IODP Expedition 352: Izu-Bonin-Mariana Forearc
Site U1440 Summary

Background and Objectives

The Izu-Bonin-Mariana (IBM) forearc is believed to have formed during the period of seafloor spreading that accompanied the rapid rollback and sinking of the newly subducting Pacific plate immediately following subduction initiation. The deepest volcanic rocks are expected primarily to be Forearc Basalts (FAB), a distinctive type of volcanic rock recovered during dredging and submersible sampling of the IBM Forearc. Current models predict that FAB are underlain by sheeted dikes, as these are characteristic of crust accreted during seafloor spreading at all but the slowest spreading rates. The reconstruction of the IBM volcanic stratigraphy also provides evidence for the inference that FAB should be overlain by the initial products of arc volcanism, specifically: lavas with compositions that are transitional between FAB and boninite, followed 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 partial sections that are typically a considerable distance apart. Drilling at this site will provide an important test of the stratigraphy of the lower part of this sequence.

Dating is also critical in the recognition and interpretation of FAB. Information is presently limited: cored boninites and lavas transitional between FAB and boninites recovered from DSDP Sites 458 and 459 in the Mariana Forearc have ages of ~49 Ma, whereas FAB and gabbros recovered from the Bonin and Mariana inner trench walls typically have ages of ~51–52 Ma. Thus, available ages indicate that subduction initiation began at ~52 Ma. Any ages obtained from Site U1440 will be valuable in refining this estimate.

The specific Site U1440 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 U1440 provides a crucial test of this hypothesis by providing a continuous section of FAB, representing the first suite of lavas generated by subduction initiation. Dikes feeding FAB lavas, and perhaps dikes associated with later transitional or boninite lavas, also could be present.

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 expect a thick section of FAB to be present at the base of the Bonin forearc volcanic succession, and a sequence of boninitic and arc-like lavas to be present at the top. To understand the significance of these vertical variations, we need to understand the nature of the transitions from one magma type to the next, which will provide important constraints on how mantle and subducted sources and processes changed with time as subduction progressed. Site U1440 was targeted to look at compositional variation in lavas erupted immediately after subduction initiation, and investigate the interplay between decompression melting of the mantle above the subducting slab and the timing and scope of the first fluid fluxes involved in magma genesis.

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, FAB compositions indicate that adiabatic decompression is the most important process at the very beginning of subduction initiation, and boninites indicate that flux melting was important shortly thereafter. Information obtained from the cores will be used to 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 U1440 will allow us to prepare a more detailed volcanic chemostratigraphy expected for subduction initiation, which will in turn allow more detailed comparisons with ophiolites with boninite overlying basalt, such as Pindos in Greece, Mirdita in Albania, Semail in Oman, and Troodos in Cyprus.

Operations

After an 8.2 nmi transit from Site U1439 (proposed Site BON-2A), the vessel arrived at Site U1440 (proposed Site BON-1A) and a positioning beacon was deployed at 0548 h (all times reported are ship local time, which is UTC + 9 h) on 9 August 2014.

Site U1440 consists of two holes. Hole U1440A was cored with the advanced piston corer (APC) down to 103.5 m below seafloor (mbsf) and then cored with the extended core barrel (XCB) to a final depth of 106.1 mbsf. Non-magnetic core barrels were used with all APC cores. Cores 352-U1440A-1H to 6H were oriented using the FlexIt tool, which was removed with Core 7H as a result of the high heave conditions experienced by the vessel. APCT-3 temperature measurements were taken with Cores 4H, 6H, 8H, and 11H. Basement contact was recorded at ~101 mbsf. The APC coring system was deployed 12 times, with 103.5 m cored and 96.4 m recovered (93%). The XCB coring system was deployed twice, with 2.6 m cored and 0.2 m recovered (8%). The total time spent on Hole U1440A was 49.25 h.

A reentry system with a reentry cone and 99 m of 10.75 inch casing was drilled into the seafloor in Hole U1440B using a mud motor, underreamer, and drilling bit assembly. Coring with the rotary core barrel (RCB) began at 102.3 mbsf in Hole U1440B and was terminated after bit failure at a final depth of 383.6 mbsf. Basement contact was estimated to be at ~125 mbsf. The RCB coring system was deployed 36 times, with 281.3 m cored and 34.7 m recovered (12%). Following coring, two logging runs were made with the triple combo–Ultrasonic Borehole Imager (UBI) and Formation MicroScanner (FMS)-sonic tool strings. As a result of deteriorating hole conditions, the triple combo-UBI tool string collected data down to 254 mbsf and the FMS-sonic tool string collected data down to 243 mbsf. The total time spent on Hole U1440B was 364.75 h. The acoustic beacon was recovered at 0612 h on 26 August 2014, and the vessel returned to Site U1439. The total time spent at Site U1440 was 414 h or 17.25 d.

Principal Results

Sedimentology

Sediments and sedimentary rocks were recovered from the seafloor to 103.5 mbsf in Hole U1440A, beneath which a thin interval of basic volcanic rocks was recovered. The sediments represent a section through the Recent to early Miocene deep-sea sedimentary cover of the IBM forearc basement. The underlying basaltic rocks recovered here are interpreted as representing the forearc basement. The sedimentary succession in Hole U1440A is divided into three lithologically distinct units, Units I–III. Unit I is further divided into three subunits, and Unit II is divided into two subunits. The main criteria used to define the lithologic units and subunits are a combination of primary lithology, grain size, color, and diagenesis.

Unit I (0–32.98 mbsf) is recognized mainly on the basis of a relatively high abundance of poorly consolidated, brown-colored mud. Subunit IA (0–13.33 mbsf) is composed of mud with calcareous nannofossil and ash layers. Subunit IB (13.33–21.61 mbsf) is composed of mud with foraminifers and minor ash layers. Subunit IC contains mud with diatoms, together with minor tuffaceous sandstone and ash layers (21.61–32.98 mbsf).

Unit II (32.98–77.50 mbsf) is recognized on the basis of a downward increase in grain size to more clastic and volcanogenic sediments. Subunit IIA (32.98–58.50 mbsf) is relatively coarse grained and volcanogenic. Subunit IIB (58.50–77.50 mbsf) is even coarser grained and includes muddy volcanogenic breccia/conglomerate with gravel.

Unit III (77.50–103.52 mbsf) exhibits a return to finer grained silty mud with subordinate volcanogenic gravel. The basalt beneath forms the top of the basement.

The proportions of the main sediment types recovered are (1) ash/tuff = 2.89 m or 2.9% of the total recovered sediments; (2) coarse-grained sediments (sand to conglomerate) = 16.5 m or 17.1%; (3) fine-grained mud, silt/mudstone and siltstone = 75.51 m or 78.5%; and (4) nannofossil ooze = 1.24 m or 1.2%.

In addition, sediment was recovered in three cores immediately below the drilled interval in Hole U1440B (Cores U1440B-2R to 4R, 102.3 to ~115.3 mbsf). These cores correspond to Unit III in Hole U1440A.

Biostratigraphy

Calcareous nannofossils were recovered intermittently at Hole U1440A, where productive intervals are interspersed with barren intervals dominated by siliceous microfossils (especially radiolarians) and volcaniclastic material. There is a long barren interval from Sample 352-U1440A-6H-CC to 10H-CC. The youngest age obtained is Late Pleistocene (Zone CN14a, ~0.44–1.04 Ma) and the oldest age obtained is Early Oligocene (Zone NP23, ~29.62–32.02 Ma). Three samples were examined from Hole

U1440B. Samples 352-U1440B-2R-CC and 4R-1, 14–15 cm, contained calcareous nannofossils sufficient for age diagnostics, whereas Sample 3R-CC was barren. Preservation was moderate to poor in each sample with many taxa showing strong dissolution and overgrowth. Both of the Hole U1440B samples have an Early Oligocene age (Zones NP22 and NP21, respectively), with a range that is difficult to constrain better than ~32.02–34.44 Ma given the lack of reliable marker taxa for the equatorial Pacific. Absolute age determinations were more difficult to make at Site U1440 compared to Site U1439, as a result of increased dissolution and a number of barren intervals.

Fluid Geochemistry

Twelve samples (one per core) were collected at Hole U1440A for headspace hydrocarbon gas analysis as part of the standard shipboard safety monitoring procedure, and twelve whole-round samples were collected for interstitial water (IW) analyses (one per core). No headspace gas or IW samples were collected at Hole U1440B. All IW samples were analyzed for salinity, alkalinity, pH, Cl^-, Br^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+} and PO_4^{2-}.

Only minor methane was detected in the headspace gas samples. The highest methane concentration (5.84 ppmv) was measured in Core 352-U1440A-1H at a depth of 1.5 mbsf and may be attributed to the decomposition of organic matter in the uppermost layers of the sediments.

The major result of the IW analyses from Hole U1440A is the distinctive behavior of Mg^{2+} and Ca^{2+}. Both of these elements have seawater concentrations at the top of the hole, but then Ca^{2+} concentrations decrease with depth to 41.2 mM at the bottom of the hole whereas Mg^{2+} concentrations increase to 36.6 mM. These variations are independent of lithologic units and are attributed to pervasive fluid input from the underlying hydrothermally altered basaltic basement and alteration of volcanic ash in the sediments.

Petrology

Igneous rocks were recovered in both Holes U1440A and U1440B. Hole U1440A tagged basement during XCB coring with low recovery (Cores 352-U1440A-13X and 14X, 1.27 m recovered), whereas Hole U1440B penetrated over 253 m of igneous basement (Cores 352-U1440B-4R to 36R). The basement/sediment contact is marked in both holes by a Mn-rich sediment layer or coating, similar to the umbers that commonly overlie ophiolites. The uppermost igneous unit in both holes comprises a mixture of volcanic rock fragments in a sediment matrix, and likely represents a talus or volcaniclastic breccia. This unit is underlain by over 175 m of volcanic rock, which transitions over 40–60 m into dikes at 329.0 mbsf. The dikes are interpreted as part of a sheeted dike complex. The igneous basement is divided into 15 lithostratigraphic units (including the uppermost breccia), numbered in order of increasing depth. The lowermost unit (Unit 15) is a dike complex, and this has been further subdivided into five chemically distinct subunits (15a–15e).

Igneous rocks at Site U1440 are typically aphyric to sparsely phyric, plagioclase-pyroxene–phyric basalts, with intergranular to intersertal textures. The coarser grained units grade into subophitic textures and are referred to as dolerites, which are found only in the dike complex and transition zone. All of the igneous rocks are petrographically similar to forearc basalts and have chemical compositions consistent with this classification. They are distinct petrographically and chemically from the boninite-suite lavas that are common in the IBM Forearc and are typically orthopyroxene- or olivine-phyric.

The degree of alteration of the igneous rocks at Site U1440 is low in the volcanic section where the secondary mineralogy is dominated by clays and zeolites, and becomes more intense in the transition zone and dike complex where the secondary mineralogy includes chlorite, amphibole, and albite. Alteration typically affects only the groundmass phases, leaving the silicate framework minerals (plagioclase, pyroxene) unaffected, except in the lower part of the dike complex where pyroxene and plagioclase may be partially replaced. Glass is commonly devitrified and, less commonly, replaced by clays and zeolite.

Although investigation of Site U1440 is still in its early stages, a number of significant scientific observations have been made, and many of the preliminary petrological scientific objectives of Expedition 352 have been met. These include the following:

- First confirmation of in situ forearc basalts (FAB) by drilling. All of the igneous rocks obtained at this site are FAB (aphyric or nearly aphyric, with MORB-like phenocryst assemblages and chemical features of both MORB and arc tholeiites).

- Wide ranges of lava types that vary geochemically with depth, including varieties transitional towards both boninite and MORB. These data show that FAB comprise a significant component of early arc magmatism, and form a complex suite of rocks that document the dynamic melting conditions immediately following subduction initiation.

- Recovery of the lowermost lava above the dike complex (Unit 15) demonstrates that FAB are the first magmas to erupt during subduction initiation.

Rock Geochemistry

Whole rock ICP-AES chemical analyses were performed on 33 igneous rocks and 16 sediment samples representative of the different lithologic units recovered at Site U1440. Twelve sediment samples were collected at Hole U1440A (one per core), and three samples were collected in the deepest part of the sediment sequence at Hole U1440B at depths ranging from 104.4 to 115.1 mbsf. Additionally, one sandstone piece was recovered within the igneous sequence in Section 352-U1440B-15R-1 (192.8 mbsf). One aphyric basalt sample was collected at the bottom of Hole U1440A and 32, mostly basaltic, samples were collected at Hole U1440B. The 16 sediment samples were analyzed for major and trace element concentrations and volatile contents. The 33 igneous rocks were analyzed for major and trace element concentrations. An aliquot of the powder used for ICP-AES analyses was subsequently used for XRF analyses, which were carried out with a Niton handheld portable XRF (pXRF) instrument.

The sediments sampled at Site U1440 are dominantly silty muds and their compositional variations reflect sedimentary unit changes. The range of compositions is more restricted than the sediments of Hole U1439A. The sediments have, on average, low CaO contents (<2 wt%), high SiO_2 contents (>55 wt%), and variable Cu concentrations of 120–240 ppm. A few samples contain slightly higher carbonate contents with total C contents >0.9 wt%, CaO of 5–22 wt%, and lower Cu concentrations (70–90 ppm). Hole U1440B sediments have the same composition as Unit III sediments in Hole U1440A. Similarly, the sandstone recovered within the Unit 4 igneous rocks overlaps in composition with Unit III sediments. This sandstone could represent an accidental fragment displaced by drilling, or an accumulation of sand in an open fracture.

Site U1440 igneous rocks have basalt and andesite compositions with SiO_2 ranging from 48 to 57 wt% and total alkali (Na_2O + K_2O) contents of 2.1 to 3.2 wt%. They are relatively depleted in incompatible trace elements (e.g., TiO_2 = 0.6–1.4 wt%), and have highly variable Cr concentrations (15–380 ppm), indicating different degrees of differentiation. Downhole profiles of major element compositions exhibit a distinct increase in SiO_2 concentrations and Mg# at ~260 mbsf. This depth marks the transition between igneous Units 7 and 8, which is tentatively interpreted as the boundary between the volcanic series and the lava/dike transition. The sampled igneous rocks overlap the major element composition range of MORB, FAB, and the least differentiated IBM arc tholeiites.

X-ray fluorescence "chemostratigraphic" analyses were conducted on archive-half pieces of cores and on thin section billets and powders. 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 15 unit lithologic subdivision of the lavas and dikes. IODP Expedition 352 is the first instance in which pXRF measurements have been successfully used to distinguish rock units chemically while core is being described. These real-time data also proved useful in targeting intervals for shipboard ICP-AES analyses on cores as they were recovered. The collaboration between the shipboard geochemists and petrologists emphasizes the importance of close coordination between differing areas of expertise during core description and analysis, and establishes a new tool for use during basement coring.

Structural Geology

Bedding planes in the sediments are marked by dark pyroclastic beds and thin sandy layers and are generally subhorizontal. Drilling-induced deformation of core features precluded meaningful structural measurements in the sediments between ~57 and 102 mbsf. In the igneous rocks, magmatic fabrics are rare and limited to a few centimeter-wide domains of grain alignment. A steep, metamorphic, chlorite-based foliation overprints primary fabrics at ~145–146, 281–291, and 358–369 mbsf. Tension veins filled with (Mg-) calcite, zeolite, chlorite, and clays are common at ~164–166, 202–264 and 319–369 mbsf. These veins typically form two sets at a high angle from each other with average dips of ~40° ± 10º and 80° ± 10º. The basalts and dolerites are overall free of plastic and cataclastic deformation features such as slickensides.

Physical Properties

Changes in the trends of physical properties are encountered at similar depths and these changes tend to be associated with different units. At ~10 mbsf in lithologic Unit I, there is a positive spike of *P*-wave velocity and natural gamma ray (NGR) accompanied by a slight increase of gamma ray attenuation (GRA) density. This is an interval rich in tephra layers. At 35–40 mbsf in lithologic Unit II, *P*-wave velocity and GRA density increase sharply whereas NGR decreases. Color reflectance parameters L*, a*, and b* decrease in the same interval. Physical properties show significant variability in lithologic Unit III. At 83–87 mbsf, magnetic susceptibility increases suddenly and color reflectance parameter L* decreases. At ~87–100 mbsf, *P*-wave velocity increases, magnetic susceptibility and NGR are variable but generally decrease with depth, the color reflectance parameters decrease with depth, GRA, dry, and bulk density increase with depth, and porosity decreases with depth. At 100–102 mbsf, there is a sudden decrease in *P*-wave velocity, magnetic susceptibility, NGR, GRA, dry, and bulk density, accompanied by a sudden increase in porosity. Physical properties parameters change in basement Units 7 and 8. At ~230 mbsf in Unit 7, porosity decreases sharply, *P*-wave velocity increases, and bulk and dry density increase. At 270–280 mbsf in Unit 8, NGR decreases and magnetic susceptibility increases, with high values observed between 280 mbsf and the bottom of the hole.

Paleomagnetism

Remanent magnetization measurements reveal that the sediments cored at Site U1440 are highly magnetic (~0.1–2 A/m natural remanent magnetization), apparently as a result of input of volcaniclastic material from nearby sources. A normal Plio-Pleistocene magnetic stratigraphy has been established for the upper sedimentary section, and includes the period from the upper Gilbert Chron (at ~4 Ma) to the Brunhes Chron at the surface. Paleomagnetic samples from the igneous basement section reveal a probable magnetic reversal sequence. The upper ~50 m and lower ~120 m of the section have normal polarity, whereas the intervening ~70 m has a reversed polarity. Until radiometric dates are available for the basement section, the pattern cannot be correlated with the geomagnetic polarity timescale.

Downhole Logging

A ~130 m open hole interval of Hole U1440B was logged over a ~24 h period with two tool strings, the triple combo-UBI and the FMS-sonic. Although borehole conditions deteriorated while downhole logging was in progress, natural gamma radiation, density, resistivity, sonic velocity, and microresistivity images were successfully acquired.

Seven logging units are defined on the basis of the character and trend of the various logs. Logging Unit 1 (~99–116 mbsf) is characterized by relatively consistent resistivity and velocity with depth whereas the underlying Logging Unit 2 (~116–122 mbsf) shows sharp increases in gamma ray, resistivity, and density downhole. Logging Units 3 (~122–164 mbsf) and 5 (~170–211 mbsf) exhibit similarities in their log responses, steadily increasing in resistivity with depth and with no net change in gamma ray. However, Logging Unit 3 does show much greater variability in bulk density compared to the range of densities measured in Logging Unit 5. Logging Units 4 (~164–170 mbsf) and 6 (~211–222 mbsf) are relatively thin by comparison to Units 3 and 5, and they are characterized by high resistivity, high velocity, and increasing density with depth. Logging Unit 7 has limited data available but is differentiated from the overlying unit by a marked changed in the character of the resistivity log. Overall, there are downward increases in density, resistivity, and sonic velocity, whereas natural gamma radiation and porosity (as derived from resistivity) exhibit decreasing downhole trends. Microresistivity images overall echo the increasing resistivity with depth, and also elucidate a range of textures and features through the logged interval.

Preliminary analysis of the data shows a reasonable agreement between the logging units and the lithostratigraphic units that have been defined on the basis of core description and geochemical analyses. It is anticipated that the logging data, although only available for the lowermost sedimentary interval and upper volcanic extrusive section, will be useful in filling in some of the gaps in core recovery.