Leg 200 Preliminary Report

Drilling at the Hawaii-2 Observatory (H2O) and the Nuuanu Landslide

16 December 2001–27 January 2002

Shipboard Scientific Party

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ABSTRACT

During Leg 200, we completed drilling operations for two distinct projects: (1) the Hawaii-2 Observatory (H2O), where we established a cased reentry borehole at Site 1224 and sampled the upper oceanic crust, and (2) the Nuuanu Landslide, where we recovered landslide deposits at Site 1223 that were derived from the Hawaiian Islands. The primary focus of the cruise was drilling at H2O, with Nuuanu Landslide drilling only being added to the Ocean Drilling Program (ODP) operations schedule about three months prior to the cruise and consuming only two days of operations. Below, we describe each project separately, focusing first on the H2O results and then the Nuuanu Landslide results.

The long-term H2O site satisfies three scientific objectives of crustal drilling: (1) it is located in one of the high-priority regions for the Ocean Seismic Network; (2) its proximity to the Hawaii-2 cable and the H2O junction box makes it a unique site for real-time, continuous monitoring of geophysical and geochemical experiments in the crust; and (3) it is on fast-spreading Pacific crust (7.1 cm/yr half-rate), which represents one end-member for models of crustal generation and evolution and crust/mantle interaction. The H2O junction box is in the eastern Pacific at 27°52.916′N, 141°59.504′W at a water depth of 4979 m, roughly halfway between California and Hawaii. The primary goal of the leg was to drill a suitable hole for a borehole seismometer that will be installed later. This was accomplished in Hole 1224D, where we installed a reentry cone and cemented casing 30 m into basaltic basement 1.48 km northeast of the H2O junction box. Above basement there was 28–30 m of soft, red clay. The cased basement interval, in which the instrument will be installed, consisted of two well-consolidated massive basalt flows. We also drilled a second single-bit hole, which was cored and logged, within 20 m of the first to a depth of 145 m into basement. The second hole was left with a free-fall funnel so that it also could be reentered using the wireline reentry technology to carry out other borehole experiments at the site. In addition to a suite of shipboard physical and chemical analyses that can be used to characterize the crust surrounding the observatory, we also conducted microbiological analyses of the recovered sediments and basalts. As a general trend, bacterial population numbers decreased with increasing depth, though the amount of metabolically active bacteria remained remarkably high at 41%–62% of the total cell counts. The successful cultivation of oxidizing bacteria and the microscopic indication of further microbial structures within a basaltic rock confirm the presence and even activity of microbial life not only in deep marine sediments, but also in the Paleogene oceanic crust from the North Pacific.

During Leg 200, we also cored the Nuuanu Landslide site on the Hawaiian Arch, ~300 km northeast of Honolulu. The upper 100 m of sediment at this site was thought to contain a record of the Nuuanu Landslide, a catastrophic event or series of events that removed ~40% (3000 to 4000 km^3) of the Koolau Volcano on the island of Oahu. We recovered several lithologic units that were transported to the site by a number of distinct landslide events. The origin of the deposits, as indicated by petrographic inspection and geochemistry, is the Hawaiian Islands. Two pyroclastic events, similar to the 1980 Mount Saint Helens' eruption but an order of magnitude larger, occurred on Koolau at ~2 Ma. These events may correlate with the collapse of the flank of the volcano and the formation of the Nuuanu debris field. The turbidites and pyroclastic material are of similar age to the Nuuanu Landslide (1.8–2.4 Ma) and are more than 38 m thick at Site 1223, >300 km from Oahu. We did not core to the bottom of the Nuuanu-related sequence. Thus the Nuuanu-related deposits may be thicker, and additional landslide events may have occurred.

HAWAII-2 OBSERVATORY

The use of submarine cables provides a tremendous opportunity for real-time data acquisition from permanent broadband seismometers on the seafloor. Programs to use retired submarine cables for this purpose have been initiated in the United States (e.g., Butler et al., 1995a) and Japan (e.g., Kasahara et al., 1998).

The Hawaii-2 submarine cable system is a retired AT&T telephone cable system between San Luis Obispo, California, and Makaha, on Oahu, Hawaii (Fig. F1). The cable system was originally laid in 1964. Incorporated Research Institutions for Seismology (IRIS) installed a long-term seafloor observatory about halfway along the cable (~140°W, 28°N). The cable was cut and terminated with a seafloor junction box (Fig. F2). The location of the junction box on the seafloor defines the location of the Hawaii-2 Observatory (H2O), which was named after the original AT&T cable.

The junction box has eight underwater make-break connections. About 500 W of power is available from the junction box, and there is ample capacity for two-way, real-time communications with seafloor instruments. Data channels from the seafloor can be monitored continuously via the Oahu end of the cable to any lab in the world. The California end of the cable cannot be used because it was cut and removed from the continental shelf.

There is a shallow buried broadband seismometer operating at the site that monitored noise from the *JOIDES Resolution* during our cruise. The sensor consists of a modified Guralp CMG-3T broadband seismometer and a conventional 1-Hz three-component geophone and it is buried in a caisson ~1 m below the seafloor (mbsf) (Duennebier et al., 2000, in press). This sensor has been transmitting seismic data to shore continuously and in real time for over 2 yr. The seismic data are forwarded to the IRIS Data Management Center in Seattle and are included in the Global Seismic Network database for use in global and regional earthquake studies. Other seafloor observatories, such as a geomagnetic observatory (Chave et al., 1995), a hydrothermal observatory (Davis et al., 1992; Foucher et al., 1995), or a broadband borehole seismic observatory (Orcutt and Stephen, 1993), can be installed at the site as funding becomes available.

Within the Ocean Drilling Program (ODP) and marine geology and geophysics communities, there has been considerable interest in the past few years in long-term seafloor observatories that include a borehole installation. Prototype long-term borehole and seafloor experiments almost exclusively use battery power and internal recording. The data are only available after a recovery cruise. One exception to this is the Columbia-Point Arena ocean bottom seismic station (OBSS), which was deployed on an offshore cable by Sutton and others in the 1960s (Sutton et al., 1965; Sutton and Barstow, 1990). For the foreseeable future, the most practical method for acquiring real-time, continuous data from the seafloor will be over cables (Chave et al., 1990). The H2O project provides this opportunity.

Geological Setting

The Hawaii-2 cable runs south of the Moonless Mountains between the Murray and Molokai Fracture Zones (Fig. F1) (Mammerickx, 1989). Between 140°W and 143°W, water depths along the cable track are typical for the deep ocean (4250–5000 m), the crustal age varies from 45 to 50 Ma (Eocene), and the sediment thickness to within the available resolution is ~100 m or less. Prior to the cable survey cruise in August 1997 (Stephen et al., 1997), sediment thickness was not well resolved along the track (Winterer, 1989).

Tectonically, the cable runs across the "disturbed zone" south of the Murray Fracture Zone, between magnetic isochrons 13 and 19 (Atwater, 1989; Atwater and Severinghaus, 1989). In the disturbed zone, substantial pieces of the Farallon plate were captured by the Pacific plate in three discrete ridge jumps and several propagating rifts. To avoid this tectonically complicated region and to be well away from the fracture zone to the south of the disturbed zone, the H2O was situated west of isochron 20 (45 Ma) at ~140°W. The crust west of 140°W was formed between the Pacific and Farallon plates under "normal" spreading conditions at a "fast" half-rate of ~7.1 cm/yr (Atwater, 1989; Cande and Kent, 1992). At the time this crust was formed, the Farallon plate had not split into the Cocos and Nazca plates, and the ridge that formed this crust was the same as the present-day East Pacific Rise.

Between 140°W and 143°W, the Hawaii-2 cable lies in the pelagic clay province of the North Pacific (Leinen, 1989). The sediments in this part of the Pacific are eolian in origin, consisting primarily of dust blown eastward from the arid regions of central Asia. This region of the Pacific is below the calcite compensation depth (~3500 m), and little or no biogenic calcite is thought to reach the seafloor (Leinen, 1989). Siliceous biogenic material is rapidly dissolved by the silica-poor bottom waters. The sediments are unfossiliferous red clays.

The H2O site lies in a smooth abyssal plane environment. The drill site, identified as Site H2O-5 during planning and now identified as ODP Site 1224, is on the same crustal block as the H2O junction box (Table T1; Figs. F3, F4).

Scientific Objectives

Drilling at the H2O site was proposed to accomplish two main objectives:

1. Drill and case a reentry hole into basement near the existing Hawaii-2 cable and the H2O junction box in order to establish a long-term borehole geophysical observatory for continuous real-time seismic monitoring, as well as other geophysical experiments.
2. Sample a section of normal, fast-spreading ocean crust for use in constraining geochemical and hydrothermal models of crustal evolution.

Ocean Seismic Network

Establishing a borehole seismometer in the H2O area is valuable for addressing both teleseismic (whole Earth) and regional seismic studies. For uniform coverage of seismic stations on the surface of the planet, which is necessary for whole-Earth tomographic studies, seafloor seismic observatories are required. This site, where there is no land in a 2000-km^2 area, is one of three high-priority prototype observatories for the Ocean Seismic Network (OSN) (Butler, 1995a, 1995b; Purdy, 1995). Global seismic tomography (GST) provides three-dimensional images of the lateral heterogeneity in the mantle and is essential in addressing fundamental problems in subdisciplines of geodynamics such as mantle convection, mineral physics, long-wavelength gravimetry, geochemistry of ridge systems, geomagnetism, and geodesy. Specific problems include the characteristic spectrum of lateral heterogeneity as a function of depth, the anisotropy of the inner core, the structure of the core/mantle boundary, the role of oceanic plates and plumes in deep mantle circulation, and the source rupture processes of Southern Hemisphere earthquakes, which are among the world's largest (Forsyth et al., 1995).

The culturally important earthquakes in California are only observed at regional distances on land stations in North America, which restrict the azimuthal information to an arc spanning ~180°. To observe California earthquakes at regional distances to the west requires seafloor stations. Regional observations are used in constraining earthquake source mechanisms. Since the H2O data will be available in real time, data could be incorporated into focal mechanism determinations within minutes of California earthquake events. Other problems that can be addressed with regional data from Californian and Hawaiian earthquakes are the structure of the 400-, 525-, and 670-km discontinuities in the northeastern Pacific and the variability of elastic and anelastic structure in the Pacific lithosphere from P_o and S_o (Butler 1995a, 1995b).

In 1998 at the OSN pilot experiment site established in seafloor west of Hawaii, we deployed seafloor, buried, and borehole broadband seismometers to compare the performance of three different styles of installation. Figures F5 and F6 summarize for vertical and horizontal component data, respectively, the improvement that we expect to see in ambient seismic noise on placing a sensor in basement rather than on or in the sediments. Above the microseism peak at 0.3 Hz, the seafloor, buried, and borehole spectra at the OSN-1 site show the borehole to be 10 dB quieter on vertical components and 30 dB quieter on horizontal components (Collins et al., 2001). Shear wave resonances (or Scholte modes) are the physical mechanism responsible for the higher noise levels in or on the sediment. The resonance peaks are particularly distinct and strong at the H2O site. Note the 15-dB peak on the vertical component and the 35-dB peak on the horizontal components near 1 Hz on the H2O spectra. By placing a borehole seismometer in basement at the H2O, we expect to eliminate these high ambient noise levels.

Basement Drilling on the Pacific Plate

In over 30 yr of deep ocean drilling prior to ODP Leg 200 at more than 1200 sites worldwide, there have been only 13 holes with >10 m penetration into “normal” igneous Pacific plate (only one hole during ODP), only one hole with >100 m penetration, and no holes in crust with ages between 29 and 72 Ma. Table T2 summarizes the boreholes drilled on “normal” crust on the Pacific plate that have >10 m of basement penetration and crustal ages <100 Ma. Holes in seamounts, plateaus, aseismic ridges, and fracture zones were not included. Holes with crustal ages >100 Ma are not included since they would be affected by the mid-Cretaceous super plume (Pringle et al., 1993).

Besides the general sparsity of sampling of oceanic crust, there are no boreholes off axis in “very fast” spreading crust. Although fast-spreading ridges represent only ~20% of the global ridge system, they produce more than half of the ocean crust on the surface of the planet, almost all of it along the East Pacific Rise. Most ocean crust currently being recycled back into the mantle at subduction zones was produced at a fast-spreading ridge. If we wish to understand the Wilson cycle in its most typical and geodynamically significant form, we need to examine ocean crust produced at fast-spreading ridges. We have also known for more than 40 yr that crust generated by fast spreading is both simple and uniform, certainly so in terms of seismic structure (Raitt, 1963; Menard, 1964). Successful deep drilling of such crust at any single location is thus likely to provide fundamental information that can be extrapolated to a significant fraction of the Earth’s surface. Seafloor spreading that generated the ~45 Ma crust at the H2O was fast, with the full rate averaging 142 mm/yr. Thus, one objective of Leg 200 was to provide a reference station in “normal,” fast-spreading ocean crust for use in constraining geochemical and hydrothermal models of crustal evolution.

Operations

We departed Site 1223 at 0130 hr on 23 December 2001 and arrived in the vicinity of the H2O junction box (27°52.916′N, 141°59.504′W) at 0000 hr on 26 December to begin a seismic and 3.5-kHz echo sounder survey. All times are reported in ship local time, which is Universal Time Coordinated – 9 hr at Site 1224. The 766-nmi voyage took 2.9 days at an average speed of 10.9 kt.

Following completion of the surveying at 0745 hr on 26 December, the *JOIDES Resolution* returned and positioned on proposed Site H2O-5 (Fig. F7) with Global Positioning System (GPS) navigation at 0845 hr on 26 December. Operations were suspended while waiting on weather (WOW) because of heave, pitch, roll, and wind up to 7.7 m, 5.2°, 4.5°, and 29 kt respectively. A total of 13.25 hr of WOW time occurred before drilling operations could proceed.

Prior to conducting drilling operations, the vibration isolated television (VIT) camera was launched to conduct a camera survey of the site for debris, while also conducting a survey with an echo sounder attached to the VIT frame to further delineate subsurface layers. The survey covered a 30 m × 30 m area, took 2.0 hr, and showed the site was flat, undisturbed, and free of debris and cables.

First Jet-in Test

Drilling operations began when seafloor was tagged at 4966.1 meters below sea level (mbsl), or 4977 meters below rig floor (mbrf), at 1525 hr on 27 December. The jet-in test was performed to confirm a refusal depth for jetting-in the reentry cone with 20-in casing. At 12 to 13 mbsf a hard layer was encountered, although the test was suspect as the ship was experiencing 4 to 5 m heave at the time of the test. Following the test, we were again forced to WOW, this time for 13.75 hr.

Hole 1224A

Hole 1224A was spudded at 1455 hr on 28 December at 4977 mbrf. Core 200-1224A-1X was advanced 6 m downhole with no recovery; hence, we could not establish a precise mudline (Table T3). On Core 4X, drilling progress was slow when we got to hard rock, which at the time was thought to be chert or basaltic basement. Recovery of 1.24 m of red clay and pieces of basalt confirmed that we had penetrated basement near the bottom of the 5.5-m interval cored, or at ~28 mbsf. We attempted one more extended core barrel (XCB) core (5X), before switching to the motor-driven core barrel (MDCB) for one last short core. We pulled out of the hole and cleared the seafloor at 0530 hr on 29 December, ending Hole 1224A.

Overall we cored 32.2 m in Hole 1224A and recovered 1.67 m of core (5.19% recovery), with 32 m cored and 1.45 m recovered (4.53% recovery) with the XCB and 0.2 m cored and 0.22 m recovered (110% recovery) with the MDCB (Table T3).

Hole 1224B

Hole 1224B was spudded with the advanced piston corer (APC) at 0650 hr on 29 December, but only 0.2 m of core was recovered. The primary goal of APC coring was to establish the mudline; therefore, we offset to spud Hole 1224C. Hole 1224B officially ended at 0745 hr on 29 December after we pulled the bit up to clear the seafloor.

Hole 1224C

The bit was positioned at 4964.1 mbsl (4975 mbrf), and Hole 1224C was spudded with the APC at 0820 hr on 29 December. We recovered 6.53 m of core and established the mudline at 4967.1 mbsl (4978.0 mbrf). Having successfully determined the mudline, the bit was pulled clear of the seafloor at 0915 hr on 29 December, marking the end of Hole 1224C.

Second Jet-In Test

Operations were delayed by bad weather, which included maximum heave, pitch, and roll of 6.3 m, 2.4°, and 8.1°, respectively, with winds up to 44 kt. Total time WOW was 16.0 hr, with operations beginning again at 0115 hr on 30 December.

A second jet-in test was deemed necessary to confirm the depth of penetration for the 20-in surface casing, which would be run with the reentry cone. A wash barrel was dropped and the bottom-hole assembly (BHA) was jetted-in to 4996.1 mbsl (5007 mbrf), ~29 mbsf, with no obstructions encountered, unlike the first jet-in test. The drill string was pulled out of the hole, with the bit clearing the rotary table at 1430 hr on 30 December.

Hole 1224D

The reentry cone was positioned over the moonpool doors, and the casing string was partially assembled at 1830 hr on 30 December 2001. Poor weather conditions and the associated large heave, roll, and pitch forced us to delay operations until 1715 hr on 1 January 2002, a loss of 46.75 hr.

With weather conditions improving, the reentry cone and ~25 m of 20-in casing were assembled and lowered through the moonpool at 2335 hr on 1 January. Hole 1224D was spudded at 1220 hr on 2 January. It took only 24 min to jet the 20-in casing string down to 5003.47 mbrf (25.47 mbsf) and set the reentry cone. VIT observation of the reentry cone confirmed that it was in a satisfactory position. The bit cleared the seafloor at 1315 hr on 2 January and the pipe was tripped back to the rig floor, with the jet-in BHA and bit clearing the rotary table at 0200 hr on 3 January.

Hole 1224D was reentered with an RCB bit at 1837 hr on 3 January, with coring beginning at 25.5 mbsf. Coring progressed down to 59 mbsf, with several delays caused by the poor weather conditions, adding up to another 26.0 hr of WOW. The marine forecast was for continued poor weather for our operating area, with very strong low-pressure systems to the west and north and large swells. It was therefore decided to prepare to take advantage of any weather window by tripping the drill string and changing to the 14.75-in bit and BHA. This would allow us to open the cored hole when a more appropriate weather window was available and be in position to run 10.75-in casing. At 0045 hr on 7 January we started to trip the pipe, with the bit clearing the rotary at 1100 hr on 7 January.

Overall we cored 33.5 m in Hole 1224D and recovered 15.65 m of core (46.72% recovery) with the RCB coring system (Table T3).

Reaming the Hole

After tripping the pipe with the 14.75-in bit to 4790 mbrf at 2345 hr on 7 January, operations were again put on hold while WOW for 19.0 hr. Operations resumed at 1845 hr on 8 January after Hole 1224D was reentered.

We reamed the hole to 64.7 mbsf before drilling difficulties halted penetration. This was sufficiently close to the planned drilling depth of 67 mbsf, so we ceased drilling at 0730 hr on 11 January, for a total depth in Hole 1224D of 64.7 mbsf. When the drill string was pulled to the surface, to the surprise of all, the bit had been left in the hole, thus explaining the drilling difficulties. The bit appeared to have been sheared off.

Installation of 10.75-in Casing

Starting at 2030 hr on 11 January, the drill crew began assembling the 10.75-in casing string, which consisted of five joints of 10.75-in (40.5 lb/ft) casing. Hole 1224D was reentered by the casing string at 1336 hr on 12 January. We noted during reentry that the reentry cone and skirt had settled by ~1.7 m below the original mudline. The casing string was run down and landed with the base at 5036.47 mbrf (58.47 mbsf) on 1515 hr on 12 January. The casing was cemented with 18.8 bbl of 15.5 ppg Class G cement. The first attempt to release from the casing hanger failed and resulted in the 10.75-in casing hanger being pulled up above the reentry cone. The casing hanger was landed again in the 20-in casing hanger and this time the 10.75-in hanger released at 1715 hr on 12 January. The pipe was tripped up, with the running tool clearing the rotary table at 0530 hr on 13 January.

The BHA was assembled with a RCB bit and run down to 4388.89 mbrf in preparation for coring in Hole 1224E. Before starting Hole 1224E, we reentered Hole 1224D to ensure that the casing and cement were properly installed.

Hole 1224E

The *JOIDES Resolution* was offset 15 m to the southwest, and Hole 1224E was spudded at 1840 hr on 13 January at 4978 mbrf. We washed down the first 8 m and then took two punch, or push, cores (1R and 2R), which were acquired by lowering the RCB bit through the soft sediments without rotating the bit. Both cores sustained substantial drilling disturbance, but we were able to recover 10.52 m of sediment core in a 19.2-m-long interval from 8.0 to 27.1 mbsf, where recovery was virtually absent in the other holes.

Coring penetrated from 27.1 to 36.7 mbsf for Core 3R. Basement was tagged at 27.7 mbsf during coring. Recovery consisted of basaltic basement underlying a 5-cm-thick piece of hyaloclastite, into which basalt glass and clay pieces had been incorporated. This likely is the top few centimeters of the basement. After completing coring on Core 3R, the bit was pulled up by one stand of drill pipe to connect another joint of pipe. This placed the bit above the sediment/basement contact. After making the connection, the driller was unable to reenter the basement hole. After 1 hr of attempting to find the hole by rotating the bit on bottom, a new hole (1224F) was started.

Overall we cored 28.7 m in Hole 1224E and recovered 14.91 m of core (51.95% recovery) with the RCB coring system (Table T3).

Hole 1224F

The start of Hole 1224F is somewhat of an anomaly in the ODP nomenclature, since the bit never pulled totally out of Hole 1224E, but it did pull out of the basement portion of Hole 1224E. The distance between Holes 1224E and 1224F is likely no more than about a meter. In any case, we began penetrating basement again at 1630 hr on 14 January in Hole 1224F.

For all the bad weather we had previously, we were due a good spell. Thus, coring proceeded without interruption except for the occasional wiper trip and one trip to replace the knobby joints with drill pipe. During the latter trip, which started at 2315 hr on 17 January after recovery of Core 11R, the bit was inadvertently pulled above the basement/sediment contact. The driller worked the drill string up and down with rotation in an attempt to reenter Hole 1224F. Instead, Hole 1224E was reentered five times before finally the bit went back into Hole 1224F. RCB coring proceeded after washing ~11 m of soft fill from the bottom of hole. Cores continued to be cut at a rate of ~6–8 hr/core, which was roughly twice as fast as cores cut from near the top of the basement. No core was recovered in Core 16R. The bit deplugger was run to remove potential obstructions, but Core 17R also had no recovery. Owing to time limitation, coring in Hole 1224F ended and preparations for logging began.

Overall in Hole 1224F, we penetrated 174.5 m, cored 146.8 m, and recovered 37.7 m of core (25.68% recovery) with the RCB coring system (Table T3).

Logging

The bit was released in the bottom of the hole at 2320 hr on 19 January. The hole was then displaced with 75 bbl of sepiolite mud. A free-fall funnel (FFF) was launched at 0442 hr on 20 January to facilitate reentries into Hole 1224F on future scientific experiments.

At 0730 hr on 20 January, the triple combo tool was prepared to run downhole. The tool reached 5152 mbrf, which is only 0.5 m off the bottom of the hole. The first logging run was completed, and the tool was through the rotary table at 1520 hr on 20 January. For each logging run, the base of the pipe was lowered to 49.9 mbsf initially. As each run was made uphole, the pipe was pulled up from 49.9 mbsf to 34.5 mbsf to increase the open-hole interval for logging.

The second logging run was with the Formation MicroScanner/dipole sonic imager (FMS/DSI) tool. Three passes of this string were run uphole at 275 m/hr from the bottom of the hole to the basement contact (27.7 mbsf). The second logging run was completed, and the tool cleared the rotary table at 0525 on 21 January.

We had planned to test the three-component well seismic tool (WST-3) if time and weather conditions permitted. While testing the tool and air gun, three problems were found: a faulty circuit in the blast hydrophone of the air gun, an air leak from the air gun, and the WST-3 telemetry worked intermittently. The experiment was thus terminated because there was insufficient time to attempt to fix the problems and complete the planned shooting program to the WST-3. The time constraint on the logging program was determined by the departure time required to make the San Diego port call. The WST was back through the rotary table at 0945 hr on 21 January.

The VIT was launched starting at 1030 hr 21 January to observe the FFF at the top of Hole 1224F. A large hole was observed in the seafloor from circulating the cuttings out of the hole. As a result the top of the FFF was observed at ~4980.5 mbrf (2.5 mbsf) with the three buoys just below the mudline, secured to the FFF by a $^{5}/_{32}$ -in steel cable. The end of the casing on the FFF is estimated to be at 6.2 mbsf.

The open end of the drill pipe cleared the seafloor and FFF at 1238 hr on 21 January. The VIT was recovered at 1445 hr, and the BHA cleared the rotary table at 2355 hr on 21 January, completing activity at Site 1224.

Principal Results

Lithology

Sedimentary Section

Sediments were obtained from parts of Holes 1224A, 1224B, 1224C, and 1224E. The sediments consist mostly of abyssal clays of varying color. Occasional coarser horizons are present as are horizons with varying densities of microfossils, both siliceous (radiolarians and sponge spicules) and calcareous (coccoliths and discoasters) (Fig. F8).

Core recovery from Holes 1224A and 1224B was not significant enough to characterize the sediments. One significant discovery, however, was the recovery of light-colored, noneffervescing granules and pebbles from a depth of between 6 and 15.6 m from Hole 1224A. These are currently thought to be fossil worm burrows or hydrothermal deposits.

The total sediment depth at Site 1224 is 28 to 30 m. The top 6.53 m, as characterized by a single piston core in Hole 1224C, is massive brown clay that gradually changes color to very dark brown. Radiolarian spicules are present throughout the section, but they increase with depth and are common at the bottom of the unit. Sponge spicules are not found near the top of the section but are common below 4.50 m.

In Hole 1224E, we recovered 10.52 m of clay in the interval from 8.0 to 27.1 mbsf, in which two punch cores were collected with the RCB coring system by pushing through the sediment without rotating. The clay varies in color between dark brown, very dark brown, black, and dark yellowish brown. The high disturbance due to the punch coring process causes the colors to be streaked and mottled throughout the hole. Most color changes are gradual. Light-colored granules and pebbles are found in the top few centimeters of Core 200-1224E-1R (~8 mbsf). Like the burrows in Hole 1224A, they do not effervesce and are thought to be infilled burrows. These sediments also contain early stage manganese nodules. They are up to 2 mm in width and may be irregular or elongated in shape. Coccoliths and discoasters are present below 17.5 m.

Hard Rock Section

The basalt stratigraphy at the site is summarized in Figure F9. In this figure, the depth for the top of each core, except for the topmost cores into basement, is taken as the top of the cored interval, as is the ODP convention. The cored interval is determined from the drill string length, which is entered into the ODP database. The top cores in all four holes, however, assume that the top of basaltic basement lies at a constant depth of 28 mbsf, which was our best estimate based on all drill holes and jet-in tests. For these cores only, the recovered basalt is placed below this fixed depth, rather than at the top of the cored intervals. The basement depth of 28 mbsf is probably uncertain by about a meter, and there may be some slight relief to the top of basalts as well. This approach avoids assigning basalt recovery to depths that actually are above the point where basement was touched by the drill string.

In Hole 1224A, we recovered 0.37 m of fine-grained, aphyric basalt from near the basement/sediment contact. A handful of broken basalt pebbles suggests that the core bit skittered over the basement surface before spudding securely.

In Hole 1224D, we penetrated 39.5 m of basalt recovering 15.67 m (46.5% recovery). The basalt is aphyric and consists of two flows that are finer grained near the flow tops and bases and coarser grained in the middle. Glass was recovered only at the top of the first flow. The rock is very little altered, but alteration is more intense near fairly widely spaced fractures that are lined with green clays, calcite, and pyrite. Flow tops are more fractured than flow interiors, and flow-top fractures are lined with Fe oxyhydroxides and calcite. Alteration halos are 1–2 cm wide near these veins. The same basalt unit was cored again in Hole 1224E in a single core that penetrated 9.6 m into basement, with 4.39 m of recovery. The first three cores from Hole 1224F again cored the upper basaltic basement. Thus, all four basement holes, which lie within 20 m of each other, cored immediately into the same fairly massive basalt flows.

Coring continued in Hole 1224F from the massive basalts into thinner flows and pillows (at ~65 mbsf), that are more intensely fractured and altered than the massive rock above. Somewhat thicker flows were encountered again beginning in Core 200-1224F-13R, at 133.5 mbsf, or 105.5 m below the top of basement at 28 mbsf. Recovery of basalt ended with Core 200-1224F-15R obtained between 152.4 and 161.8 mbsf. Drilling continued without recovery to 174.5 mbsf. Total penetration at Hole 1224F was 146.5 m into basement making it the deepest hole cored into the basaltic basement of “normal” Pacific crust younger than 100 Ma since Deep Sea Drilling Project (DSDP) Leg 65.

Based on the subdivision into massive basalt with high recovery, thin flows and pillows with low recovery, and a return to somewhat thicker flows, and because of the general correspondence of this sequence with physical properties and downhole logs, we divide the basaltic section into three lithologic units as follows:

Unit 1. Massive basalt flows. This unit includes all basalt cores of Holes 1224A, 1224D, and 1224E, and down to interval 200-1224F-4R-6, 10 cm (bottom of Piece 1). The base of the unit in Hole 1224F is curated at 62.7 mbsf, and its thickness in Hole 1224F as curated is 34.7 m. Over all holes, recovery in Unit 1 was 52.6%.

Unit 2. Thin flows and pillows. This unit extends from interval 200-1224F-4R-6, 10 cm, top of Piece 2, to interval 200-1224F-12R-1, 129 cm, Piece 15. The base of the unit is curated at 133.5 mbsf, and its thickness as curated is 70.8 m. Recovery in Unit 2 was 14.6%. Two hyaloclastites were recovered in this unit (Fig. F10).

Unit 3. Basalt flows of intermediate thickness alternating with thin flows and pillows. This unit includes Core 200-1224F-13R through the end of Core 15R. The base of the unit is taken to be the bottom of Core 200-1224F-15R at 161.7 mbsf, and its thickness as curated is 28.2 m. Recovery in Unit 3 was 21.4%.

Based on downhole logs, the base of Unit 1 corresponds to a change in porosity and density at 63 mbsf. This is almost exactly the curated depth. The base of Unit 2 in the logs is less precise, but probably deeper than the curated depth of 133.5 mbsf. A zone of very high porosity occurs between 135 to 140 mbsf (Fig. F9). The temperature in the hole also increased at 135–137 mbsf, suggesting that seawater flowing down the hole, or introduced to it by drilling operations, encountered a permeability barrier at this depth. The relatively massive rock in Core 200-1224F-13R is unlikely to have been cored above this depth. In the formation, then, the base of Unit 2 appears to be ~2 to 4 m deeper than the curated depth.

Petrography

Thin section examination of volcanic basement at Site 1224 (Holes 1224A, 1224D, 1224E, and 1224F) evidenced a relatively homogeneous mineral paragenesis. The main phases are plagioclase, clinopyroxene, opaque minerals, and rare pigeonite; therefore, the rocks can be classified as tholeiitic basalts. Olivine is rare and only a few small iddingsitized euhedral to anhedral groundmass crystals have been found. Iddingsite is a typical alteration of olivine and is made up by a mixture of goethite and layer silicates (e.g., smectite). The majority of the basalts are holocrystalline (almost 100% crystals) to hypocrystalline (glass concentration <50%) and can be ascribed to lava flows. With increasing depth of coring, hypohyaline textures and volcanic glass contents >90% become common and indicate the presence of pillow fragments with chilled margins. The deepest samples recovered (~153 mbsf) also show textural features of holocrystalline massive lava flows. With regard to their granularity, the basalts range from aphanitic (difficult to distinguish the crystals in the groundmass with the naked eye) to aphyric (absence of phenocrysts), though rare plagioclase or plagioclase-clinopyroxene sparsely phyric basalts (phenocryst content <2%) have been also found. The relative size of the crystals in the groundmass is equigranular, and their distribution is isotropic. The groundmass is hypidiomorphic with the presence of euhedral to anhedral shaped crystals. The texture of the massive lava flow basalts is intergranular (with clinopyroxene in interstitial relationships with plagioclase) to subophitic (with plagioclase laths partially enclosed in clinopyroxene) and, more rarely, intersertal (with microcrystalline to glassy material between plagioclase). Hyalopilitic (with plagioclase laths and clinopyroxene crystals in a glassy matrix) to, more rarely, intersertal textures have been found in the pillow lavas. The grain size of the groundmass ranges from very fine grained (0.001–0.5 mm) to fine grained (0.5–1 mm).

Geochemistry

Inductively coupled plasma–atomic emission spectroscopy (ICP-AES) data for K_2O, TiO_2, MgO, Ba, and Zr were obtained on samples from Hole 1224D. The rocks recovered consist mainly of massive fresh basalt, with only widely spaced and narrow veins containing carbonate minerals, clays, and pyrite. The above elements tell virtually the entire story.

The basalts are differentiated normal mid-ocean-ridge basalt (N-MORB) with 2–2.7 wt% TiO_2. The samples selected for analysis are scarcely altered, with loss-on-ignition (LOI) values ranging from 0–0.45 wt%. Concentrations of K_2O (0.11–0.27 wt%) may be slightly elevated in three of ten samples analyzed, but most values, and all those for Ba (9 to 18 ppm) are consistently lower than in many comparably differentiated MORB glasses from the East Pacific Rise. This may indicate a greater-than-average depletion of the mantle sources of basalts from Hole 1224D. Alternatively, the rocks may have experienced a slight nonoxidative alteration in which these components were partially removed from the rock. This seems unlikely, however, given the more extensive oxidative alteration observed in rocks from Holes 1224E and 1224F, obtained only a few meters away.

Both TiO_2 contents and Zr concentrations are determined precisely enough to enable their use in defining chemical stratigraphy (Fig. F11). Most of the basalts from Hole 1224D belong to one chemically uniform, extensively differentiated basalt flow more than 20 m thick. This overlies a second flow that is not quite so differentiated.

X-ray diffraction (XRD) analysis was carried out on one clayey pebble from the sediment and twenty-five vein materials within the basalt. Five distinct vein types were documented by XRD analysis: clay, carbonate, zeolite, quartz, and smectite (Fig. F12). Many vein minerals in the basement at Site 1224 are stable at low temperature and pressure (i.e., zeolite). Phillipsite, the principal zeolite present at Site 1224, is a low-temperature member of the zeolite group (Miyashiro, 1973). Smectite is also commonly found as a product of the alteration of volcanic ashes and rocks from the seafloor and occurs in most of the low-grade metamorphic terranes in the world.

Four of the vein types observed at Site 1224, smectite-illite, calcite-aragonite, quartz, and zeolite, are similar to veins observed at Sites 896 and 504 near the Costa Rica Rift (Alt, Kinoshita, Stokking et al., 1993). These minerals occur in relatively lower temperature hydrothermal assemblages (probably <100°C) (Laverne et al., 1996). No truly high temperature vein assemblages, such as the actinolite and epidote veins found >2000 mbsf at Site 504, occur at Site 1224. The mineral laumontite in the illite vein indicates a higher zeolite facies (Miyashiro, 1973). Aragonite generally forms at a higher temperature than calcite. These minerals indicate the local influence of warm hydrothermal fluids.

Paleomagnetism

We used progressive alternating-field (AF) demagnetization of archive-half sections, one whole-core section, one working-half section, and discrete samples to characterize the paleomagnetic signal and resolve the magnetization components recorded in the recovered core. An unambiguous magnetostratigraphy could not be obtained from the only undisturbed core (Core 200-1224C-1H) that was recovered in the sedimentary section; the other sediment cores were extremely disturbed by drilling. In addition, we only had time for a cursory interpretation of the magnetization of the basaltic units, though fairly detailed demagnetization experiments were conducted on split cores and discrete samples.

Given that ~15 basalt units were recovered, the magnetization of the basalts should provide a valuable paleolatitude estimate for the Pacific plate at ~45 Ma. This age corresponds to the Pacific plate's abrupt change in motion relative to the hotspots as marked by the kink in the Hawaiian-Emperor hotspot track. A cusp in the Pacific plate apparent polar wander path (APWP) may also occur at this age, marking a change in the motion of the Pacific plate relative to the spin axis. The Pacific APWP and hotspot tracks together provide key constraints on estimates of the size of motions between hotspots, ultimately extending our understanding of mantle dynamics (Acton and Gordon, 1994). Additionally, the age also lies within the period (39–57 Ma) when the Hawaiian hotspot has been shown to have moved rapidly southward relative to the spin axis (Petronotis et al., 1994). If geomagnetic secular variation has been averaged by the basalt units and if secondary overprints caused by alteration do not mask the primary magnetization, then we should be able to obtain an accurate paleolatitude. Finally, rock magnetic studies of the basalts should help refine our understanding of the magnetization of the upper oceanic crust and its role in generating lineated marine magnetic anomalies.

Microbiology

Samples of different sediment types and from basaltic rock were collected at Site 1224 for aerobic and anaerobic cultivation, for deoxyribonucleic acid (DNA) extraction and analysis, for phylogenetic characterization, for total cell counts, and for determination of the live/dead ratio of indigenous microbial communities. Sediment suspensions and ground basalt material were used under oxygen depleted conditions in the anaerobic chamber for the establishment of enrichment cultures. Aerobic cultivation was conducted using both seawater-based media and commercial methylene blue agar (MBA). Anaerobic cultures were based on reduced mineral media.

To evaluate the microbial background at Site 1224, ambient seawater samples were collected at 1 m below sea surface upwind of the *JOIDES Resolution.* The microscopically enumerated total cell counts in the surface water at Site 1224 were 1.4×10^4 cells/mL.

Sediment samples from Holes 1224C, 1224D, and 1224E were obtained from different depths ranging from the near-surface layer down to 24.9 mbsf. Bacteria were present in all sediment samples taken to 24.9 mbsf.

The amount of active bacteria was assessed in two representative sediment samples taken from the near-surface layer (interval 200-1224C-1H-1, 0–5 cm) and from a depth of 25 mbsf (interval 200-1224E-2R-5, 143–150 cm). As indicated by fluorescent signals after hybridization with the bacteria-specific probe EUB338, the amount of metabolically active bacteria ranged in these sediment layers from 62% to 41% of the total cell counts, respectively (Fig. F13).

The microscopic investigation of a thin section of basalt showed textures which resembled microbial structures. This might be a further hint for putative microbial activity in deep subsurface environments.

Physical Properties

In Hole 1224A, *P*-wave velocities of aphyric basalt from Cores 200-1224A-5X and 6N are ~5900 m/s and ~5800 m/s, respectively.

In Hole 1224C, the gamma ray attenuation (GRA) densities of sediments gradually decrease with increasing depth between 0 and 6.4 mbsf, corresponding to a color change from light brown to dark brown. Similarly we observed an unusual trend for bulk and dry densities in Hole 1224C, which decreases from ~1.52 to ~1.36 gm/cm^3 and from ~0.8 to 0.54 gm/cm^3, respectively. Porosities in Hole 1224C gradually increase from 71% to 80%. *P*-wave velocities from the *P*-wave logger (PWL), however, show a small increase from 1460 to 1500 m/s with depth between 0 and 6.4 mbsf. *P*-wave velocities from PWS3 contact probe measurements from Core 200-1224C-1H to 4H (between 0 and ~5.70 mbsf) range from 1525 to 1535 m/s. The *P*-wave velocity in Core 200-1224C-5H is ~1555 m/s, which is greater than other sections. Grain densities in Hole 1224C show a small increase from 2.782 to 2.831 g/cm^3 for depths shallower than 2 mbsf. Between 2 and 6 mbsf, grain densities remain fairly constant between ~2.70 and ~2.74.

In Hole 1224D, bulk and dry densities increase from 2.7 to 2.9 g/cm^3 and 2.6 to 2.8 g/cm^3, respectively, in Core 200-1224D-2R. In Core 200-1224D-3R, bulk and dry densities decrease from 2.9 to 2.8 g/cm^3 and from 2.8 to 2.7 g/cm^3, respectively. In Cores 200-1224D-4R and 5R, they also decrease from 2.85 to 2.80 g/cm^3 and from 2.8 to 2.7 g/cm^3, respectively. Porosities remain at low values ranging from 4% to 9%. PWS velocities range from 4200 to 6500 m/s. Compressional wave velocity anisotropies for each sample are around 2%–10%. PWS velocities have a sinusoidal depth variation. They decrease between 25 and 35 mbsf, increase between 35 and 45 mbsf, and decrease again between 45 and 55 mbsf. This sinusoidal depth variation is also identified for Hole 1224F.

Between 25 and 60 mbsf, PWS velocity in Holes 1224E and 1224F has a similar trend to Hole 1224D. PWS velocities have a strong depth dependence. Compressional velocities separate into seven depth zones (Fig. F14):

1. 5500–6000 m/s,
2. 4200–5500 m/s,
3. 5000–6000 m/s,
4. 4500–5000 m/s,
5. 4700–6000 m/s,
6. 4000–4700 m/s, and
7. 5500 m/s.

Zones 1–3 may be characterized as rather uniform basalt flow zones with a thin low-velocity (fractured) layer. Zone 4 is characterized as a slightly low velocity zone. Velocities of Zone 5 are higher than those for Zones 4 and 6. Zone 6 is highly fractured, characterized by the lowest velocities. Zone 7 corresponds to more uniform basalt layers.

P-wave velocities are scattered with increasing bulk density. Compressional wave velocity vs. porosity, however, has a good inverse correlation, as *P*-wave velocity decreases with increasing porosity. These two relations imply that compressional velocities are not controlled by bulk densities, but are well controlled by porosities. Large porosities are associated with more fractured zones. If this is true, Zones 2 and 6 are intensively fractured.

Logging

Based on shipboard preliminary log analysis at this site during ODP Leg 200, we conclude that basement in Hole 1224F consists of at least five distinctive units (Fig. F15), with unit contacts at roughly 45, 63, 103, and 142 mbsf. These layered formations can be distinguished using the continuous electrical resistivity, density, sonic, neutron porosity, magnetic field, and possibly spectral gamma ray logs. The existence of a conduit or large-scale fracture between 138 and 142 mbsf was detected by all the log tools including the temperature tool. In addition, the temperature tool reveals that the “hot” fluid had a temperature of 4.6°C at the time of the logging. The vicinity of this conduit is much more highly altered than other rocks penetrated by the hole, as indicated by the gamma ray logs. Because of the relative position of the tools located in the tool strings, some tools can resolve the top logged intervals like gamma ray, porosity, density, and sonic logs. On the other hand, the resistivity tools and FMS placed at the bottom of the tool string can resolve the formation properties near the bottom of the hole. The values of the magnetic fields calculated from the three-component inclinometer tool are invalid near the bottom of the pipe (~35 mbsf). In the logged intervals where all the tools overlapped, they provide consistent information to support the layered structural units based on these geophysical properties.

Core lithology, physical properties, well logs, and seismic reflection data from the site were compared. Based on downhole variations observed in the data, particularly the well logs and physical properties data, we have divided the drilled interval into a sediment unit and basement into five distinct logging units (Fig. F16):

Sediments: 0–28 mbsf,
Unit I: 28–45 mbsf,
Unit II: 45–63 mbsf,
Unit III: 63–103 mbsf,
Unit IV: 103–142 mbsf, and
Unit V: Deeper than 142 mbsf.

The upper sediment unit (0–28 mbsf) is a brown clay layer with radiolarians at shallow depth. The mean velocities by physical properties measurements are ~1500 m/s. Logging Units I and II, between 28 and 63 mbsf, are two massive basalt flows with fractures at roughly 45 mbsf. These two logging units combined thus correspond to lithologic Unit 1. The compressional wave velocities in logging Units I and II based on core measurements are ~5500 m/s. Smecite veins were found in these units. Logging Unit III (63–103 mbsf) is characterized by fractured basalt layers both in core recovered and in data collected by the FMS/DSI logging tool. Calcite veins were found in this unit. The compressional velocity is ~5000 m/s. Logging Unit IV (103–142 mbsf) is characterized by stacks of small pieces of pillow lavas. This layer has compressional velocities slightly higher than 5.0 km/s as measured on discrete core samples. Logging data, however, indicate that this unit is highly porous. Logging Unit IV also contains smectite veins. At the base of logging Unit IV, large variations occur on the caliper log, resistivity log, compressional and shear velocity logs, U and Th content, and the temperature log. Physical properties measurements also indicate that this unit is highly fractured. The presence of high U and Th contents suggests that this unit is a highly altered zone. Logging Units III and IV combined correspond to lithologic Unit 2. In logging Unit V, below ~142 mbsf, basalt sheet flows were found. This logging unit corresponds to lithologic Unit 3. The single-channel seismic (SCS) data suggest that this is the top of a massive basalt unit that extends deeper than our deepest drilling depth (174.5 mbsf). In comparing the above units with the SCS records, these unit boundaries extend many kilometers away from the site. With further analysis it should be possible to understand the nature of oceanic Layers 2A and 2B and their relationship to lithologic boundaries in ~45-Ma fast-spreading oceanic crust.

3.5-kHz Deep-Source Experiment

A long-standing problem in the red clay province of the eastern Pacific Ocean is to adequately resolve chert layers and basement in the presence of sediments <50 m thick. By lowering a battery-powered, free-running 3.5-kHz pinger to the seafloor on the VIT sled and recording the pulse on the ship's 3.5-kHz acquisition system, we hoped to increase the sound level incident on the seafloor, to improve the penetration into the subbottom, to reduce the footprint of the sound on the seafloor, and to increase the received signal levels. The deep-source 3.5-kHz experiment was carried out whenever the VIT camera was lowered to the seafloor either for reconnaissance surveys or reentries.

Examination of the deep-source 3.5-kHz records shows two prominent reflections at 13 and 38 ms below the seafloor. Depending on the sound velocity in the seabed, these reflectors would be 10 to 13 m and 28 to 38 m deep. The continuity of these reflectors varies with time throughout the survey, whereas the ship moves only a few meters.

Our preliminary interpretation had been that the 13-ms reflection occurs at an intermittent chert layer. The first jet-in test stopped abruptly at 13 m. Although chert layers within the sediments have been encountered at other drill sites in the eastern Pacific, nowhere at Site 1224 did we sample chert. The 13-ms reflection may correlate with a radiolarian rich layer which was cored. Basalt cores were regularly acquired at 28–30 m depth, corresponding to the 38-ms reflector.

In summary, the deep-source 3.5-kHz experiment identified a previously unrecorded reflector at 38 ms below the seafloor that corresponded to basaltic basement. This reflector was not observed in the traditional 3.5-kHz survey conducted in 1997 or in the shipboard 3.5-kHz survey acquired while we came on site (Fig. F4). The 38-ms reflector, however, was observed beneath the H2O junction box.

Broadband Seismic Observations during the Leg

Drilling at the H2O provides a unique opportunity to observe drilling related noise from the *JOIDES Resolution* on a seafloor seismometer in the frequency band 0.1–80 Hz. The University of Hawaii operates a Guralp CMG-3T three-component broadband seafloor seismometer and a conventional three-axis geophone at the H2O. Data are acquired continuously and are made available to scientists worldwide through the IRIS Data Management Center in Seattle. During the cruise, Jim Jolly and Fred Duennebier at the University of Hawaii relayed sample data files to the *JOIDES Resolution* by file transfer protocol (ftp) over marine telephone. We were then able to process data and study correlations with on-site activities and weather. The University of Hawaii also maintained a Web site showing H2O seismic data collected during the cruise (http://lmina.soest.Hawaii.edu/H2O/).

Seismic activity could be associated with wind speed, sea state, shear resonance effects in the sediments, whales, water gun shooting, earthquakes, passing ships, and drilling related activities such as bit noise and running pipe (Fig. F17).

Summary

1. Site 1224 (27°53.367′N, 141°58.755′W) was selected for the seismometer installation (Fig. F7). This is 1.48 km northeast (a bearing of 056°) of the H2O junction box location. Hole 1224D (27°53.370′N, 141°58.753′W in 4967 m water depth) has a reentry cone and 58.5 m of 10.75-in casing that was cemented into 30 m of well-consolidated, massive basalt underlying 28–30 m of soft, red clay.
2. A single-bit hole (1224F) was drilled to 174.5 mbsf, and we sampled a 146.5-m-thick section of basaltic oceanic crust. Hole 1224F is <20 m to the southeast of Hole 1224D. Cores and well logs were acquired to characterize the site. The physical properties measured from well logs indicate that the basaltic basement can be divided into five distinct units at 28–45 mbsf, 45–63 mbsf, 63–103 mbsf, 103–142 mbsf, and below 142 mbsf. This hole was equipped with a FFF so that it also could potentially be used for long-term borehole seismic experiments in the future.

3. A suite of experiments and observations was conducted to investigate the role of microbial life in the deep biosphere. As a general trend, bacterial population numbers decreased with increasing depth, though the amount of metabolically active bacteria remained remarkably high at 41% to 62% of the total cell counts. Both the high total cell counts as well as the amount of bacteria with apparent physiological potential within the sediment layers suggest a higher contribution of sediment bacteria than has been previously assumed. The successful cultivation of oxidizing bacteria and the microscopic indication of further microbial structures within a cavity of basaltic rock confirm the presence and even activity of microbial life not only in deep marine sediments, but also in the Paleogene oceanic crust from the North Pacific.
4. We tested a deep 3.5-kHz source that could be deployed on the VIT frame to inspect the shallow structure of the seafloor at a higher spatial resolution than conventional echo sounding.

NUUANU LANDSLIDE

Recent studies have shown that the collapse of large volcanoes due to gravitational instability plays an important role in shaping volcanic environments. Detailed offshore bathymetric surveys of the Hawaiian Ridge (Moore and Normark, 1994), Reunion Island (Lenat et al., 1989), and the Canary Islands (Masson et al., 2002) reveal extremely large landslides. In the case of Hawaii, one of the Nuuanu Landslides caused by the collapse of Koolau Volcano on Oahu extends more than 200 km from the island. In the Canary Islands, the debris extends to 30 km. Landslides on both island chains might have generated huge tsunamis (Moore, 1964; Moore and Moore, 1988; Moore et al., 1989). Herrero-Bervera et al. (2002) estimated the age of Nuuanu Landslides at 2.1–1.8 Ma. However, the size, the age, and the number of Nuuanu Landslides are still in question. Site 1223 is ~300 km from Oahu and ~100 km to the northeast of the presently defined Nuuanu Wailau Debris Field (Fig. F18).

Geological Setting

The Nuuanu Landslide, which broke away from the northeast flank of Koolau Volcano on the island of Oahu, is the largest Hawaiian landslide. It is a debris avalanche that contains enormous blocks such as the Tuscaloosa Seamount, which is ~30 km long, 17 km wide, and at least 2 km tall. The landslide is spread over a 23,000-km^2 area (Normark et al., 1993; Naka et al., 2000), with distal portions extending up the Hawaiian Arch. To reach the upper portion of the arch, the target site for drilling, the landslide would have had to traverse the deep moat on the northeast side of Oahu and travel over 100 km uphill.

Reaching the landslide deposit by gravity or piston coring has proven difficult because the deposit is overlain by a carapace of younger debris such as turbidites and associated deposits. Thus, the thickness and depositional history of the landslide are poorly known. Prior to drilling, the thickness of the distal portion of the landslide was estimated to be from 1 to 100 m (Rees et al., 1993; Naka et al., 2000). Similarly, the age of the landslide is poorly constrained, although it apparently occurred near the end or after the formation of the Koolau Volcano, which has surface flows with ages 1.8–2.6 Ma based on K-Ar dating by Doell and Dalrymple (1973).

Scientific Objectives

The objectives of drilling at the Nuuanu Landslide Site are

1. To resolve whether the Nuuanu landslide occurred as a single distinct event or as multiple collapses;

2. To determine the age of the landslide(s);
3. To determine the thickness of the landslide deposit at the distal site and to obtain ground truth for the available seismic data in order to estimate the volume of the slide;
4. To study the deposition history of the landslide(s); and
5. To gain insight into potential hazards related to giant landslides on the flanks of ocean island volcanoes.

Operations

The *JOIDES Resolution* departed from the Honolulu Harbor at 1404 hr on 20 December for the Nuuanu Landslide Site NU-1 (ODP Site 1223). The 170-nmi voyage to Site 1223 required 17.0 hr at an average speed of 10.0 kt.

Hole 1223A

Hole 1223A was spudded with the APC at 2030 hr on 21 December at a depth of 4235.1 m (4245.8 mbrf). We took two APC and four XCB cores. We cored 41 m and recovered 23.54 m of core (57.4% recovery), with 12.7 m cored and 10.87 m recovered (85.6% recovery) with the APC and 28.3 m cored and 12.67 m recovered (44.8% recovery) with the XCB (Table T4). After two APC cores, we switched to XCB coring. The use of the XCB system at these shallow depths and the long time needed for coring was unexpected as was the presence of lithified volcanic rocks. Core 5X was advanced only 1.0 m when it was recovered because there were indications of jamming. Core 6X was advanced 8.0 m to a depth of 41.0 mbsf when it was recovered because the time on site had expired. The drill bit cleared the rig floor at 0130 hr on 23 December, and we departed for Site 1224 (H2O).

Principal Results

Major Discoveries

The core recovered from Hole 1223A (Fig. F19) answered several of the questions posed precruise, but also resulted in some unexpected discoveries. One of the objectives of coring at this site was to determine if the Nuuanu Landslide occurred as a single or as a multistage event as indicated by the number of turbidites recovered. Several unconsolidated volcaniclastic turbidites of varying thickness were recovered in the first two cores in Hole 1223A. At least seven of these were >10 cm thick at 0.86–1.01, 2.11–2.53, and 3.76–3.99 mbsf in lithologic Unit 1 and the four or more turbidites that comprise nearly all of lithologic Unit 2, spanning the interval from 5.11 to 7.32 mbsf. Other turbidites that were <1 cm thick were also observed. Paleomagnetic data indicate that all but the uppermost turbidite have an age between 1.77 and 1.95 Ma. The top turbidite has an estimated age between 0.99 and 1.07 Ma.

A surprising discovery was the recovery of the two crystal vitric tuff layers. Preliminary geochemical analyses indicate these tuffs are MgO-rich tholeiitic basalts and are geochemically similar to Hawaiian tholeiitic basalts. The olivines in the vitric tuff are fresh. Kink banding and fibrous structures were observed in some olivines. The fibrous structure may have been caused by crystallization of hematite. These textures, kink banding and fibrous structures, indicate that the source for these olivines may be mantle derived under shear stress. Paleomagnetic data indicate that the vitric tuffs are older than 1.95 Ma.

Another important result is the identification of wairakite in the vitric tuff. Wairakite is stable at a temperature range from 200° to 300°C. This suggests that considerable heat was involved when the crystal vitric tuff was deposited. Tentative interpretations for the origin of crystal vitric tuffs are given in the summary part of the lithologic results specification.

Lithology

We identified 14 distinct lithologic units (Fig. F19):

Unit 1 (0–5.11 mbsf) contains yellowish brown clay and volcaniclastic turbidites.
Unit 2 (5.11–7.32 mbsf) consists of volcaniclastic turbidites only.
Unit 3 (7.32–7.90 mbsf) is a thin layer of dark brown clay.
Unit 4 (7.90–10.78 mbsf) is unconsolidated black sand.
Unit 5 (12.70–15.06 mbsf) is a crystal vitric tuff.
Unit 6 (15.06–15.29 mbsf) is bioturbated claystone.
Unit 7 (15.29–16.10 mbsf) is volcaniclastic sandy siltstone.
Unit 8 (22.30–22.80 mbsf) is volcaniclastic silty claystone with carbonate granules.
Unit 9 (22.80–22.91 mbsf) is volcaniclastic claystone.
Unit 10 (22.91–24.92 mbsf) is volcaniclastic silty claystone.
Subunit 11A (32.00–33.00 mbsf) is altered vitric tuff, highly disturbed by drilling.
Subunit 11B (33.00–36.99 mbsf) is palagonatized crystal vitric tuff.
Unit 12 (36.99–37.47) is volcaniclastic silty claystone with scapolite amygdales.
Unit 13 (37.47–38.31 mbsf) is volcaniclastic silty claystone.
Unit 14 (38.31–38.70 mbsf) is volcaniclastic clayey siltstone.

Coring gaps of several meters exist between some of the cores, so additional units may exist or those identified may be thicker by several meters.

Volcanic material occurs throughout the stratigraphic column. Although we identified 14 distinct lithologic units, they may be grouped into three main types of lithologies:

1. Unconsolidated clay and volcanic sediments,
2. Weakly consolidated clay stones and siltstones, and
3. Crystal vitric tuffs.

The turbidites are concentrated in the upper 12.7 m of the core. They are dominated by a volcanic fraction that varies from 45% to 100%. The main constituents are, in order of increasing abundance, glassy shards, vitric fragments, olivine phenocrysts and clasts, plagioclase, palagonitized glass, lithic fragments, and clinopyroxene clasts. An MgO-rich olivine and Ca-rich plagioclase composition indicates equilibrium with mafic magmas. The mudstones and siltstones are found both in the middle and the bottom of the sections cored; they have high contents of clay, indicating detrital sources, and they have a low but variable volcanic fraction (~1%–25%). The silty claystone at the bottom of the deepest crystal vitric tuff (Subunit 11B) is characterized by the presence of relatively large (up to 3.5 mm) amygdules filled by scapolite, a metamorphic mineral associated with hydrothermally altered basic rocks. The vitric tuffs were found just below the sand and at the top and in the middle of the mudstones and siltstones cored. The “nonvolcanic” fraction is made up of claystone clasts, micritic clasts, and, more rarely, by radiolarians (generally <1%).

Whole rock ICP-AES analyses were conducted on the two vitric tuffs, as well as several of the siltstones and claystones. They have high MgO concentrations (12.4–15.8 wt%), which are not surprising because of the high percentage of olivine present. The tuff’s major elements are SiO_2 (47.6–49.6 wt%), TiO_2 (~2 wt%),

Al_2O_3 (11.3–11.9 wt%), Fe_2O_3 (11.3–12.7 wt%), MgO (12.4–15.8 wt%), CaO (6.74–7.17 wt%), Na_2O (2.19–3.07 wt%), K_2O (0.47–0.83 wt%), and P_2O_3 (0.16–0.23 wt%). Their trace elements are Ba (50–70 ppm), Sr (22–330 ppm), Y (~20 ppm), Zr (~120 ppm), and Ni (~430–580 ppm). Siltstones and claystones show similar values as those of the above tuffs. The geochemistries of whole-rock crystal vitric tuff, siltstone, and claystone were compared with the basalt glass geochemistry of MORB, Kilauea tholeiitic basalt, Haleakala alkali basalt, North Arch alkali basalt, and Koolau tholeiitic basalt. The crystal vitric tuff, siltstones, and claystones have the most in common, geochemically, with the Hawaiian tholeiitic lavas. There are some ambiguities in the measurements and samples, however, because the tuff contains clay minerals, which may affect the chemical compositions.

Several of the claystones and siltstones contain effervescing white amygdules. XRD analysis of the filling from interval 200-1223A-6X-4, 0–20 cm, gave a complex spectrum. The major component of the material is interpreted to be paragonite, a mica group mineral. Additional components include wairakite and analcime, with pumpellyite of varying compositions as a minor component. Grains from two intervals in the turbidite were analyzed by XRD (intervals 200-1223A-1H-5, 94–95 and 114–115 cm). The upper interval has brown grains with dominant XRD peaks at wavelengths consistent with phillipsite. In addition, some of the smaller peaks have spectra consistent with clay minerals, mainly smectite and illite and minor plagioclase. Therefore, the composition of the material analyzed is mainly phillipsite with clay minerals and minor plagioclase. The lower interval has white granules that give sharp XRD peaks at wavelengths consistent with calcite and some lower-amplitude peaks interpreted to be plagioclase.

Wairakite was originally found in hot springs in the geothermal fields of Wairakei in New Zealand and of Onikobe in Japan (Miyashiro, 1973). It has also been found in hydrothermal areas in the Mariana Trough (Natland and Hekinian, 1982). Wairakite is stable at a temperature range from 200° to 300°C. This suggests that considerable heat was involved when the crystal vitric tuff was deposited sometime thereafter.

Some of the olivine clasts in the tuffaceous layers show kink banding. Many mantle rocks such as lehrzolites and dunites show kink banding in olivine crystals. Also, tectonized peridotites often show such microstructures (e.g., Ishii et al., 1983). The kink bands are formed where shear is applied to the olivine crystal as shown by Kirby's deformation experiment (Kirby, 1983). Dislocations by shear stress in the olivine crystals generate the kink bands. Another interesting feature is the mass of fibrous lines identified in the olivine crystals. Iron oxide crystallization may be the cause of this structure. The presence of kink bands and fibrous structures indicates that olivine crystals in the crystal vitric tuffs may have been subjected to tectonic deformation.

Other Observations

We measured bulk density using GRA, magnetic susceptibility, natural gamma ray (NGR), and compressional velocity (V_P) on whole-core sections with the multisensor track (MST). Index properties and compressional wave velocities were also measured on selected individual samples. The yellowish brown clay in Core 200-1223A-1H has 83% porosity and a compressional velocity of 1.5 km/s. GRA density values from 0 to 10 mbsf gradually increase downhole from 1.2 to 2.2 g/cm^3. The GRA densities agree with the bulk densities of the individual measurements, except for Core 200-1223A-3X, where GRA densities of the vitric tuff in Core 20-1223A-3X average 1.8 g/cm^3, but bulk densities are slightly higher. Corresponding compressional velocity values for the vitric tuff in Core 200-1223A-3X average ~3.3 km/s. Bulk density, grain density, and compressional velocity for the siltstone in Core 200-1223A-4X are 1.6–2.0 g/cm^3, 2.8 g/cm^3, and 1.8–3.3 km/s, respectively. The vitric tuff in Core 1223A-6X has a 2.1 g/cm^3 bulk density, a 2.6 g/cm^3 grain density, and a 4.0 km/s compressional velocity. Grain densities of vitric tuff in Core 200-1223A-6X are lower than those in Core 200-1223A-3X. This is caused by the higher levels of alteration in Core 200-1223A-6X. The compressional wave velocities of the crystal vitric tuffs in lithologic Unit 5 (just below sand) and lithologic Unit 11 are ~3 and ~4 km/s, respectively. However, the bulk densities for both are similar, at ~2.2 g/cm^3. The compressional wave velocity for the upper crystal vitric tuff deviates from the generally expected compressional velocity-density relationship (e.g., Johnston and Christensen, 1997), possibly because of the weak consolidation of lithologic Unit 5. Compressional velocity and density increase with depth within the turbidites of lithologic Units 1 and 2, and the gradients can be associated with the graded bedding in the turbidites. Using this velocity and density increase with depth, we can identify the presence of the turbidite layers.

The magnetostratigraphy for Hole 1223A appears to record all the major chrons and subchrons from Chron C1n (the Brunhes Chron; 0.0–0.780 Ma) through Chron 2r (1.95 – 2.581 Ma). The Brunhes normal polarity interval spans only the top 14 cm of Core 200-1223A-1H, which is thinner than expected by ~1 m based on prior piston coring in the vicinity. Thus, we may not have recovered the very upper meter or so of the sedimentary section or sedimentation rates may vary locally. The top and base of the normal polarity interval interpreted as Subchron C1r.1n (Jaramillo Subchron; 0.99–1.07 Ma) are at 0.79 and 1.23 mbsf, respectively. The top and base of the normal polarity interval interpreted as Chron C2n (the Olduvai Chron; 1.77–1.95 Ma) are at 2.02 and ~7 mbsf, respectively. All recovered core below ~7 mbsf appears to be of reversed polarity, which is interpreted to be the upper part of Chron C2r, possibly with the entire interval lying within Subchron C2r.1r (1.95–2.14 Ma).

Microbiological analyses from Site 1223 were conducted on sediments and tuffs. Most probable number (MPN) series were prepared from all samples in order to determine the concentration of sulfate-reducing as well as fermentative bacteria. From Site 1223, 25 distinct microbial colonies could be isolated to pure cultures and could be further characterized as facultatively anaerobic organisms forming stable cell aggregates under appropriate conditions.

Interpretation

As noted above, three types of material—unconsolidated clay and volcanic sediments, weakly consolidated claystones and siltstones, and crystal vitric tuffs—were recovered in the cores from Hole 1223A. The first type consists of interbedded layers of pelagic clays and volcaniclastic sediments thought to be turbidites. These turbidites potentially originated from one of the Hawaiian Islands. The sand, which occurs in the upper 15 m of the section, has a high vitric component suggesting a volcanic source. The claystones and siltstones, on the other hand, which occur in both the middle and the bottom of the section cored, have a lower percentage of coarse volcanic material.

There are two hypotheses describing the origin of these claystones and siltstones. The first describes them as sedimentary rocks derived from detrital material from the Hawaiian Islands and emplaced by turbidity currents. The second hypothesis describes them as volcanic tuffs derived from submarine pyroclastic flows either from the Hawaiian Islands or from a local vent. Unwelded submarine pyroclastics in general tend to have a massive to poorly bedded and poorly sorted lower unit and an upper thinly bedded unit (Fiske and Matsuda, 1964; Bond, 1973; Niem, 1977). Unlike turbidite units, the massive lower pyroclastic unit at Site 1223 forms 50% or more of the total sequence. Fisher and Schmincke (1984) state that it is very difficult to distinguish between the deposits of these two types of events.

The vitric tuffs that occur below the sands and at the top and in the middle of the claystones and siltstones are also problematic. Hypotheses for their origin must address the following questions:

1. Why are they indurated at such a shallow depth?
2. Why are they so glass rich?
3. Why do they have so much fresh olivine?
4. Why is their general character tholeiitic?
5. Were they warm to fairly hot at, or shortly after, deposition?

Alteration and cementation in the lower tuff, and the transformations in sediments at its lower contact, probably occurred at an elevated temperature, perhaps 150°–250°C, consistent with zeolite metamorphic conditions and the occurrences of wairakite/analcime, pumpellyite, and scapolite described above. The compositions of these minerals, and of the enigmatic paragonite, remain to be determined, and the details of this unusual mineral paragenesis, including temperatures, worked out more carefully. The formation of palagonite and its associated zeolites in the lower tuff was undoubtedly linked to this.

Formation of palagonite was not isochemical. In this case, it involved loss of both CaO and Sr and addition of K_2O to the bulk compositions of the rocks (see "Geochemistry"). These exchanges required substantial flow of fluids derived from seawater through the porous tuffs. The occurrence of scapolite suggests that some of the fluids were brines.

We consider two origins for the crystal vitric tuffs, a Hawaiian Island source and a local source. If the source of the tuffs was local, they were presumably produced by igneous activity, either intrusion or extrusion, that has not yet been documented for this part of the Hawaiian Arch. Neither lava fields nor fissures associated with such hypothetical volcanism are evident in seismic data of the smoothly sedimented crest of the arch near Site 1223, but no high resolution bathymetry data has been taken of the surrounding area. The nearest known young volcanism on the arch occurred at the North Arch volcanic field, some 350 km to the northwest. There, lavas and tuffs are alkalic olivine basalts, basanites, and olivine nephelinites (Dixon et al., 1997), very unlike the tholeiitic precursors to the indurated tuffs and other sedimentary rocks of Hole 1223A. Similar volcanism near the drill site thus would only coincidentally have driven hydrothermal fluids through the sediments that we cored.

A possible scenario for the Hawaiian Island source hypothesis is that a very large eruption of primitive Hawaiian tholeiite occurred when a deep magma reservoir was breached by catastrophic failure of the flank of a volcano, similar to the 1980 eruption of Mount Saint Helens (Fig. F20) (Moore and Albee, 1981). This may have occurred on Oahu when the northeast flank of Koolau volcano collapsed, producing the giant Nuuanu debris avalanche. Sudden decompression caused pressure release, vesiculation, and expansion of the magma. The magma erupted as a directed blast and passed over the collapsing blocks now strewn on the seafloor as a submarine pyroclastic debris flow that reached over the Hawaiian Arch. In this scenario, if the material reached the area of Site 1223 (300 km away) quickly enough in a bottom-hugging density flow, it may have retained enough heat to cause the alteration and induration of the two crystal vitric tuffs. Water surrounding a hot pyroclastic flow may become vaporized, creating a water vapor barrier around the flow which helps to insulate the flow and prevent mixing (Kato et al. 1971; Yamazaki et al., 1973).

Subaerial pyroclastic flows have observed velocities ranging from 14 km/h (Tsuya, 1930) to 230 km/hr (Moore and Melson, 1969) and travel great distances (>100 km) moving over and around obstacles (surmount >600 m) (Fisher and Schmincke, 1984). Their ability to move has been attributed to several factors, namely exsolution of gas from glassy particles, gas being released when particles are broken, and the heating of the medium causing thermal expansion (e.g., Sparks, 1979). The gas reduces the friction between particles allowing the flow to travel faster. In addition to moving at tremendous speeds, pyroclastic flows are very good at retaining heat. Boyd (1961) calculated that cold air has a minimal effect on a hot pyroclastic flow. Therefore, a hot pyroclastic flow may remain at almost magmatic temperatures during transport and even after deposition.

The above applies to subaerial pyroclastic eruptions, subaqueous pyroclastic flows are less well understood. A massive, coarse-grained, subaqueous pyroclastic flow deposit over 4.5 m thick and extending up to 250 km from its source was recovered in the Grenada Basin, Lesser Antilles. Carey and Sigurdsson (1980) interpreted the deposit to be a debris flow that originated when a hot subaerially erupted pyroclastic flow entered the ocean. The debris flow incorporated pelagic sediment and seawater, decreasing internal friction, giving the flow great mobility and the ability to suspend large fragments. Thermal remanent magnetism of a similar deposit (Pliocene–Miocene in age) was interpreted by Kato et al. (1971) to have been deposited at temperatures around 500°C.

An alternative is that the tuffs were deposited containing some heat. Nevertheless, the amount of heat in a few meters of such materials is unlikely to have driven fluid flow for very long, at least if the deposit was small. On the other hand, a widespread blanket of hot material deposited suddenly might have acted as a compressive load on uncompacted surface sediments, and, where sufficiently thick, as a impermeable barrier to fluids mobilized by sudden compaction. The fluids, thus forced to flow laterally, may have sustained high temperatures at the base of the tuff for some time, and there produced the most concentrated effects of alteration and contact metamorphism. A somewhat similar effect was postulated for the pattern of fluid flow at the top of basaltic basement, beneath ~100 m of volcaniclastic turbidites in the eastern Mariana Trough at DSDP Site 456 (Natland and Hekinian, 1982). Greenschist-facies hydrothermal conditions were reached, and both wairakite and cristobalite formed in the sediments at the contact.

This hypothesis provides a mechanism for directing fluid flow and thus concentrating the most pronounced alteration effects in the tuff beds themselves, rather than in adjacent sediments. This probably would not have been the case if hydrothermal flow was directed along vertical fissures associated with local igneous action. Admittedly, the geometry of fluid flow in variably permeable sediments is difficult to extrapolate over long distances from the vantage of a single hole.

At Site 1223, the two tuffs, although about equally indurated, experienced alteration that was different either in type or in degree. The upper tuff is not palagonitized, although it is cemented by clay minerals and zeolites, and almost all of its original glass is still fresh. Probably the essential difference was temperature—lower for the upper tuff—although the upper tuff may have experienced less fluid flow as well. Lower temperature and reduced fluid flow should mean the same thing, less heat was available to drive fluids, whether or not it was derived locally or from a more distant source.

Provenance

It is necessary to determine the provenance of the Site 1223 materials in order to confirm whether these materials did or did not originate in the Nuuanu Landslide event(s). An island provenance would be a prerequisite if this were indeed the case. On the other hand, a local source of heat seemed required to explain the induration of the two welded tuffs so near the seafloor. A local provenance for the tuffs, perhaps a nearby seamount, would be consistent with this hypothesis. Accordingly, we compared bulk compositions of samples from Hole 1223A with varieties of Hawaiian basaltic rocks, with lavas of the North Arch volcanic field, some 300 km to the northwest, and with both normal and enriched abyssal basalts (N-MORB and E-MORB). Our initial petrographic interpretation was that the olivine-bearing glass shards in the tuffs resembled types of Hawaiian picritic tholeiite, but the issue still remained whether tholeiite itself might have erupted recently along the Hawaiian Arch and provided a local source for the tuffs essentially identical to the islands.

Existence of a significant component of aluminous detrital clay, produced ultimately by subaerial erosion, confirmed by chemical analyses, sets most of these issues at rest. The source of the aluminous component in all of the sediments and tuffs was clearly the islands, making it extremely unlikely that a separate local source provided the volcanic glass shards and associated minerals and lithic fragments. But what can now be said in more detail about the composition of source materials? Tholeiitic basalt is, of course, the most voluminous of Hawaiian lava types (e.g., Macdonald and Katsura, 1964; Clague and Dalrymple, 1987). However, alkalic olivine basalts, basanites, and olivine nephelinites erupted during both the earliest and latest stages of Hawaiian volcanism, and it is possible that these at least contributed volcaniclastic materials to the sedimentary succession at Site 1223.

Major oxide discriminant diagrams (Fig. F21A, F21B) show the similarity of analyzed samples from Hole 1223A to Hawaiian tholeiite, represented by basalt glasses from Kilauea volcano and its undersea extension, Puna Ridge (Clague et al., 1995). The diagrams also show strong differences between our samples (as well as Kilauea tholeiites) and Hawaiian alkalic olivine basalts, basanites, and olivine nephelinites from three localities—the North Arch volcanic field (Dixon et al., 1997), the Honolulu Volcanic Series of Oahu (Jackson and Wright, 1970; Clague and Frey, 1982), and the Hana Volcanic Series of Haleakala volcano on the island of Maui (Chen et al., 1991). Data are also plotted for a representative suite of abyssal tholeiites from the East Pacific Rise (J. Natland, Y. Niu, and P. Castillo, unpubl. data). This suite includes a wide range of primitive and differentiated abyssal tholeiites (N-MORB). Samples from Site 1223 clearly differ from these as well.

Because we compare bulk sediment compositions with compositions of glasses from Kilauea and the East Pacific Rise, the effects of abundant olivine in Site 1223 samples need to be taken into account. Olivine forms 9%–13% of the mode of the vitric tuffs. If its composition is about Fo_{85}, the effect of subtracting 13% of olivine from the bulk composition of a tuff with 10.5% Al_2O_3, 47.5% SiO_2, and 11% iron as Fe_2O_3 is shown by the arrows in Figure F21A and F21B. This is about the composition of Group 1 tuff in Figure F22 with the least amount of detrital clay in its makeup. The tip of the arrows in Figure F21 therefore is approximately that of an aphyric basalt or basalt glass still very closely resembling the composition of Kilauea tholeiite. In amounts of these oxides, it is far from the compositions of Hawaiian alkalic basaltic lavas and from MORB.

In Figure F21C and F21D, compositions of samples from Hole 1223A are explicitly compared with E-MORB glasses, using a compilation drawn from the literature, and with eight analyses of magnesian tholeiites and tholeiitic picrites from Koolau volcano (Frey et al., 1994). E-MORB resembles N-MORB, except in being slightly more aluminous. Most of the several Koolau lavas have slightly higher SiO_2 contents and lower iron as Fe_2O_3 than Kilauea tholeiitic glasses. In these diagrams, the effects of the addition of detrital clays and of authigenesis make it difficult to describe samples from Hole 1223A as more like one of the Hawaiian volcanoes than the other.

Figure F23 provides additional hints about the particular Hawaiian provenance of samples from Hole 1223A. Again, data for MORB, E-MORB, Kilauea-Puna Ridge, and Koolau are plotted for comparison. Again, samples from Hole 1223A resemble Hawaiian tholeiites rather than MORB or E-MORB. Several of the tuff samples from Hole 1223A, including those falling in Group 1 in Figure F22A and F22B, have higher SiO_2, lower Ba, and lower Zr than Kilauea glasses at given MgO content (Fig. F23). In all these respects, they more closely resemble Koolau. For SiO_2 and Ba, these estimations may be complicated by the presence of some detrital clay, and in two samples, Ba clearly is too high. However, the comparison holds for those samples with the least amounts of clay or, that is, highest CaO contents. In addition, Zr is an element that is usually unaffected by alteration. It is also usually precisely and consistently measured from one laboratory to the next. The measurements should give a relatively solid estimation of its original concentration in volcanic glass and lithic fragments in the sediments and tuffs, diluted by up to 13% with olivine and only small amounts of clay in several of the tuffs. The effect of subtraction of olivine with ~45% MgO and no Zr is given by the arrow in Figure F23C. Addition or subtraction of olivine cannot direct residual liquid compositions from Koolau into the field of Kilauea tholeiites. Dilution by clays in samples of Hole 1223A will draw compositions nearly toward the origin (no Zr and <1% MgO), but in several samples, this effect should not be too important. The diagram suggests, then, a Koolau provenance for the vitric tuffs. The higher SiO_2, lower Ba, and lower iron as Fe_2O_3 (Fig. F21C) of the same samples support this contention.

These data, of course, are not definitive. The compositions of fresh glasses will provide a more direct and unequivocal comparison. The evaluation here, however, suggests that certain trace elements, including Ba and Zr, should also be measured on glasses in the final provenance evaluation.

Comments on Petrogenesis

A great number of glass shards in the vitric tuffs have olivine phenocrysts that enclose small Cr-spinel crystals. The bulk samples are fairly olivine rich, approaching the bulk compositions of Hawaiian tholeiitic picrites in many respects. The high Ni, Cr, and MgO contents of all the samples indicate the importance of olivine tholeiite, and perhaps even picrite, in their provenance. Olivine tholeiite is not atypical of Hawaiian volcanoes at the shield-building stage, but many Hawaiian tholeiites are far more differentiated than this and either have no olivine on the liquidus or very little olivine in their general petrography. Average Hawaiian tholeiite has ~7.5%–8% MgO (Engel and Engel, 1970).

Picritic Hawaiian tholeiite is thought to reside at deep levels in the conduit-reservoir systems of Kilauea and Mauna Loa volcanoes, where it crystallized to produce abundant dunite, a common type of xenolith in late-stage Hawaiian basalts (Jackson, 1968). More differentiated lavas develop in the shallow reaches of rift zones, where they mix with more primitive lavas during eruptive cycles (e.g., Wright and Fiske, 1971). If the magmas that supplied most of the glass in the two vitric tuffs of Hole 1223A are truly primitive with, for example, high MgO in the glasses; if, in addition, the associated olivines are also forsteritic; and if, in particular, the tuffs each have a restricted range of primitive glass compositions; this evidence together would indicate that the sources were very large eruptions of tholeiitic magma, dwarfing the volume of any eruptions known from the islands themselves. Such a quantity of magma could only be derived from the deep, high-temperature reaches of Hawaiian magma reservoirs during the main shield-building stage. To reach into the main reservoir, below the shallow active rift system, would require one or more massive failures of the flank of the volcano of the type inferred for the Nuuanu Landslide.

Summary

One of the objectives of coring at this site was to try to determine if the Nuuanu Landslide occurred as a single or as a multistage event by inference from the number of turbidites recovered. Several unconsolidated volcaniclastic turbidites of varying thickness were recovered. Paleomagnetic data indicate that the uppermost turbidite has an estimated age between 0.99 and 1.07 Ma, that the other turbidites have an age between 1.77 and 1.95 Ma, and that other underlying units are older than 1.95 Ma. A surprising discovery was the recovery of the two crystal vitric tuff layers. Preliminary geochemical analyses indicate these tuffs are MgO-rich tholeiitic basalts and have geochemical similarities to Hawaiian tholeiites. However, there remain some other possibilities for the sources of crystal vitric tuffs such as a part of the Hawaiian Arch or a nearby seamount. The genesis of crystal vitric tuffs can be complicated. Questions arise about why they are indurated so close to the seafloor, why they are so glassy, why they are so rich in fresh olivine, why they include kink banding and fibrous structures in the olivine crystals, and why they were warm or even hot when emplaced.

Preliminary results are summarized below:

1. We recovered several lithologic units that were transported to the site most likely by a number of distinct landslide events. The origin of the deposits, as indicated by petrographic inspection and geochemistry, is the Hawaiian Islands. Furthermore the age of the transported units is coeval with the age estimate for the Nuuanu Landslides. The turbidites associated with the landslides were also identified by physical properties changes.
2. Two pyroclastic events similar to the 1980 Mount Saint Helens' eruption but an order of magnitude larger occurred on Koolau at ~2 Ma. These events may correlate with the collapse of the flank of the volcano and the formation of the Nuuanu debris field.
3. The thickness of turbidites and pyroclastic material corresponding in age with the Nuuanu Landslide (1.8–2.4 Ma) is more than 38 m at Site 1223, over 300 km from Oahu. We did not core to the bottom of this sequence; thus, the related deposits may be thicker and additional landslide events may be recorded.

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TABLE CAPTIONS

Table T1. Leg 200 operations summary.

Table T2. Summary of holes drilled in normal crust on the Pacific plate with an age <100 Ma and penetration into basement >10 m.

Table T3. Coring summary for Site 1224.

Table T4. Coring summary, Site 1223.

FIGURE CAPTIONS

Figure F1. Locations of Site 1224 and the Hawaii-2 Observatory (H2O) junction box (large star), repeater locations along the Hawaii-2 cable (crosses), major fracture zones (FZ), and previous drill sites (circles) from DSDP Legs 5 (Sites 38, 39, 40, and 41) and 18 (Site 172). Superimposed on the map is the satellite-derived bathymetry.

Figure F2. This artist's conception of the Hawaii-2 Observatory (H2O) summarizes some of the important components of the installation (© copyright Jayne Doucette, Woods Hole Oceanographic Institution [WHOI]. Reproduced with permission of WHOI).

Figure F3. The location of the Hawaii-2 Observatory (H2O) junction box is shown on the Hydrosweep bathymetry acquired during the site survey in August 1997 (Stephen et al., 1997). The locations of the repeaters (AT&T waypoints) on the cable are also shown (filled triangles).

Figure F4. A 3.5-kHz echo sounder record showing that the seafloor dips smoothly ~6 m from the H2O junction box to Site 1224 (proposed Site H2O-5). One subbottom horizon at ~9 m is fairly uniform throughout the area. Based on drilling results, this is a midsediment reflector. A second reflector at ~30 m below the junction box may be associated with basaltic basement, although it appears only occasionally in the record. PDR = precision depth recorder.

Figure F5. Vertical component spectra from the seafloor, buried, and borehole installations at the OSN-1 (Ocean Seismic Network) are compared with the spectra from the buried installation at the H2O and from the KIP GSN station on Oahu. The H2O has extremely low noise levels above 5 Hz and near the microseism peak from 0.1 to 0.3 Hz. The H2O has high noise levels below 50 mHz. Otherwise, the H2O levels are comparable to the OSN borehole and KIP levels. The sediment resonances at the H2O near 1.1 and 2.3 Hz are very prominent. Power spectral density is given in decibels relative to 1 $(m/s^2)^2$/Hz.

Figure F6. Horizontal component spectra from the seafloor, buried, and borehole installations at the OSN-1 (Ocean Seismic Network) are compared with the spectra from the buried installation at the H2O and from the KIP GSN station on Oahu. The sediment resonance peaks in the band 0.3 to 8 Hz are up to 35 dB louder than background levels and far exceed the microseism peak at 0.1 to 0.3 Hz. That the resonance peaks are considerably higher for horizontal components than for vertical components is consistent with the notion that these are related to shear wave resonances (or Scholte modes). Power spectral density is given in decibels relative to 1 $(m/s^2)^2$/Hz.

Figure F7. All drilling at the Hawaii-2 Observatory (H2O) took place at Site 1224 (proposed Site H2O-5), which is 1.48 km northeast of the junction box at the H2O. Alternate drilling sites (H2O-1 through H2O-4) that were discussed in the Leg 200 Prospectus are also shown (circles with crosses). Circles are drawn at 1-, 2-, and 3-km radius from the junction box. Also shown are the location of the single-channel seismic lines acquired during the site survey cruise in 1997 (dashed lines) and the track line taken by the *JOIDES Resolution* on 26 December 2001 (solid line). Echo sounder recordings were made along this line.

Figure F8. Coccoliths (spherical) and discoasters (star shaped) from Section 200-1224E-2R-7.

Figure F9. Lithologic summary of basalts cored at Site 1224. Basalt recovered in cores that penetrated basement are placed below the average depth estimated for the basement contact, which is 28 mbsf. Otherwise, the top of the recovered core is assumed by convention to start at the top of the cored interval. Locations of thin section samples are shown by red dots. Sediments are shown down to the presumed basement contact at 28 mbsf, but, as with the basalts, the depth of recovery is only known to lie somewhere within the cored interval and somewhere above the basalt.

Figure F10. Flow-top hyaloclastite from lithologic Unit 2 cemented by calcite (interval 200-1224F-6R-1 [Piece 6, 29–33 cm]). Fresh glass is very dark gray; altered glass is gray; palagonitized glass is orange; and calcite is white and light gray.

Figure F11. Chemical compositions vs. depth for basalts from Hole 1224D. **A.** TiO_2 vs. depth. **B.** Zr vs. depth. The vertical lines suggest the possible breakdown of the hole into two chemical types based on TiO_2 and three types based on Zr concentrations.

Figure F12. Sampling point and identification of the main secondary minerals in the basement section at Site 1224. Colored symbols show typical minerals. Green = clay, blue = carbonate, gray = quartz, and yellow = zeolite.

Figure F13. Microphotograph showing bacterial cells from an upper sediment layer from a depth of 1.45 mbsf (interval 200-1224C-1H-4, 145–150 cm). **A.** After staining with the DNA-binding fluorochrome SYBR Green I. **B.** Hybridization with the bacteria-specific, CY3-labeled probe EUB338. Note the numerous bacteria responding to the specific hybridization, indicating the high amount of metabolically active bacteria within the sediment.

Figure F14. Compressional wave velocities vs. depth in Holes 1224D, 1224E, and 1224F. Seven depth zones are introduced, as seen on the far right. Compressional wave velocities in the three holes have similar depth dependence between 27 and 53 mbsf. Zones 1 and 2 correspond to logging Unit I (Fig. F15), Zone 3 corresponds to logging Unit II, Zone 4 corresponds to logging Unit III, Zones 5 and 6 correspond to logging Unit IV, and Zone 7 corresponds to logging Unit V.

Figure F15. Composite log of the temperature, spontaneous potential (SP), and electrical resistivity logs recorded in Hole 1224F during Leg 200. Track 1: temperature. Track 2: SP. Track 3: deep induction resistivity (ILD). Track 4: spherically focused resistivity log (SFLU).

Figure F16. Logging data in Hole 1224F: caliper, resistivity, neutron porosity (NPHI), and gamma ray bulk density (RHOB). The arrows indicate the boundaries of the five logging units shown in Figure F15 and discussed in the text.

Figure F17. Tracking RMS (root-mean square) levels in one-octave bands is a convenient way to observe time-dependent effects in the broadband seismic data from the Hawaii-2 Observatory. The spikes around 5 and 20 s in this figure correspond to T-phases from earthquake events. The intense activity between 10 and 15 hr can be associated with the drawworks.

Figure F18. Location of Site 1223 and the Nuuanu Landslides. Line 12 shows the seismic reflection profile collected during the 1988 *Thomas Washington* cruise (Rees et al., 1993). The bathymetry shows that Site 1223 is near a seamount.

Figure F19. Lithologic units of Site 1223.

Figure F20. Schematic drawing of a landslide and the resulting directed blast eruption (from Moore and Albee, 1981).

Figure F21. Major-oxide discriminant diagrams. **A, C.** Al_2O_3 vs. Fe_2O_3. **B, D.** SiO_2 vs. Al_2O_3. Symbols distinguish vitric tuffs (red left-pointing triangles) and siltstones (gray triangles). Arrows in A and B indicate the effects of subtraction of 13% olivine = Fo_{85} from a representative tuff composition. Additional symbols in A and B are large open triangles = basaltic glasses from Kilauea and Puna Ridge (Clague et al., 1995); half-filled squares = Honolulu Volcanic Series (Jackson and Wright, 1970; Clague and Frey, 1982); downward-pointing triangles = North Arch Volcanic Series (Dixon et al., 1997); blue diamonds = Hana Volcanic Series, Haleakala Volcano, Maui (Chen et al., 1991). Additional symbols in C and D are dark green squares = high-MgO basalts from Koolau Volcano, Oahu (Frey et al., 1994); light green right-pointing triangles = enriched mid-ocean-ridge basalt (E-MORB) (data compilation of J. Natland, from several literature sources).

Figure F22. Ternary diagrams showing effects of addition of detrital and authigenic clays to basaltic volcaniclastic material. Inset diagrams show placement of enlarged portions of ternary diagrams on which data are plotted. **A.** $CaO-Al_2O_3-K_2O$ (CAK) diagram. **B.** Total iron as $MgO-Al_2O_3-Fe_2O_3$(T) (MAF) diagram. Symbols distinguish vitric tuffs (red left-pointing triangles) and siltstones (gray triangles). Fields 1 and 2 distinguish vitric tuff samples having, respectively, higher proportions of detrital clay, inferred from their proportionate increase in Al_2O_3. Small triangles = glasses from Kilauea and Puna Ridge (Clague et al., 1995); small dots = normal mid-ocean-ridge basalt (N-MORB) glasses from the Pacific-Antarctic East Pacific Rise; large purple dots = N-MORB glass from DSDP Site 501 and three portions of its palagonitized rim (Noack et al., 1983). Fields for kaolinite (K), illite (I), and continental montmorillonite (M) are from Grim (1964). Average pelagic clay (PC) is from Cronan and Toombs (1969). The saponite nontronite (sap and non) fields (inset diagrams only) are for vein and replacement clays in basalts of DSDP Hole 504B (Honnorez et al., 1983).

Figure F23. Comparison of analyses of samples from Hole 1223A with Kilauea-Puna Ridge and Koolau tholeiites plus enriched mid-ocean-ridge basalt (E-MORB) and MORB. **A.** MgO vs. SiO_2. **B.** MgO vs. Ba. **C.** MgO vs. Zr. The general effect of subtraction of olivine with 45% MgO is indicated by the arrow. Symbols distinguish vitric tuffs (red left-pointing triangles) and siltstones (gray triangles). Large open triangles = basaltic glasses from Kilauea and Puna Ridge (Clague et al., 1995); dark green squares = high-MgO basalts from Koolau Volcano, Oahu (Frey et al., 1994); light green right-pointing triangles = E-MORB (data compilation of J. Natland, from several literature sources); small dots = normal mid-ocean-ridge basalt (N-MORB) glasses from the Pacific-Antarctic East Pacific Rise.

Table T1. Leg 200 operations summary.

Hole	Latitude	Longitude	Water depth (mbsl)	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Interval drilled (m)	Penetration (m)	Time on site (hr)	Time on site (days)
1223A	22°58.410′N	155°39.259′E	4235.1	6	41	23.5	57.4	0	41	29	1.21
		Site 1223 totals:		6	41	23.5	57.4	0	41	42	1.75
1224A	27°53.369′N	141°58.754′E	4966.1	6	32.2	1.7	5.2	0	32.2	14.58	0.61
1224B	27°53.370′N	141°58.754′E	4970.4	1	0.2	0.2	100	0	0.2	2.25	0.09
1224C	27°53.369′N	141°58.757′E	4967.1	1	6.5	6.5	100.5	0	6.5	30.75	1.28
1224D	27°53.370′N	141°58.752′E	4967.1	5	33.5	15.6	46.7	31.2	64.7	268.90	11.20
1224E	27°53.363′N	141°58.757′E	4967.1	3	28.7	14.9	52	8	36.7	20.00	0.83
1224F	27°53.363′N	141°58.757′E	4967.1	17	146.8	37.7	25.7	0	174.5	176.90	7.37
		Site 1224 totals:		33	247.9	76.7	30.9	39.2	314.8	592.17	24.67
		Leg 200 totals:		39	288.9	100.2	34.7	39.2	355.8	634.17	26.42

Table T2. Summary of holes drilled in normal crust on the Pacific plate with an age <100 Ma and penetration into basement >10 m.

Leg, hole	Age (Ma)	Lattitude/ longitude	Basement penetration (m)	Sediment thickness (m)
DSDP				
16-163	72.0	11°N, 150°W	18	176
54-420	3.4	09°N, 106°W	29	118
54-421	3.4	09°N, 106°W	29	85
54-429A	4.6	09°N, 107°W	21	31
63-469*	17.0	33°N, 121°W	58	391
63-470A	15.0	29°N, 118°W	48	167
63-471	12.0	23°N, 112°W	82	741
63-472	15.0	23°N, 114°W	25	112
65-483B	1.7	23°N, 109°W	157	110
92-597B†	29.0	19°S, 130°W	25	48
92-597C‡	29.0	19°S, 130°W	91	53
92-599B	8.0	19°S, 120°W	10	41
ODP				
136-843B**	95.0	19°N, 159°W	71	243
200-1224D	46.3	28°N, 142°W	36	29
200-1224F	46.3	28°N, 142°W	145	29

Notes: * = At the foot of Patton Escarpment. † = This hole is in crust generated by fast spreading (55 mm/yr half rate). ‡ = A reentry cone was emplaced at this site. ** = This is the location of Hole OSN-1.

Table T3. Coring summary for Site 1224. (Continued on next page.)

Hole 1224A
Latitude: 27°53.3723′N
Longitude: 141°58.7494′W
Time on Site: 592.17 hr (0845 hr, 28 December 2001 - 2355 hr, 21 January 2002)
Time on Hole: 14.58 hr (1455 hr, 28 December - 0530 hr, 29 December 2001)
Seafloor (drill pipe measurement from rig floor, mbrf): 4977.0
Distance between rig floor and sea level (m): 10.9
Water depth (drill pipe measurement from sea level, m): 4966.1
Total depth (drill pipe measurement from rig floor, mbrf): 5009.2
Total penetration (meters below seafloor, mbsf): 32.2
Total length of cored section (m): 32.2
Total core recovered (m): 1.67
Core recovery (%): 5.19
Total number of cores: 6

Hole 1224B
Latitude: 27°53.3690′N
Longitude: 141°58.7538′W
Time on Hole: 0 days, 2.25 hr; 2.25 hr (0530 hr, 29 December - 0745 hr, 29 December 2001)
Seafloor (drill pipe measurement from rig floor, mbrf): 4981.3
Distance between rig floor and sea level (m): 10.9
Water depth (drill pipe measurement from sea level, m): 4970.4
Total depth (drill pipe measurement from rig floor, mbrf): 4981.5
Total penetration (meters below seafloor, mbsf): 0.2
Total length of cored section (m): 0.2
Total core recovered (m): 0.20
Core recovery: %100.0
Total number of cores: 1

Hole 1224C
Latitude: 27°53.369′N
Longitude: 141°58.7571′W
Time on Hole: 1 day, 6.75 hr; 30.75 hr (0745 hr, 29 December - 1430 hr, 30 December 2001)
Seafloor (drill pipe measurement from rig floor, mbrf): 4978.0
Distance between rig floor and sea level (m): 10.9
Water depth (drill pipe measurement from sea level, m): 4967.1
Total depth (drill pipe measurement from rig floor, mbrf): 4984.5
Total penetration (meters below seafloor, mbsf): 6.5
Total length of cored section (m): 6.5
Total core recovered (m): 6.53
Core recovery (%): 100.46
Total number of cores: 1

Hole 1224D
Latitude: 27°53.3699′N
Longitude: 141°58.7525′W
Time on Hole: 11 days, 4.9 hr; 268.9 hr (1220 hr, 2 January - 1815 hr, 13 January 2002)
Seafloor (drill pipe measurement from rig floor, mbrf): 4978.0
Distance between rig floor and sea level (m): 10.9
Water depth (drill pipe measurement from sea level, m): 4967.1
Total depth (drill pipe measurement from rig floor, mbrf): 5042.7
Total penetration (meters below seafloor, mbsf): 64.7
Total length of cored section (m): 33.5
Total core recovered (m): 15.65
Core recovery (%): 46.72
Total number of cores: 5

Hole 1224E
Latitude: 27°53.3627′N
Longitude: 141°58.7568′W
Time on Hole: 0 days, 20 hr; 20 hr (1900 hr, 13 January - 1500 hr, 14 January 2002)
Seafloor (drill pipe measurement from rig floor, mbrf): 4978.0
Distance between rig floor and sea level (m): 10.9
Water depth (drill pipe measurement from sea level, m): 4967.1
Total depth (drill pipe measurement from rig floor, mbrf): 5014.7
Total penetration (meters below seafloor, mbsf): 36.7
Total length of cored section (m): 28.7
Total core recovered (m): 14.91
Core recovery (%): 51.95
Total number of cores: 3

Table T3 (continued).

Hole 1224F
Latitude: 27°53.3634′N
Longitude: 141°58.7567′W
Time on Hole: 7 days, 8.9 hr; 176.9 hr (1500 hr, 14 January - 2355 hr, 21 January 2002)
Seafloor (drill pipe measurement from rig floor, mbrf): 4978.0
Distance between rig floor and sea level (m): 10.9
Water depth (drill pipe measurement from sea level, m): 4967.1
Total depth (drill pipe measurement from rig floor, mbrf): 5152.5
Total penetration (meters below seafloor, mbsf): 174.5
Total length of cored section (m): 146.8
Total core recovered (m): 37.7
Core recovery (%): 25.68
Total number of cores: 17

			Depth (mbsf)		Length (m)		
Core	Date	Ship time (local)	Top	Bottom	Cored	Recovered	Recovered (%)
200-1224A-							
1X	28 Dec 2001	1610	0.0	6.0	6.0	0.00	0.00
2X	28 Dec 2001	1720	6.0	15.6	9.6	0.02	0.21
3X	28 Dec 2001	1835	15.6	25.2	9.6	0.01	0.10
4X	28 Dec 2001	2210	25.2	30.7	5.5	1.24	22.55
5X	29 Dec 2001	0105	30.7	32.0	1.3	0.18	13.85
6N	29 Dec 2001	0430	32.0	32.2	0.2	0.22	110.00
				Totals:	32.2	1.67	5.19
200-1224B-							
1H	29 Dec 2001	0725	0.0	0.2	0.2	0.20	100.00
				Totals:	0.2	0.20	100.00
200-1224C-							
1H	29 Dec 2001	0850	0.0	6.5	6.5	6.53	100.46
				Totals:	6.5	6.53	100.46
200-1224D-							
DI	2 Jan 2002	1315	0.0	25.5			
1R	4 Jan 2002	0530	25.5	35.1	9.6	4.15	43.23
2R	4 Jan 2002	1710	35.1	44.7	9.6	4.81	50.10
3R	5 Jan 2002	0025	44.7	49.3	4.6	3.30	71.74
4R	5 Jan 2002	0555	49.3	51.3	2.0	1.99	99.50
5R	6 Jan 2002	0100	51.3	59.0	7.7	1.40	18.18
DI	11 Jan 2002	0700	59.0	64.7			
				Totals:	33.5	15.65	46.72
200-1224E-							
DI	13 Jan 2002	1645	0.0	8.0			
1R	13 Jan 2002	2005	8.0	17.5	9.5	1.03	10.84
2R	13 Jan 2002	2110	17.5	27.1	9.6	9.49	98.85
3R	14 Jan 2002	1505	27.1	36.7	9.6	4.39	45.73
				Totals:	28.7	14.91	51.95
200-1224F-							
1R	15 Jan 2002	0455	27.7	39.7	12.0	6.13	51.08
2R	15 Jan 2002	0930	39.7	47.3	7.6	5.32	70.00
3R	15 Jan 2002	2125	47.3	56.4	9.1	4.13	45.38
4R	16 Jan 2002	0650	56.4	65.9	9.5	6.20	65.26
5R	16 Jan 2002	1225	65.9	75.0	9.1	0.95	10.44
6R	16 Jan 2002	2035	75.0	84.5	9.5	1.50	15.79
7R	17 Jan 2002	0240	84.5	93.5	9.0	1.20	13.33
8R	17 Jan 2002	0750	93.5	102.7	9.2	1.31	14.24
9R	17 Jan 2002	1225	102.7	111.8	9.1	0.60	6.59
10R	17 Jan 2002	1645	111.8	121.1	9.3	1.40	15.05
11R	17 Jan 2002	2315	121.1	128.5	7.4	1.71	23.11
12R	18 Jan 2002	1130	128.5	133.5	5.0	1.20	24.00
13R	18 Jan 2002	1505	133.5	143.2	9.7	2.73	28.14
14R	19 Jan 2002	0300	143.2	152.4	9.2	2.02	21.96
15R	19 Jan 2002	1045	152.4	161.8	9.4	1.30	13.83
16R	19 Jan 2002	1700	161.8	171.0	9.2	0.00	0.00
17R	19 Jan 2002	2250	171.0	174.5	3.5	0.00	0.00
				Totals:	146.8	37.70	25.68

Table T4. Coring summary, Site 1223.

Hole 1223A
Latitude: 22°58.4095′N
Longitude: 155°39.2590′W
Time on Site: 42 hr (0730 hr, 21 December - 0130 hr, 23 December 2001)
Time on Hole: 29 hr (2030 hr, 21 December - 0130 hr, 23 December, 2001)
Seafloor (drill pipe measurement from rig floor, mbrf): 4245.8
Distance between rig floor and sea level (m): 10.7
Water depth (drill pipe measurement from sea level, m): 4235.1
Total depth (drill pipe measurement from rig floor, mbrf): 4286.8
Total penetration (meters below seafloor, mbsf): 41
Total length of cored section (m): 41.0
Total core recovered (m): 23.54
Core recovery (%): 57.4
Total number of cores: 6

Core	Date (Dec 2001)	Ship time (local)	Depth (mbsf)		Length (m)		Recovered (%)
			Top	Bottom	Cored	Recovered	
1H	21	2055	0.0	7.7	7.7	7.79	101.2
2H	21	2225	7.7	12.7	5.0	3.08	61.6
3X	22	0515	12.7	22.3	9.6	3.34	34.8
4X	22	0915	22.3	32.0	9.7	2.62	27.0
5X	22	1115	32.0	33.0	1.0	1.01	101.0
6X	22	1700	33.0	41.0	8.0	5.70	71.2
				Totals:	41.0	23.54	57.4

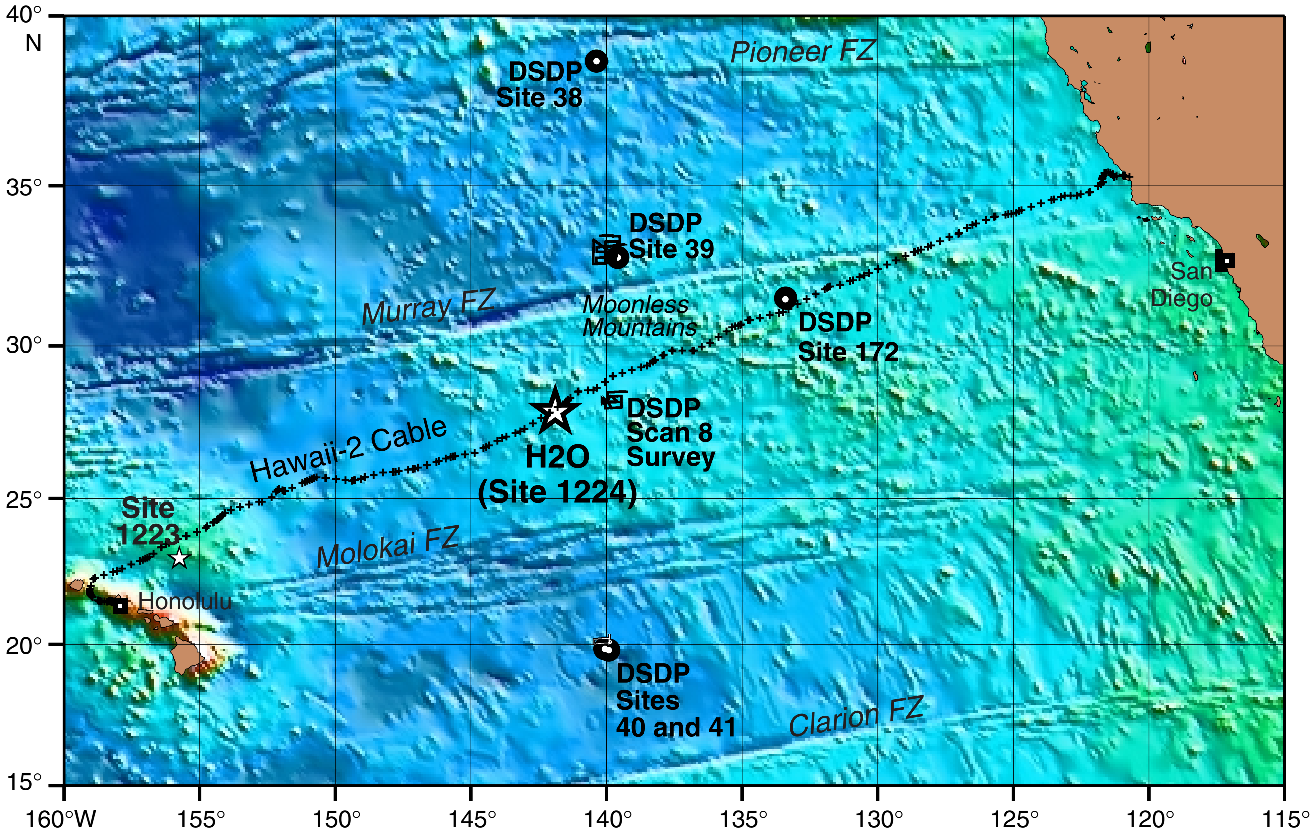
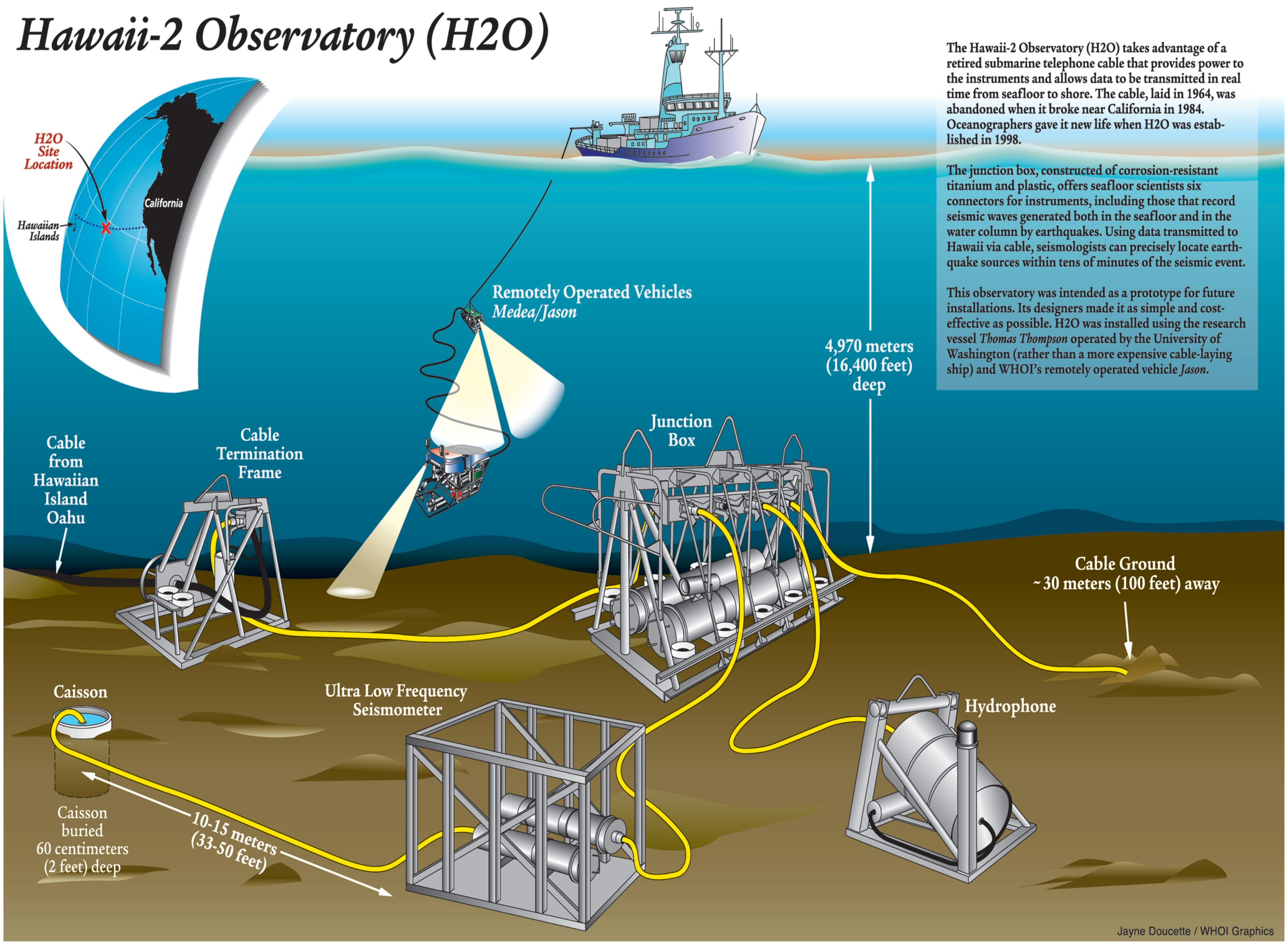

40°
N
35°
30°
25°
20°
15°
160°W
155°
150°
145°
140°
135°
130°
125°
120°
115°
Pioneer FZ
DSDP
Site 38
DSDP
Site 39
Murray FZ
Moonless
Mountains
DSDP
Site 172
San
Diego
DSDP
Scan 8
Survey
H2O
(Site 1224)
Hawaii-2 Cable
Site
1223
Molokai FZ
Honolulu
DSDP
Sites
40 and 41
Clarion FZ

Figure F1



The Hawaii-2 Observatory (H2O) takes advantage of a retired submarine telephone cable that provides power to the instruments and allows data to be transmitted in real time from seafloor to shore. The cable, laid in 1964, was abandoned when it broke near California in 1984. Oceanographers gave it new life when H2O was established in 1998.

The junction box, constructed of corrosion-resistant titanium and plastic, offers seafloor scientists six connectors for instruments, including those that record seismic waves generated both in the seafloor and in the water column by earthquakes. Using data transmitted to Hawaii via cable, seismologists can precisely locate earthquake sources within tens of minutes of the seismic event.

This observatory was intended as a prototype for future installations. Its designers made it as simple and cost-effective as possible. H2O was installed using the research vessel *Thomas Thompson* operated by the University of Washington (rather than a more expensive cable-laying ship) and WHOI's remotely operated vehicle *Jason*.

Jayne Doucette / WHOI Graphics

Figure F2

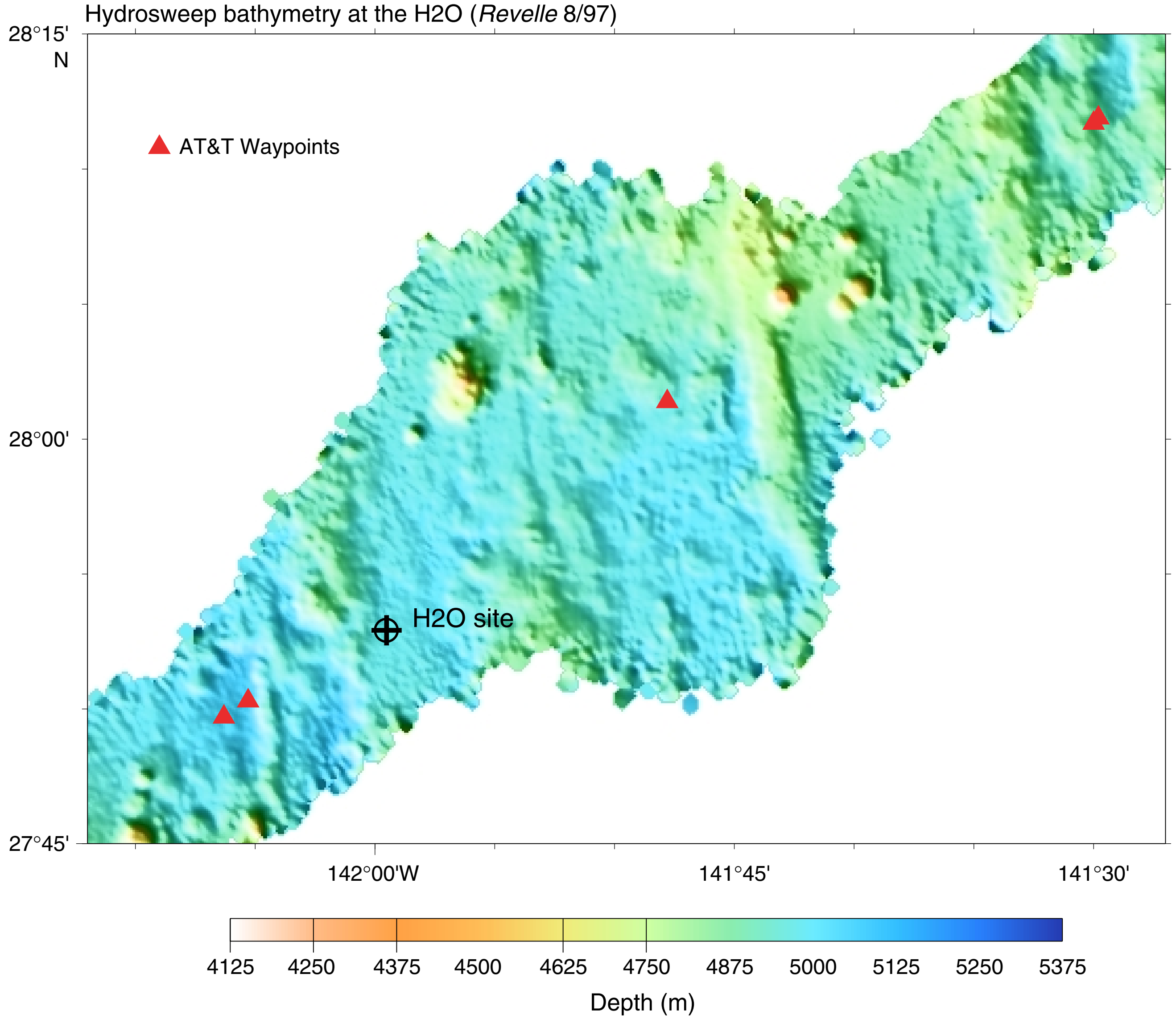

Hydrosweep bathymetry at the H2O (*Revelle* 8/97)
28°15' N
28°00'
27°45'
142°00'W
141°45'
141°30'
▲ AT&T Waypoints
H2O site
4125
4250
4375
4500
4625
4750
4875
5000
5125
5250
5375
Depth (m)

Figure F3

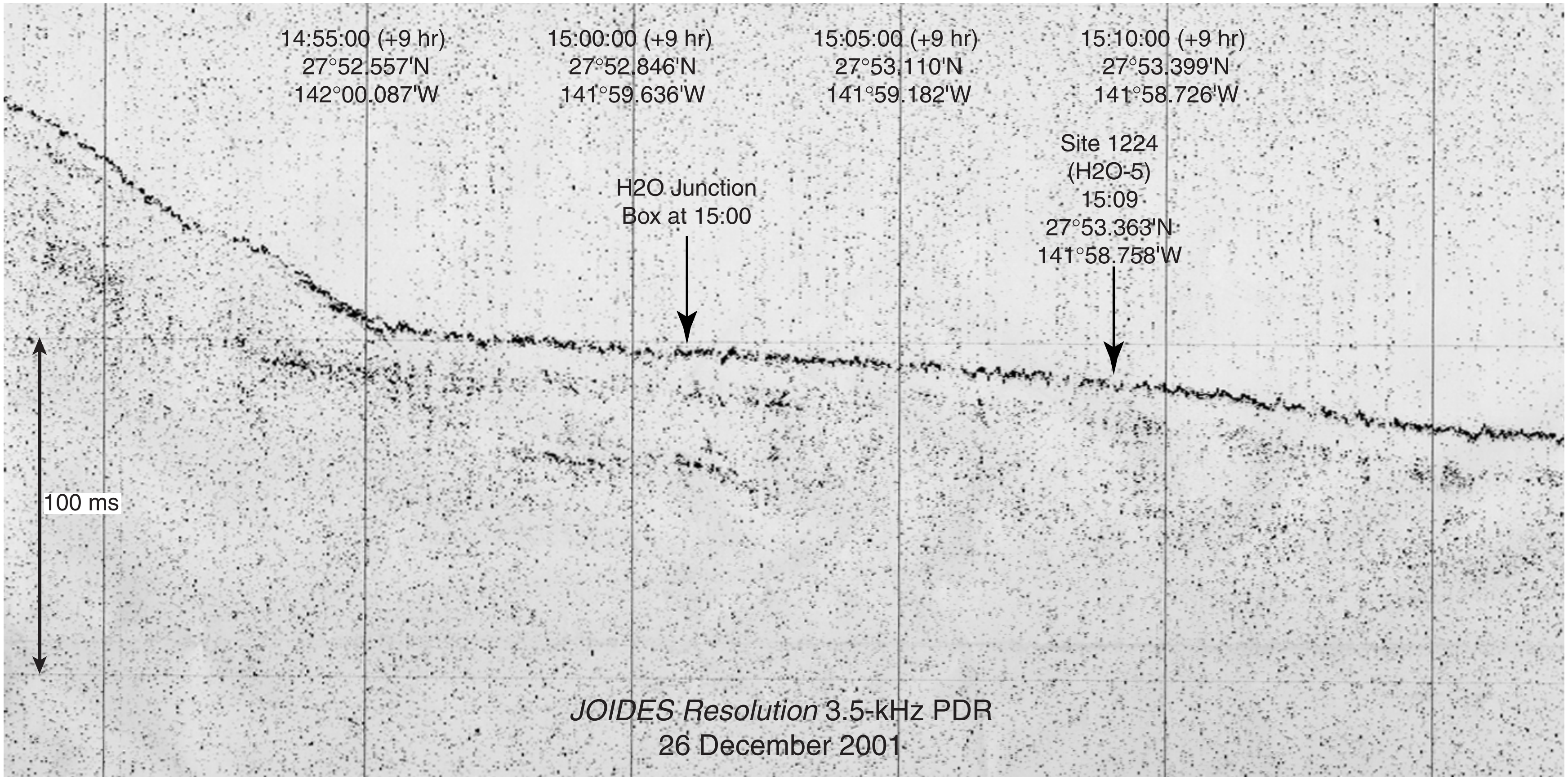

14:55:00 (+9 hr)
27°52.557'N
142°00.087'W
15:00:00 (+9 hr)
27°52.846'N
141°59.636'W
15:05:00 (+9 hr)
27°53.110'N
141°59.182'W
15:10:00 (+9 hr)
27°53.399'N
141°58.726'W
Site 1224
(H2O-5)
15:09
27°53.363'N
141°58.758'W
H2O Junction
Box at 15:00
100 ms
JOIDES Resolution 3.5-kHz PDR
26 December 2001

Figure F4

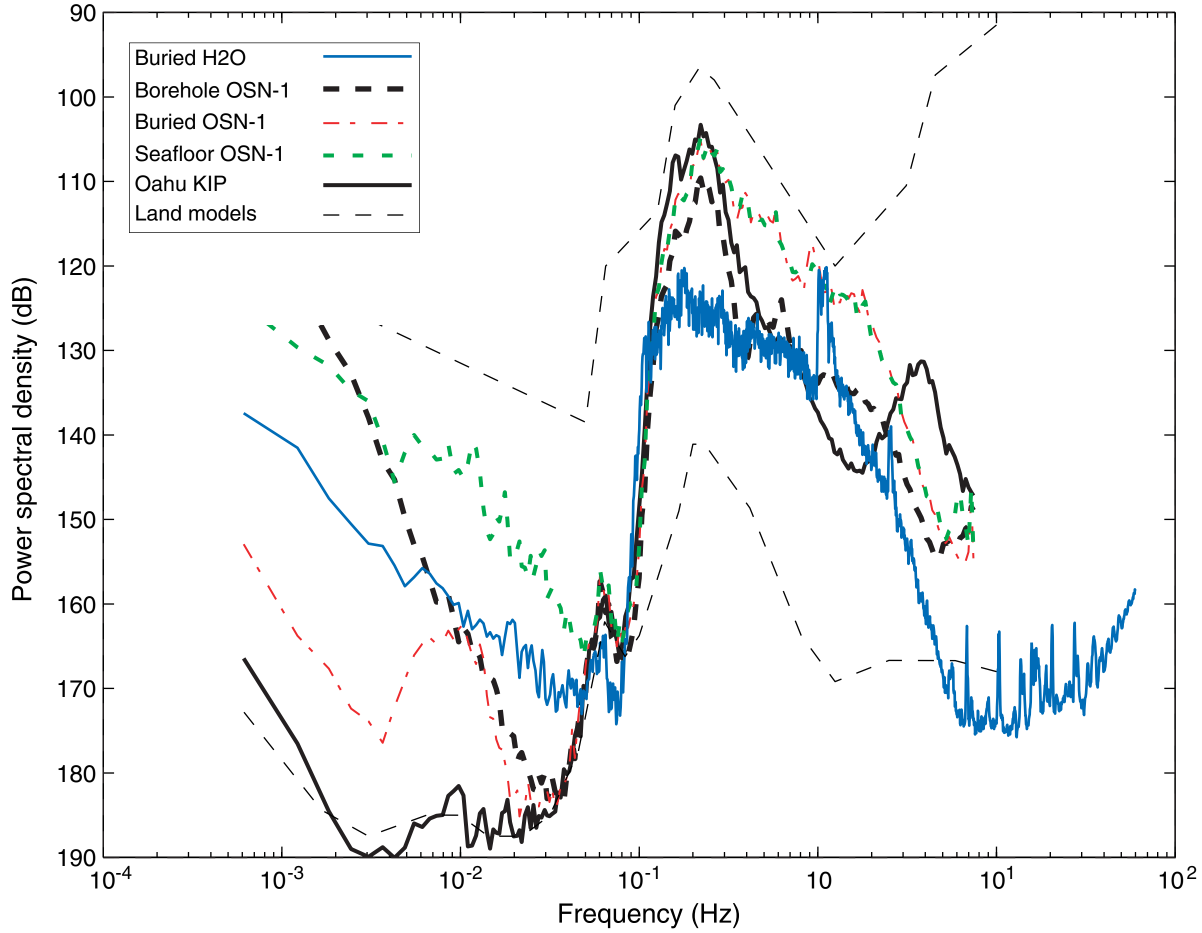

Buried H2O
Borehole OSN-1
Buried OSN-1
Seafloor OSN-1
Oahu KIP
Land models
Power spectral density (dB)
90
100
110
120
130
140
150
160
170
180
190
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10
10^{1}
10^{2}
Frequency (Hz)

Figure F5

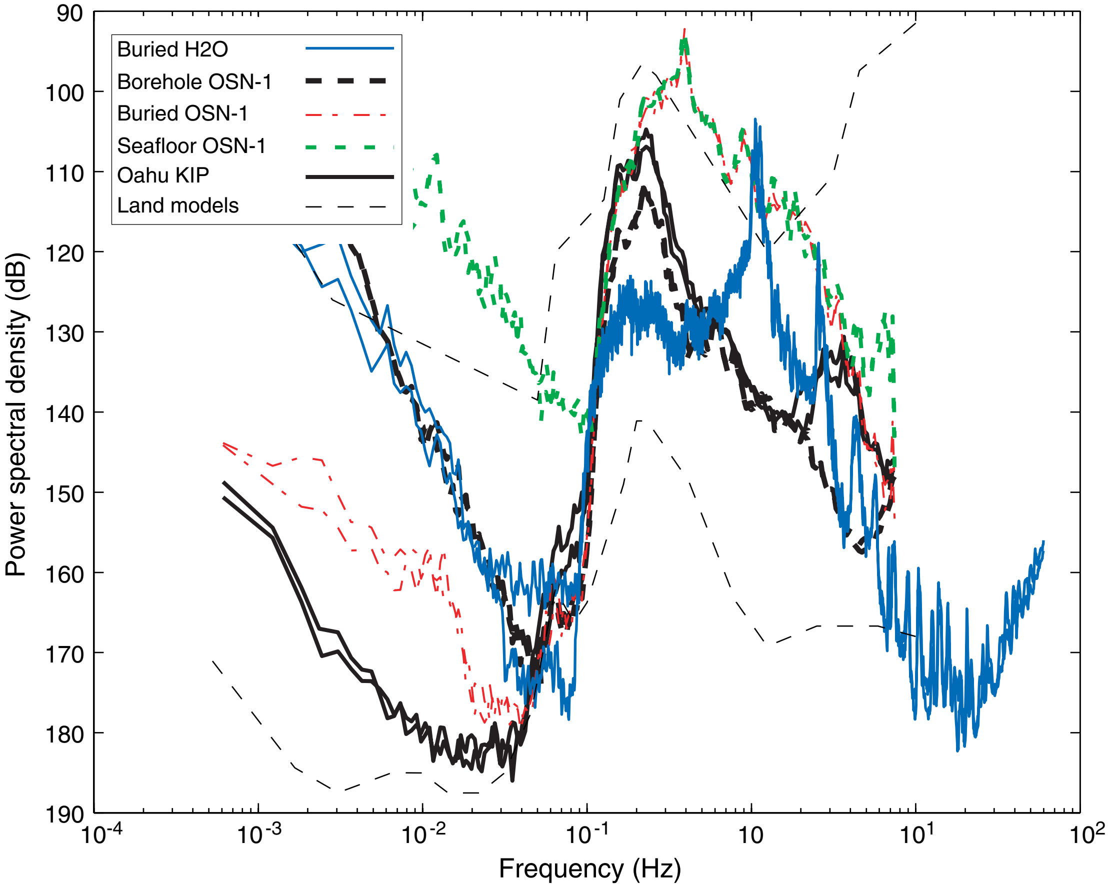

Buried H2O
Borehole OSN-1
Buried OSN-1
Seafloor OSN-1
Oahu KIP
Land models
Power spectral density (dB)
90
100
110
120
130
140
150
160
170
180
190
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10
10^{1}
10^{2}
Frequency (Hz)

Figure F6

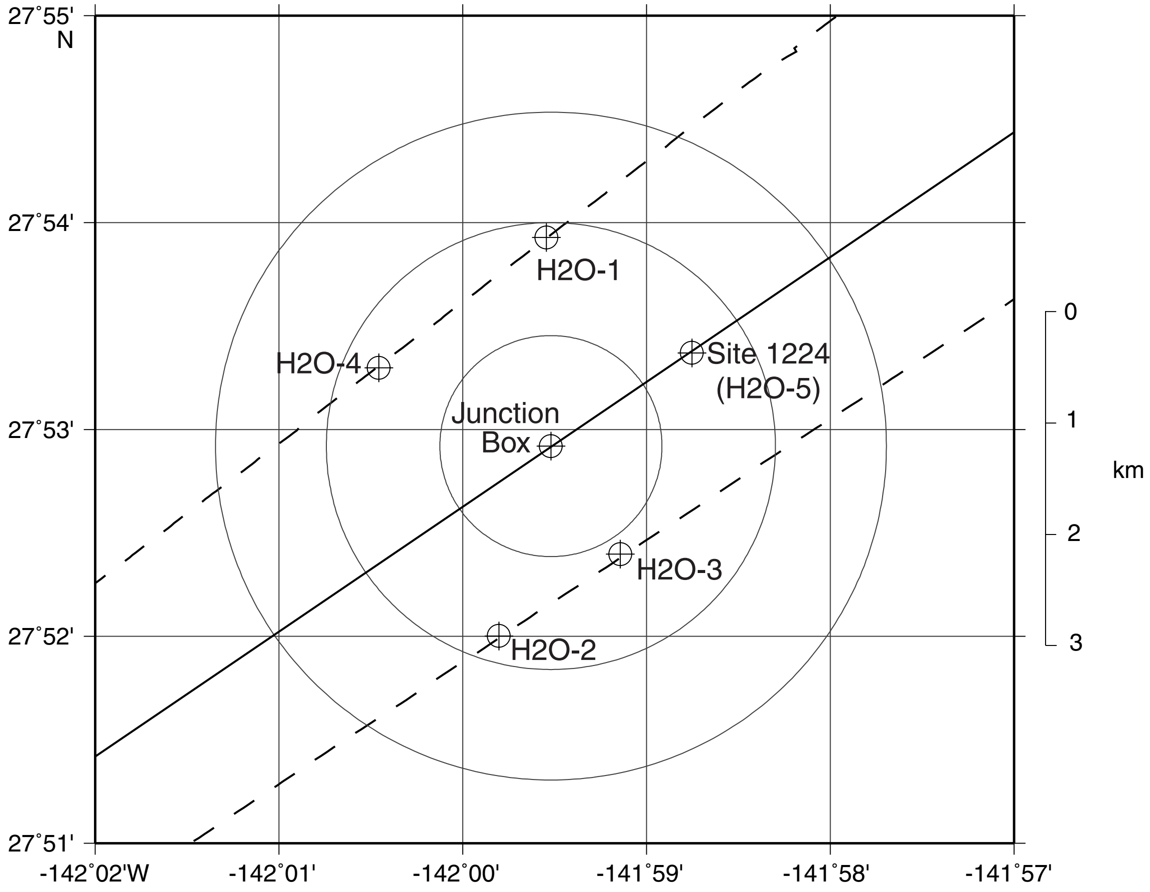

27°55' N
27°54'
27°53'
27°52'
27°51'
-142°02'W
-142°01'
-142°00'
-141°59'
-141°58'
-141°57'
H2O-1
H2O-4
Site 1224 (H2O-5)
Junction Box
H2O-3
H2O-2
0
1
2
3
km

Figure F7

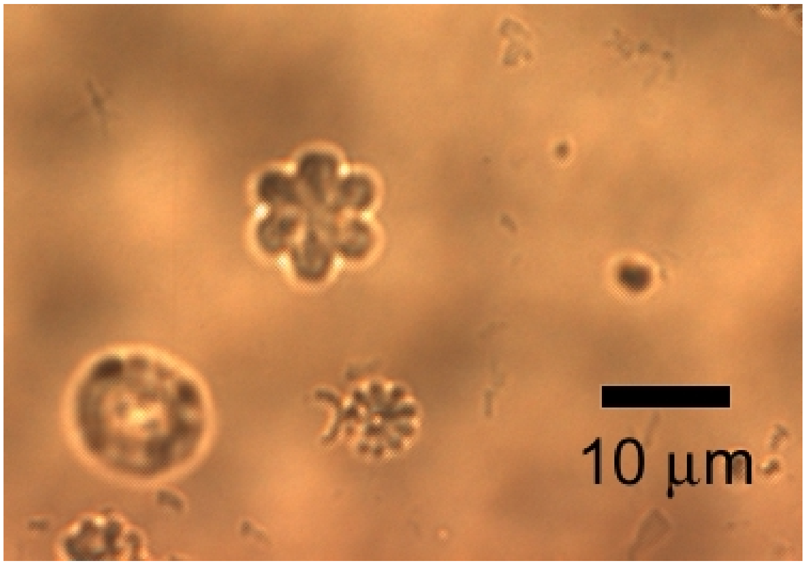


Figure F8

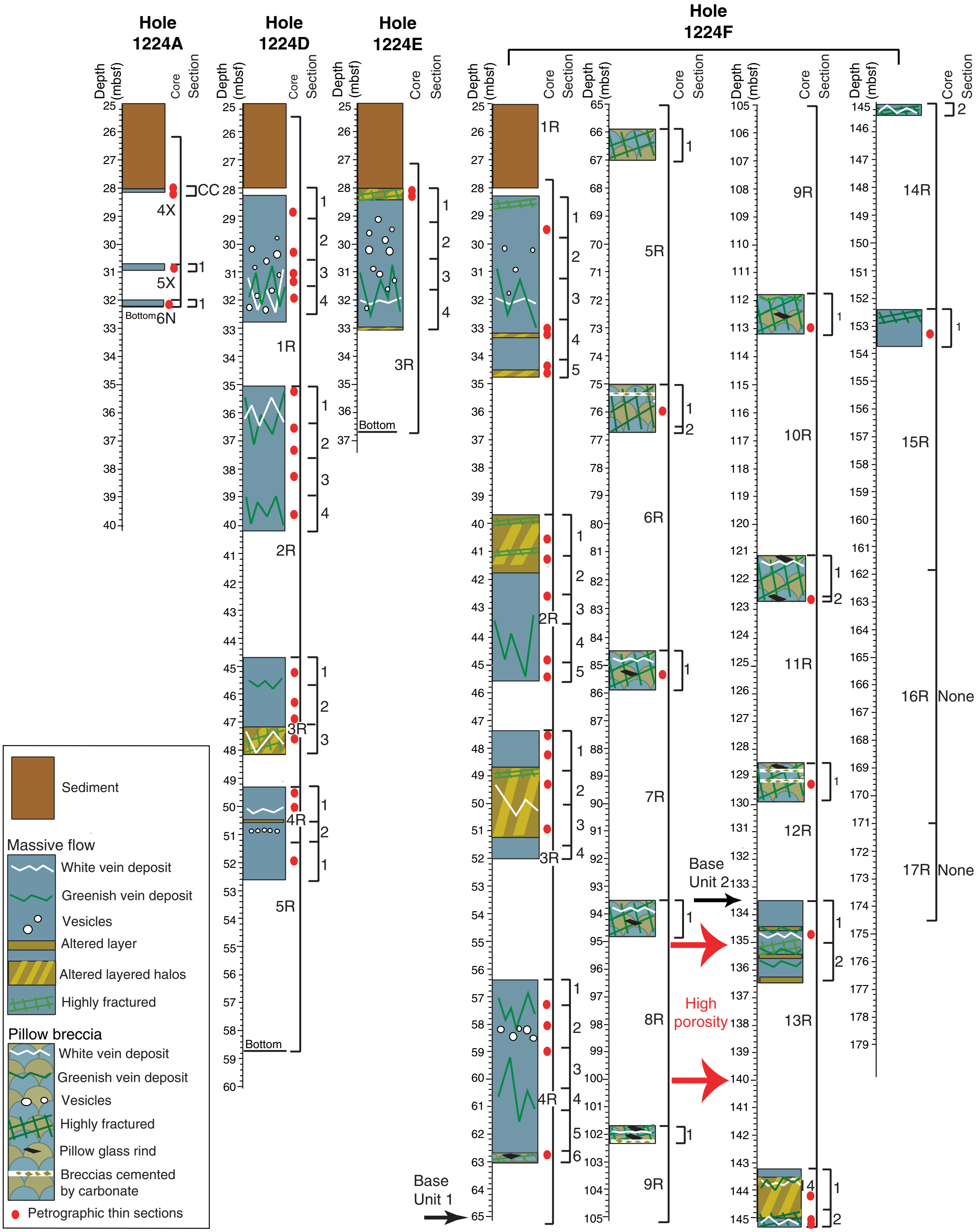

Hole 1224A
Hole 1224D
Hole 1224E
Hole 1224F
Depth (mbsf)
Core
Section
4X
5X
6N
CC
Bottom
1R
2R
3R
4R
5R
5R
6R
7R
8R
9R
10R
11R
12R
13R
14R
15R
16R None
17R None
Base Unit 1
Base Unit 2
High porosity
Sediment
Massive flow
White vein deposit
Greenish vein deposit
Vesicles
Altered layer
Altered layered halos
Highly fractured
Pillow breccia
White vein deposit
Greenish vein deposit
Vesicles
Highly fractured
Pillow glass rind
Breccias cemented by carbonate
Petrographic thin sections

Figure F9

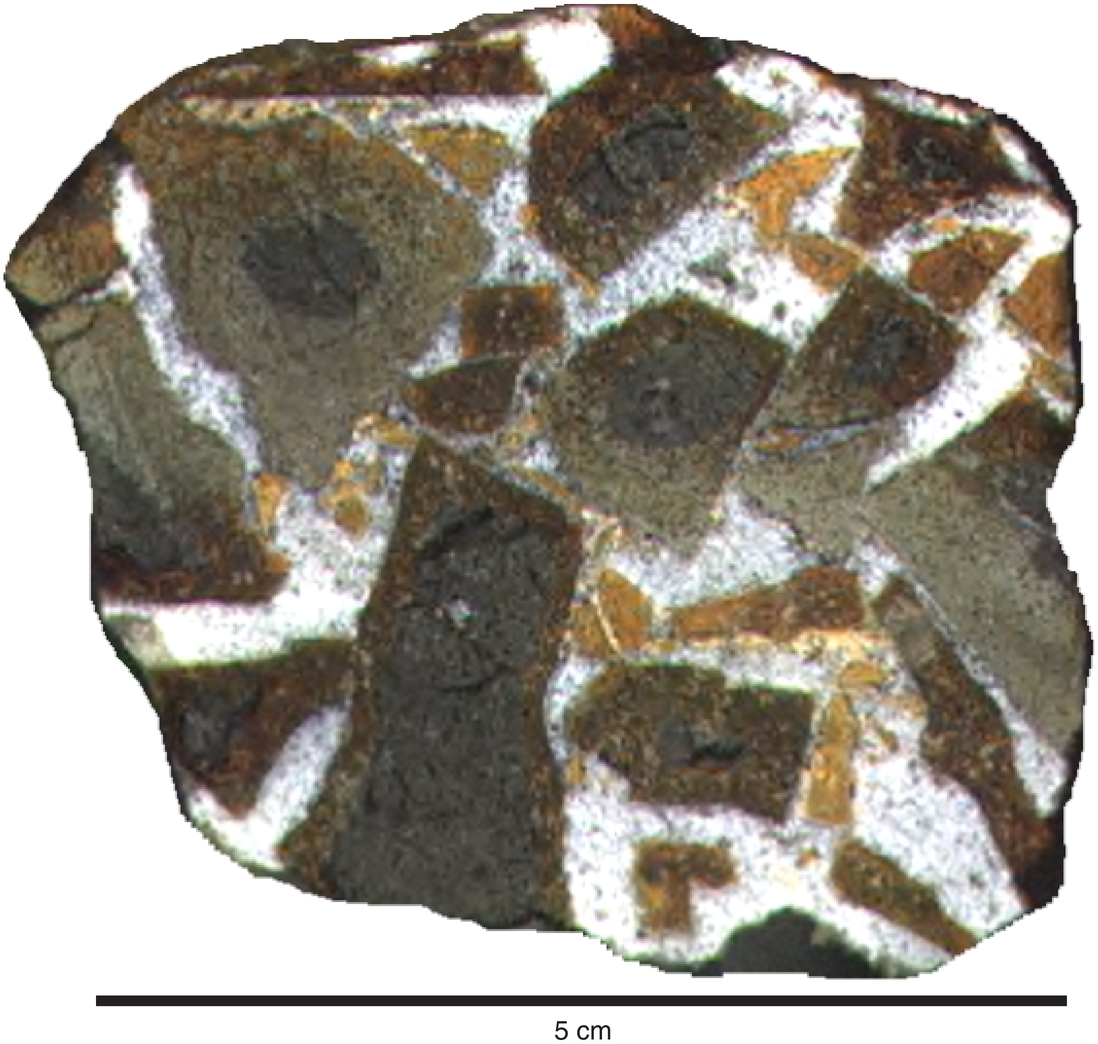


Figure F10

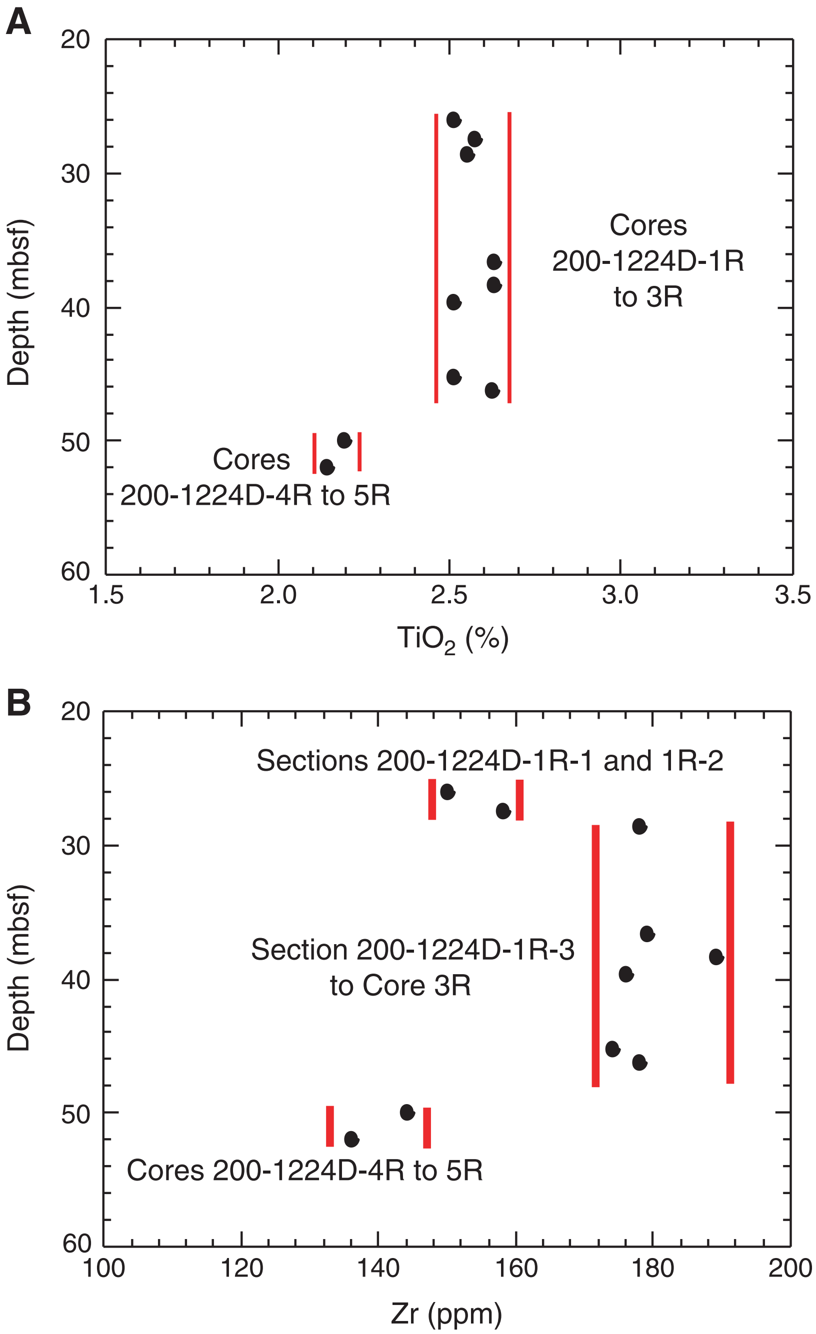

A
Depth (mbsf)
20
30
40
50
60
1.5
2.0
2.5
3.0
3.5
TiO_2 (%)
Cores 200-1224D-1R to 3R
Cores 200-1224D-4R to 5R
B
Depth (mbsf)
20
30
40
50
60
100
120
140
160
180
200
Zr (ppm)
Sections 200-1224D-1R-1 and 1R-2
Section 200-1224D-1R-3 to Core 3R
Cores 200-1224D-4R to 5R

Figure F11

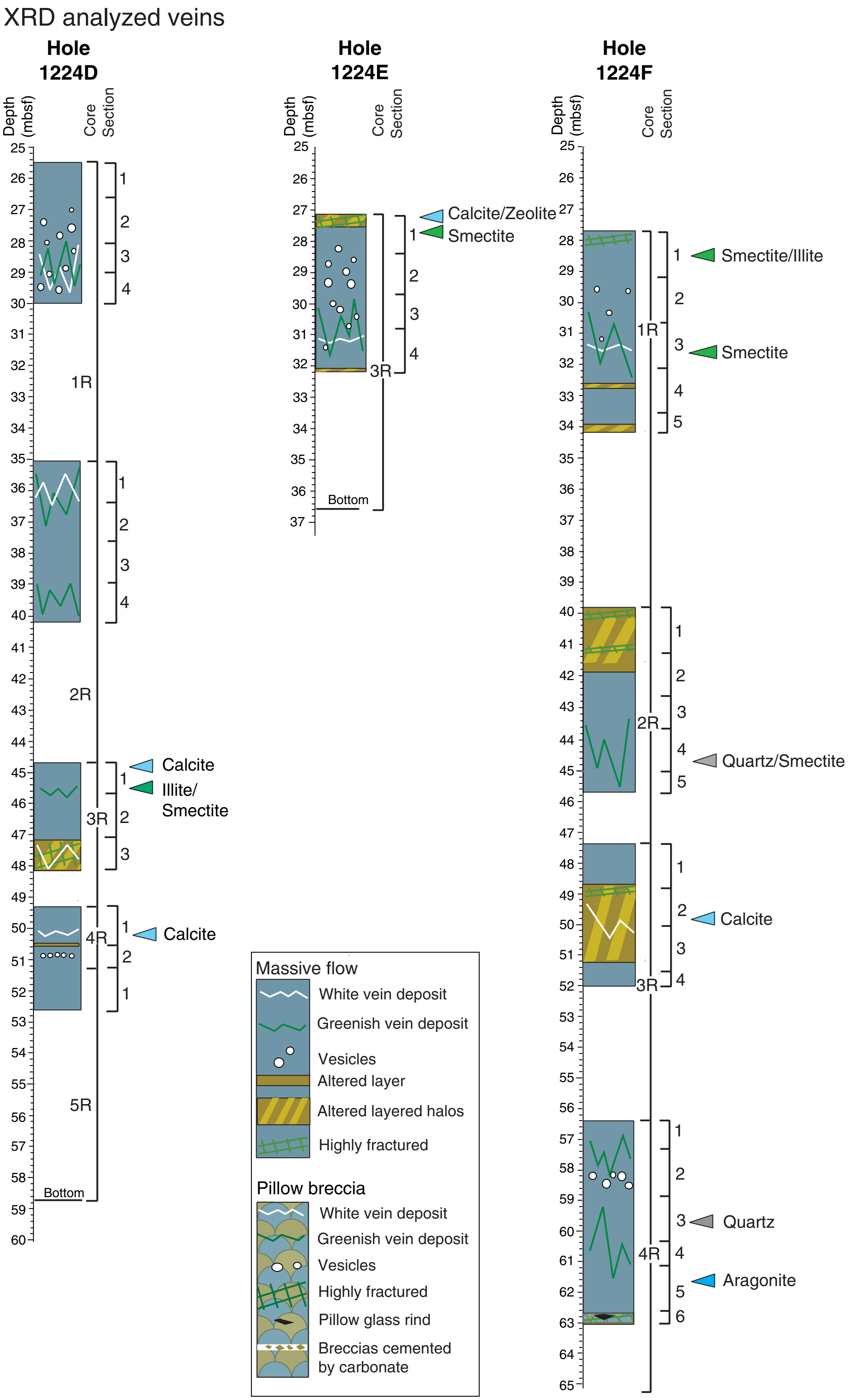

XRD analyzed veins
Hole 1224D
Hole 1224E
Hole 1224F
Depth (mbsf)
Core
Section
1R
2R
3R
4R
5R
Bottom
Calcite
Illite/ Smectite
Calcite
Calcite/Zeolite
Smectite
Smectite/Illite
Smectite
Quartz/Smectite
Calcite
Quartz
Aragonite
Massive flow
White vein deposit
Greenish vein deposit
Vesicles
Altered layer
Altered layered halos
Highly fractured
Pillow breccia
White vein deposit
Greenish vein deposit
Vesicles
Highly fractured
Pillow glass rind
Breccias cemented by carbonate

Figure F12

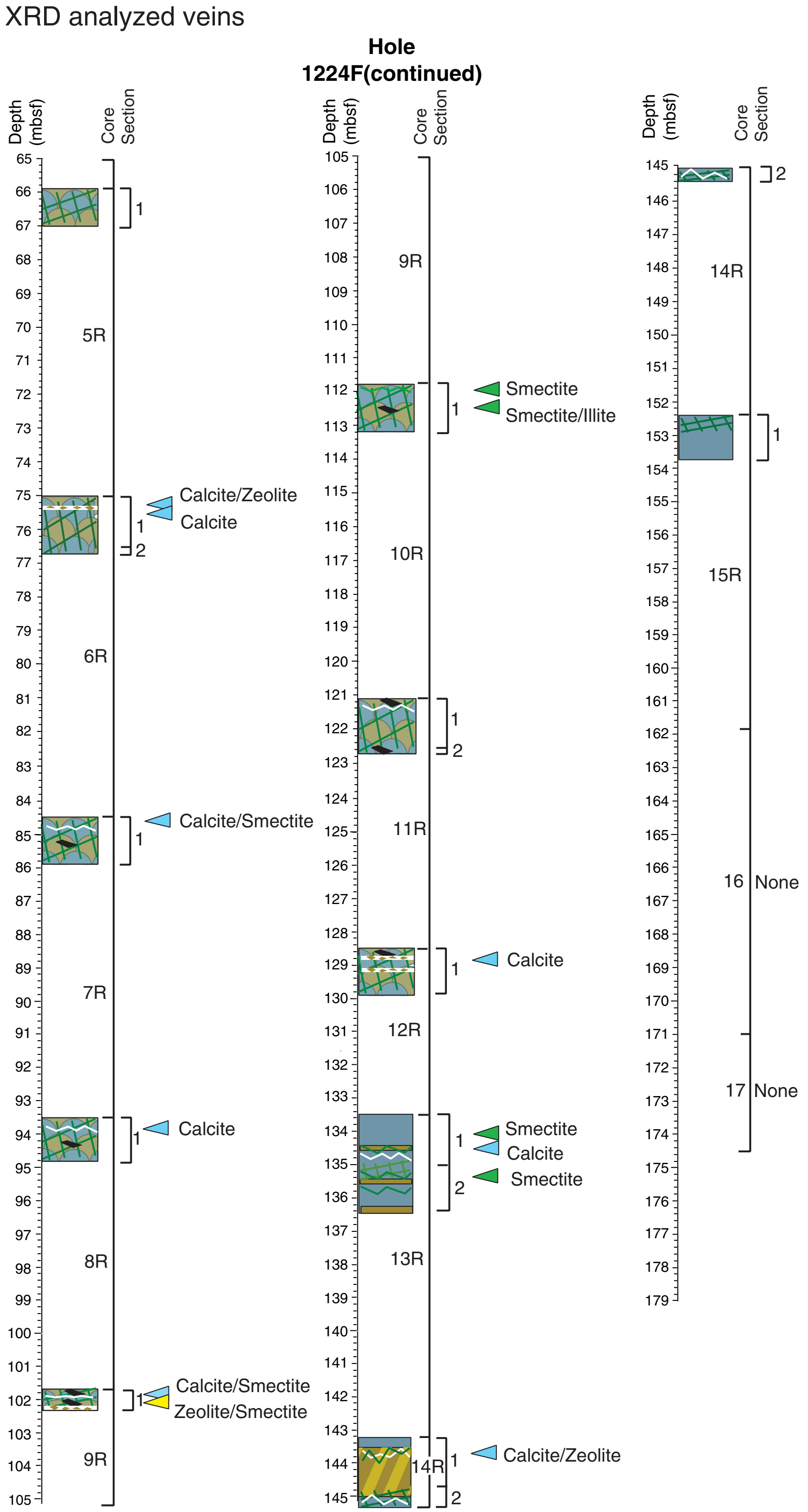


Figure F12 (continued)

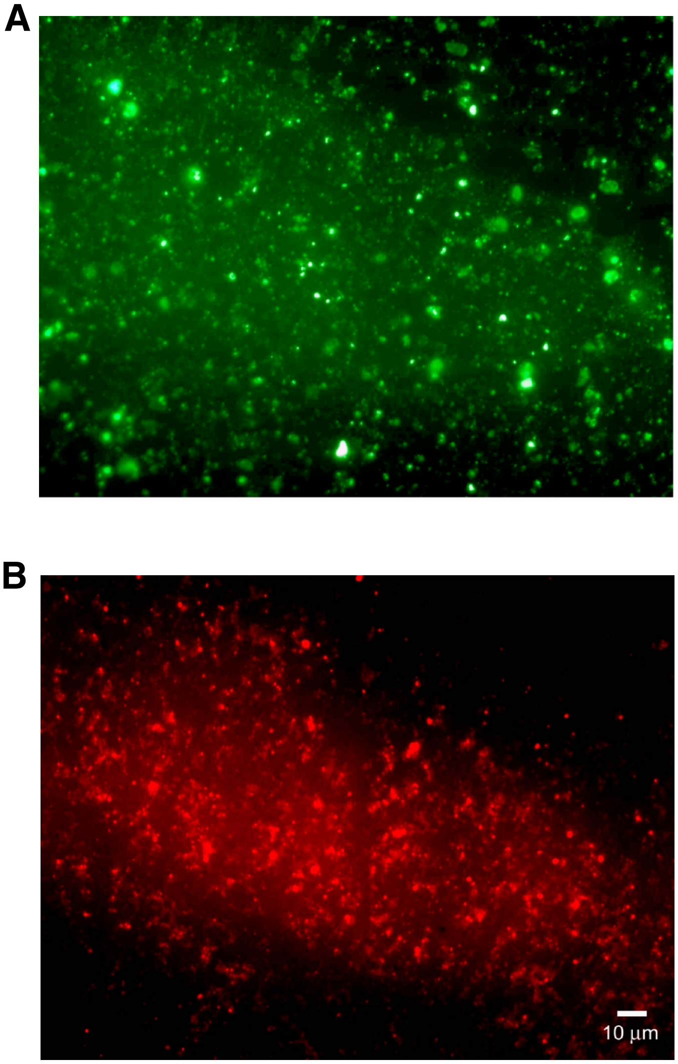


Figure F13

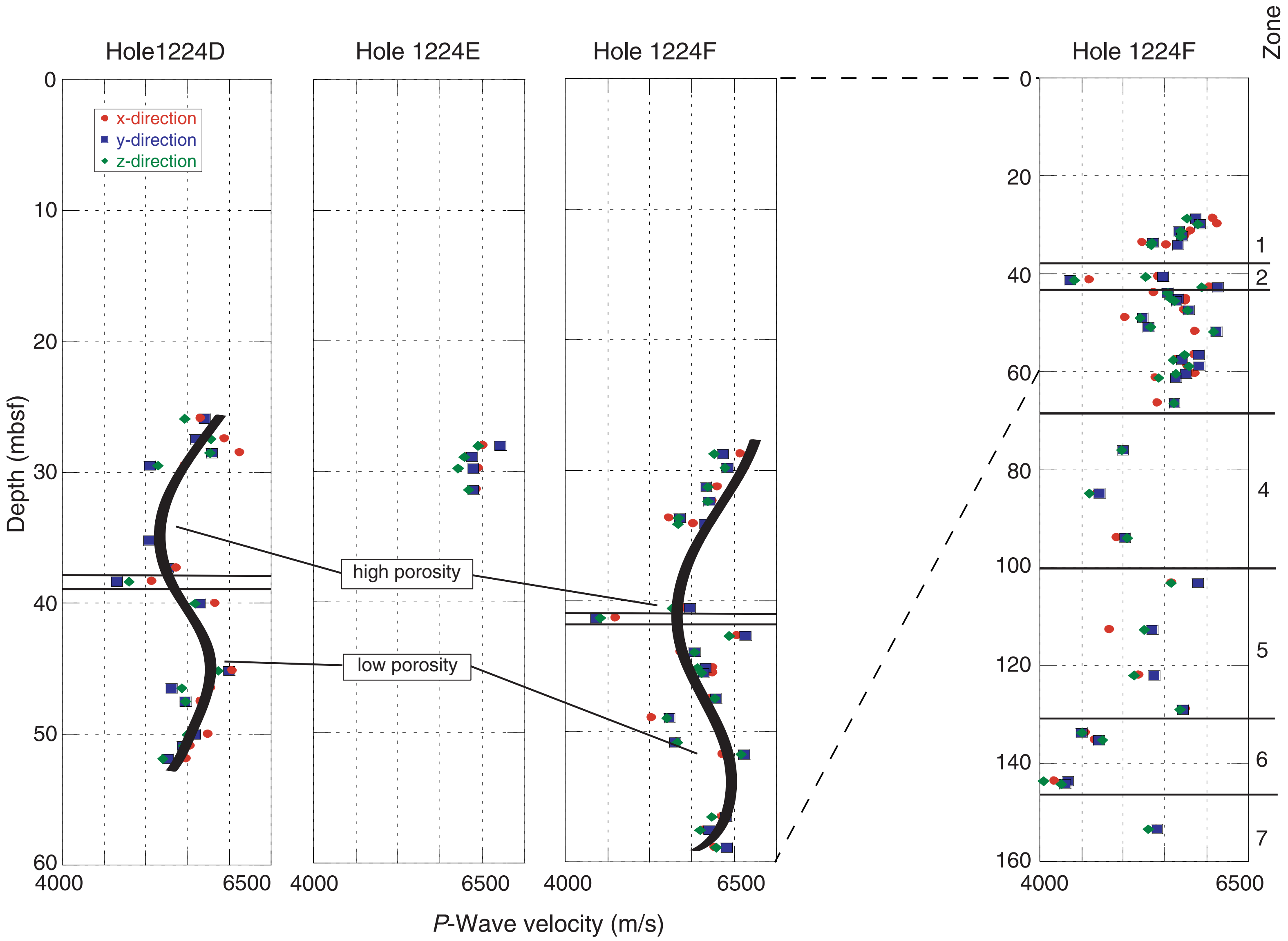

Hole1224D
Hole 1224E
Hole 1224F
Hole 1224F
Zone
x-direction
y-direction
z-direction
Depth (mbsf)
0
10
20
30
40
50
60
4000
6500
4000
6500
4000
6500
high porosity
low porosity
P-Wave velocity (m/s)
0
20
40
60
80
100
120
140
160
4000
6500
1
2
4
5
6
7

Figure F14

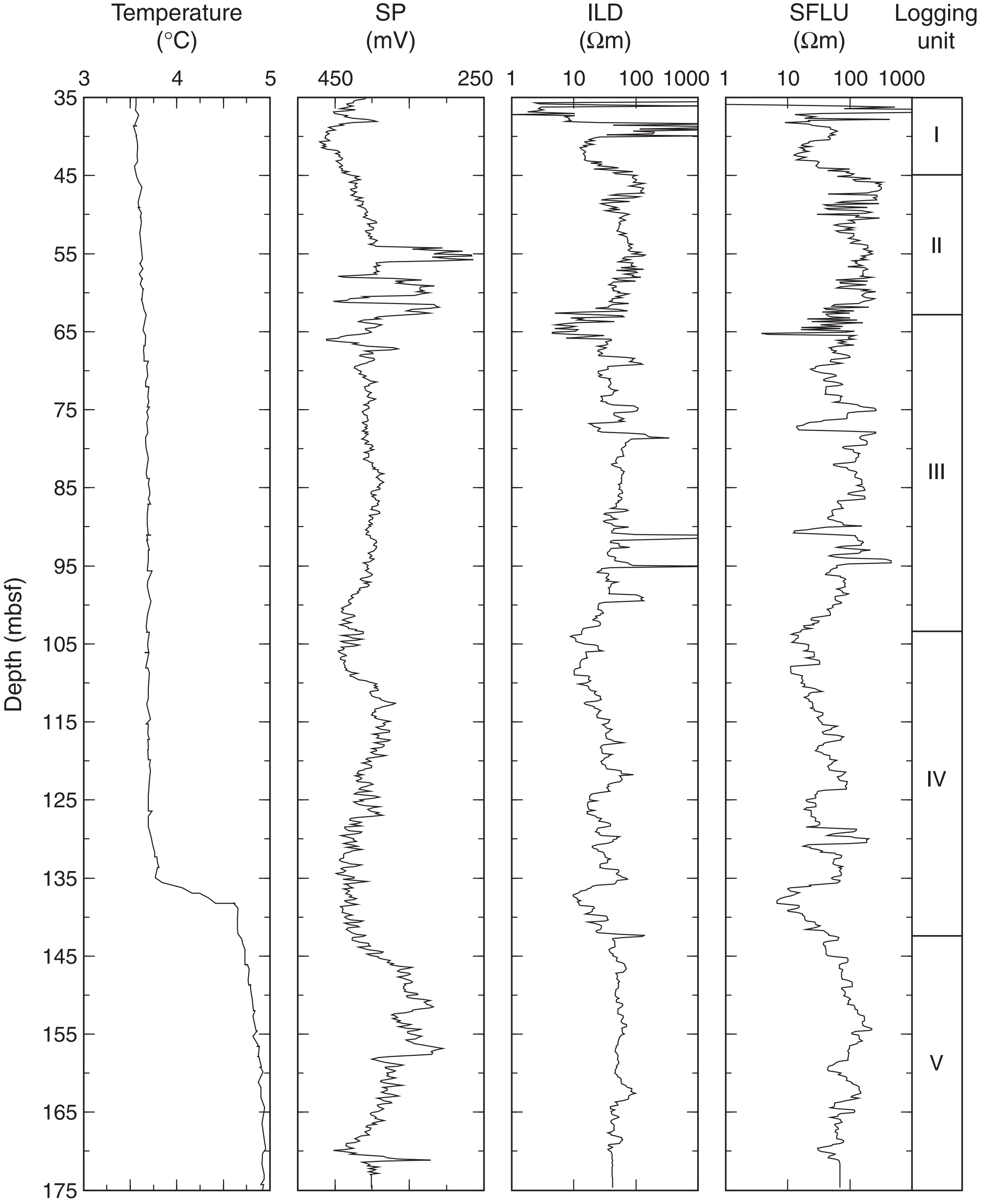

Temperature
(°C)
3
4
5
SP
(mV)
450
250
ILD
(Ωm)
1
10
100
1000
SFLU
(Ωm)
1
10
100
1000
Logging
unit
Depth (mbsf)
35
45
55
65
75
85
95
105
115
125
135
145
155
165
175
I
II
III
IV
V

Figure F15

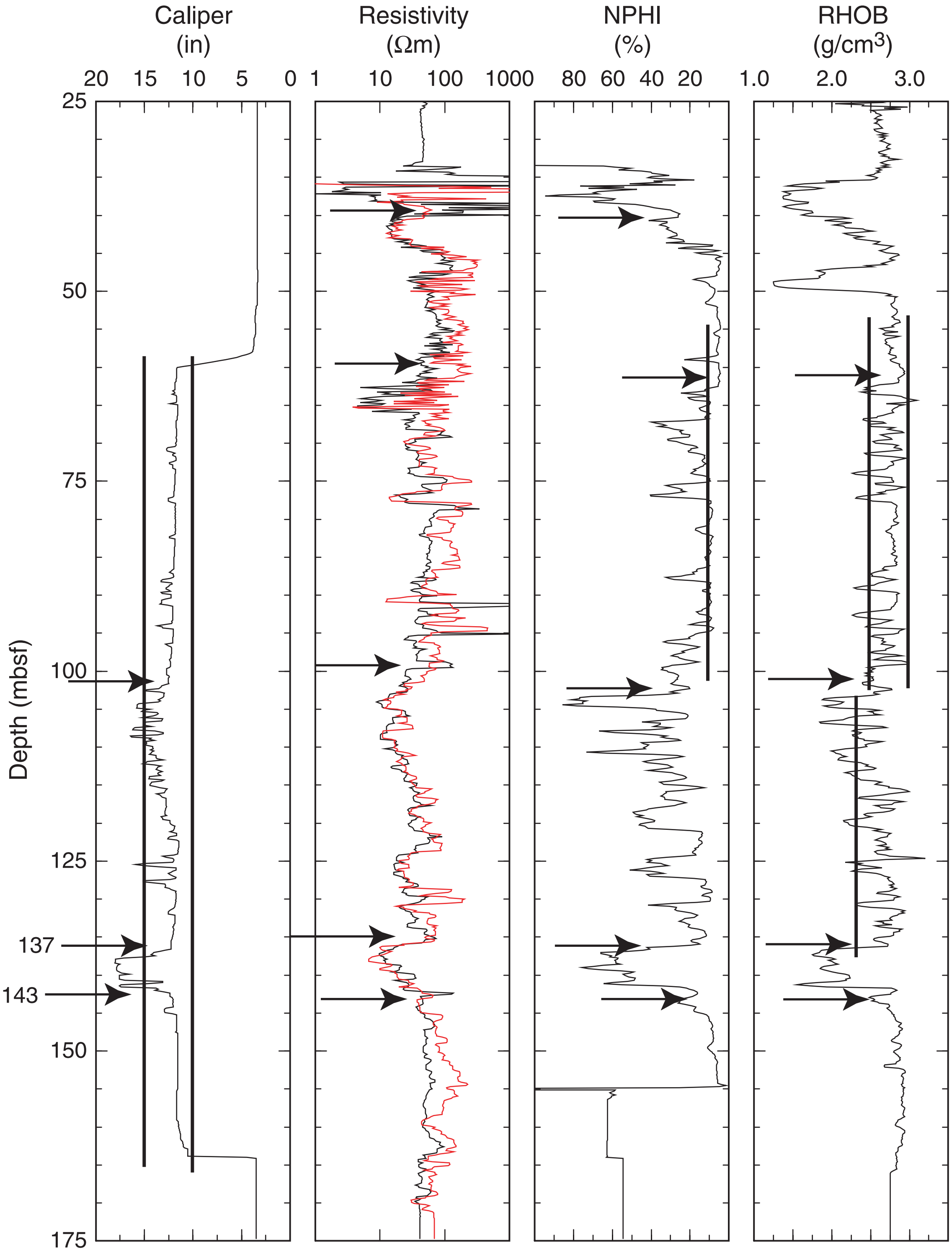

Caliper
(in)
20
15
10
5
0
Resistivity
(Ωm)
1
10
100
1000
NPHI
(%)
80
60
40
20
RHOB
(g/cm^3)
1.0
2.0
3.0
Depth (mbsf)
25
50
75
100
125
137
143
150
175

Figure F16

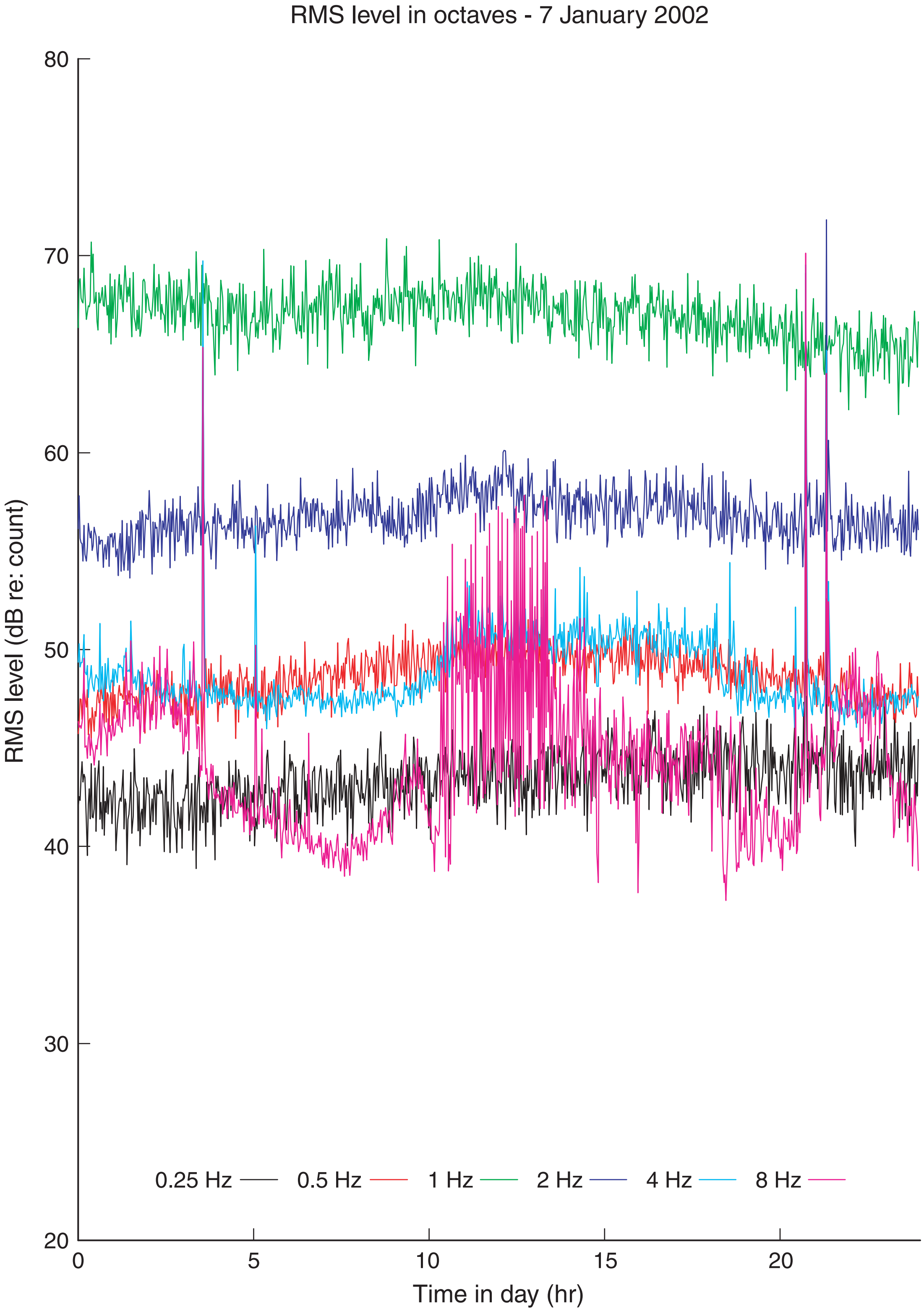

RMS level in octaves - 7 January 2002
RMS level (dB re: count)
80
70
60
50
40
30
20
0
5
10
15
20
Time in day (hr)
0.25 Hz
0.5 Hz
1 Hz
2 Hz
4 Hz
8 Hz

Figure F17

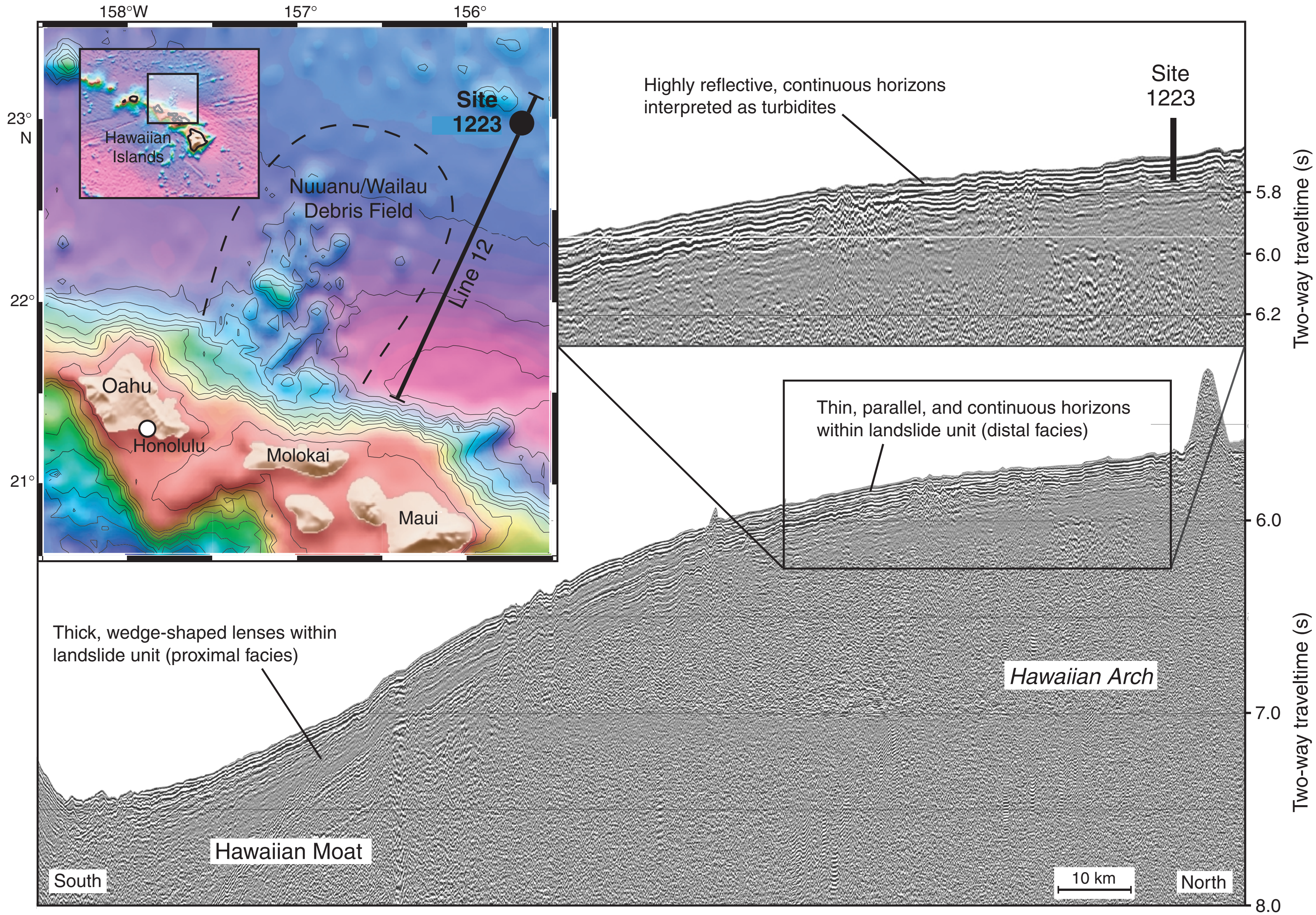
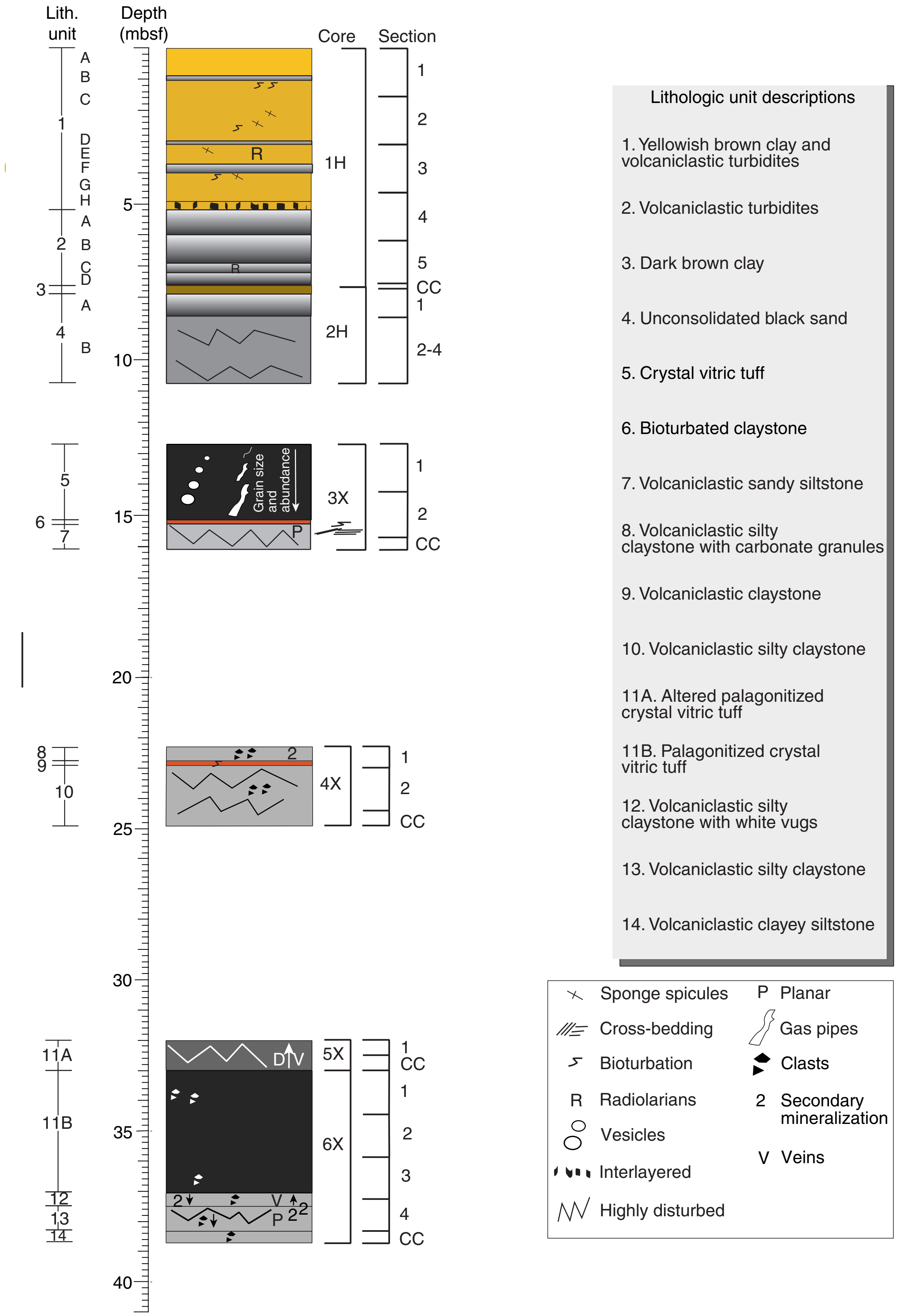

158°W
157°
156°
23°
N
22°
21°
Hawaiian
Islands
Site
1223
Nuuanu/Wailau
Debris Field
Line 12
Oahu
Honolulu
Molokai
Maui
Highly reflective, continuous horizons
interpreted as turbidites
Site
1223
5.8
6.0
6.2
Two-way traveltime (s)
Thin, parallel, and continuous horizons
within landslide unit (distal facies)
6.0
Thick, wedge-shaped lenses within
landslide unit (proximal facies)
Hawaiian Arch
7.0
Two-way traveltime (s)
Hawaiian Moat
South
10 km
North
8.0

Figure F18



Lithologic unit descriptions

1. Yellowish brown clay and volcaniclastic turbidites
2. Volcaniclastic turbidites
3. Dark brown clay
4. Unconsolidated black sand
5. Crystal vitric tuff
6. Bioturbated claystone
7. Volcaniclastic sandy siltstone
8. Volcaniclastic silty claystone with carbonate granules
9. Volcaniclastic claystone
10. Volcaniclastic silty claystone
11A. Altered palagonitized crystal vitric tuff
11B. Palagonitized crystal vitric tuff
12. Volcaniclastic silty claystone with white vugs
13. Volcaniclastic silty claystone
14. Volcaniclastic clayey siltstone

Figure F19

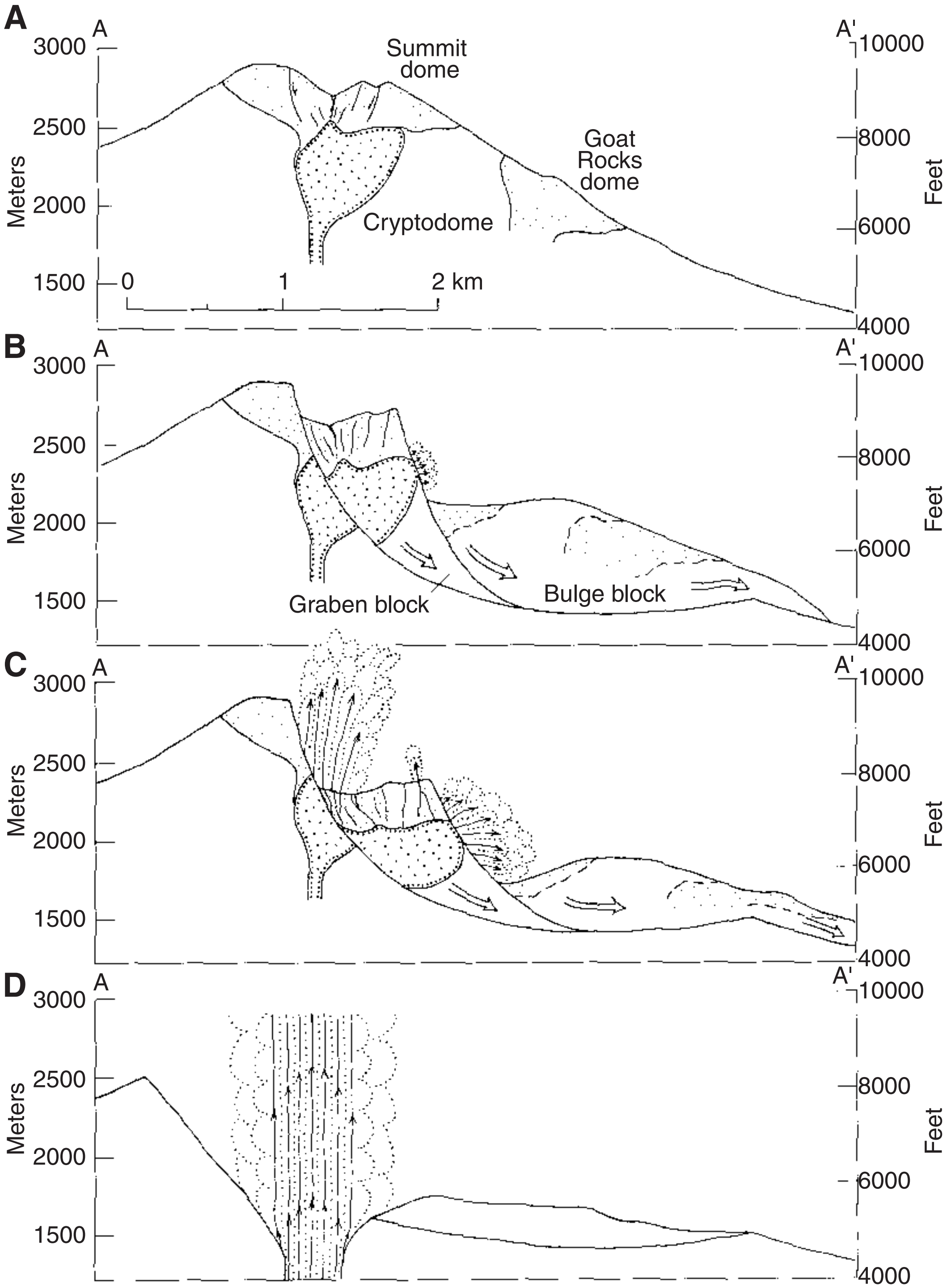

A
A
A'
3000
2500
2000
1500
Meters
10000
8000
6000
4000
Feet
Summit dome
Goat Rocks dome
Cryptodome
0
1
2 km
B
Graben block
Bulge block
C
D

Figure F20

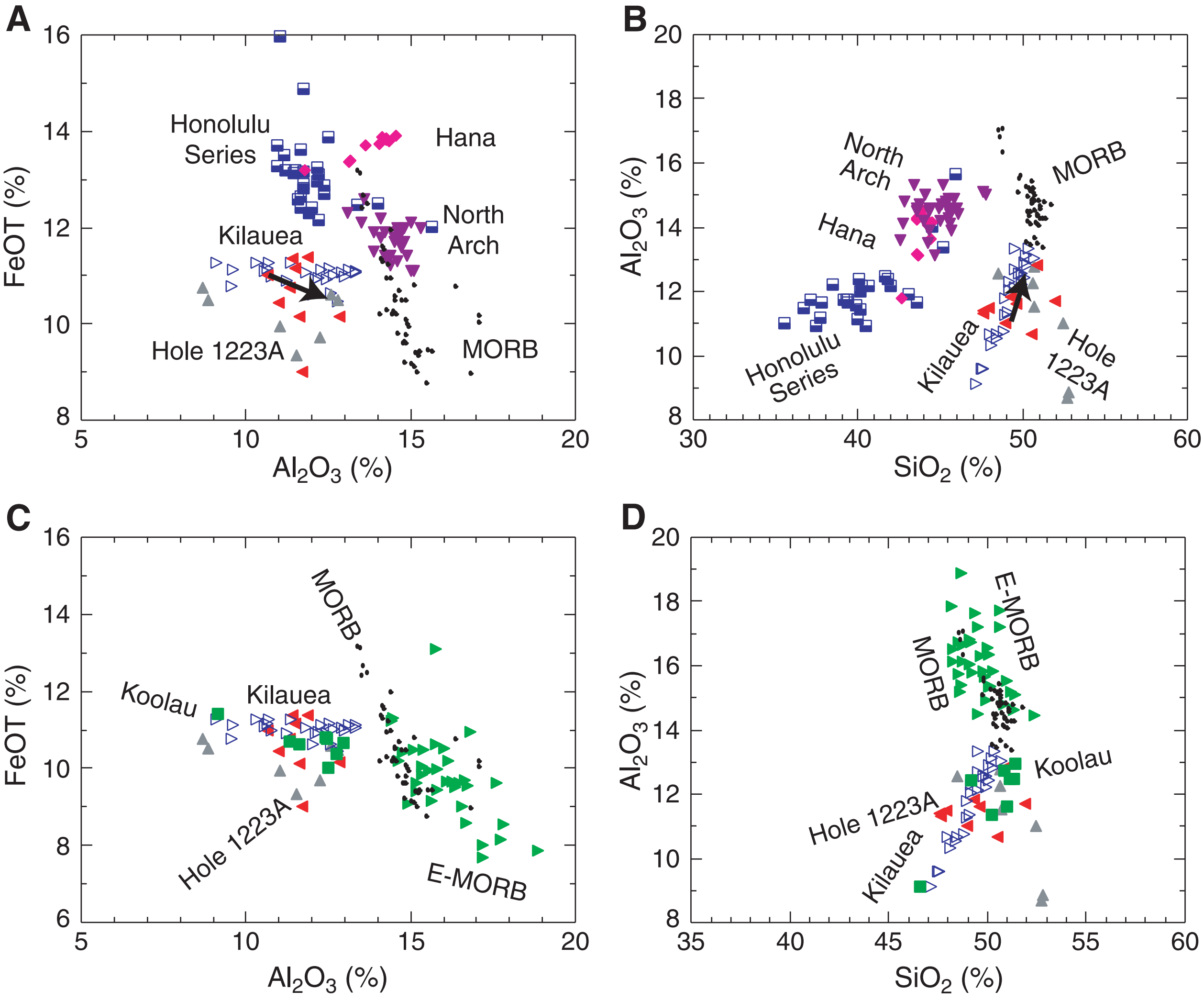

A
FeOT (%)
Al$_2$O$_3$ (%)
Honolulu Series
Hana
North Arch
Kilauea
Hole 1223A
MORB
B
Al$_2$O$_3$ (%)
SiO$_2$ (%)
North Arch
Hana
MORB
Honolulu Series
Kilauea
Hole 1223A
C
FeOT (%)
Al$_2$O$_3$ (%)
MORB
Koolau
Kilauea
Hole 1223A
E-MORB
D
Al$_2$O$_3$ (%)
SiO$_2$ (%)
E-MORB
MORB
Koolau
Hole 1223A
Kilauea

Figure F21

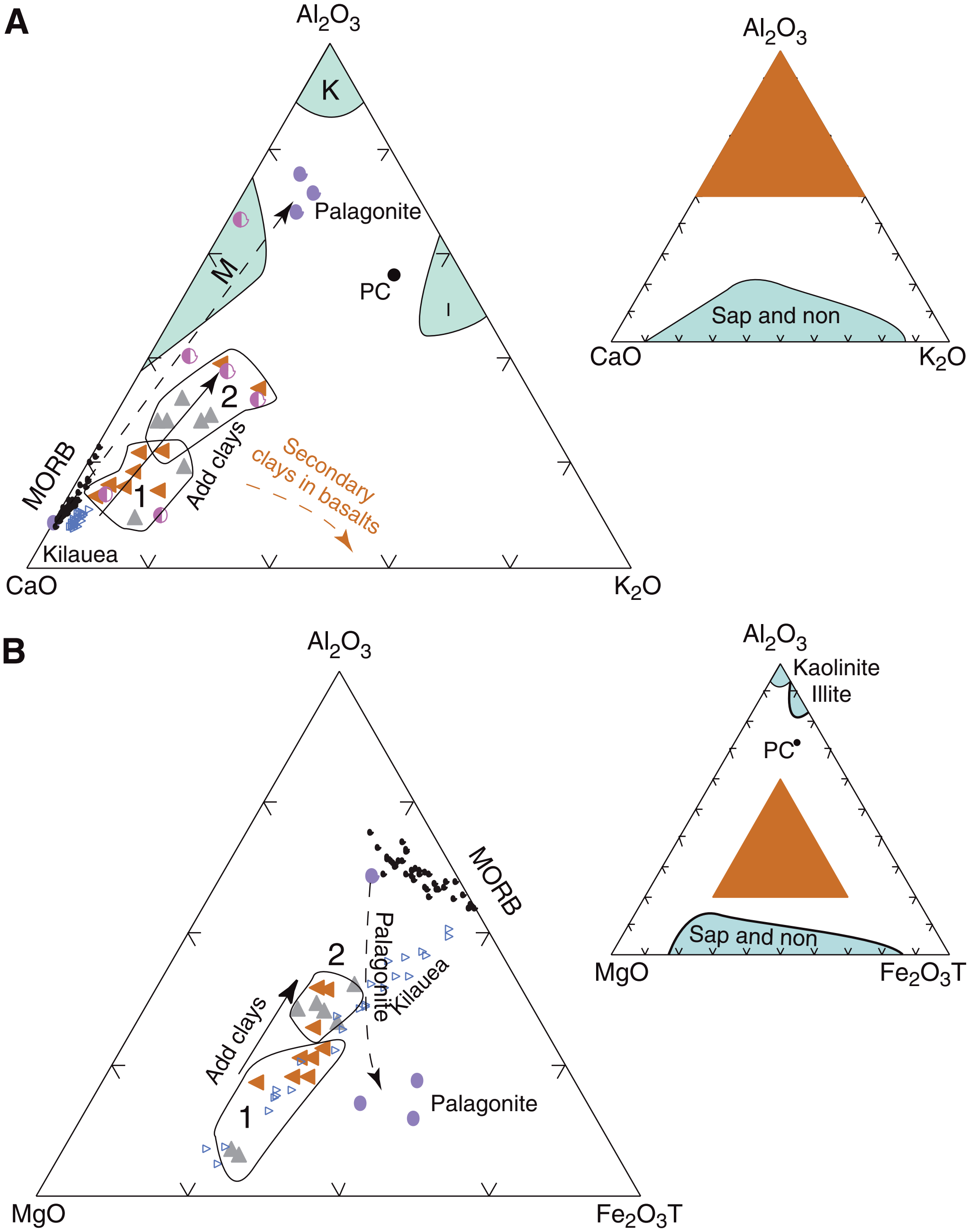

A
Al_2O_3
K
Palagonite
M
PC
I
2
1
MORB
Add clays
Secondary clays in basalts
Kilauea
CaO
K_2O
Al_2O_3
Sap and non
CaO
K_2O
B
Al_2O_3
MORB
Palagonite
Kilauea
2
Add clays
1
Palagonite
MgO
Fe_2O_3T
Al_2O_3
Kaolinite
Illite
PC
Sap and non
MgO
Fe_2O_3T

Figure F22

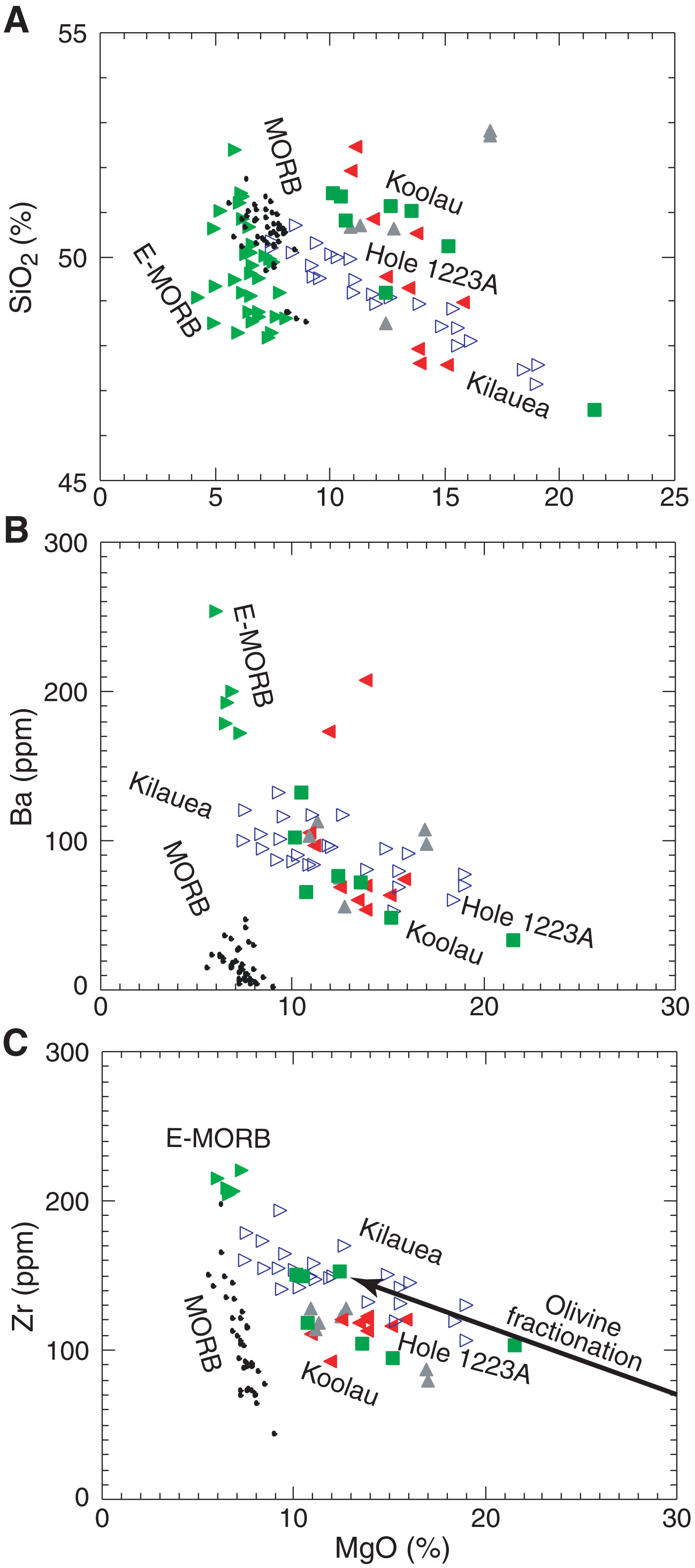

A
55
50
45
SiO$_2$ (%)
0
5
10
15
20
25
MORB
E-MORB
Koolau
Hole 1223A
Kilauea
B
300
200
100
0
Ba (ppm)
0
10
20
30
E-MORB
Kilauea
MORB
Hole 1223A
Koolau
C
300
200
100
0
Zr (ppm)
0
10
20
30
MgO (%)
E-MORB
Kilauea
MORB
Olivine fractionation
Hole 1223A
Koolau

Figure F23