IODP Expedition 350: Izu Bonin Mariana Rear Arc
Site U1437 Summary

Background and Objectives

Site U1437 is located in the Izu rear arc, about 330 km west of the axis of the Izu-Bonin Trench, and about 90 km west of the arc front volcanoes Myojinsho and Myojin Knoll at 2117 m below sea level (mbsl). Expedition 350 was the first expedition to be drilled in the Izu rear arc; all other ODP/IODP sites have been in or near the Izu-Bonin arc front or forearc, leading to an incomplete view of Izu arc magmatism as a whole. The main objective of Expedition 350 was to reveal the history of this “missing half” of the subduction factory.

Site U1437 (proposed Site IBM-3C) was chosen to provide a temporal record of rear arc magma compositions, ideally from Eocene to Neogene time, allowing comparison with the previously drilled forearc magmatic record, and determination of across-arc geochemical variation throughout the history of the arc system. A striking characteristic of volcanic arcs is the asymmetry in geochemical characteristics with distance from the trench, which was known prior to the advent of plate tectonics. The Izu arc shows this asymmetry, and its rear arc magmas are much more similar to continental crust than the Izu arc front magmas. The Izu rear arc is therefore important for understanding how intracrustal differentiation produces crust that is similar to the “average continent.”

The Izu arc front is a ~900 km long volcanic chain whose Quaternary geology can be characterized by (1) basalt-dominated volcanoes spaced at ~100 km intervals, some of which form islands, and (2) submarine rhyolite-dominated calderas. All Neogene volcanic rocks behind the Izu arc front are referred to as rear-arc volcanic rocks, and include three types: (1) the ENE-trending basaltic to dacitic rear-arc seamount chains (~17–3 Ma); (2) a broad extensional zone with small bimodal volcanoes referred to the back arc knolls, which overlaps with the eastern part of the rear-arc seamount chains (<3 Ma); and (3) a narrow, active rift with bimodal volcanic rocks, which lies immediately behind the arc front (<1.5 Ma). The chemistry of the arc front magmas should be distinguishable from that of the rear-arc seamount chains, because the rear-arc seamount chains are enriched in alkalis, high–field strength elements and other incompatible elements, and have less enriched Sr, Nd, Hf, and Pb isotopes, compared to the volcanic front. However, the <3 Ma bimodal volcanism is transitional between the two in chemistry as well as space; therefore, we can distinguish rear arc and arc front magmas for all rocks >3 Ma, but not for rocks <3 Ma. Because the objective was to study the temporal evolution of rear arc magmatism, Site U1437 was chosen in a location that should be topographically shielded from arc front-derived sediment gravity flows (although arc-front-derived ash fall may be present). Another objective at Site U1437 was to determine if arc geochemical asymmetry was present early in the history of the arc (in the Paleogene), or if it is strictly a Neogene feature.

Site U1437 lies in a volcano-bounded basin that formed between the Manji and the Enpo rear-arc seamount chain, which are two of several Izu rear-arc seamount chains that are up to ~50 km long and strike N60°E. Three main hypotheses have been proposed for the origin of the seamount chains: (1) They are related to compression caused by collision between the southwest Japan and Izu arcs, associated with the Japan Sea opening, (2) They formed along Shikoku Basin transform faults, (3) They overlie diapirs in the mantle wedge, such as the "hot fingers" proposed for northeast Japan, which predicts that the rear-arc seamount chains young from west to east. Site U1437 was chosen to learn about the temporal evolution of the Manji and Enpo seamount chains.

Principal Results

Operations overview

After the 7.5 h, 77 nmi transit from Site U1436 to Site U1437, operations at this site were conducted from 10 April to 24 May (44 days).

Five holes were completed at Site U1437. Hole U1437A (11–12 April) was a jet-in test with an APC/XCB bottom hole assembly (BHA). A seafloor camera survey was first conducted to confirm that no subsea cables were present at the site.

Hole U1437B (12–14 April), located 10 m north of Hole U1437A, was cored with the APC (0–89.2 mbsf), the half-length APC (89.2–145.7 mbsf), and the XCB (145.7–439.1 mbsf), with a total recovery of 243 m (55%).

The plan for Hole U1437C (14–15 April), located 20 m south of Hole U1437B, was to drill without coring to 425 mbsf, several meters above the total depth cored in Hole U1437B, and then start RCB coring. At 309.7 mbsf, the bit got stuck and had to be dropped at the bottom of the hole to free the pipe, ending operations in this hole.

Hole U1437D (15–26 April) was positioned 10 m west of Hole U1437A in a second attempt to drill and core a deep RCB hole. Drilling without coring extended from the seafloor to 427.2 mbsf. RCB coring from 427.2–980.4 m recovered 434.56 m (79% recovery). At this time, the bit had been rotating for 51.5 h and required changing, so we decided to stop coring, deploy a free fall funnel, and collect wireline log data.

Three logging strings were successfully deployed in Hole U1437D: the Triple Combo with the Magnetic Susceptibility Sonde (MSS) (92–~960 mbsf), the FMS-Sonic (92–950 mbsf), and the vertical seismic profile (VSP; 14 stations, 175–875 mbsf). The hole was in excellent condition, with a diameter barely exceeding the bit size for most of the hole. The data recorded were therefore of high quality.

RCB coring in Hole U1437D resumed with a new bit and the hole was deepened from 980.4–1104.6 mbsf, recovering 69.29 m (56%). Drilling problems forced us to pull out of the hole at this point. The total cored interval in Hole U1437D was 677.4 m, with 503.8 m recovered (74%).

We decided to drill and case a new hole to the total depth of Hole U1437D, then core and log it as deep as time allowed. This decision was prompted by (1) the increasing risk with penetration depth of not being able to clean the hole; and (2) the fact that the ship was carrying ~1100 m of 11.75 inch casing, just enough to cover the interval cored to date, which made this the optimal time to install the casing.

The ship moved ~20 m northeast to begin operations in Hole U1437E (26 April–24 May). The casing deployed in this hole consists of a 20.7 m long, 20 inch casing connected to the reentry cone; a 264 m long, 16 inch casing string hung from the casing hanger in the reentry cone; and a *JOIDES Resolution* record-breaking, 1085.6 m long 10.75 inch casing string, also hung from the reentry cone. It took ~12 days to complete the total casing installation.

RCB coring for the duration of three 50 h bit life cycles extended Hole U1437E from 1104.0 to 1806.5 mbsf and recovered 387.45 m of core (55% recovery). When readying for the fourth bit deployment, the fiber optic cable for the camera needed to reenter Hole U1437E had broken. This prematurely ended our expedition's operations in Hole U1437E. Hole U1437E is currently in excellent condition for logging and/or further coring operations, preferably attempted soon, before the hole deteriorates.

At 0930 h on 24 May, the ship was underway for contingency operations at Site U1436.

Lithostratigraphy

Cores from three consecutively cored holes at Site U1437 recovered a coherent stratigraphy from 0 to 1806.50 mbsf. This includes Cores U1437B-1H to -55X (0 to 439.10 mbsf), Cores U1437D-2R to -73R (427.20 to 1104.60 mbsf), and Cores U1437E-4R to -79R (1104.00 to 1806.5 mbsf). Overlap between the bottom of one hole and the top of the next is minimal. The majority of the recovered core is sedimentary, dominated by tuffaceous mud and mudstone with intercalated volcaniclastic layers in the uppermost 1300 m (Units I to V), with a gradual change to dominantly volcaniclastic layers in the lowermost 500 m (Units VI and VII). Overall, 62% of the cored depth interval was recovered and described. Tuffaceous mud and mudstone comprise 58.5% of the described rocks, ash and tuff 21.0%, and lapilli-sized volcaniclastics 20.3% (with <0.5% volcaniclastics coarser than lapilli).

The seven lithostratigraphic units (Units I–VII) are distinguished from each other based on the proportion and characteristics of volcaniclastic intervals relative to tuffaceous mud and mudstone. Their tops and bottoms are defined by the appearance or reappearance of distinct marker layers as described in the following paragraphs.

The tuffaceous mud and mudstone in all units contain clay minerals, foraminifers, igneous crystals, and glass shards in varying proportions. Bioturbation is intense. Ash and tuff intervals often are normally graded, consist of glass shards and crystals, and commonly have a crystal-rich layer at the base of the interval. Layer bases usually are sharp whereas tops often grade into increasingly bioturbated tuffaceous mud and mudstone such that there is a continuum between the lithofacies. Matrix- and clast-supported polymictic lapilli-tuff intervals become very thick and highly abundant at certain depths and are typically the basis of unit boundaries. The clasts in these coarse-grained intervals become more lithic-rich towards the bottom of the recovered sequence. Only one igneous unit was defined (igneous Unit 1) based on the presence of a 1.2 m thick rhyolite with chilled margins and peperitic contacts with surrounding volcaniclastic material.

Compaction of sediment at Site U1437 increases linearly from ~0% above ~410 mbsf to ~36% at the base of Hole U1437D. Although the transition from unconsolidated to lithified rocks occurred progressively, sediments were considered lithified from 427 mbsf (top of Hole U1437D) downhole. Alteration becomes more pervasive and increases in intensity downhole in Holes U1437B and U1437D; initially it is predominantly glauconitic-smectitic, and eventually becomes more chloritic. Fresh glass is observed from Unit I to the top of Unit III. Within Unit III, glass is progressively altered to cryptocrystalline aggregates of clay minerals, probably dominated by smectite. From Unit IV to Unit VII, glass is totally altered with the exception of the uppermost vitric-rich part of Unit VII where colorless glass is preserved. Crystals are not affected by alteration until Unit VII where orthopyroxene is replaced by cryptocrystalline brown aggregates of clay minerals, and plagioclase is partly altered to clay minerals and epidote. The downhole increase in alteration intensity and the transition from smectite to chlorite and prehnite indicates alteration is partly related to burial. Iron sulfides occur as aggregates throughout all holes, especially as replacements of worm burrows, and according to rock magnetic properties, greigite is progressively replaced by pyrite downhole in Hole U1437D. Glauconite layers and reduced iron sulfides associated with burrows are a result of biogenic alteration under reducing conditions. Some volcanic clasts in Units IV to VII display higher temperature alteration assemblages comprising prehnite, biotite and epidote, related to high-temperature (>300°C) alteration before final deposition.

Unit I extends from 0 to 682.12 mbsf and encompasses all of Hole 350-U1437B to Interval 350-U1437D-28R-2, 112 cm in Hole U1437D. Unit I is dominated by tuffaceous mud and mudstone (88% of total described material) alternating with thin evolved, mafic, or bimodal ash/tuff intervals, and minor lapilli-ash/lapilli-tuff intervals. Average bed thicknesses are 0.36 m for mud and mudstone, 0.08 m for ash and tuff, and 0.06 m for lapilli-ash and lapilli-tuff. The tuffaceous mud and mudstone from this unit is interpreted to result from background sedimentation of hemipelagic clay and carbonate mixed with substantial volumes (>25%) of dispersed volcanic material. This background sedimentation is punctuated by episodic deposition of ash layers, derived by eruption-fed or resedimented seafloor-hugging density currents, or suspension settling of subaerially distributed ash through the water column. The boundary between Unit I and Unit II is marked by the first appearance of monomictic lapilli-tuff, which is the characteristic lithofacies within Unit II; this change is reflected in the physical properties (e.g., increase in magnetic susceptibility, see below).

Unit II extends from 682.12 to 726.50 mbsf in Hole U1437D (Interval 350-U1437D-28R-3, 0 cm, to 32R-CC, 7 cm). It is characterized by abundant intervals of evolved thick- to very thick-bedded evolved tuff (40% of total described rocks) and monomictic pumice lapilli-tuff and lapillistone (37%) intercalated with lesser tuffaceous mudstone (23%). The top of Unit II is defined by the first lapilli-tuff in a 44.38 m thick sequence dominated by intervals of lapilli-sized tephra. Average bed thicknesses are 0.16 m for evolved tuff, 0.20 m for lapilli-tuff and lapillistone, and 0.19 m for tuffaceous mudstone. Unit II volcaniclastics are interpreted to have been deposited by seafloor-hugging density currents that transported lapilli, pumice grains, and crystal fragments. The thickest and graded intervals are inferred to be eruption-fed. Minor (22%) intercalated tuffaceous mudstone indicates periods of volcanic quiescence during deposition of Unit II. The boundary between Unit II and III is marked by the first interval of tuffaceous mudstone below the last occurrence of intercalated lapilli-tuff and lapillistone.

Unit III extends from 726.50 to 1017.88 mbsf in Hole U1437D (Interval 350-U1437D-32R-CC, 7 cm, to 64R-1A, 8 cm). It is dominated by tuffaceous mudstone (63% of the described rocks) with intercalated intervals of evolved tuff and minor evolved lapilli-tuff and lapillistone. Average bed thicknesses are 0.23 m for the tuffaceous mudstone, 0.11 m for the tuff, and 0.15 m for the lapilli-tuff. Near the top of Unit III (Interval 350-U1437D-34R-3, 78 cm, to 34R-4, 118 cm) lies a single distinctive 1.91 m thick tuffaceous breccia with mudstone intraclasts (up to ~20 cm in size) interpreted as a submarine debris flow deposit. The overall abundance of mudstone and lack of coarse-grained volcaniclastic material in Unit III suggests an origin similar to that described for Unit I. Unit III shows an increase in fine-grained tuff (relative to tuffaceous mudstone) in its basal ~80 m, possibly produced by phreatomagmatism. The boundary between Units III and Unit IV is defined by an increase in grain size and abundance of pumiceous lapilli-tuff; tuffaceous mudstone decreases below this boundary.

Unit IV extends from 1017.88 to 1120.11 mbsf, from the bottom of Hole U1437D and into Hole U1437E (Interval U1437D-64R-1A, 8 cm, to U1437E-6R-3, 122 cm). The unit is characterized by coarse sand-sized tuff (53% of described rocks), polymictic lapilli-tuff and minor polymictic lapillistone (25%). Tuffaceous mudstone is only a minor part of the unit (22% of the described rocks), becoming more frequent towards the base. The top of Unit IV is defined by the top of the uppermost interval of a succession of massive intervals of clast-supported, polymictic lapilli-tuff intervals. Two tuff lithofacies are found in Unit IV: a light green tuff showing planar and convolute stratifications, and a massive and coarser dark gray to black tuff. Average bed thicknesses are 0.24 m for tuff, 0.43 m for lapilli-tuff, and 0.16 m for tuffaceous mudstone. Volcaniclastic intervals in Unit IV are interpreted to have been deposited by voluminous high concentration density currents derived from mass wasting of islands or seamounts, or by pyroclastic eruptions that remobilized large volumes of lithic clasts. The base of Unit IV is defined by the last interval of polymictic lapilli-tuff thicker than 0.50 m for the next 146.66 m (well into Unit V).

Unit V (1120.11 to 1320.00 mbsf; Intervals 350-U1437E-6R-3, 122 cm, to 27R-CC, 15 cm) is similar to Units I and III in that it is dominated by tuffaceous mudstone and tuff. However, a distinctive characteristic of Unit V is the presence of multiple intervals of monomictic, reversely-graded fiamme-rich lapilli-tuff with mudstone. The top of Unit V is defined by the interval immediately beneath the final >70 cm thick polymictic lapilli-tuff of Unit IV. Heavily bioturbated, silt-sized, tuffaceous mudstone comprises 69% of the described rocks in the unit, evolved tuff comprises 15%, and lapilli-tuff (of all types) and lapillistone constitutes 16%. Average bed thicknesses are 0.27 m for tuffaceous mudstone, 0.06 m for evolved tuff, and 0.18 m for lapilli-tuff. The distinctive monomictic, reversely-graded lapilli-tuff lithofacies is thin- to medium-bedded, and consists of a sharp basal contact filled with tuff that grades upward into a matrix-supported, reversely coarse-tail graded, fiamme-rich lapilli-tuff with tuffaceous mudstone. The pumice lapilli-tuff and lapillistone lithofacies occurs as ~5–10 cm thick intervals in the middle of the unit; it is similar to the dominant lithofacies in Unit IV. Unit V is interpreted to have an origin similar to Units I and III, with the addition of monomictic lapilli-tuff similar in origin to the seafloor-hugging density currents described for Unit II. The bottom of Unit V is defined as the last interval above the first thick interval of polymictic lapilli-tuff of Unit VI.

Unit VI extends from 1320.00 to 1459.80 mbsf (Interval 350-U1437E-28R-1, 0 cm, to 42R-3, 60 cm). As with Units II and IV, this unit is characterized by a higher abundance of tuff (32% of described rocks) and lapilli-tuff (57%) and lesser tuffaceous mudstone (11%) than in the unit above it. The top of Unit VI is marked by the first appearance of multiple intervals of thickly to very-thickly bedded (up to 2.8 m) matrix-supported, polymictic lapilli-tuff, and continues downward through intervals that are dominated by tuff and lapilli-tuff rather than tuffaceous mudstone. Unit VI is intruded by the 1.2 m thick rhyolite-dacite sheet of igneous Unit 1 (see below). Lapilli-tuff intervals include monomictic and polymictic varieties, and matrix- and clast-supported varieties. Average bed thicknesses are 0.25 m for tuffaceous mudstone, 0.24 m for tuff, and 0.41 m for all lapilli-tuffs and lapillistone. Igneous vitric and lithic clasts >2 cm become more common towards the bottom of the unit. Unit VI is interpreted similarly to Unit IV. The bottom of Unit VI is marked by the first normally-graded dense-glass-rich interval of Unit VII.

Unit VII begins at 1459.80 mbsf and extends to the bottom of Hole U1437E at 1806.50 mbsf (Interval 350-U1437E-42R-3, 60 cm, to 79R-03, 83 cm). The bulk (89%) of Unit VII consists of thin to extremely thick intervals of graded or non-graded, lapilli-tuff, lapillistone, tuff-breccia and breccia (0.63 m average bed thickness), and contains angular lithic andesite clasts ranging from pebble to cobble in size. The remaining 11% is tuff (0.21 m average bed thickness). There is only one thin-bedded (0.11 m) tuffaceous mudstone in the entire 340 m thick unit. Unit VII comprises two main lithofacies. A distinctive black evolved lapilli-tuff and lapillistone occurs mostly in the upper part of the unit, and has a matrix of slightly- to moderately-altered glass plus isolated plagioclase and pyroxene crystals. Polymictic evolved lapilli-tuff, lapillistone, tuff-breccia and volcanic consolidated breccia exclusively occur in the lower part of the unit. It is more altered (green-colored, altered glass) and coarser than is the upper lithofacies. Clasts with unbroken quench margins suggest proximity to the source. Evidence of in-situ emplacement is restricted to a few levels, where jigsaw fit textures (hyaloclastite) and/or baked and peperitic margins are observed.

Igneous Unit 1 occurs at 1388.86 to 1390.07 mbsf (Interval 350-U1437E-35R-1, 76 cm, to 35R-2, 55 cm). It is a 1.21 m thick moderately phyric hornblende-quartz-feldspar rhyolite-dacite, interpreted as an intrusive sheet with chilled margins and basal peperite. It occurs within a continuous interval of clast-supported, polymictic pumice lapilli-tuff that is baked at both contacts with igneous Unit 1. The unit has a porphyritic texture with sieve-textured subhedral plagioclase (up to 4 mm, ~7%), euhedral hornblende (up to 0.5 mm, ~3%), anhedral to subhedral quartz (up to 8 mm, ~1%) with fresh glassy melt inclusions, minor opaque minerals, and rare zircon (20 μm in size). The groundmass varies from cryptocrystalline near the upper and lower contacts, to fine-grained in the center of the unit. Flow banding is observed across the entire unit in various orientations.

Geochemistry

Headspace

Samples for hydrocarbon gas analysis from headspace (n = 184) were collected and analyzed for every core at Site U1437 in compliance with the shipboard hydrocarbon safety program. At shallow depths, methane abundances gradually increase with depth with the highest abundances at ~750–1459 mbsf. The zone of methanogenesis is unusually deep due to a release of sulfate below the sulfate reduction zone, which may be buffering the methanogenesis by anaerobic methanogens. Below ~1459 mbsf, methane concentrations decrease again. Minor amounts of ethane occur at1105 mbsf. In samples with detectable methane (C_1) and ethane (C_2), C_1/C_2 values are <100, consistent with mature organic matter producing thermogenic aliphatic hydrocarbons. C_1/C_2 never reached critical thresholds for drilling operations according to the shipboard safety program.

Pore water

Chemical analyses for interstitial water samples from Site U1437 (0–684 mbsf; n = 67) display systematic downhole trends. Depth variations in pore fluid chemistry suggest at least three major processes controlling the changes in major and trace element distribution in a fluid that started out as sediment-trapped seawater. These processes may be interdependent and operate simultaneously, but can be ranked according to increasing impact with depth: (1) biologic activity (0–100 mbsf) which is primarily controlled by sulfate reduction of organic material; (2) lateral fluid transport (>100 mbsf) interpreted from increasing alkalinity and sulfate back towards near-seawater values away from the zone of microbial sulfate reduction, with spikes in Li indicating that this process is likely fracture or formation controlled; and (3) diagenesis (0–684 mbsf) evident through progressive downhole alteration of volcanic glass and dissolution of siliceous diatoms producing gradual decreases in Mg and increases in Si, respectively. Below ~450–500 mbsf, increases in Ca and Na coupled with a sharp decrease in Mg may indicate progressive clay formation by alteration of volcanic ash.

Mud and mudstone bulk geochemistry

A total of 218 sediment samples were collected at Site U1437 and analyzed for concentrations of calcium carbonate ($CaCO_3$), TC (total carbon), TOC (total organic carbon), and total nitrogen (TN). The atomic ratios of TOC and TN (TOC/TN) were calculated to determine the source of the sedimentary organic matter. Total carbon contents as well as $CaCO_3$ contents are highly variable and show generally the same trend over the cored sequence, suggesting that most of the TC consists of inorganic carbon. Highly variable sedimentary $CaCO_3$ abundances over short vertical distances likely result from varying inputs of volcanic ash or terrigeneous clay, which dilute biogenic carbonate. Total organic carbon and nitrogen contents are generally low, but TOC and TN are comparatively elevated in the uppermost ~230 m of the cored sequence. Below that depth, TN contents decrease continuously, probably as a result of nitrogen loss during diagenesis. Atomic TOC/TN ratios vary from 2.33 to 213 with an average of 18.6 suggesting a mixed input of both marine-derived and terrestrial-derived organic matter.

Bulk mud compositions by ICP-AES (n = 11) and pXRF (n = 38) indicate downhole increases in clay and ash content (represented by TiO_2) relative to calcium carbonate. The increasing prevalence of clay and ash correlates approximately with the transition from lithostratigraphic Unit III to IV (~1019 mbsf) and continues to the bottom of Hole U1437E where mud intervals become rare. Zr/Y in mud decreases with depth from ~4 (6 mbsf) to ~2 (1424 mbsf), paralleling a decrease in Rb from 103 to 11 ppm. These depth trends suggest that shallow mud intervals are more strongly influenced by terrigenous clay or distal ash (e.g., from the Ryukyu arc where Zr/Y and Rb are high relative to proximal Izu arc front and rear-arc volcanoes) than deeper intervals.

Volcanic geochemistry

In an effort to constrain the geochemistry of various volcanic deposits observed at Site U1437 (tuff, lapilli, and lava), both a portable XRF (n = 227) and ICP-AES (n = 50) were utilized. ICP-AES analyses were completed for samples of ash and tuff (n = 26), lapilli-tuff and lapillistone (n = 14), igneous clasts (n = 10), and a rhyolite intrusion (n = 1). The discrete ash layers in lithostratigraphic Unit I (0–682 mbsf) plot within the low-K field relative to SiO_2 and have low Zr/Y. Their low K_2O and Zr/Y values indicate that these ashes are likely derived from the Izu volcanic front. A few deposits, commonly coarser grained with cross bedding and hornblende, have elevated K_2O and Zr/Y. The samples younger than 3 Ma (0–440 mbsf), containing elevated K_2O and Zr/Y relative to SiO_2, are more ambiguous in origin. Pervasive alteration at depths >720 mbsf compromises most major and trace elements. Major element compositions of samples >720 mbsf trend towards compositions equivalent to hydrothermally altered Manji seamount rocks. Fluid-immobile Zr and Zr/Y is elevated for coarse-grained volcaniclastic rocks between ~684 and 1120 mbsf (top of Unit II to Unit IV), indicating the effects of higher degrees of differentiation, higher abundances of incompatible trace elements in the source, and possibly hornblende fractionation. All three characteristics are consistent with a proximal rear arc origin. The presence of low Zr/Y samples within the same depth interval, however, indicates continued deposition of tephra and volcaniclastic sediment from sources similar to modern Izu arc front volcanoes. Variability in Zr/Y and K_2O values in Unit V (1120 to 1312 mbsf) indicates a mixture of lithologies similar to dredged rear arc and quaternary volcanic front lavas from a comparable stratigraphic interval. Below 1320 mbsf to total depth of 1807 mbsf (comprising Units VI and VII), most ICP-AES samples (typically representing large single clasts) are dominantly intermediate in composition. They have Zr abundances as low as 34 ppm and Zr/Y <3, which are characteristic for modern basalt dominant island arc volcanoes of the Izu arc front. One exception is a conspicuous quartz-, hornblende-, and zircon-bearing rhyolite (Igneous Unit 1) in Sections 350-U1437E-35R-1 and 35R-2 (1388.9–1391.1 mbsf) which has the lowest CaO analyzed for any rock collected at Site 1437, but comparatively high Zr/Y = 5.9. Overall, the presence of Manji seamount chain-like rocks identified by high Zr/Y is well established for Units II to IV, whereas such rocks are more infrequently encountered in Units I, V, VI, and VII. Preliminary geochemical modeling using major and trace element compositions for mud and volcaniclastic sediment or rock, weighed by their abundance throughout the section drilled at Site U1437, indicates that the Izu rear arc is significantly depleted in incompatible trace elements (e.g., K_2O, Rb) relative to upper continental crust, but less so than the arc front magmas.

Physical properties

Physical properties measurements were performed to obtain information on the density, porosity, natural gamma radiation (NGR), shear strength, thermal conductivity, magnetic susceptibility (MS), *P*-wave velocity, and reflectance of the recovered sequence. After letting the core reach thermal equilibrium with the ambient temperature at ~20°C, gamma ray attenuation (GRA) density, MS, and *P*-wave velocity were measured using a Whole-

Round Multisensor Logger (WRMSL), and NGR was measured on the whole-round Natural Gamma Radiation Logger (NGRL). Thermal conductivity was measured in soft sediments and rocks with the needle and puck probes, respectively. Discrete measurements of *P*-wave velocity, moisture and density (MAD), and shear strength were performed on working section halves. Finally, color reflectance and MS were measured on the archive section halves using a spectrophotometer and the Magnetic Susceptibility Point (MSP) sensor on the Section Half Multisensor Logger (SHMSL).

Thirteen physical properties (PP) units were differentiated based on distinct offsets in otherwise continuous profiles that define boundaries between intervals, and interval characteristics such as magnitude, rate of change and relative scatter of measurements.

PP unit 1 (0–430 mbsf) is characterized by a downhole increase in bulk density and *P*-wave velocity, and a corresponding downhole decrease in porosity. The top of PP unit 2 (430–550 mbsf) is marked by an initial increase in porosity, followed by a downhole continuation of the decrease observed through PP unit 1, as well as a decrease in the reflectance L* and a* values. The upper part of PP unit 3 (550–682 mbsf) is characterized by a sharp increase in porosity and corresponding decrease in bulk density. This initial offset is followed by more gradual downhole trends, similar to those seen in PP unit 2. Reflectance ratio of a*/b* data show a decrease in the scatter, indicating that color is less variable through PP unit 3 than in PP units 1 and 2. The upper boundary of PP unit 4 (682–728 mbsf) corresponds to the lithostratigraphic Unit I/Unit II boundary, and is marked by an increase in the scatter of density and porosity, an increase in *P*-wave velocity and MS values, a decrease in the NGR and reflectance b* values. The top of PP unit 5 (728–794 mbsf) corresponds to the upper boundary of lithostratigraphic Unit III and is defined by an increase in the NGR values, and a decrease in the scatter of *P*-wave velocity. This is followed downhole by the continuation of the increasing *P*-wave trend observed in PP unit 3. PP unit 6 (794–846 mbsf) is defined by an increased scatter in *P*-wave velocity and reflectance a*/b* values. The upper boundary of PP unit 7 (846–1018 mbsf) is marked by an initial decrease in bulk density and a corresponding increase in porosity, followed downhole by trends similar to those in PP unit 6. The top of this unit is also characterized by an abrupt decrease in the MS values. The top of PP unit 8 (1018–1140 mbsf) corresponds with the top of lithostratigraphic Unit IV, and is defined by an increase in the MS values and an abrupt decrease in *P*-wave velocity and thermal conductivity. The upper boundary of PP unit 9 (1140–1315 mbsf) is 20 m below the upper boundary of lithostratigraphic Unit V, and is defined by a decreased scatter in density, porosity, *P*-wave velocity, and NGR measurements, as well as a downhole decrease in the thermal conductivity. The upper boundary of PP unit 10 (1315–1460 mbsf) coincides with the top of lithostratigraphic Unit VI, and is marked by an abrupt decrease in the NGR values relative to PP unit 9, as well as a slight downhole increase in the thermal conductivity values. The top of PP unit 11 (1460–1580 mbsf) corresponds with the top of lithostratigraphic Unit VII. PP unit 11 is characterized by an abrupt decrease in MS and decreased scatter in density, porosity, and *P*-wave velocity values. NGR data from the upper part of PP unit 11 are higher than in PP unit 10 and then decrease again in the lower part of PP unit 11. The upper boundary of PP unit 12 (1580–1742 mbsf) is defined by an abrupt increase in MS relative to PP unit 11. Density and *P*-wave velocity increase downhole, whereas porosity decreases. The top of PP unit 13 (1742–1800.3 mbsf) is marked by a decrease in the *P*-wave velocity and thermal conductivity, which then increase downhole to the maximum drilling depth.

The upper boundaries of PP units 2, 3, 6, 7, 9, 12, and 13 do not correspond to lithostratigraphic boundaries. Therefore, we suggest that changes in the physical properties at the mentioned boundaries may reflect post-depositional processes like diagenetic and hydrothermal dissolution and recrystallization, which may affect primary color, porosity, density, and consequently *P*-wave velocity of the recovered sediments and rocks.

Magnetostratigraphy

Magnetostratigraphy at Site U1437 was determined from 30 mT demagnetization and measurement of natural remanent magnetization (NRM) of archive section halves using the superconducting rock magnetometer (SRM), supported by polarity identified by measurement of discrete samples after AF or thermal demagnetization. A total of 29 magnetostratigraphic datums, marking tops and bases of normal polarity chrons and subchrons, were identified. Every chron and subchron in the sequence down to C3An.2n (6.436 Ma; 1056.65 mbsf) was recognized. Where biostratigraphic datums were available, these agreed very well and consistently with the magnetostratigraphic interpretation, but magnetostratigraphy became the main control on the depositional age model below 550 mbsf.

Normal polarity of C3An.2n persisted to the bottom of Hole U1437D, but cores in Hole U1437E, which started at the same sub-bottom depth as the base of U1437D, commenced immediately in reversed polarity. We suggest that a normal fault at or near the base of Hole U1437D has caused a loss of section between the two holes. Pattern matching of the polarity record in Hole U1437E indicated that the reversed polarity interval began immediately above normal subchron C4n.1n, and the magnetostratigraphy could then be followed down as far as the top of C4An (8.771 Ma) at 1302 mbsf. Magnetostratigraphy in Units VI and VII was impossible to recognize, with the exception of reversed polarity seen in Sample U1437E-35R-1, 125 cm from igneous Unit 1, which was the first indication that coring had proceeded below the base of normal Chron C5n.2n (9.984 to 11.056 Ma) spanning the upper part of the lowest nannofossil age-range.

Extrapolating the magnetostratigraphy from the last datum at 8.771 Ma (1302 mbsf), near the base of Lithostratigraphic Unit V, to the core catcher of Core U1437E-36R (1402 mbsf) substantially underestimates the age of the nannofossil datum of 10.97–11.85 Ma at this depth. The most likely explanation is a hiatus at the boundary between lithologic Units V and VI.

Although magnetostratigraphy was surprisingly successful at Site U1437, this is not to say that the polarity record was easily obtained; magnetic sulfides in Holes U1437B and U1437D, and a dominantly multidomain magnetite mineralogy in Hole U1437E, required a variety of strategies for recognizing polarity, including the use of liquid nitrogen cooling in field-free space to reduce the effect of high-stability overprints in discrete samples.

The paleomagnetic team also provided direct support to the lithostratigraphers. The sample in Igneous Unit 1 demagnetized along a simple, single component path after removal of the drilling overprint, and this had an appropriate inclination; this provided part of the evidence that this feature was indeed emplaced in situ. Demagnetization analyses of samples of selected clasts in Unit VII were also conducted in order to determine if they were emplaced hot or cold. These experiments were only partly successful due to multidomain overprinting, but clasts hosting Samples U1437E-66R-5, 106–108 cm, and 66R-6, 16–18 cm, display characteristic reverse polarity that might be consistent with hot emplacement.

Rock magnetism

Rock-magnetic studies at Site U1437 spanned the gamut of techniques available onboard, including saturation isothermal remanence (SIRM) acquisition, back-field demagnetization of SIRM by a 300 mT field to yield the $S_{-0.3T}$ ratio, stepwise acquisition of partial anhysteretic remanence (pARM), thermal demagnetization analysis, and anisotropy of magnetic susceptibility. Both pARM coercivity spectra and thermal demagnetization behavior confirmed the presence of a magnetic iron sulfide (presumed to be greigite in the absence of shipboard X-ray diffraction data on Expedition 350), at least within the interval cored in Holes U1437B and U1437D. This sulfide is present in addition to magnetite, which is the dominant magnetic mineralogy.

Sooty black sulfides typically including greigite, were visibly identified in association with worm burrows, bioturbation and glaucony/glauconite. They are likely to host concentrated magnetic sulfides and were avoided in sampling discrete paleomagnetic samples. This practice, and the weaker intensity of the drill-string overprinting field near the center of the core, made the record of polarity in discrete samples often more reliable than the SRM record.

Through Holes U1437B and U1437D a number of significant features in the downhole distribution of rock magnetic properties correlated with features of the physical properties, interstitial water geochemistry, and organic geochemistry records. Overall, the rock magnetic properties show a downhole trend suggesting that after initial biologically mediated reduction in the sulfate reduction zone to produce greigite, the proportion of greigite gradually decreased, presumably though slow completion of the iron sulfide reduction chain to convert this ferrimagnetic sulfide to paramagnetic pyrite. Superimposed on this trend is a break at about 400 mbsf, where SIRM/k, $S_{-0.3T}$, and magnetic foliation all show step changes: this represents a sudden downhole increase in the proportion of magnetic sulfides, followed by gradual returns to trend over the 300 m below. The return to trend in SIRM and $S_{-0.3T}$ occurs in the lower part of lithostratigraphic Unit I, and appears to be complete by the Unit I/II boundary at about 680 mbsf, corresponding also to the top of Physical Properties unit 2. After initial sulfate reduction, sulfate recovers and reaches a plateau concentration from about 275 mbsf to about 400 mbsf; over this interval $S_{-0.3T}$ values drop to below 0.97, suggesting renewed and enhanced production of greigite. Below about 400 mbsf sulfate increases again downhole to near-seawater concentrations at about 460 mbsf, corresponding to the highest value of SIRM/k in all samples measured at Site 1437, and remains high to the deepest IW sample taken at 700 mbsf. Transport of sulfate in pore fluid appears to have been responsible for a history of renewed magnetic authigenesis. The step reduction in AMS foliation at about 400 mbsf can also be explained by renewed growth of magnetic sulfides, which would have a compaction history reset at zero at this sub-bottom depth. The deep methanogenesis zone also matches the rock magnetic record, corresponding to the highest $S_{-0.3T}$ values encountered at this site to date. Such high $S_{-0.3T}$, indicating a very low-coercivity magnetic assemblage, suggests not only complete conversion of greigite to pyrite, but probably also dissolution of fine-grained magnetite; both may reflect further reduction of the sediments related to deep and ongoing microbial activity stimulated by influx of sulfate-rich pore fluids.

Surprisingly, given the apparent continuity of broadly similar lithologies through lithostratigraphic Units I through V across Holes U1437B, U1437D, and U1437E, rock magnetic properties in Hole U1437E do not follow the trends seen through Holes U1437B and U1437D. The background log-linear downhole decrease in SIRM/k that persists throughout Units I through IV is absent from Units V and VI. Instead, SIRM/k values appear to be randomly scattered over a wide range. Coercivity spectra from partial anhysteretic remanence (pARM) analysis also show a wide range, from very magnetically soft (peak coercivity <20 mT) to harder (broad coercivity peak from 20–30 mT) without any systematic downhole trends.

Biostratigraphy

The biochronology for Site U1437 was established based on planktonic foraminifers and calcareous nannofossils. Core catcher samples, as well as several extra samples from within the core, from Holes U1437B, U1437D and U1437E were analyzed for their planktonic foraminifer and calcareous nannofossil content. Below 1403 mbsf, no age diagnostic microfossils were found. Both fossil groups show that the upper 1403 mbsf part of the succession spans from the lower Pleistocene to the upper Miocene (maximum age detectable ~12 Ma). The timing of bioevents agrees well with magnetostratigraphic data. Below 1403 mbsf, the bioevents were difficult to establish due to poor preservation and low microfossil abundance. The decrease in preservation/abundance corresponds to a lithological change, from a succession dominated by mud and mudstone to one dominated by volcanic material.

Foraminifers

A total of 146 core catcher samples were examined for their planktonic and benthic foraminifer content. In the upper ~543 m of the succession (Samples U1437B-1H-CC through U1437D-13R-CC; Recent to lower Pliocene) planktonic foraminifers are generally abundant, diverse, and show moderate to good preservation. Recognizing foraminifer datums below ~543 mbsf (from Sample U1437D-14R-CC downwards) became increasingly challenging due to a combination of low foraminifer abundance, lack of age diagnostic species in most of the assemblages, poor preservation, and/or induration of sediments. Induration posed great difficulties in extracting the foraminifers. In Interval U1437D-40R-CC through 63R-CC (805–1009 mbsf, lithostratigraphic Unit III), many samples are barren of foraminifers or, where foraminifers are present, they show strong evidence of both plastic deformation and recrystallization, presumably due to compaction. Less deformed foraminifers were recovered from Samples U1437D-64R-CC through 72R-CC (1021–1088 mbsf) but most are present only as internal molds.

In terms of datums, the Pliocene–Pleistocene boundary (2.588 Ma) is placed somewhere between 372 and 416 mbsf based on the recognition of T *Globoturborotalita decoraperta* (T 2.75 Ma ± 0.03 Ma) in Sample U1437B-53X-CC (416 mbsf), and T *Globorotalia pseudomiocenica* (T 2.39 Ma) in Sample U1437B-48X-CC (372 mbsf). Many typical age diagnostic fauna, e.g. *Globigerinoides fistulosus*, *Globoturborotalita nepenthes*, are very rare or absent in this succession. The datums in the lower part of the succession (below ~570 mbsf) are tentatively assigned to include T and B *Globorotalia margaritae* (3.85 ± 0.03 Ma, 6.08 ± 0.03 Ma, respectively), B *Globorotalia crassaformis sensu lato* (4.31 ± 0.04 Ma) and T *Sphaeroidinellopsis kochi* (4.53 ± 0.17 Ma). An additional bioevent, the extinction of the benthic foraminifer genus Stilostomella in the middle Pleistocene (Sample U1437B-11F-CC; 94 mbsf), is not used to establish the biochronology but corroborates it.

Calcareous nannofossils

Calcareous nannofossils were abundant and well preserved throughout Holes U1437B and U1437D down to Sample U1437D-26R-CC (669 mbsf). From U1437D-27R-CC downhole (677–1806 mbsf) moderate to poor preservation is recorded and several samples are barren in nannofossils. The middle-upper Pleistocene sequence is defined by B *Emiliania huxleyi* in Sample U1437B-3H-CC (19.51 mbsf) and T *Pseudoemiliania lacunosa* in Sample U1437B-6H-5, 75–76 cm (51.48 mbsf). The Tc (top common occurrence) and Bc (bottom common occurrence) *Reticulofenestra asanoi* (Sample U1437B-15F-3; 80–81 cm, 110 mbsf, and Sample U1437B-16F-CC, 113 mbsf, respectively), and B *Gephyrocapsa omega* (113 mbsf) define the bottom of Cn14a. The bottoms of CN13a, CN12d, and CN12c are defined by T *Discoaster brouweri* (248 mbsf), T *Discoaster pentaradiatus* (337 mbsf), and T *Discoaster surculus* (367 mbsf), respectively. In Hole U1437D, the succession spans the upper Miocene to Pliocene. The bottom of CN12b is defined by T *Discoaster tamalis* (384 mbsf). T *Reticulofenestra pseudoumbilicus* in Sample U1437D-19R-3; 32 cm (595 mbsf) defines the bottom of CN12a. The last reliable datum indicator is T *Triquetrorhabdulus rugosus* (Sample U1437D-48R-CC, 871 mbsf). Since the preservation of nannofossils quickly deteriorates below Sample U1437D-27R-CC (677 mbsf), it was not possible to recognize other bioevents in the middle Pliocene to upper Miocene part of the succession. The preservation in Hole U1437E is very poor, and from Sample U1437E-27R-CC (1312 mbsf) downwards the majority of the samples are barren in nannofossils. A broad age range is provided for the Sample U1437E-36R-CC (1403 mbsf) by the presence of the species *Coccolithus miopelagicus* (T 10.97 Ma) and the absence of *C. floridanus* (T 11.85 Ma), which confirms a sequence falling within the biozone CN5b. Biozones from CN10a to CN6 are not identifiable because preservation issues affect the presence of markers, e.g., the different species of *Discoaster*, *Catinaster,* and *Minylitha convallis*.

Age model

At Site U1437 it was possible to identify a Pleistocene to upper Miocene succession. Fourteen biostratigraphic and 29 magnetostratigraphic datums obtained in the upper 1303 mbsf of the succession were selected to construct the age-depth model. The age model has not been extended below 1303 mbsf because no biostratigraphic or magnetostratigraphic datums are detectable in the Interval 1303–1806 mbsf. Also, no biostratigraphic datums are recognized below 867 m; thus, the age model for the Interval 867–1303 mbsf was constructed only using magnetic reversal datums. Below 1303 mbsf the only age constraint from microfossils is given by a calcareous nannofossil assemblage, which suggests a range of age between 10.97 to 11.85 Ma at 1403 mbsf. This age range is consistent with the magnetostratigraphic datums.

Seven intervals were selected to calculate the LSR, assuming constant sedimentation rates within those intervals. The LSRs range from a minimum of 98 m/m.y. to a maximum of 259 m/m.y. The highest LSR (259 m/m.y.) is found from the top of Lithostratigraphic Unit II through the upper part of Unit III, to ~825 mbsf. A minimum LSR of 98 m/m.y. is recorded from 825 to 844 mbsf. Lithostratigraphic Unit IV and V record an increase in LSR with values of 157 m/m.y. and 105 m/m.y.

An offset in LSR between intervals 868–1056 mbsf and 1122–1302 mbsf corresponds to the change from Hole U1437D to Hole U1437E, and also to a missing interval in the magnetostratigraphy. The probable explanation is a normal fault between the two holes, resulting in a partial loss of section within Lithostratigraphic Unit IV. If LSR within Lithostratigraphic Unit V are extrapolated to Unit VI, ages are not consistent with the age constraint given by the nannofossil assemblage in Sample U1437E-36R-CC (10.97–11.85 Ma at 1403 mbsf); a hiatus is the most likely explanation for this.

The total mass accumulation rate (MAR), calculated from dry bulk density, ranges between 12 and 35 g/cm^2/k.y., with the highest values in the intervals 2–2.5 Ma and 4.2–4.7 Ma. High MAR (29 g/cm^2/k.y.) is also recorded in the lower part of Unit III (860 mbsf) to the upper part of Unit IV.

The carbonate accumulation rates (CAR) are low over the entire succession ranging between 3 g/cm^2/k.y. to 8.3 g/cm^2/k.y., with the highest values in the intervals 4.2–4.7 Ma and 5.2–6.4 Ma.