th>GRAPHIC LITHOLOGY</th>
<th>LITHOLOGIC DESCRIPTION</th>
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<tbody>
<tr>
<td>5Y 5/1</td>
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<td>VITRIFIC TUFF, alternating black dunes and very dark gray to grayish intervals, the latter with either parallel burrows or gray bioturbation. Some vesicular basalt fragments at 80 cm in Section 2. Similar beds with rare massive black layers, 1.0 cm thick, show LITHIC and VITRIFIC VOLCANICLASTIC CONGLOMERATE.</td>
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<td>5Y 2/1</td>
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<td>SMEAR SLIDE SUMMARY</td>
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<td>1-14 (0.1, 0.2, 0.1)</td>
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</tbody>
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SITE 451 HOLE 
CORE 35 CORED INTERVAL: 398.0-406.0 m

<table>
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<tr>
<th>AGE</th>
<th>NAMENS</th>
<th>FOSSILS</th>
<th>RADIOCARBON</th>
<th>BIOCSTR. CHARACTER</th>
<th>FOSSIL CHARACT.</th>
<th>FISH REMAINS</th>
<th>GRAPHIC LITHOLOGY</th>
<th>LITHOLOGIC DESCRIPTION</th>
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<tbody>
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<td>5Y 5/1</td>
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<td>VITRIFIC TUFF, black, grading down to LITHIC and VITRIFIC VOLCANICLASTIC CONGLOMERATE, dark greenish gray. Fragments of basalt, glass, and pumice up to 1.0 cm in diameter, in the Core-Catcher some of them exceed 4 cm.</td>
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<td>5Y 2/1</td>
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<td>Volcanic glass 35 65</td>
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<td>Micronodules 1 0</td>
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<td>1-14 (0.1, 0.2, 0.1)</td>
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</tbody>
</table>
**SITE 451 HOLE**
**CORE 38 CORED INTERVAL: 347.5-356.5 m**

**LITHOLOGIC DESCRIPTION**

- **General color**: SY 2/1

**VITRIC TUFF, black, interbedded with LITHIC and VITRIC VOLCANOCLASTIC CONGLOMERATE.**

- Vitrification tuff, black, interbedded with LITHIC and VITRIC VOLCANOCLASTIC CONGLOMERATE. Vitrification tuff is very fine-grained, with the matrix ratio of about 4:1. The average grain size is 4 mm, maximum 3 cm. Diatomaceous sediment is characterized by polygonal shapes and replaced with spiral to dichotomous rhizomes. In the matrix, small bivalve shells and barnacles are present. At the base of the tuff, lenses of VITRIC VOLCANOCLASTIC CONGLOMERATE are present, characterized by a high concentration of pumice clasts and matrix.

**SMEAR SLIDE SUMMARY**

<table>
<thead>
<tr>
<th>TEXTURE:</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>17%</td>
<td>90%</td>
<td>3%</td>
<td></td>
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<tr>
<td>30%</td>
<td>53%</td>
<td>17%</td>
<td></td>
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</tbody>
</table>

**COMPOSITION:**

<table>
<thead>
<tr>
<th>Feldspar</th>
<th>Heavy Minerals</th>
<th>Clay Minerals</th>
<th>Volcanic Glass</th>
<th>Micronodules</th>
</tr>
</thead>
<tbody>
<tr>
<td>7%</td>
<td>1%</td>
<td>30%</td>
<td>53%</td>
<td>9%</td>
</tr>
</tbody>
</table>

**CARBON/CARBONATE:**

- CARBONATE BONN: 1-15 (0.0, 0.8, 0.1)
- CARBON/CARBONATE: 1-5 (0.0, 0.1, 0.5)

**BULK ANALYSIS:**

- SiO₂: 49.7
- TiO₂: 0.63
- Al₂O₃: 19.0
- Fe₂O₃: 1.27
- FeO: 8.41
- MnO: 0.19
- MgO: 11.16
- CaO: 2.16
- Na₂O: 0.72
- K₂O: 0.06

**PHYSICAL PROPERTIES:**

- Section: 120 cm
- Core: 205
- Na₂O: 2.16
- K₂O: 0.72
- Quartz: 0.56
- Biotite: 0.11
**SITE 451 HOLE**

**CORE 40 CORED INTERVAL:** 366.0-375.5 m

**LITHOLOGIC DESCRIPTION**

- Clay
- Silt
- Texture: with calcareous clay. Dip and flow fabric also contain small grains.
- Volcanic glass
- Heavy minerals

**TOTAL DETRITAL**

<table>
<thead>
<tr>
<th>Component</th>
<th>Sand</th>
<th>Zeolites</th>
<th>Clay minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>87</td>
<td>93</td>
<td>87</td>
</tr>
</tbody>
</table>

**SMEAR SLIDE SUMMARY**

- Layer of black well bedded, with glass (20%), subaerially weathered basalt (5%), and volcanic glass (20%).
- Clasts:matrix 4:1
- CONGLOMERATE, LITHIC and VITRIC VOLCANICLASTIC
- Basalt:andesite. The vitric tuff shows frequent parallel lamination and bedding. Grain density: 4649, with a few lithic fragments.

**CARBONATE**

- General color: dark gray to black
- Contains disseminated planktonic foraminifers, and carbonaceous material.

**LITHOLOGY**

- Wet bulk density: 1.80
- Grain density: 2.65
- Porosity (%): 50

**AGE**

- NANNOS: 1
- FORAMS: 2
- RAIDS: 3
- FOSSIL: 4
- ABUNDANCE: 5
- PRESERV: 6

**PHYSICAL MEASUREMENTS**

- METER: 1
- LITHOLOGIC INTERVAL: 366.0-375.5 m

**SITE 451 HOLE**

**CORE 41 CORED INTERVAL:** 375.5-385.0 m

**LITHOLOGY**

- Wet bulk density: 1.80
- Grain density: 2.65
- Porosity (%): 50

**CONGLOMERATE**

- LITHIC and VITRIC VOLCANICLASTIC
- Basalt:andesite. The conglomerate has a clasts:matrix ratio of 2:1, with a few lithic fragments.

**SMEAR SLIDE SUMMARY**

- Layer of black well bedded, with glass (20%), subaerially weathered basalt (5%), and volcanic glass (20%).
- Clasts:matrix 4:1
- CONGLOMERATE, LITHIC and VITRIC VOLCANICLASTIC
- Basalt:andesite. The vitric tuff shows frequent parallel lamination and bedding. Grain density: 4649, with a few lithic fragments.

**CARBONATE**

- General color: dark gray to black
- Contains disseminated planktonic foraminifers, and carbonaceous material.
### Lithologic Description

**Site 451 Hole**

**Core 43**

**Cored Interval:** 394.5-404.0 m

<table>
<thead>
<tr>
<th>Age</th>
<th>Biostr. Zone</th>
<th>Fossil Character</th>
<th>Graphic Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>2/1 + 2/1</td>
<td>VITRIC TUFF, massive where coarse grained; carbonate-hematite and with intercalated light gray laminae where fine grained.</td>
<td></td>
</tr>
</tbody>
</table>

**Core 44**

**Cored Interval:** 404.0-413.5 m

<table>
<thead>
<tr>
<th>Age</th>
<th>Biostr. Zone</th>
<th>Fossil Character</th>
<th>Graphic Lithology</th>
</tr>
</thead>
</table>
| C3 | 2/1 | VITRIC TUFF, black, bioturbated with dark olive-gray, rich in planktonic foraminifers alternating with zones of very fine-grained.

**Core 45**

**Cored Interval:** 413.5-416.5 m

<table>
<thead>
<tr>
<th>Age</th>
<th>Biostr. Zone</th>
<th>Fossil Character</th>
<th>Graphic Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>2/1</td>
<td>VITRIC TUFF, black, with intercalations of gray and carbonate-rich tuff.</td>
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</tbody>
</table>

**Core 46**

**Cored Interval:** 416.5-423.0 m

<table>
<thead>
<tr>
<th>Age</th>
<th>Biostr. Zone</th>
<th>Fossil Character</th>
<th>Graphic Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>2/1</td>
<td>BOLUER VOLCANIClastic CONGLOMERNATE, very dark gray, with intercalations of gray and carbonate-rich tuff.</td>
<td></td>
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</tbody>
</table>

**Smear Slide Summary**

**Texture:** Silt, clay, silt-clay, very fine-grained.

**Composition:**
- Feldspar: 20-45%
- Silt: 10-30%
- Clay: 5-15%
- Pores: 1-30%
- Organic material: 0-5%
- Carbonate: 0-10%
- Volcanic rock fragments: 0-10%
- Matrix: 0-10%

**Bulk Analysis**

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<tr>
<th>Element</th>
<th>wt. %</th>
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<tbody>
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<td>48.3</td>
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<tr>
<td>TiO₂</td>
<td>0.60</td>
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<tr>
<td>Al₂O₃</td>
<td>19.8</td>
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<tr>
<td>Fe₂O₃</td>
<td>1.21</td>
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<tr>
<td>MnO</td>
<td>0.19</td>
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<tr>
<td>MgO</td>
<td>7.97</td>
</tr>
<tr>
<td>CaO</td>
<td>12.30</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.13</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Physical Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Wet bulk density</td>
<td>2.71</td>
</tr>
<tr>
<td>Density</td>
<td>2.75</td>
</tr>
</tbody>
</table>

**Site 451 Hole**

**Core 48**

**Cored Interval:** 415.6-423.0 m

<table>
<thead>
<tr>
<th>Age</th>
<th>Biostr. Zone</th>
<th>Fossil Character</th>
<th>Graphic Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3</td>
<td>2/1</td>
<td>BOLUER VOLCANIClastic CONGLOMERNATE, very dark gray, with intercalations of gray and carbonate-rich tuff.</td>
<td></td>
</tr>
</tbody>
</table>

**Smear Slide Summary**

**Texture:** Silt, clay, silt-clay, very fine-grained.

**Composition:**
- Feldspar: 20-45%
- Silt: 10-30%
- Clay: 5-15%
- Pores: 1-30%
- Organic material: 0-5%
- Carbonate: 0-10%
- Volcanic rock fragments: 0-10%
- Matrix: 0-10%

**Bulk Analysis**

<table>
<thead>
<tr>
<th>Element</th>
<th>wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>48.3</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.60</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>19.8</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.21</td>
</tr>
<tr>
<td>MnO</td>
<td>0.19</td>
</tr>
<tr>
<td>MgO</td>
<td>7.97</td>
</tr>
<tr>
<td>CaO</td>
<td>12.30</td>
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<td>K₂O</td>
<td>0.19</td>
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</tbody>
</table>

**Physical Properties**

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</tr>
<tr>
<td>Density</td>
<td>2.75</td>
</tr>
</tbody>
</table>
SITE 451 HOLE
CORE 47 CORED INTERVAL: 423.0-432.5 m
(Hole deviation of 3.0" at 423.0 m)

SITE 451 HOLE
CORE 48 CORED INTERVAL: 432.5-442.0 m

VITRIC TUFF, black, vitric tuff, black, with moderately fine general color laminations and cross-bedding and -10% biogenic component.

SITE 451 HOLE
CORE 49 CORED INTERVAL: 442.0-451.5 m

LITHOLOGIC DESCRIPTION
VITRIC TUFF, black, massive and structureless, contains 2% white biogenic grains which include benthonic foraminifers.

SITE 451 HOLE
CORE 50 CORED INTERVAL: 451.5-461.0 m

AGE BIOSTR.
ZONE
NANNOS
FORAMS
RADS
FOSSIL
ABUNDANCE
PRESERV.

SECTION METERS

TEXTURE: Sand Silt Clay
TOTAL DETRITAL COMPOSITION: Feldspar Heavy minerals Clay minerals Volcanic glass Micronodules Zeolites

TR TR TR TR (M) 0 50 50 80 1-62 2-33 10 87 3 8 3 _ _ 3 5 1 _ _ 5

BIOSTR. FORAMS RADS FOSSIL CHARACT FOSSIL ABUNDANCE PRESERV.

SECTION CC METERS

GRAPHIC LITHOLOGY

SITE 451 HOLE
CORE 51 CORED INTERVAL: 461.0-470.5 m

N5 VOLCANICLASTIC CONGLOMERATE, light to medium gray.
FINE VITRIC TUFF, and large medium gray.
FINE VITRIC TUFF, all drilling fragments, with approximately 30% biogenic material and minor bioturbation. This fine vitric tuff grades downward into a coarser dark gray VITRIC TUFF with one erosional contact visible in the transition zone.

SITE 451 HOLE
CORE 52 CORED INTERVAL: 470.5-480.0 m

SITE 451 HOLE
CORE 53 CORED INTERVAL: 480.0-488.5 m

SITE 451 HOLE
CORE 54 CORED INTERVAL: 488.5-500.5 m

SITE 451 HOLE
CORE 55 CORED INTERVAL: 500.5-510.5 m

SITE 451 HOLE
CORE 56 CORED INTERVAL: 510.5-520.5 m

SITE 451 HOLE
CORE 57 CORED INTERVAL: 520.5-530.5 m

SITE 451 HOLE
CORE 58 CORED INTERVAL: 530.5-541.0 m

SITE 451 HOLE
CORE 59 CORED INTERVAL: 541.0-550.5 m

SITE 451 HOLE
CORE 60 CORED INTERVAL: 550.5-561.0 m

SITE 451 HOLE
CORE 61 CORED INTERVAL: 561.0-570.5 m

SITE 451 HOLE
CORE 62 CORED INTERVAL: 570.5-581.0 m

SITE 451 HOLE
CORE 63 CORED INTERVAL: 581.0-591.0 m

SITE 451 HOLE
CORE 64 CORED INTERVAL: 591.0-601.0 m

SITE 451 HOLE
CORE 65 CORED INTERVAL: 601.0-611.0 m

SITE 451 HOLE
CORE 66 CORED INTERVAL: 611.0-621.0 m

SITE 451 HOLE
CORE 67 CORED INTERVAL: 621.0-631.0 m
SITE 451 HOLE
CORE 52 CORED INTERVAL: 470.5-473.5 m

LITHOLOGIC DESCRIPTION

VOLCANIClastic CONGLOMERATE, black matrix, the majority of clasts are coarse and angular, surrounded by thin green-gray tuff and bluish-black andesite. It grades downward into 80 cm of dark green-black VITRIC TUFF, which contains a small amount of basalt clasts. In Core-Catcher a pumiceous FINE VITRIC TUFF with faint laminations dipping 20 degrees and minor bioturbation. The sediment is uniformly hard, drilling disturbance moderate.

SMEAR SLIDE SUMMARY

TEXTURE:
Sand 5
Silt 68
Clay 25

COMPOSITION:
Feldspar TR
Heavy minerals 1
Clay minerals 24
Volcanic glass 75
Micronodules 0

CARBON/CARBONATE: CARBONATE BOMB:
3-45(0.0, 4.0, 0.5) 3,46-47(3)

BULK ANALYSIS:
SiO₂ 48.4
TiO₂ 0.78
Al₂O₃ 19.4
Fe₂O₃ 1.07
FeO 7.05
MnO 0.13
MgO 7.76
CaO 10.99
Na₂O 2.40
K₂O 0.85
P₂O₅ 0.11

SITE 451 HOLE
CORE 53 CORED INTERVAL: 473.5-480.0 m

LITHOLOGIC DESCRIPTION

VITRIC TUFF, greenish black, massive, coarsens below 80 cm to 103 cm with clasts up to 3 mm diameter of green-gray tuff and tuff. Below 103 cm VOLCANIClastic CONGLOMERATE the matrix is green-gray tuff, black basalt, and rare pumice with diameters of 3 mm. Scattered, 8 cm diameter, medium dark gray, basalt clasts in thin-graded tuffs are present in Sections 1, 2, and the Core-Catcher. The sediment is uniformly hard, drilling disturbance slight.

SMEAR SLIDE SUMMARY

TEXTURE:
Sand 3
Silt 68
Clay 25

COMPOSITION:
Feldspar TR
Heavy minerals 1
Clay minerals 24
Volcanic glass 75
Micronodules TR

CARBON/CARBONATE: CARBONATE BOMB:
3-45(0.0, 4.0, 0.5) 3,46-47(3)

BULK ANALYSIS:
SiO₂ 48.4
TiO₂ 0.78
Al₂O₃ 19.4
Fe₂O₃ 1.07
FeO 7.05
MnO 0.13
MgO 7.76
CaO 10.99
Na₂O 2.40
K₂O 0.85
P₂O₅ 0.11
### Lithologic Description

**SITE 451 HOLE CORE 56 CORED INTERVAL: 490.5-499.0 m**

<table>
<thead>
<tr>
<th>Age</th>
<th>Layers</th>
<th>Lithology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-5.5</td>
<td>Vitric Tuff</td>
<td>Black, interbedded with Volcaniclastic Conglomerate. Graded contacts common. The clast ratio is ~2:1. Angular to rounded clasts of pyroclastic tephra breakage, and small lithic clasts occur in matrix of silt to sand-sized and altered glass often replaced by green smectite and intergranular and cavity-filling zeolitic and carbonate cement. Hydrothermal pyrite occurs sporadically in altered volcanic rocks. The tuff ranges from silt to very coarse sand-sized, and shows in places, graded bedding. <strong>Carbonate Bomb:</strong> 2, 24-25 (2).</td>
</tr>
<tr>
<td>2</td>
<td>5.5-20</td>
<td>Vitric Tuff</td>
<td>Black, interbedded with Volcaniclastic Conglomerate. Graded contacts common. The clast ratio is ~2:1. Angular to rounded clasts of pyroclastic tephra breakage, and small lithic clasts occur in matrix of silt to sand-sized and altered glass often replaced by green smectite and intergranular and cavity-filling zeolitic and carbonate cement. Hydrothermal pyrite occurs sporadically in altered volcanic rocks. The tuff ranges from silt to very coarse sand-sized, and shows in places, graded bedding. <strong>Carbonate Bomb:</strong> 2, 24-25 (2).</td>
</tr>
<tr>
<td>3</td>
<td>20-40</td>
<td>Vitric Tuff</td>
<td>Black, interbedded with Volcaniclastic Conglomerate. Graded contacts common. The clast ratio is ~2:1. Angular to rounded clasts of pyroclastic tephra breakage, and small lithic clasts occur in matrix of silt to sand-sized and altered glass often replaced by green smectite and intergranular and cavity-filling zeolitic and carbonate cement. Hydrothermal pyrite occurs sporadically in altered volcanic rocks. The tuff ranges from silt to very coarse sand-sized, and shows in places, graded bedding. <strong>Carbonate Bomb:</strong> 2, 24-25 (2).</td>
</tr>
</tbody>
</table>

**SMEAR SLIDE SUMMARY**

**Texture:**
- Sand
- Silt

**Detrital Composition:**
- Feldspar: 3
- Heavy minerals: 2
- Volcanic glass: 7
- Organic carbon: 90

<table>
<thead>
<tr>
<th>CARBON/Carbonate</th>
<th>Clay/Silt</th>
<th>Texture</th>
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</thead>
<tbody>
<tr>
<td>2.0-2.2</td>
<td>3</td>
<td>Sand</td>
</tr>
<tr>
<td>2.0-2.2</td>
<td>3</td>
<td>Silt</td>
</tr>
</tbody>
</table>

**Physical Properties:**
- Bulk Density: 2.25
- Porosity (%): 43.0
- Grain density: 2.94
<table>
<thead>
<tr>
<th>AGE</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
<th>LITHOLOGIC DESCRIPTION</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
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<td>1.6</td>
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**SMEAR SLIDE SUMMARY**

<table>
<thead>
<tr>
<th>TEXTURE:</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>50</td>
<td>25</td>
<td>9.0</td>
</tr>
</tbody>
</table>

**CARBON/CARBONATE**

- **CARBONATE BOMB**: 2, 14.5 (47)

**LITHOLOGIC DESCRIPTION**

- **VITRIC and LITHIC TUFF and TUFFACEOUS VOLCANICLASTIC BRECCIA, gray**: The tuff is very fine to coarse sand-sized, vitric and vitrichy, containing a mottled texture (TIV), scattered or clustered in intervals among the tuff layers. Their composition is the same as the previous core.

**TEXTURE:**

- Sand: 25
- Silt: 50
- Clay: 25

**COMPOSITION:**

- Feldspar: 25
- Heavy minerals: 25
- Clay minerals: 25
- Volcanic glass: 50
- Micronodules: 5
- Zeolites: 5
- Recrystallized carbonates: 5
- Foraminifers: 5

**PHYSICAL PROPERTIES**

- Wet bulk density: 2.61
- Porosity (%): 25
- Grain density: 2.86

---

<table>
<thead>
<tr>
<th>AGE</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
<th>FOSSIL</th>
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<tr>
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<td>1.0</td>
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<td></td>
<td></td>
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<tr>
<td>1.6</td>
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**SMEAR SLIDE SUMMARY**

<table>
<thead>
<tr>
<th>TEXTURE:</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>25</th>
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<tbody>
<tr>
<td></td>
<td>25</td>
<td>50</td>
<td>25</td>
<td>9.0</td>
</tr>
</tbody>
</table>

**CARBON/CARBONATE**

- **CARBONATE BOMB**: 2, 14.5 (47)
### Lithologic Description

**SITE 451 HOLE**

**CORE 63 CORED INTERVAL:** 565.5 - 575.0 m

**SITE 451 HOLE**

**CORE 64 CORED INTERVAL:** 575.5 - 584.5 m

**Greenish-black VOLCANICLASTIC BRECCIA and VITRIC TUFF, as in Core 62.**

Section 2, the zones consists several layers of very dark, reddish-brown to black VITRIC TUFF and of carbonaceous VITRIC TUFF, dark brown to gray, intensely bioturbated and dark red gray. These lithotypes contain intervals with calcite brecciation, and are affected by normal faulting.

**VITRIC TUFF, dark gray to very dark gray to black, fine to coarse grained.**

**TOTAL DETRITAL COMPOSITION:**

- **Feldspar:** 3 - 10
- **Heavy minerals:** 2 - 5
- **Clay minerals:** 2 - 20
- **Carbonate:** 35 - 60
- **Magnetite:** 4 - 4
- **Zoisite:** 1 - 1
- **Pyrite:** 1 - 1

**CARBONATE:**

- **Carbonate bomb:** 3 - 97 (1)

**PHYSICAL PROPERTIES:**

- **Porosity:** 37%
- **Density:** 2.92
- **Grain density:** 2.64

**Carbonate bomb:**

- **Porosity:** 50%
- **Density:** 2.64

---

**SITE 451 HOLE**

**CORE 64 CORED INTERVAL:** 575.5 - 584.5 m

**Lithologic Description**

**VITRIC TUFF, dark gray to very dark gray to black, fine to coarse grained.**

The zones consist of several layers of very dark, reddish-brown to black VITRIC TUFF and of carbonaceous VITRIC TUFF, dark brown to gray, intensely bioturbated and dark red gray. These lithotypes contain intervals with calcite brecciation, and are affected by normal faulting.

**TOTAL DETRITAL COMPOSITION:**

- **Feldspar:** 3 - 10
- **Heavy minerals:** 2 - 5
- **Clay minerals:** 2 - 20
- **Carbonate:** 35 - 60
- **Magnetite:** 4 - 4
- **Zoisite:** 1 - 1
- **Pyrite:** 1 - 1

**CARBONATE:**

- **Carbonate bomb:** 3 - 97 (1)
LITHOLOGIC DESCRIPTION

VITRIC TUFF, black to dark gray, and TUFFACEOUS VOLCANICLASTIC BRECCIA, dark gray with dark greenish-gray clasts. The vitric tuff is a mixture of tuff, felsic or rhyolitic glass, and matrix. The clasts are subangular to sub-rounded, and the matrix is a fine-grained material. The ratio of vitric to matrix is 0.3 and unsorted, angular to subangular.

CARBON/Carbonate:
2-43 (>1, 0, 0)

CARBONATE BOMB:
2-41 (1, 0, 0)

BIOSTRATIGRAPHIC ZONE CHARACT.

PHYSICAL PROPERTIES:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet bulk density</td>
<td>2.21</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>39.8</td>
</tr>
<tr>
<td>Grain density</td>
<td>2.01</td>
</tr>
</tbody>
</table>
SITE 451 HOLE CORE 67 CORED INTERVAL: 622.5-632.0 m

LITHOLOGIC DESCRIPTION

<table>
<thead>
<tr>
<th>LITHOLOGIC</th>
</tr>
</thead>
</table>
| VITRIC TUFF, black and grayish black, fine to medium sand-sized with graded beds. In several intervals are dark blue-green vitric clasts. From 112 to 140 cm, Section 1, the rock is ovoid and brecciated. Dips 20°.
| CARBON/Carbone: |
| 1-26 (0.0, 0.3, 0.1) |

PHYSICAL PROPERTIES:

<table>
<thead>
<tr>
<th>Section</th>
<th>Wet bulk density</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.15</td>
<td>49.4</td>
</tr>
<tr>
<td>2</td>
<td>3.24</td>
<td></td>
</tr>
</tbody>
</table>

SITE 451 HOLE CORE 68 CORED INTERVAL: 632.0-641.5 m

LITHOLOGIC DESCRIPTION

<table>
<thead>
<tr>
<th>LITHOLOGIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITRIC TUFF, medium dark gray to dark gray and black in Sections 1 and 2; ranging from silt to coarse sand-size, with some medium to fine pebbles and occasional thin and very fine dusty blue-green laminated tuff.</td>
</tr>
<tr>
<td>CARBON/Carbone:</td>
</tr>
<tr>
<td>2-26 (0.0, 0.5, 0.1)</td>
</tr>
</tbody>
</table>

PHYSICAL PROPERTIES:

<table>
<thead>
<tr>
<th>Section</th>
<th>Wet bulk density</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.07</td>
<td>50.2</td>
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<tr>
<td>2</td>
<td>2.07</td>
<td></td>
</tr>
</tbody>
</table>

SITE 451 HOLE CORE 70 CORED INTERVAL: 613.0-622.5 m

LITHOLOGIC DESCRIPTION

<table>
<thead>
<tr>
<th>LITHOLOGIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITRIC TUFF, medium gray to dark gray and black in Sections 1 and 2; ranging from silt to coarse sand-size, with some medium to fine pebbles and occasional thin and very fine dusty blue-green laminated tuff.</td>
</tr>
<tr>
<td>CARBON/Carbone:</td>
</tr>
<tr>
<td>2-26 (0.0, 0.5, 0.1)</td>
</tr>
</tbody>
</table>

PHYSICAL PROPERTIES:

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<td>50.2</td>
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<tr>
<td>2</td>
<td>2.07</td>
<td></td>
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SITE 451 HOLE CORE 67 CORED INTERVAL: 622.5-632.0 m

LITHOLOGIC DESCRIPTION

<table>
<thead>
<tr>
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</tr>
</thead>
</table>
| VITRIC VOLCANICLASTIC BRECCIA, black with blue-gray clasts, occurs in Sections 1 to 3 and in the Core-Catcher. The clasts:matrix ratio is 4:1, the vitric clasts account for 95% of the total; they are mostly devitrified pumice with some pyroxene. The matrix is fine tuff. Dips 30°.
| CARBON/Carbone: |
| 2-26 (0.0, 0.5, 0.1) |

SHEAR SLIDE SUMMARY

<table>
<thead>
<tr>
<th>Texture:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand: 0</td>
</tr>
<tr>
<td>Silt: 0</td>
</tr>
<tr>
<td>Clay: 0</td>
</tr>
<tr>
<td>TOTAL DETRITAL COMPOSITION:</td>
</tr>
<tr>
<td>Feldspar: 1</td>
</tr>
<tr>
<td>Heavy minerals: 1</td>
</tr>
<tr>
<td>Clay minerals: 1</td>
</tr>
<tr>
<td>Volcanic glass: 1</td>
</tr>
<tr>
<td>Micronodules: 1</td>
</tr>
<tr>
<td>Zeolites: 1</td>
</tr>
<tr>
<td>Amorphous Fe oxide: 1</td>
</tr>
</tbody>
</table>

PHYSICAL PROPERTIES:

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<td>50.2</td>
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SHEAR SLIDE SUMMARY

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<td>Clay: 0</td>
</tr>
<tr>
<td>Total detrital composition:</td>
</tr>
<tr>
<td>Feldspar: 1</td>
</tr>
<tr>
<td>Heavy minerals: 1</td>
</tr>
<tr>
<td>Clay minerals: 1</td>
</tr>
<tr>
<td>Volcanic glass: 1</td>
</tr>
<tr>
<td>Micronodules: 1</td>
</tr>
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<tr>
<td>Amorphous Fe oxide: 1</td>
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</table>

PHYSICAL PROPERTIES:

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>2.07</td>
<td>50.2</td>
</tr>
<tr>
<td>2</td>
<td>2.07</td>
<td></td>
</tr>
</tbody>
</table>
SITE 451 HOLE

LITHOLOGIC DESCRIPTION

VOLCANICLASTIC BRECCIA, dark gray, 2 mm clasts in the upper 40 cm of Section 1. Clasts consist of distinct fragments with minor glass inclusions. The matrix is a fine to medium-grained, black, 2 mm diameter "waxy" calciclastic matrix. Below this is fine VITRIC TUFF; a well-rounded, well-sorted, normally graded unit that contains abundant fragments of glass and vesicles, and rare amorphous silica and rutile clasts (~5 mm diameter).

CARBONATE:
1.62 (0.0, 3.4, 0.4)

CARBONATE BOND:
1.02 (0.0, 0.0)

PHYSICAL PROPERTIES:
Section 1

Wet bulk density: 3.14
Porosity (%): 34.7
Grain density: 2.99

SITE 451 HOLE

LITHOLOGIC DESCRIPTION

VOLCANICLASTIC CONGLOMERATE, greenish gray; clasts are angular to subrounded, ~1 cm diameter; a mixture of volcanic, pyroclastic, and altered basaltic fragments. Below this is fine VITRIC TUFF; a well-rounded, well-sorted, normally graded unit through Section 4, increasing in thickness through Section 5 and the Core-Catcher, becoming coarser downward. The matrix is a fine-grained, well-sorted, normally graded unit that contains abundant fragments of glass and vesicles, and rare amorphous silica and rutile clasts (~5 mm diameter).

CARBONATE:
3.56 (0.0, 3.4, 0.4)

CARBONATE BOND:
3.96 (0.0, 0.0)

PHYSICAL PROPERTIES:

Wet bulk density: 2.25
Porosity (%): 34.7
Grain density: 3.14

SITE 451 HOLE

LITHOLOGIC DESCRIPTION

VOLCANICLASTIC BRECCIA, dark gray, 2 mm clasts in the upper 40 cm of Section 1. Clasts consist of distinct fragments with minor glass inclusions. The matrix is a fine to medium-grained, black, 2 mm diameter "waxy" calciclastic matrix. Below this is fine VITRIC TUFF; a well-rounded, well-sorted, normally graded unit that contains abundant fragments of glass and vesicles, and rare amorphous silica and rutile clasts (~5 mm diameter).

CARBONATE:
1.62 (0.0, 3.4, 0.4)

CARBONATE BOND:
1.02 (0.0, 0.0)

PHYSICAL PROPERTIES:
Section 1

Wet bulk density: 3.14
Porosity (%): 34.7
Grain density: 2.99
**LITHOLOGIC DESCRIPTION**

**SITE 451 HOLE**

**CORE 73**

**CORED INTERVAL:** 680.5-670.0 m

**GENERAL COLOR:**
- 9G3 Y 2/1, 7YR 2/1, 5GY 2/1

**TUFFACEOUS VOLCANIClastic CONGLOMERATE,** greenish black and brownish black. The greenish-black conglomerate contains subangular to subrounded 0.5 cm clasts of vesicular aphyric basalts, basaltic andesites, hydrothermally altered glass, and altered andesites with eburnoid pseudomorphs containing fragments of olivine, pyroxenes, and carbonates. The matrix is mainly altered glass with carbonate cement. This greenish-black tuff is interbedded with a massive brownish-black tuff of fine sandstone.

**SMEAR SLIDE SUMMARY**

**TEXTURE:**
- Sand: 1-87
- Silt: 4-96
- Clay: 0-3

**TOTAL DRETIAL COMPOSITION:**
- Feldspar: 1-15
- Quartz: 20
- Micas: 76
- Clays: 5

**CARBON/CARBONATE:**
- Carbonate Bomb: 1-41

**AGE BIOSTR. ZONE NANNOS FORAMS RADS FOSSIL CHARACT FOSSIL ABUNDANCE PRESERV. SECTION METERS GRAPHIC LITHOLOGY DRILLING DISTURBANCE**

**SITE 451 HOLE**

**CORE 74**

**CORED INTERVAL:** 670.0-679.5 m

**GENERAL COLOR:**
- 9G3 Y 2/1, 7YR 2/1, 5GY 2/1

**VITRIC AND LITHIC AND TUFFACEOUS CONGLOMERATE TUFFS,** black to dark gray, interbedded throughout section. The tuffaceous matrix contains 0.5 cm clasts of altered olivine, plagioclase, and pyroxenes. Both clasts and matrix contain small grains of disseminated pyrite. The sediment is unevenly hard; drilling disturbance is slight.

**CARBON/CARBONATE:**
- Carbonate Bomb: 1-41 (0.0, 0.7, 0.1)
### Lithologic Description

**SITE 451 HOLE**

**Cored Interval:** 702.5-708.0 m

**CORED INTERVAL:** 708.0-717.5 m

**FOSSIL**

- **CHARACTER**
  - **LITHOLOGIC DESCRIPTION**
    - Color:
      - 5Y 4.5/1, 5G 4.5/1
      - 10YR 6.5/1
      - 7.5YR 5/2, 7.5YR 4/2
    - Texture:
      - VITRIC TUFF, greenish black
    - Structure:
      - Concretionary, banded, interbedded with vitric tuffs
    - Sedimentary Structures:
      - Mottled, bioturbated
    - Other:
      - TUFFACEOUS VOLCANICLASTIC BRECCIA

**TEXTURE:**

- **TOTAL DETRITAL**
  - **COMPOSITION**
    - *Sand*:
      - 1
    - *Silt*:
      - 1
    - *Clay*:
      - 1
    - *Vitreous glass*:
      - 1
    - *Calcareous fragments*:
      - 1
    - *Fossils*:
      - 1

**CARBONATE CONTENT:**

- **CARBONATE BOMB**
  - **CARBONATE BOMB:**
    - 1, 101-102 (1)

**PHYSICAL PROPERTIES:**

- **Wet bulk density**
  - **Porosity (%)**
    - 2.12
  - **Grain density**
    - 2.97

---

**SITE 451 HOLE**

**Cored Interval:** 700.0-717.5 m

**FOSSIL**

- **CHARACTER**
  - **LITHOLOGIC DESCRIPTION**
    - Color:
      - 5B 4/1, 5BG 4/1
    - Texture:
      - TUFFACEOUS VOLCANICLASTIC BRECCIA
    - Structure:
      - Concretionary, banded
    - Other:
      - TUFFACEOUS VOLCANICLASTIC BRECCIA

**TEXTURE:**

- **TOTAL DETRITAL**
  - **COMPOSITION**
    - *Sand*:
      - 1
    - *Silt*:
      - 1
    - *Clay*:
      - 1
    - *Vitreous glass*:
      - 1
    - *Calcareous fragments*:
      - 1
    - *Fossils*:
      - 1

**CARBONATE CONTENT:**

- **CARBONATE BOMB**
  - **CARBONATE BOMB:**
    - 1, 101-102 (1)

**PHYSICAL PROPERTIES:**

- **Wet bulk density**
  - **Porosity (%)**
    - 2.12
  - **Grain density**
    - 2.97
### Lithologic Description

**SITE 451 HOLE**

**CORE 92**

**CORED INTERVAL:** 717.0-727.0 m

**LITHOLOGIC DESCRIPTION**

- **NS. SG 3/1**
  - Large transform zone

- **NS. B6**
  - Bornite

- **NS. B6**
  - Bornite

- **NS. SG 3/1**
  - TUFF, ACIDUS, VOLCANICLASTIC BRECCIA, medium dark gray to greenish-black; objets are large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

- **NS. SG 2/1**
  - TUFF, ACIDUS, VOLCANICLASTIC BRECCIA, medium dark gray to greenish-black; objets are large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

**PHYSICAL PROPERTIES:**

- **Wet bulk density:** 2.11
- **Porosity (%):** 44.7
- **Grain density:** 3.01

**BIOSTRAT. FOSSIL ZONE:**

- MCE
- ABUNDANT
- PRESERV.

### Lithologic Description

**SITE 451 HOLE**

**CORE 82**

**CORED INTERVAL:** 727.0-736.5 m

**LITHOLOGIC DESCRIPTION**

- **VITRIC TUFF, gray:**
  - Massive to massive-foliated; objets are medium to dark gray; objets are large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

- **CARBONATE BOMB:**
  - Medium to dark gray; objets are large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

**CARBONATE BOMB:**

- **1.114 (0.6, 0.8, 0.1)**

**CARBONATE BOMB:**

- **1.114 (0.6, 0.8, 0.1)**

**PHYSICAL PROPERTIES:**

- **Wet bulk density:** 2.11
- **Porosity (%):** 44.7
- **Grain density:** 3.01

**BIOSTRAT. FOSSIL ZONE:**

- MCE
- ABUNDANT
- PRESERV.

### Lithologic Description

**SITE 451 HOLE**

**CORE 81**

**CORED INTERVAL:** 727.0-736.5 m

**LITHOLOGIC DESCRIPTION**

- **VOLCANICLASTIC BRECCIA:**
  - Angular to subangular; objets are medium to large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

- **CARBONATE BOMB:**
  - Medium to dark gray; objets are large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

**CARBONATE BOMB:**

- **1.114 (0.6, 0.8, 0.1)**

**PHYSICAL PROPERTIES:**

- **Wet bulk density:** 2.11
- **Porosity (%):** 44.7
- **Grain density:** 3.01

**BIOSTRAT. FOSSIL ZONE:**

- MCE
- ABUNDANT
- PRESERV.

### Lithologic Description

**SITE 451 HOLE**

**CORE 93**

**CORED INTERVAL:** 736.5-746.0 m

**LITHOLOGIC DESCRIPTION**

- **VOLCANICLASTIC BRECCIA:**
  - Angular to subangular; objets are medium to large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

- **CARBONATE BOMB:**
  - Medium to dark gray; objets are large 3 to 5 m, uninterpreted and unzoned. Detritus variably zoned from 0.1 to 0.5 mm in diameter.

**CARBONATE BOMB:**

- **1.114 (0.6, 0.8, 0.1)**

**PHYSICAL PROPERTIES:**

- **Wet bulk density:** 2.11
- **Porosity (%):** 44.7
- **Grain density:** 3.01

**BIOSTRAT. FOSSIL ZONE:**

- MCE
- ABUNDANT
- PRESERV.
SITE 451 HOLE
CORE 64
CORE INTERVAL 755-765 m

LITHOLOGIC DESCRIPTION
VOLCANICLASTIC BRECCIA, greenish black.
The clasts:matrix ratio is 3:1, the vitric:lithic ratio is 1.5 cm, with rare 3 cm fragments. The clasts are crudely parallel oriented. The dip is ~30°. Trace amounts of biogenous carbonate debris are also present (large belemnite foraminifer).

CARBONATE: CARBONATE 2-71
CARBONATE BOMB: 2, 72-73 (11)

SITE 451 HOLE
CORE 65
CORE INTERVAL 765-774.5 m

LITHOLOGIC DESCRIPTION
INTERBEDDED TUFFACEOUS VOLCANICLASTIC BRECCIA, greenish black, and VITRIC TUFF, black to grayish black.
The breccia has a clasts:matrix ratio of 2:1 and a vitric:lithic ratio of 1:3 to 4. Clasts have maximum size of 1.3 to 1.6 cm, and rarely contains 10 to 15% scattered fragments up to 5 cm, carbonate-rich and bioturbated. Dip is -25°.

CARBONATE BOMB: 2, 95-96 (>1)
### Site 451 Hole 08 Core 88 Cored Interval: 774.5-784.0 m

#### Lithologic Description

<table>
<thead>
<tr>
<th>Layer</th>
<th>Color</th>
<th>Texture</th>
<th>Grains</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Green</td>
<td>Volcaniclastic Conglomerate</td>
<td>75%</td>
<td>25%</td>
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<tr>
<td>2</td>
<td>Gray</td>
<td>Volcaniclastic Conglomerate</td>
<td>50%</td>
<td>50%</td>
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<tr>
<td>3</td>
<td>Brown</td>
<td>Tuffaceous Volcaniclastic Conglomerate</td>
<td>60%</td>
<td>40%</td>
</tr>
</tbody>
</table>

### Site 451 Hole 09 Core 89 Cored Interval: 784.5-794.0 m

#### Lithologic Description

<table>
<thead>
<tr>
<th>Layer</th>
<th>Color</th>
<th>Texture</th>
<th>Grains</th>
<th>Matrix</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Green</td>
<td>Volcaniclastic Conglomerate</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>2</td>
<td>Gray</td>
<td>Volcaniclastic Conglomerate</td>
<td>60%</td>
<td>40%</td>
</tr>
<tr>
<td>3</td>
<td>Brown</td>
<td>Tuffaceous Volcaniclastic Conglomerate</td>
<td>70%</td>
<td>30%</td>
</tr>
</tbody>
</table>

### Site 451 Hole 08 Core 90 Cored Interval: 793.5-803.0 m

#### Lithologic Description

<table>
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<tr>
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<th>Color</th>
<th>Texture</th>
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<th>Matrix</th>
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<tbody>
<tr>
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<td>Volcaniclastic Conglomerate</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Gray</td>
<td>Volcaniclastic Conglomerate</td>
<td>80%</td>
<td>20%</td>
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<tr>
<td>3</td>
<td>Brown</td>
<td>Tuffaceous Volcaniclastic Conglomerate</td>
<td>75%</td>
<td>25%</td>
</tr>
</tbody>
</table>

### Site 451 Hole 09 Core 91 Cored Interval: 803.0-813.0 m

#### Lithologic Description

<table>
<thead>
<tr>
<th>Layer</th>
<th>Color</th>
<th>Texture</th>
<th>Grains</th>
<th>Matrix</th>
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<tbody>
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<td>Green</td>
<td>Volcaniclastic Conglomerate</td>
<td>85%</td>
<td>15%</td>
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<tr>
<td>2</td>
<td>Gray</td>
<td>Volcaniclastic Conglomerate</td>
<td>70%</td>
<td>30%</td>
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<tr>
<td>3</td>
<td>Brown</td>
<td>Tuffaceous Volcaniclastic Conglomerate</td>
<td>75%</td>
<td>25%</td>
</tr>
</tbody>
</table>

### Site 451 Hole 08 Core 92 Cored Interval: 812.0-822.0 m

#### Lithologic Description

<table>
<thead>
<tr>
<th>Layer</th>
<th>Color</th>
<th>Texture</th>
<th>Grains</th>
<th>Matrix</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Green</td>
<td>Volcaniclastic Conglomerate</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Gray</td>
<td>Volcaniclastic Conglomerate</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>3</td>
<td>Brown</td>
<td>Tuffaceous Volcaniclastic Conglomerate</td>
<td>75%</td>
<td>25%</td>
</tr>
</tbody>
</table>

---

**SITE 451**

**HOLE**

**CORE 88**

**CORED INTERVAL: 774.5-784.0 m**

**LITHOLOGIC DESCRIPTION**

VITRIC and LITHIC TUFF, interbedded with VOLCANICLASTIC CONGLOMERATE, dark greenish-gray. The rock has clasts:matrix ratio of 5:1, and includes a variety of clasts of altered greenish-gray tuff and carbonate rocks. The matrix is a vitric tuff with some pumice and altered tuff. The rock has subrounded to subangular clasts of altered glassy pumice and fine-grained volcanic ash. The rock has a wet bulk density of 2.07 g/cm³ and a porosity of 42.4%.

**CARBON/CARBONATE**

1-81 (0.0, 38.4, 4.7)

**PHYSICAL PROPERTIES**

- Wet bulk density: 2.07 g/cm³
- Porosity: 42.4%
- Grain density: 2.85 g/cm³

---

**SITE 451**

**HOLE**

**CORE 89**

**CORED INTERVAL: 784.5-794.0 m**

**LITHOLOGIC DESCRIPTION**

TUFFACEOUS VOLCANICLASTIC CONGLOMERATE, black, interbedded with dark greenish-gray carbonate-rich tuff. The rock has clasts:matrix ratio of 2:1, and includes a variety of clasts of altered greenish-gray tuff, vitrophyric basalt, and oxidised andesite. The matrix consists of smaller clasts of the same lithologies with some low-temperature hydrothermal calcite and zeolite cement. The tuff shows some gradation and parallel lamination; the carbonate-rich tuff has a clasts:matrix ratio of 4:1, and includes pumice and rare andesite. Some intercalated clasts are apparent in the vitric tuff.

**CARBON/CARBONATE**

1-129 (0.0, 0.2, 0.1)

**PHYSICAL PROPERTIES**

- Wet bulk density: 2.07 g/cm³
- Porosity: 42.4%
- Grain density: 2.85 g/cm³

---

**SITE 451**

**HOLE**

**CORE 90**

**CORED INTERVAL: 793.5-803.0 m**

**LITHOLOGIC DESCRIPTION**

VITRIC TUFF, greenish black, interbedded with VOLCANICLASTIC CONGLOMERATE, dark greenish-gray. The rock has clasts:matrix ratio of 5:1, and includes a variety of clasts of altered greenish-gray tuff and volcaniclastic rock. The rock has a wet bulk density of 2.07 g/cm³ and a porosity of 42.4%.

**CARBON/CARBONATE**

3-60 (0.0, 0.4, 0.1)

---

**SITE 451**

**HOLE**

**CORE 91**

**CORED INTERVAL: 803.0-813.0 m**

**LITHOLOGIC DESCRIPTION**

VITRIC TUFF, greenish black, interbedded with VOLCANICLASTIC CONGLOMERATE, dark greenish-gray. The rock has clasts:matrix ratio of 5:1, and includes a variety of clasts of altered greenish-gray tuff and volcaniclastic rock. The rock has a wet bulk density of 2.07 g/cm³ and a porosity of 42.4%.

**CARBON/CARBONATE**

1-130 (0.0, 0.4, 0.1)
**SITE 451 HOLE**

**CORE** 90

**CORED INTERVAL:** 812.5-822.0 m

<table>
<thead>
<tr>
<th>AGE</th>
<th>NANNOS</th>
<th>FORAMS</th>
<th>RADS</th>
<th>FOSSIL</th>
<th>CHARACT</th>
<th>LITHOLOGIC DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>N3</td>
<td>SB-4(1)</td>
<td>Hexitic debris</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>VITRIFIED TUFF, dark gray, interbedded with VOLCANIClastic CONGLOMERATE. Same lithology as in previous ones. Small plant debris present in the bottom. Sections are 1.0 cm thick. The vitric:clastic ratio is 1:3.</td>
</tr>
</tbody>
</table>

**PHYSICAL PROPERTIES:**
Section CC
- Wet bulk density: 2.04
- Porosity (%): 40.1
- Grain density: 2.73

**SITE 451 HOLE**

**CORE** 91

**CORED INTERVAL:** 822.0-831.5 m

<table>
<thead>
<tr>
<th>AGE</th>
<th>NANNOS</th>
<th>FORAMS</th>
<th>RADS</th>
<th>FOSSIL</th>
<th>CHARACT</th>
<th>LITHOLOGIC DESCRIPTION</th>
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<tbody>
<tr>
<td>N3</td>
<td>SB-4(1)</td>
<td>Hexitic debris</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>VITRIFIED TUFF, dark gray, and VOLCANIClastic CONGLOMERATE, dark gray to medium dark gray. Same lithology as in previous cores. The vitric:clastic ratio is 1:3; some clasts reach 4 cm. Two thin layers of gray, carbonaceous sedimentary rocks, if present, and small laminae are found in lower Section 2.</td>
</tr>
</tbody>
</table>

**SITE 451 HOLE**

**CORE** 92

**CORED INTERVAL:** 831.5-841.0 m

<table>
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<tr>
<th>AGE</th>
<th>NANNOS</th>
<th>FORAMS</th>
<th>RADS</th>
<th>FOSSIL</th>
<th>CHARACT</th>
<th>LITHOLOGIC DESCRIPTION</th>
</tr>
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<tbody>
<tr>
<td>N3</td>
<td>SB-4(1)</td>
<td>Hexitic debris</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>VITRIFIED TUFF, dark gray, and VOLCANIClastic CONGLOMERATE, dark gray to medium dark gray. Same lithology as in previous cores. The vitric:clastic ratio is 1:3; rare clasts reach 4 cm. The tuff contains 10 to 25% of gravel-sized, grayish material, and rare fossil debris. The vitric:clastic ratio is 1:3.</td>
</tr>
</tbody>
</table>

**LITHOLOGIC DESCRIPTION**

VITRIFIED TUFF, dark gray, and VOLCANIClastic CONGLOMERATE, dark gray to dark greenish gray; and VITRIFIED TUFF, dark gray, and VOLCANIClastic CONGLOMERATE, dark gray to medium dark gray. Same lithology as in previous cores. The vitric:clastic ratio is 1:3; rare clasts reach 4 cm. Two thin layers of gray, carbonaceous sedimentary rocks, if present, and small laminae are found in lower Section 2.
SITE 451 HOLE
CORE D 51
CORED INTERVAL: 860.0-869.5 m

LITHOLOGIC DESCRIPTION
N3 general color
VITRIC TUFF, dark gray and greenish black, interbedded with VOLCANIClastic BRECCIA, greenish black. The tuff contains cross, tabular, and parallel laminae displaying a variety of colors from brownish gray to dark greenish gray by dark gray. Rare bioturbation by individual burrows. The tuff is massed to breccia, which has a coarse matrix ratio of 3:1, a micro-falce ratio of 5:1, and contains mostly volcanic and glass fragments, some of which are angular, and oriented parallel to the bedding. Dip is 28 to 30°.

PHYSICAL PROPERTIES: Section 1
Wet bulk density: 2.20
Porosity (%): 35.4

SITE 451 HOLE
CORE D 51
CORED INTERVAL: 869.5-879.0 m

LITHOLOGIC DESCRIPTION
N3 general color
VITRIC TUFF, dark gray and greenish black, interbedded with VOLCANIClastic BRECCIA, greenish black. The tuff contains cross, tabular, and parallel laminae displaying a variety of colors from brownish gray to dark greenish gray by dark gray. Rare bioturbation by individual burrows. The tuff is massed to breccia, which has a coarse matrix ratio of 3:1, a micro-falce ratio of 5:1, and contains mostly volcanic and glass fragments, some of which are angular, and oriented parallel to the bedding. Dip is 28 to 30°.

PHYSICAL PROPERTIES: Section 1
Wet bulk density: 2.20
Porosity (%): 35.4

SITE 451 HOLE
CORE D 51
CORED INTERVAL: 889.5-899.0 m

LITHOLOGIC DESCRIPTION
FINE VITRIC TUFF, dark gray, with rounded lithic clasts to 3 mm in diameter. The tuff contains cross, tabular, and parallel laminae displaying a variety of colors from brownish gray to dark greenish gray by dark gray. Rare bioturbation by individual burrows. The tuff is massed to breccia, which has a coarse matrix ratio of 3:1, a micro-falce ratio of 5:1, and contains mostly volcanic and glass fragments, some of which are angular, and oriented parallel to the bedding. Dip is 28 to 30°.
### SITE 451 HOLE  CORE 99 CORED INTERVAL: 898.0-907.5 m

<table>
<thead>
<tr>
<th>AGE</th>
<th>NODULE</th>
<th>FOSSILS</th>
<th>FAUCES</th>
<th>FOSSILS</th>
<th>CHARACT.</th>
<th>GRAPHIC LITHOLOGY</th>
<th>METERS</th>
<th>LITHOLOGY DESCRIPTION</th>
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<tbody>
<tr>
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<td>93.37</td>
<td>0.14</td>
<td>4.30</td>
<td>0.03</td>
<td>0.30</td>
<td>0.14</td>
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<td>2</td>
<td>94.79</td>
<td>0.10</td>
<td>4.21</td>
<td>0.03</td>
<td>0.22</td>
<td>0.09</td>
<td>2.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**GRAPHIC LITHOLOGY**
- TUFFACEOUS VOLCANIClastic CONGLOMERATE
- Nodules, fine-grained sandstone, containing glass shards and other clasts.
- Carbonaceous material.

**LITHOLOGY DESCRIPTION**
- Dark gray, fine-grained sandstone, containing glass shards and other clasts.
- Carbonaceous material.

### SITE 451 HOLE  CORE 101 CORED INTERVAL: 917.0-926.5 m

<table>
<thead>
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<th>NODULE</th>
<th>FOSSILS</th>
<th>FAUCES</th>
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<th>GRAPHIC LITHOLOGY</th>
<th>METERS</th>
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<tbody>
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<td>4.30</td>
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<td>0.30</td>
<td>0.14</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
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**GRAPHIC LITHOLOGY**
- TUFFACEOUS VOLCANIClastic CONGLOMERATE
- Nodules, fine-grained sandstone, containing glass shards and other clasts.
- Carbonaceous material.

**LITHOLOGY DESCRIPTION**
- Dark gray, fine-grained sandstone, containing glass shards and other clasts.
- Carbonaceous material.

### SITE 451 HOLE  CORE 102 CORED INTERVAL: 926.5-930.5 m

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<th>NODULE</th>
<th>FOSSILS</th>
<th>FAUCES</th>
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<th>CHARACT.</th>
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<th>METERS</th>
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