IODP Expedition 352: Izu-Bonin-Mariana Forearc
Site U1439 Summary

Background and Objectives

The Izu-Bonin-Mariana (IBM) Forearc displays one of the best records worldwide of the initiation of subduction. If current models are correct, subduction began with a period of rapid rollback and sinking of a newly subducting Pacific plate, continued through a transitional period of reorganization, and ended with the stable, trench-parallel subduction that we see today. In geological terms, it evolved from seafloor spreading through proto-arc volcanism to normal arc volcanism. The reconstruction of the IBM volcanic stratigraphy is key to the understanding and dating of this evolutionary sequence. At the base is a distinctive magma type known as forearc basalts (FAB). This is followed by lavas with compositions that are transitional between FAB and boninite, then by boninite lavas themselves, and finally, by members of the tholeiitic and calc-alkaline series typical of normal island arcs. This stratigraphy is speculative, however, having been pieced together from a series of dredge and dive sites that are typically a considerable distance apart. Drilling at this site will provide an important test of the stratigraphy of the middle part of this sequence, namely the period that records the transition from spreading to arc volcanism. It will thus record the birth of an island arc.

Information on this part of the volcanic stratigraphy is currently limited and dispersed. While FAB from both the Izu-Bonin and Mariana forearcs typically give ages between 51 and 52 Ma, compositions that are transitional between FAB and boninite have only been dated (at about 49 Ma) at DSDP Sites 458 and 459 in the Mariana forearc. Boninite, and boninite series, lavas erupted either above these transitional lavas and/or farther to the west, both on the Bonin Islands and offshore of Guam, give ages between about 48 and 43 Ma. They vary from low-Ca to high-Ca boninites. The basal lavas from the type locality of Chichijima (Bonin Island) have these characteristics, as do some samples from dive sites near Site U1439. These low-Ca boninites are distinct from most reported “high-Mg andesites” and “boninite-series” lavas, many of which have chemical compositions that are transitional between boninite and arc basalts. The oldest lavas of this type are ~46 Ma, slightly younger than the oldest low-Ca boninites. The start of normal arc volcanism may not have been the same in every location. The oldest arc lavas recovered to date are the ~44 Ma lavas exposed on and around Hahajima Island, and the ~45 Ma rhyolites from Saipan. Thus, we believe that by about 45–44 Ma (some 7–8 Ma after subduction initiation) near-normal, subduction-related configurations of mantle flow and melting conditions were established along the IBM arc.

The specific Site U1439 objectives fit into the four overall expedition objectives as follows.

1. Obtain a high-fidelity record of magmatic evolution during subduction initiation by coring volcanic rocks down to underlying intrusive rocks, including radiometric and biostratigraphic ages.

Coring of the volcanic succession at Site U1439 provides a crucial test of this hypothesis by providing a potentially continuous section through the proto-arc into underlying oceanic crust containing lavas of FAB composition and dikes. Thus coring provides the opportunity to understand the age and petrogenetic progression from spreading to nascent arc volcanism.

2. Use the results of Objective 1 to test the hypothesis that forearc basalt lies beneath boninites and to understand chemical gradients within these units and across their transitions.

We aim to discover whether the transition from spreading to arc volcanism following subduction initiation is continuous, gradual, and progressive or whether it is accomplished by alternations of one magma type with another. A key question is whether the boninites vary systematically up-section, for example from high-Ca boninite at the base to low-Ca boninite near the top or vice versa. We also aim to determine whether the sequence from FAB to boninite forms a vertically stacked stratigraphy, or if these lavas erupted at different distances from the trench. The nature of these transitions and variations should provide important constraints on how mantle subducted materials and petrogenetic processes change with time as subduction initiation progresses.

3. Use drilling results to understand how mantle melting processes evolve during and after subduction initiation.

Assuming that we are able to accomplish Objectives 1 and 2, we will use the results to better understand how the mantle responds to subduction initiation. For example, existing data indicate that the initiation of the arc is marked by influx of more depleted mantle, or by remelting of mantle already depleted at the oceanic ridge that produced the FAB. Lava compositions will allow us to monitor the changes in mantle depletion and degree of melting with time and so construct more realistic geodynamic and petrologic models.

4. Test the hypothesis that the forearc lithosphere created during subduction initiation is the birthplace of supra-subduction zone ophiolites.

Results from drilling at Site U1439 will allow us to prepare a more detailed volcanic chemostratigraphy expected for subduction initiation, especially in the part of the sequence formed by the transition from spreading to arc volcanism. This will, in turn, allow more detailed comparisons with ophiolites where boninite overlies basalt, such as Pindos in Greece, Mirdita in Albania, Semail in Oman, and Troodos in Cyprus, as well as ophiolites overlain by, or associated with, more complex arc-like sequences such as the Coast Range ophiolite in California or Baie Verte in Newfoundland.

Operations

After a 457 nmi transit from Yokohama, the vessel arrived at Site U1439 (BON-2A). The vessel stabilized over the site at 0324 h (UTC + 9 h) on 6 August. Because of the short initial period planned at this site, no seafloor positioning beacon was deployed and GPS was used for positioning the ship. A seafloor beacon was subsequently deployed once the vessel returned later in the expedition to Site U1439 on 26 August.

Site U1439 consists of three holes. Hole U1439A was cored using the APC/XCB system to 199.4 mbsf. Non-magnetic core barrels were used for Cores U1439A-1H to 10H. Core orientation was performed using the FlexIt tool on Cores 2H–9H. Temperature measurements were taken with the APCT-3 temperature tool on Cores 4H, 6H, 8H, and 10H. Basement was tagged with the XCB system for the purpose of identifying where in the volcanic stratigraphy this section belongs. Ten APC cores were taken over a 92.3 m interval and recovered 84.3 m (91%). Thirteen XCB cores were taken over a 107.1 m interval and recovered 86.4 m (81%). Overall recovery at Hole U1439A was 86%. The total time spent on Hole U1439A was 59.75 h.

The vessel was offset 20 m to the east on 8 August and Hole U1439B was drilled without coring to 42.2 mbsf for a jet-in test to determine the length of casing that would be deployed with a reentry cone in Hole U1439C. After the completion of the jet-in test, the drill string was raised to 100 m above the seafloor and at 2030 h on 8 August the vessel started the move to Site U1440 using the dynamic positioning system.

After completion of operations at Site U1440, the vessel moved back to Site U1439 on 26 August. A reentry system was prepared, and 178.5 m of 10.75 inch casing was assembled and landed in the reentry cone in the moon pool. A drilling BHA assembly, including a mud motor, underreamer, and bit were picked up and installed. The casing with the reentry system attached was lowered to the bottom, drilled into the seafloor, and released on 27 August. Hole U1439C was cored with the RCB system to 544.3 mbsf. Coring was terminated on 8 September as a result of poor hole conditions. A total of 45 rotary cores were taken over a 362.3 m interval and recovered 107.8 m (30%). An additional 1.5 m of material was recovered during hole cleaning operations. The hole was logged to ~402 mbsf with the triple combo–magnetic susceptibility sonde (MSS) and Formation MicroScanner (FMS)–sonic tool strings. The total time spent on Hole U1439C was 382.75 h. The total time spent on Site U1439 was 447.75 h or 18.66 days. The vessel moved to Site U1441 on 11 September 2014.

Principal Results

Sedimentology

Sediments and sedimentary rocks were recovered from the seafloor to 176.47 mbsf in Hole U1439A, beneath which a thin interval of basic volcanic and volcaniclastic rocks was recovered within the igneous basement. The sediments represent the Late Eocene–Recent deep-sea sedimentary cover of the Izu-Bonin forearc basement. The underlying volcanogenic rocks are interpreted as the forearc basement. The sedimentary succession is divided into five lithologically distinct units. Units I and II are further divided into two subunits. The main criteria for the recognition of the lithologic units and subunits are a combination of primary lithology, grain size, color and diagenesis. Within the overall succession, 44 ash or tuff layers were observed.

Unit I (0–50.43 mbsf) is recognized mainly on the basis of a relatively high abundance of calcareous nannofossils compared to the sediments beneath. Unit I is subdivided into an upper, relatively nannofossil-poor subunit (0–5.54 mbsf) and a lower, relatively nannofossil-rich subunit (5.54–50.43 mbsf).

Unit II (50.43–100.50 mbsf) is recognized on the basis of a downward change to silty mud and fine to coarse sand, in which the higher subunit (50.43–82.80 mbsf) is relatively fine grained and the lower subunit (82.80–100.50 mbsf) relatively coarse grained.

Unit III (100.50–110.93 mbsf) is easily recognizable because of a predominance of pale-colored nannofossil ooze.

Unit IV (110.93–129.76 mbsf) is marked by a distinct downward change to more clastic sediments dominated by clay, with minor silt, sand, and nannofossil-bearing sediments.

Unit V (129.76–178.50 mbsf) is characterized by a diverse mixture of fine- to coarse-grained clastic sediments, interbedded with fine-grained nannofossil-rich sediments and sedimentary rock. The base of Unit V is defined as a thin (<3 cm) layer of dark gray to black, weakly consolidated, manganese oxide–rich sediment.

Biostratigraphy

Calcareous nannofossils were present in 19 of 22 Hole U1439A core catcher samples and Sample U1439A-20X-2, 0–2 cm. Preservation of calcareous nannofossils is variable, ranging from "good" in the most recent samples to "poor" in certain taxa and intervals. The oldest samples in the hole exhibit more diagenesis than younger samples. Reworking may be common throughout the section, making initial age constraints somewhat difficult. Close examination reveals a somewhat continuous recovery from the Late Pleistocene to the Upper Eocene with a few gaps, especially in Miocene-aged sediments. The youngest age obtained was Late Pleistocene (Zone CN14a, ~0.44–1.04 Ma), whereas the oldest age was Late Eocene/Early Oligocene (Zones NP19/20 or NP21, ~34.44–35.92 Ma).

Fluid Geochemistry

Twenty-one samples were collected at Hole U1439A for headspace hydrocarbon gas analysis as part of the standard shipboard safety monitoring procedure; one sample per core was collected from Cores U1439A-1H to 23X, except for Cores 21X and 22X in which no sediment was recovered. Thirteen whole-round samples were collected for interstitial water (IW) analyses at Hole U1439A; one per core from Cores U1439A-1H to 10H and one every three cores from Cores 13X to 19X. No headspace gas or IW samples were collected from the basement rocks in Hole U1439C. All IW samples were analyzed for salinity, alkalinity, pH, Cl^-, Br^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+} and PO_4^{2-}.

Methane concentrations range from 2.49 to 12.44 ppmv in Hole U1439A, with the highest methane concentration measured in Core U1439A-1H at a depth of 5.9 mbsf. This high value is attributed to decomposition of organic matter in the uppermost layers of the sedimentary column. No ethane or propane was detected in Hole U1439A samples. The major result of the IW analyses from Hole U1439A is a broad correlation with the described lithologic units, with the exception of Mg^{2+} and Ca^{2+}. The distribution of these elements in the sedimentary column is invariant of lithology and shows a downhole increase in Ca^{2+} to 40.5 mM and a decrease in Mg^{2+} to 39.2 mM. These variations can probably be attributed to hydrothermal alteration via fluids released from the basaltic basement.

Petrology

Igneous rocks were recovered in Holes U1439A and U1439C. Hole U1439A tagged basement during XCB coring (Cores U1439A-20X-2 through U1439A-23X; 3.53 m recovery), whereas Hole U1439C penetrated over 362 m of igneous basement (Cores U1439C-2R through 45R; 109.3 m recovery). The uppermost part of the section comprises heterolithic breccias, which represent seafloor colluvium. In contrast, the lowermost part of the section is composed of mafic dikes or sills. The volcanic rocks in between are dominated by pillow lava, with intercalations of massive sheet flows, igneous breccias, and pyroclastic flow deposits. This site is notable for the variety of boninites cored, and for the intercalation of boninites and basalt at several levels throughout the section. In one unit, these magmas appear to have erupted simultaneously, forming magma mingling textures. Phenocrysts are common throughout Holes U1439A and U1439C. However, the variation in phase assemblages and abundances are not always diagnostic. As a result, chemical distinctions based on portable XRF (pXRF) spectrometry were also used to assess changes in rock composition and to track the occurrence of different magma series.

Ten lithostratigraphic units were identified in the basement at Site U1439. Unit boundaries represent an abrupt change in chemical characteristics, phenocrysts, and groundmass assemblages. Subunits typically represent changes in the eruptive nature of a unit (e.g., from hyaloclastite to pillow lava or massive lava), although minor changes in chemical composition may also occur at subunit boundaries.

Igneous rocks at Site U1439 are dominantly boninites characterized by phenocrysts of olivine and orthopyroxene, and are typically set in a groundmass of pale glass and acicular pyroxene prisms. Phenocryst and groundmass assemblages document a range in boninite compositions: (1) orthopyroxene > olivine phenocrysts with an orthopyroxene-dominated groundmass (Units 1–3), (2) olivine + orthopyroxene + augite phenocrysts in subequal proportions with an augite-rich groundmass (Unit 5), and (3) olivine > orthopyroxene ± augite phenocrysts with augite + orthopyroxene in the groundmass (Units 6 and 8). Based on pXRF analyses (see "Rock Geochemistry" below), these units are also discriminated by variations in Ti/Zr ratios with (1) having very low Ti/Zr (<60), (2) having significantly high Ti/Zr (80–110), and (3) having intermediate Ti/Zr (65–75). Boninites in the first group are canonical boninites, whereas those in the second and third groups have lower silica concentrations and were assigned an informal shipboard classification of "low-Si boninites." Basalts at Site U1439 are classified based on the presence of abundant modal plagioclase in the groundmass and high magnetic susceptibilities. They are notable, however, for their low TiO_2 contents and Ti/Zr compared with those of the forearc basalts of Site U1440.

Rock Geochemistry

Whole rock chemical analyses were performed on 48 igneous rocks and 22 sediment samples representative of the different lithologic units recovered from Site U1439. The 22 sediment samples were collected at Hole U1439A (one per core). They were analyzed for major and trace element concentrations and volatile contents. Hole U1439A sediments show a broad range of compositions, mainly marking the downhole changes in lithology from the carbonate-rich calcareous ooze (CaO > 50 wt%, Sr up to 2000 ppm, total C up to 11 wt%, and Zr ~30–40 ppm) to the clay- and volcaniclastic-rich silty muds (CaO < 2 wt%, Sr up to ~200 ppm, and Zr up to 150 ppm). The downhole transition to igneous basement is marked by a thin, muddy, manganese-rich layer (MnO = 2–5 wt%) and enrichments in Cu (>500 ppm), V (>200 ppm), and Zr (>150 ppm).

One orthopyroxene-phyric volcanic rock and one volcanic glass were sampled at the bottom of Hole U1439A. In addition, 46 igneous rocks were selected by the shipboard science party as representative of the different lithologies recovered from Hole U1439C. They were grouped as (1) olivine-pyroxene–phyric and (2) plagioclase-bearing volcanic rocks, the latter being observed mainly at the bottom of the hole. The 48 igneous rocks were analyzed for major and trace element concentrations via ICP-AES, and for CO_2 and H_2O contents via gas chromatography for samples with LOI > 2 wt%. An aliquot of the powder used for ICP-AES analyses was subsequently used for XRF analyses that were carried out with a Niton handheld portable XRF (pXRF). In addition, pXRF "chemostratigraphic" analyses were conducted on 350 archive-half pieces from Hole U1439C cores. The results of these chemical analyses, in conjunction with observations on core material and thin sections carried out by the petrology team, contributed to the lithological subdivision of the lavas into different units.

Site U1439 igneous rocks range from slightly to highly altered with LOI values from 2.5 to 16.2 wt%. LOI values primarily vary with H_2O contents (0.5–8.8 wt%) and, thus, the amount and type of secondary hydrous minerals. However, several samples from the upper Units 1 to 8 also show high CO_2 values (up to 6.4 wt%) together with higher Ca content, the result mostly of late carbonate addition. This suggests that the primary composition of several samples may have been modified significantly by alteration. For this reason, the igneous rocks of Hole U1439C were screened for alteration based on petrology and selected chemical criteria, before further description and interpretation of their primary geochemical signature.

The igneous samples recovered at Hole U1439C are mainly basalts, low-Si boninites, and boninites with SiO_2 concentrations ranging from 50.5 to 60.2 wt% at total alkali contents of 1.60–4.70 wt%. Olivine-pyroxene–bearing igneous rocks are characterized by high Cr concentrations (221–1562 ppm), high Mg# (cationic Mg/[Mg+Fe], with all Fe as Fe^{2+}) of 64–80, and CaO/Al_2O_3 of 0.49–0.93. These rocks were interpreted as part of the boninite series. The plagioclase-bearing samples, which are observed mainly below 480 mbsf (Units 9 and 10) in Hole U1439C, have lower Cr concentrations (51–750 ppm) and Mg# (59–76). These values are generally higher than those of the Site U1440 basaltic series.

A characteristic feature of Site U1439 samples is the progressive increase in Fe_2O_3/TiO_2 and decrease in TiO_2 concentrations that characterize the transition from the plagioclase-bearing igneous rocks sampled deep in Hole U1439C to the shallower boninite type samples. Another characteristic feature is the enrichments in highly incompatible and mobile elements (e.g., Ba) in igneous rocks sampled at Site U1439 compared to those from Site U1440. These enrichments are not correlated with indices of alteration and appear to be of magmatic origin.

Structural Geology

Structures observed in Site U1439 cores originated from drilling-induced, sedimentary, igneous, and tectonic processes. Drilling-induced deformation in the sediments, including dragging-down, rotational shear, and post-retrieval core dilation, prevented observation of sedimentary structures between ~92 and 155 mbsf. Sedimentary structures, such as bedding planes, stylolites, dewatering structures, and cross-bedding, point to an overall nearly horizontal bedding attitude. Igneous structures, although rarely observed, consist of local magmatic foliation marked by alignment of primary minerals, and a few centimeter-long enclaves in zones of magmatic mingling.

Tectonic structures, present mostly in igneous rocks, comprise tension fractures (veins), shear fractures, breccias, cataclasites, and fault zones. Veins are generally filled with (Mg-) calcite, zeolite, and clay. These veins typically dip steeply and do not correlate with the presence of faults. Vein thickness varies with depth and decreases from 350 to 500 mbsf. Three major fault zones occur at the following intervals: 348–401, 420–446, and 475–535 mbsf. The dominant sense of slip determined on slickensides is normal. Calcite microstructures in the deepest intervals include type I and type II twins, as well as subgrain boundaries, which suggests a relatively high differential stress.

Physical Properties

Many of the physical properties measurements display variability at similar depths, suggesting a few major boundaries. There is a distinct increase in natural gamma ray (NGR) values at 100–130 mbsf in sediment Units III–IV. At 135–180 mbsf in sediment Unit V, there are increases in magnetic susceptibility and *P*-wave velocity. The reflectance parameters L*, a*, and b* decrease with depth from 0 to 130 mbsf in sediment Units I–IV, and display an abrupt increase in values at 128–130 mbsf at the boundary between sediment Units IV and V. Bulk, dry and grain densities show no systematic variation with depth. Porosity increases with depth from 0 to 130 mbsf in sediment Units I–IV, and decreases in sediment Unit V.

There are distinct increases in magnetic susceptibility and decreases in density at 478–540 mbsf in basement Units 9–10. NGR values decrease with depth from 180 to 390 mbsf in basement Units 1–6, and are low from 390 to 540 mbsf in basement Units 8–10, with some peaks correlated to magnetic susceptibility peaks. At 200–240 mbsf in basement Subunit 3a, there is an increase in density and *P*-wave velocity and a decrease in porosity. The reflectance parameters a* and b* have a small peak at 330 mbsf in basement Unit 3.

Paleomagnetism

Sediments cored in Hole U1439A are relatively strongly magnetic and have low coercivities, so they acquired a strong drill string overprint. This overprint was easily removed by alternating field demagnetization, revealing a Plio-Pleistocene magnetic stratigraphy in Cores U1439A-1H to 10H (0–85 mbsf). Magnetic chrons down to the Gilbert Chron (~4.5 Ma) were clearly identified. The identification of older chrons down to Chron 3B is less certain. Cores U1439A-15X to 19X show clear magnetic polarity zones tentatively correlated with Chrons 8 through 13 (~25–34 Ma).

Igneous rock samples from Hole U1439C have mostly low inclinations with absolute values below ~30° and an average of ~5°. This is consistent with the hypothesis that the Izu-Bonin arc formed near the paleoequator. Several zones of outlier paleoinclinations occur near observed fault zones. These anomalous values may be explained by remagnetization or tectonic rotation.

Downhole Logging

A ~220 m interval of basement rocks in Hole U1439C was logged over an ~18 h period with two tool strings, the triple combo-MSS and FMS-sonic. The borehole conditions were relatively stable during logging operations, but weather conditions and sea state deteriorated. Natural gamma radiation, density, resistivity, magnetic susceptibility, sonic velocity and microresistivity images were successfully acquired. Changes in the character and trend of these logs are used to define seven logging units in this hole.

Logging Unit 1 (~180–189 mbsf) is characterized by increasing values in gamma ray, resistivity, density and velocity, in combination with decreasing magnetic susceptibility downhole. Logging Unit 2 (~189–202 mbsf) shows decreases in density, resistivity and magnetic susceptibility, whereas the gamma ray is high relative to the units above and below. Logging Unit 3 (~202–213 mbsf) exhibits overall decreases in resistivity, magnetic susceptibility and gamma ray values with coincident, discrete peaks in gamma ray and density. High frequency variations in both resistivity and magnetic susceptibility, in combination with anti-correlated profiles of density and gamma ray, characterize Logging Unit 4 (~213–246 mbsf). Logging Unit 5 (~246–314 mbsf), the thickest of the logging units, is characterized by a wide range in magnetic susceptibility, with a significant high in the top 6 m of the unit. Logging Unit 6 (~314–365 mbsf) is delineated from Logging Unit 5 by a major washed-out zone. The resistivity, magnetic susceptibility, and velocity profiles through this interval are very variable, which can, in part, be attributed to increased borehole rugosity. The deepest unit, Logging Unit 7 (~365–402 mbsf, the bottom of the logged interval), has limited data available, but is differentiated from the overlying unit by higher values of resistivity, magnetic susceptibility, and gamma ray. Overall there are increases in density, velocity, and resistivity with depth. Gamma ray and magnetic susceptibility values do not show such systematic changes with depth. The oriented microresistivity images show a wide range of features and textures in the walls of the borehole, including fracture networks, vesicles, and through-going planar features.

Although the logging unit boundaries do not correspond perfectly with the petrologic unit boundaries, there are clear relationships between the logging data and the physical properties and geochemistry of the core. Ongoing integration of the core and logging data sets will be essential in filling in some of the gaps in core recovery in the volcanic extrusive sequence of this hole.