IODP Expedition 350: Izu Bonin Mariana Rear Arc
Site U1436 Summary (updated with return to site)

Background and Objectives

Site U1436 is located at 32°23.88′N, 140°21.93′E (1776 m water depth), in the western half of the Izu-Bonin forearc basin, ~60 km east of the arc front volcano Aogashima, and ~170 km west of the axis of the Izu-Bonin Trench.

The plan for Site U1436 was to carry out a one-day operation to core 150 m below the seafloor and collect geotechnical samples in preparation for potential future drilling at proposed site IBM-4. Here, the *Chikyu* is proposed to drill 5.5 km below seafloor to reach arc middle crust, which is inferred to represent juvenile continental crust. The origin of continental crust remains one of the biggest unsolved problems in Earth science because continental crust, though volumetrically insignificant on a planetary scale, is an important reservoir for many trace and minor elements. The "andesite model" proposes that oceanic arcs produce the nuclei of new continental crust. However, the processes involved (e.g., partial melting of mantle sources, crystallization differentiation, or other processes) remain poorly understood. Ultra-deep drilling into arc crust is the best way to sample unprocessed juvenile continental-type crust as it is first generated at intra-oceanic arcs, before its primary features are overprinted by accretion or incorporation into a larger or more mature continent. This geotechnical Site U1436 is important for assessing the suitability of near-surface conditions for this ambitious undertaking.

Although Site U1436 was scheduled as a geotechnical hole for IBM-4, it yielded a rich, relatively complete record of Late Pleistocene forearc sedimentation, strongly influenced by frontal arc explosive volcanism. This is highly complementary to the main objective of Expedition 350, the rear-arc subduction factory (Site U1437), in terms of understanding the Izu arc system as a whole. In addition, Site U1436 gave scientists the opportunity to "test drive" a newly-devised descriptive scheme for volcaniclastic rocks, drafted at an IODP workshop in January, and elaborated during the early part of Expedition 350. This scheme was devised to facilitate the understanding of volcano-sedimentary processes by making reproducible and quantifiable observations of volcanic input to the sedimentary record.

The Izu forearc is a repository of ashes/tuffs erupted in the Izu-Bonin frontal arc, because the wind blows from west to east. Mafic effusive eruptive products are better preserved on the frontal arc islands, whereas more silicic materials from explosive volcanism are preserved in adjacent deep ocean basins. Rhyolites are also abundant in other oceanic arcs; thus, models for the crustal evolution of oceanic arcs must explain their bimodal volcanism. Basalts and rhyolites of the Izu arc front share radiogenic isotope characteristics that make them clearly distinguishable from active rift lavas immediately behind the arc front, as well as from rear-arc lavas behind (west of) the active rifts. However, a puzzling feature of the arc front is that basalt volcanoes lie on thick middle crust and rhyolite volcanoes lie on thin middle crust, in apparent contrast with continental margin arcs. A major objective of Site U1436, therefore, is to characterize the chemistry, age, provenance and textural characteristics of mafic and silicic explosive volcanic products from the arc front, to better understand outputs that are not preserved on land.

Principal Results

Operations overview

The transit from Keelung started on 4 April and ended at 1142 h on 8 April, marking the beginning of operations at Site U1436. A seafloor survey was conducted first and verified that no sub-sea communications cables exist in the drilling area. Hole U1436A (9–10 April) cored from 0 to 150 mbsf using the APC, half-length APC, and XCB, recovering 71.6 m (48% recovery) of tephra and mud.

After operations were prematurely terminated at Site U1437 on 25 May, the science party decided to use the limited remaining expedition time to recover two or three additional copies of one or two conspicuous black ash layers found seven weeks earlier in Hole U1436A at ~50 mbsf. The short transit from Site U1437 to Site U1436 took from 0930–1700 h on 25 May, and the contingency operations were conducted from 25–27 May.

Hole U1436B was positioned 20 m north of Hole U1436A and cored from 0 to 61.8 mbsf, obtaining 61.79 m (100% recovery). Hole U1436C is located 20 m south of Hole U1436A and cored 0 to 70.4 mbsf, obtaining 70.38 m (100% recovery). The final Hole U1436D was positioned 20 m east of Hole U1436A, and after washing down to 40 mbsf, coring from 40–62.0 mbsf obtained 22.07 m (100% recovery).

The ship remained on station at Site U1436 until 0900 h on 29 May before the short voyage to Yokohama, arriving on 30 May and ending Expedition 350.

Lithostratigraphy

Coring at Site U1436 recovered 71.64 m, 61.79 m, 70.38 m, and 22.07 m of sediment from Holes U1436A, U1436B, U1436C, and, U1436D, respectively. These sediments are described as a single lithostratigraphic unit (Unit I) consisting of intercalated (1) tuffaceous mud, (2) mafic ash and scoria lapilli ash (~80 intervals in Hole U1436A), and (3) evolved ash and pumice lapilli ash (~70 intervals in Hole U1436A), culminating in a total of ~40 m of tuffaceous mud and ~26 m of volcaniclastic sediment. The mafic intervals in Hole U1436A are 50% thicker than the evolved beds, giving a mafic to evolved thickness ratio of 1.5:1. Ash and lapilli-ash layers make excellent stratigraphic markers for hole-to-hole correlations. Tuffaceous mud intervals are massive, average 0.25 m in thickness, and are up to 4.20 m thick. They comprise >25% of vitric and crystal particles; foraminifers and bioturbation are present. The tuffaceous mud is light gray to dark gray brown, commonly with a greenish hue. Rare glauconite (0.01–0.02 m thick layers) occurs at the top contacts with evolved ash intervals.

The mafic ash and scoria lapilli-ash intervals average 0.14 m in thickness, and are up to 2.30 m thick (350-U1436A-8H). Mafic ash and scoria lapilli layers are commonly severely disturbed due to their granular fabric. The evolved ash and pumice lapilli-ash intervals are 0.09 m thick on average, and up to 0.60 m. Pumice and scoria lapilli are ~30 mm (commonly less than 10 mm) and small lapilli are angular, whereas coarser ones are subrounded. Most mafic and evolved intervals are normally graded, with sharp bottom contacts and diffuse/gradational tops showing upward increase in mud content. Most lapilli ash intervals are polymictic.

One very distinctive facies, the black, glassy mafic ash, occurs in all holes between 49.1 mbsf and 53.6 mbsf (350-U1436A-8H-1, 0 cm, to 8H-2, 108 cm; 350-U1436B-10H-1, 0 cm, to 10H-2, 26 cm; 350-U1436C-11F-1, 106 cm, to 11F-2, 40 cm; and 350-U1436D-7F-2, 15–73 cm). It consists of massive, non-graded, non-stratified, very well-sorted, glass shards with minor feldspar and pyroxene crystals and foraminifers. It is 55 cm thick, and has sharp upper and lower boundaries. The glass is brown to greenish brown, with few microlites; glass particles are flat, blocky, curviplanar and/or plastically deformed, and contain vesicles.

The tuffaceous mud is interpreted to record hemipelagic background sedimentation, with substantial ash contribution from explosive eruptions or resedimentation, presumably predominantly from the Izu-Bonin arc front. Mafic and evolved ash and lapilli-ash intervals may record distinct explosive events, also from the Izu-Bonin arc front, although evolved ashes may include far-field volcanism. The mode of transport and deposition of the mafic and evolved volcaniclastic layers include both vertical settling through the water column and/or water-supported density currents. The distinctive 0.55 m thick black, glassy mafic ash facies is unusually homogeneous in componentry, grain size and texture, suggesting an eruption-fed origin, and the angular and fluidal shapes of the ash particles suggest they are products from a subaqueous explosive eruption.

Geochemistry

Inorganic and organic geochemistry measurements at Site U1436 aimed to characterize the interstitial water chemistry and elemental composition of igneous rocks and sediment samples as well as to determine the hydrocarbon gas concentrations within the sediments. Headspace samples were analyzed routinely from every core in Hole U1436A as part of the shipboard hydrocarbon safety program. No hydrocarbon gases other than methane were detected in the cored sequences. Methane was either present in very low concentrations near or below the detection limit with an average concentration of 2.5 ppmv.

Downhole interstitial water compositions obtained from selected whole-round samples (~1/core) from Hole U1436A are generally in good concordance with previous observations at nearby Site 792 (ODP Leg 126). Pore water Na/Cl scatters around an average of 0.86 throughout the sampled interval, equivalent to modern seawater. Variations in pore water compositions may be controlled by stronger seawater infiltration into porous ash-rich sections compared to muddy deposits. The most prominent deviations occur in pore waters from mud collected at ~13–27 mbsf, where sulfate concentrations subtly decrease (minimum 25.8 mM) compared to seawater (28.9 mM), with concomitant subtle increases in pH, alkalinity, and decreases in calcium. Magnesium concentrations are slightly elevated compared to Site 792 values at the same depths, and show no evidence for magnesium sequestration due to volcanic glass alteration and clay mineral precipitation observed in the deeper sections of Site 792.

Concentrations of major elements and several trace elements in solid samples from Hole U1436A were measured by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) and additional portable X-ray fluorescence (pXRF) analysis. Reconnaissance pXRF and ICP-AES results show excellent agreement for K_2O and CaO; ICP-AES data include light elements (SiO_2, Al_2O_3, Na_2O) not reliably obtained by pXRF, and pXRF data appear more reliable for zirconium. Composite lapilli (n = 11) and bulk ash samples (n = 3) were analyzed for a complete set of major elements by ICP-AES. Loss on ignition (LOI) values range between 0.54 and 3.8 wt% (9.8 wt% for impure mud with ash), and are generally higher in evolved ash and lapilli samples compared to mafic samples. These LOI values are elevated compared to those from regional fresh subaerial volcanic rocks, and indicative of secondary hydration of volcanic glass. All but one of the Hole U1436A tephra samples define broadly linear trends in Harker diagrams (SiO_2 = 54.4–70.1 wt%). They classify as low-K rocks, and are indistinguishable from intermediate to acidic rocks from basalt dominant island volcanoes of the arc front (e.g., Aogashima volcano ~56 km to the west) although basalt (having <53% SiO_2; present in arc front volcanoes) has not been found in the tephras at Site U1436. The most mafic samples are from the black glassy ash lithofacies, but these are basaltic andesite. One interval of evolved lapilli-ash (at ~45 mbsf) has elevated K_2O, indicating that it did not come from Aogashima or East Aogashima Caldera ~45 km to the west, which have lower K_2O. However, rhyolite dominant submarine volcanoes with elevated K_2O are common in the arc front, including three within 65 km of the drill site (Myojin Knoll, South Hachijo, and Myojinsho).

Physical properties

A significant shift in all physical properties is observed at ~50 mbsf: shear strength, natural gamma radiation and color reflectance L* parameter all decrease in the interval below 50 mbsf, likely related to an increase in relative abundance of mafic ash layers in that interval. Physical properties data were examined for the specific intervals identified as mafic and evolved ash layers. Mafic ash layers have an average magnetic susceptibility value that is over twice as high as the average value for evolved layers. Results from one dominant evolved ash layer with four high NGR values, and a few mafic intervals with low NGR values, suggest that the average value for mafic layers is approximately half that for evolved layers. Reflectance L* values for mafic and evolved ash layers can be grouped into three luminance (lightness) ranges: 17–35 includes only mafic layers, 35–50 includes a mixture of mafic and evolved layers, and 50–78 includes only evolved layers.

The 2.2 m thick mafic ash layer at ~50 mbsf yields a wide range of *P*-wave values, supporting the suspicion that the layer is affected by core disturbance (stretching). The general downhole shift in physical properties and ash types at ~50 mbsf also coincides with an inferred hiatus and significant decrease in sedimentation rate (see below).

Paleomagnetism

Paleomagnetic analysis at Hole U1436A comprised archive-half demagnetization and remanence measurement at 10 mT steps up to 40 mT. Severe core disturbance resulted in complete destruction of the depositional remanence in many intervals, and discontinuous recovery compromised the recognition of magnetostratigraphy in the lower half of the hole. Nevertheless, intervals of continuous mud recovery yielded a good paleomagnetic record, with the drill string overprint largely removed. The base of normal chron C1n (the Brunhes/Matuyama boundary; 0.781 Ma) was recorded in one of the last continuous mud intervals, at U1436A-9H-3, 25 cm (56.8 mbsf). The reversal appears sharp because it occurred in the time interval between two successive depositional events.

One discrete paleomagnetic cube was sampled per section in undisturbed muds and silts. We demagnetized these at 5 mT steps up to 20 mT. Less intense and magnetically softer overprinting of these discrete samples meant that the demagnetized inclination at 20 mT tightly clustered around the expected geocentric axial dipole (GAD) inclination of ±51°. For this reason, we halted demagnetization and measurement of most discrete samples at this level, continuing to 25 mT only in samples near and below the base of chron C1n to improve the isolation of the reverse polarity remanence. Discrete samples in the discontinuous record below the hiatus allowed us to recognize two additional datums: top of normal chron C1r.1n (0.988 Ma) between Samples U1436A-9H-4, 66–68 cm (reversed) and 10F-2, 64–66 cm (normal); and base of normal chron C1r.1n (1.072 Ma) between Samples U1436A-10F-2, 64–66 cm and 16X-2, 53–55 cm (reversed). Discrete samples, and a patchy record in the archive half SRM measurements, indicate that Core U1436A-17X is all reversed polarity and probably still lies in the Matuyama interval (<1.778 Ma).

Biostratigraphy

The biochronology at Site U1436 was primarily based on planktonic foraminifers and calcareous nannofossils. Despite poor core recovery below Core U1436A-12F, nineteen core catcher samples were examined (Samples U1436A-1H-CC through 20X-CC) and studies of both fossil groups showed that the upper 132 m of the cored interval in Hole U1436A spans the last 2.7 Ma (late Pliocene–Recent). The timing of bioevents in the undisturbed part of the succession agrees with paleomagnetic data down to the Brunhes/Matuyama reversal (0.781 Ma) in Section U1436A-9H-3. Below this interval (in Samples U1436A-10F-CC through 13X-CC), several nannofossil and foraminifer bioevents were missing, indicating the presence of a hiatus. Below this potential hiatus, the rarity of markers and the occurrence of reworked specimens made identifying bioevents difficult.

Planktonic foraminifers were generally well preserved and abundant, except in some layers where the concentration of biogenic constituents was reduced via dilution by volcaniclastics. The Pleistocene/Pliocene boundary (2.588 Ma) was placed within cores U1436A-18X and 20X based on the presence of T *Globorotalia pseudomioceanica* (2.39 Ma) in Sample U1436A-18X-CC and T *Globoturborotalita decoraperta* (2.75 Ma) in Sample U1436A-20X-CC. Benthic foraminifer assemblages (i.e. extinction of Stilostomelidae) corroborate this biochronology.

Calcareous nannofossils were also generally abundant and well preserved. The late-middle Pleistocene sequence is defined by the presence of *Emiliania huxleyi* in Sample U1436A-3H-CC (16.9 mbsf) and *Pseudoemiliania lacunosa* in Sample 5H-6, 134–139 cm (34.6 mbsf). Between Samples U1436A-10F-CC (62.1 mbsf) and 13X-CC (65.05 mbsf), no additional Pleistocene bioevents were recorded. Sample U1436A-15X-CC (83.29 mbsf) contained *Calcidiscus macintyrei*, a marker for the early Pleistocene. The sequence below Sample U1436A-17X-CC (104.3 mbsf) contained few markers that characterize the Pleistocene/Pliocene boundary. Only rare specimens of diagnostic Discoasterids were present and some could be reworked. In this interval, the biozones CN12d, CN12c, and CN12b were tentatively identified on the basis of T *Discoaster brouweri*, T *Discoaster pentaradiatus,* and T *Discoaster surculus*, respectively.

Age model

Twelve out of 15 biostratigraphic datums and one magnetostratigraphic datum were selected to construct an age-depth relationship for Site U1436. The model consists of two linear segments above (0–57 mbsf) and below (74–127 mbsf) the inferred hiatus, with linear sedimentation rates of 72 and 45 m/m.y., and mass accumulation rates of 0.8 and 0.53 g/cm^2/k.y., respectively.