IODP Expedition 351: Izu Bonin Mariana Arc Origins
Site U1438 Summary

Background and Objectives

Site U1438 (proposed Site IBM-1) is located in the Amami Sankaku Basin (ASB), <100 km west of the northern portion of the Kyushu-Palau Ridge (KPR), a remnant arc of the intraoceanic Izu-Bonin-Mariana (IBM) arc in the western Pacific on the northern part of the Philippine Sea Plate. It is a representative intraoceanic arc that can aid in our understanding of how subduction zones are initiated and continental crust forms. An intraoceanic setting is mandatory to avoid the obscuring geochemical, geophysical, and structural veils of pre-existing continental crust and the practicality of basement core recovery by drilling.

Site U1438 was selected because there are remnants of drillable arc basement (i.e., oceanic crust that existed in the region immediately before arc inception), the initial IBM magmatic record (sequence of volcaniclastic sediment and tephra), as well as geological evidence of the tectonic setting at the time of subduction initiation.

There were two primary targets for Site U1438: the basement and the overlying sedimentary sequence. Recovering oceanic basement samples allows the determination of petrological, geochemical, and age characteristics of the pre-KPR (IBM) crust in the region. Overlying sediments preserve the volcanic and geologic record spanning pre-arc, arc initiation and remnant arc stages, which permits testing of processes concurrent with subduction initiation and subsequent arc evolution. The sedimentary record also preserves an ash record of the evolution of the Ryukyu-Kyushu arc, located west of the ASB, as well as a paleo-environmental record.

Operations

Expedition 351 departed Yokohama, Japan, at 0552 h on 4 June 2014 and arrived at Site U1438 at 0245 h on 7 June (all times reported are ship local time which was UTC + 9 h). Prior to commencing rig floor operations, a visual seafloor survey (50 m box pattern) was conducted using the subsea camera system to confirm there were no subsea cables at the site. Operations at Site U1438 (4700 m water depth) encompassed the entire operational time of Expedition 351. Six holes were occupied during the expedition with a total of 189 cores recovered utilizing each of the available coring systems. Logging operations occurred in three of the six holes.

Hole U1438A

Hole U1438A (27°23.0108′N, 134°19.1020′E) was spudded on 8 June and three advanced piston corer (APC) cores were recovered to a depth of 26.5 mbsf before hole termination. Recovery for the entire hole was 94% (24.9 m recovered). This hole was intended only to gain additional material for higher resolution sampling of the upper 20 m for post-expedition research, so no discrete samples were taken for shipboard analyses.

Hole U1438B

Hole U1438B (27°23.0111′N, 134°19.1087′E), offset 10 m east of Hole U1438A, was spudded at 1510 h on 8 June and occupied until 0525 h on 10 June. Six successful temperature measurements were made using the APCT-3 tool when collecting the upper nine cores recovered with the APC system. Oriented APC coring continued in this hole to a depth of 168.9 mbsf, at which point we switched to the half-length APC system. The half-length APC system was used to a depth of 180.6 mbsf, where we then used the extended core barrel (XCB) to core to our total depth of 257.3 mbsf. In total, 19 full length APC cores were recovered (168.9 m penetration; 159.2 m recovered; 94% recovery), three cores were collected with the half-length (4.7 m core barrels) APC (11.7 m penetration; 11.96 m recovered; 102% recovery), and eight cores were recovered (76.6 m penetration; 55.9 m recovered; 73% recovery) with the extended core barrel system (XCB). The overall recovery for the hole was 227.04 m (88%).

Hole U1438C

Hole U1438C (27°22.9963′N, 134°19.0883′E), 10 m west of Hole U1438A, consisted of a reentry cone jet-in test for casing emplacement. This test took place on 10 June and reached a depth of 65 mbsf in ~2.5 h.

Hole U1438D

Hole U1438D (27°23.0218′N, 134°19.1023′E) was offset 20 m north of Hole U1438A and was an RCB-cored pilot hole to help provide information for our subsequent reentry hole. It was spudded at 1330 h on 11 June and drilled without coring to 219 mbsf. Coring with the rotary core barrel (RCB) system began with non-magnetic core barrels to 286.7 mbsf, when coring was suspended due to bad weather at 0400 h on 12 June. RCB coring resumed at 1045 h and continued until 17 June, reaching a total depth of 897.8 mbsf. In all, 71 cores were collected over a cored interval of 678.9 m, totaling 523.2 m of material (77% recovery).

Hole conditions during Hole U1438D operations were good enough that we decided to utilize a single casing string (10.75 inch) for the subsequent reentry hole (Hole U1438E). After RCB coring was completed, Hole U1438D was swept and displaced with heavy mud in preparation for wireline logging. Before logging, however, the drill string was raised to a depth of 304 mbsf and a free-fall funnel (FFF) was deployed so that we could release the bit on the seafloor and reenter the hole to log; this also was a contingency plan for potential deeper coring in this hole. After releasing the bit on the seafloor at 2135 h on 18 June, the FFF was reentered and the end of the drill string was positioned at logging depth (95 mbsf). The triple combination (triple combo) tool string run, measuring temperature, resistivity, density, porosity, and natural gamma, started at 0633 h on 19 June and reached a depth of 303 mbsf, where the tool string encountered a bridge. An uplog began at 0823 h and the tool was recovered at 1200 h. As the depth of the obstruction corresponded to the depth of the pipe during deployment of the FFF, it was concluded that the pipe itself may have created the bridge. To attempt to further logging, the pipe was lowered to a depth of 328.15 mbsf (below the bridge), and the triple combo tool string was run back into the hole at 1525 h and reached the end of the pipe by 1800 h. Unfortunately, another bridge was encountered at 362 mbsf. Due to the difficulty of passing through the bridge and the shallow depth, it was decided to halt logging operations for Hole U1438D. No uplog was recorded for this second logging run. The drill string was recovered and Hole U1438D ended at 1130 h on 20 June.

Hole U1438E

Hole U1438E (27°23.0153′N, 134°19.0898′E), offset 10 m south of Hole U1438A, was our deep reentry hole. It was spudded at 1415 h on 21 June when the reentry cone and casing assembly was jetted in (no rotation) to a depth of 60.1 mbsf. We then drilled a 14.75 inch hole to a total depth of 613.0 mbsf, which concluded at 1445 h on 24 June. The hole was swept multiple times with high viscosity sepiolite mud and only one wiper trip was conducted due to the good borehole condition. No overpull or drag was present during the wiper trip and there was no fill identified on the bottom. On 25 June, preparations began for assembling and deploying the 10.75 inch casing string. At 0145 h on 27 June, the 10.75 inch casing string was lowered into the hole escorted by a mud motor-powered underreamer and 9.875 inch tri-cone pilot bit to a depth of 605 mbsf. After changing out the drill string, we reentered Hole U1438E with a rotary core barrel (RCB) and drilled without coring (center bit) to a depth of 867.3 mbsf.

At 0900 h on 30 June, RCB coring began in Hole U1438E. Coring continued through to 1319.6 mbsf. Coring stopped at 1825 h on 5 July due to impending severe weather. A typhoon necessitated our transit to a safe standby location east of Site U1438. At 0600 h on 7 July, the ship was positioned 144 nmi east of Site U1438. Upon arriving back on site at 0830 h on 10 July, we continued to wait for the sea conditions to moderate enough to resume operations. At 1315 h on 11 July, we deployed the subsea camera system and Hole U1438E was reentered at 1655 h. RCB coring resumed with non-magnetic core barrels on 12 July. Coring continued to 1460.9 mbsf where the sediment-basement contact was identified (Core U1438-69R). RCB coring continued through basaltic basement rocks to a total depth for the hole, and site, of 1611 mbsf (on 20 July). Eighty-eight RCB cores were recovered from this hole; of a total of 743.7 m cored, 450.73 m were recovered (61%). More specifically, 407 m of sediments were recovered from 593.6 m cored (69%) and 44 m of basement were recovered from 150 m cored (29%).

In general, coring conditions were good, but there were several times when remedial hole conditioning was required. The sediment-basement contact was the depth at which the drill string had the most trouble. As a result, a wiper trip was conducted prior to wireline logging operations. Heavy mud was not used, as it was believed to have affected conditions in Hole U1438D. The drill pipe was pulled to 190.2 mbsf (well inside the 10.75 inch casing) and the rig up of the triple combo began at 1511 h on 21 July. Due to the hole conditions, the source was not included in the tool deployed and a "hole finder" was attached at the bottom of the tool string to help pass the sediment-basement contact. The triple combo was deployed at 1656 h and reached 1186 mbsf, where it encountered a bridge and was unable to pass despite several attempts. During the uplog, caliper measurements indicated the hole diameter was >18 inch the entire logged depth. This precluded the use of the Versatile Seismic Imager (VSI) and FMS-sonic tool strings. However, use of the Göttingen tri-axial borehole magnetometer (GBM) is not constrained by borehole diameter so this instrument was deployed and reached the same total depth as the triple combo (1186 mbsf). Logging operations were completed by 1320 h on 22 July.

Hole U1438F

Hole U1438F (27°23.0167′N, 134°19.0905′E), offset 10 m north of Hole U1438C and 20 m west of Hole U1438A, was a dedicated wireline logging hole. The hole was drilled to 700 mbsf and logging operations began on 25 July. The hole preparation for logging included a wiper trip and circulation with seawater, after which the pipe was pulled to 95 mbsf. The triple combo began a downlog started at 2117 h on 25 July. The tool string reached the ~700 mbsf at 2151 h and began an uplog began at 2250 h. The triple combo was recovered at 0224 h on July 26, after which the Versatile Seismic Imager (VSI) was run since using a seismic source is constrained to times with full daylight. The VSI was rigged up by 0355 h and deployed. Protected species observation began at sunrise (~0500 h) and the ramp-up of the seismic sources began one hour later as no protected species were observed in the 940-m diameter exclusion zone for this site. The seismic source was activated when the VSI tool string was clamped in at each of the nine measurement depths on the uplog. The last deployment was the FMS-sonic tool string to 689 mbsf. Logging operations were completed at 2209 h on 26 July. With the recovery of the drill string on 27 July, drilling operations for Expedition 351 concluded.

Principal Results

Lithostratigraphy

The lithostratigraphic record at Site U1438 is composed of sediments, sedimentary rocks, and igneous rocks recovered in Holes U1438A, U1438B, U1438D, and U1438E. Sediments and sedimentary rocks at Site U1438 were sampled from the seafloor to a depth of 1461 mbsf and were divided into four lithostratigraphic units. Unit I (recovered in both Holes U1438A and U1438B) is 160.3 m thick, and is Recent to latest Oligocene age (Pleistocene in Hole U1438A). The sediments of Unit I are primarily terrigenous, biogenic, and volcaniclastic mud and ooze with interspersed discrete ash layers. Unit II is 139.4 m thick and is Oligocene age. Unit II sedimentary rocks are tuffaceous mudstone, siltstone, and fine sandstone, with localized slumping-induced deformation features. The mudstone-to-sandstone intervals in Unit II are typically normally-graded beds with sharp lower boundaries to the sandstone bases, and moderately to strongly bioturbated mudstone caps. Unit III is 1046.4 m thick and is Oligocene to Eocene age. Unit III sedimentary rocks are on average coarser-grained than those of Unit II, and include tuffaceous mudstone, tuffaceous sandstone, tuffaceous medium to coarse sandstone with gravel, and tuffaceous breccia-conglomerate with volcanic and sedimentary clasts commonly up to pebble and rarely cobble size. At the largest scale, Unit III comprises five intervals of coarser clastic sedimentary rocks, separated by intervening mudstone-dominant intervals lacking discrete breccia-conglomerate beds. Unit IV is 99.7 m thick. Unit IV is composed of radiolarian-bearing mudstone underlain by medium to coarse sandstone, breccia-conglomerate, and tuffaceous siltstone and mudstone. Unit IV overlies basement rocks that comprise igneous Unit 1. Unit 1 is comprised of a sequence of basaltic lava flows. Within Unit 1, several cooling contacts were recognized, but substantial drilling disturbance made consistent recognition of individual volcanic unit boundaries and estimation of thicknesses impractical, so all igneous basement rocks are grouped together in a single unit. Unit 1 is 150 m thick.

Biostratigraphy

Calcareous nannofossils generally range from medium to low abundance, although many samples are barren particularly at the top and towards the bottom of Site U1438. Nannofossil marker species for Zones NP25 to NP19/20 are present. The base of Zone NP25 (26.84 Ma) was assigned between depths 180.65–189.44 mbsf (Hole U1438B), based on the last occurrence (LO) of *Sphenolithus distentus*. Between 269.84–280.66 mbsf (Hole U1438D) material was constrained to the base of Zone NP24 (29.62 Ma) based on the first occurrence (FO) of *Sphenolithus ciperoensis*. The LO of *Reticulofenestra umbilica*, encountered between 548.7–555.71 mbsf, identified the base of Zone NP23 (32.02 Ma). Cores recovered between 565.7–576.79 mbsf were assigned to the base of Zone NP22 (32.92 Ma) based on the LO of *Coccolithus formosus.* The base of Zone NP21 (34.44 Ma) was identified as between 729.58–733.07 mbsf based on the LO of *Discoaster saipanensis.* The interval 733.07–809.11 mbsf was assigned to Zone NP19/20 (34.44–36.97 Ma) based on the presence of *Discoaster saipanensis, Discoaster barbadiensis,* and *Isthmolithus recurvus.* One final interval in Hole U1438E (~1181 mbsf) could be constrained to the Zones NP20–NP17 (top) (34.44–38.25 Ma) based on the occurrences of *Discoaster saipanensis*, *Discoaster barbadiensis,* and *Reticulofenestra bisecta.* Below this depth, the samples are barren of nannofossils.

Planktonic foraminifers are barren in the majority of samples, although many samples do contain age-diagnostic species and so are able to contribute to the age model for Site U1438. Samples from 0 to ~177 mbsf (Hole U1438B) are largely barren apart from several foraminifer oozes at ~8, 12.5, 16 and 27 mbsf. These contain rich assemblages of typical Pleistocene species, which include the age diagnostic *Globorotalia tosaensis*, *Globorotalia hessi,* and *Globorotalia inflata*, constraining the samples to Zones PL4 to Pt1 (<3.6 Ma). The interval between 223–235.2 mbsf is constrained to the base of Zone O6 (26.93 Ma) based on the presence of the species *Paragloborotalia mayeri* and *Paragloborotalia opima*. The interval at ~483 mbsf (Hole U1438D) is constrained to Zones O2 to E15 (30.28–36.18 Ma) based on the occurrence of *Turborotalia ampliapertura*, and the sample at ~576 mbsf is constrained to Zones O2 to E15 (30.28–32.1 Ma) based on the high abundance of *T. ampliapertura*.

Benthic foraminifers exhibit a similar occurrence pattern to planktonic foraminifers, but several intervals of moderate recovery allow the definition of four assemblage zones. Assemblage 1 (0–28 mbsf) ranges from ~0–1.6 Ma, and is characterized by a relatively high diversity of bathyal to abyssal benthics including typical Neogene species *Uvigerina peregrina*, *Cibicidoides mundulus,* and *Planulina weullerstorfi*. The core top "mudline" sample contained agglutinated species including *Rhizammina* sp., *Reophax* sp., and *Saccammina* sp., confirming that Site U1438 (4700 m water depth) is below the CCD today. A barren interval follows, which passes into Assemblage 2 (166–245 mbsf; Hole U1438B), ranging from 25.5–29 Ma. It is characterized by sparse samples that include the species *Cibicidoides* spp., *Nodosaria* spp., *Globocassidulina moluccensis,* and *Gyroidina* sp. Assemblage 3 (257–430 mbsf; Hole U1438D) ranges from ~29–30.2 Ma, and is characterized by very low abundances of the genera *Amphistegina* spp. and *Lepidocyclina* spp. Assemblage 4 (520–587 mbsf) ranges from 31–33.2 Ma, and is characterized by low abundances of benthic species including bathyal to abyssal *Cibicidoides havanensis* and *Stilostomella* spp. One sample includes *Sigmavirgulina tortuosa* and *Cibicidoides pachyderma*. The interval ~597–1460 mbsf is barren of benthic foraminifera.

In general, most of the samples recovered from Site U1438 are barren of radiolarians, or only contain very low diversity and poorly preserved radiolarian assemblages. However, some samples yielded moderately preserved radiolarian faunas, which provide some biostratigraphic control in the Pleistocene–Holocene, Early–Middle Miocene and latest Paleocene–Middle Eocene. The interval 0–15.3 mbsf is constrained to Zones RN13–17 (<1.26 Ma), based on the presence of the species *Lamprocyrtis nigriniae*. The interval 121.3–127.7 mbsf (Hole U1438B) is constrained to Zones RN2–5 (20.05–12.6 Ma), based on the presence of the species *Stichocorys delmontensis*. At about 127.8 mbsf, the radiolarian age is constrained to Zones RN4–5 (17.59–12.6 Ma), based on the presence of the species *Calocycletta costata*.

Geochemistry

In total for Site U1438, 67 interstitial water (IW) samples for pH and chemical analyses, 160 headspace samples for hydrocarbon gas analyses, 111 samples for total carbon/total nitrogen (TC/TN) and carbonate analysis, and 70 samples for bulk chemical analysis of the solid phase. These samples were collected in Holes U1438A, U1438B, U1438D, and U1438E, and span lithostratigraphic Units I, II, III, IV, and igneous Unit 1. Methane concentrations were low in all headspace samples with an average of 2.35 ppmv. TOC and TN concentrations were low (<0.52 wt% and <0.06 wt%, respectively) through all the cores. Carbonate content was generally low in Unit I except for a few intervals containing foraminifera oozes, higher but variable in Unit II, and very low in Units III and IV except in a few intervals.

At Site U1438, IW chemical analyses indicate a pH increase downhole to a maximum of 9.9, and a decrease in alkalinity to a minimum of 0.6 mM. The depletion of ammonium and phosphate below 250 mbsf (bottom of Hole U1438B) may be related to a sharp downhole decline of microbial activity. The downhole increase of salinity is related to the increase of Ca and Cl concentrations. Mg concentrations show an opposite trend with respect to Ca, suggesting an exchange occurs between Mg and Ca during alteration of volcaniclastic sediments. Aqueous concentrations of K and Na also decrease with depth, balancing the gain in Ca. This has been well documented in volcaniclastic settings in Western Pacific marginal basins and is observed in the Izu-Bonin Forearc at Sites 792 and 793, as well as the West Philippine Sea Basin including Site 1201. Ba concentrations increase downhole, similarly to Ca, again reflecting the alteration of volcaniclastic sediments. An additional source is probably the basement, which could release these cations into the IW. The correlation between Li/B and pH suggests these elements may be released in the upper sediment where pH is low, as a result of silicate dissolution and desorption from clay minerals, but are retained in secondary minerals downhole where pH increases.

The downhole increase of Sr concentration in IW across Units I and II is most likely the result of low temperature alteration of volcaniclastic sediments. Cl and Br concentrations are nearly constant in Unit I and increase with depth in Units II and III, possibly due to a low permeability layer at the Unit I/ Unit II boundary, which acts as a semi-permeable "membrane," as well as mineral hydration processes at greater depth.

Bulk analysis of sediments shows a loss on ignition (LOI) ranging from 3.91–14.47%. The highest LOI values are from unconsolidated sediments in Unit II. In Unit III, CaO decreases in the sediments from 9.17 wt% (~466 mbsf) to 3.04 wt% (~1260 mbsf), and is inversely correlated with the increase of Ca in the IW. The silica content of the volcaniclastic-dominated sediments is extensive, ranging from levels equivalent to basalt to dacite, but with a majority of bulk compositions in the basaltic andesite to andesite compositional range. The Si/Mg maxima, observed near conglomerate layers, suggested that during these time intervals, the source of volcaniclastic debris was rhyolitic/dacitic in composition.

Paleomagnetism

Paleomagnetic analyses of the sedimentary succession and underlying igneous rocks from Site U1438 have provided a continuous record of the geomagnetic field inclination. A total of 87 geomagnetic reversals have been recognized in the studied succession based on the inclination of the paleomagnetic vectors. This allowed precise dating of the cores down to 847 mbsf, extending back to ~36 Ma. Below this level, in Hole U1438E, higher magnetic coercivities of some intervals and more extensive overprinting by drilling-induced magnetic components in others prevented reliable identification of geomagnetic reversals, and no ages could be determined based on the shipboard paleomagnetic data alone. Archive half core remanent inclination data are insufficient to allow accurate determination of changes in paleolatitude of the Philippine Sea Plate, as isolation of characteristic remanences in many intervals requires demagnetization to higher levels than can be achieved using shipboard systems. However, discrete samples analysed during the expedition indicate that shore-based demagnetization of additional discrete samples will allow a robust determination of plate latitudinal motion. Discrete samples obtained from APC cores will provide additional constraints on plate rotation, as these cores were oriented using the FlexIT tool. Finally, postcruise integration of remanence data and analysis of wireline FMS logs may potentially allow magnetic declinations to be recovered in some deeper intervals, allowing plate rotation to be documented beyond 25 Ma.

Physical Properties

Physical properties of recovered core were analyzed to help characterize lithostratigraphic units while providing the basis for linking the lithostratigraphy to downhole logging data and the crossing seismic lines. Reflecting the compaction and lithification of sediments, there is an overall reduction in porosity through Units I to IV that fits with an exponential decay typical of that seen for shales, sandstones, and mudstones. There are significant jumps in sonic velocity, grain density, and magnetic susceptibility at the boundaries between Units I and II, II and III, and oscillations in sonic velocity and magnetic susceptibility within the top of Unit III indicative of the changing proportions of sands and conglomerates to muds. Higher velocities are correlated to mudstones with clasts, and lower velocities in mudstones without clasts. These major changes occur between 160 and ~700 mbsf (Holes U1438B and U1438D), and are likely responsible for the most prominent seismic reflectors seen in the crossing seismic lines of the site. Within Hole U1438E, the anisotropy of the sonic velocities were also measured. The azimuthal variations in sonic velocities are small but the differences between the horizontal and the vertical velocities can be much larger and correlated with lithology; mudstones and fine sandstones with and without apparent bedding planes are generally more anisotropic than the coarser sandstones. There is also a prominent spike in the level of natural gamma radiation within Unit IV most likely due to elevated concentrations of U, Th, and K.

Successful temperature measurements were made at seven depths using the advanced piston corer temperature tool (APCT-3) from the mudline to 83.2 mbsf, and give a linear geothermal gradient without any substantial deviation from 77.6°C/km. Together with nearly constant values of thermal conductivity, it is concluded from this observation that the geotherm is undisturbed by local processes, such as sediment compaction, fluid flow within the porous sediments, and internal heat production from radioactive decay. The calculated heat flow is 73.7 mW/m^2.

Downhole Logging

Logging occurred in three holes (Holes U1438D, U1438E, U1438F) over 1200 m of sediments with the best-covered interval between 100–700 mbsf. Natural gamma radiation, resistivity, density, porosity, self-potential, magnetic susceptibility, sonic velocities, and magnetic orientation data were obtained in the sediments section. In addition, resistivity images of the borehole were acquired, and creation of a synthetic seismogram to link core, log, and seismic data was initiated.

Three intervals can be described from the logging data. The first one (0–160 mbsf) corresponds to lithostratigraphic Unit I. This interval is characterized by (1) high gamma ray values; (2) mean density of 1.3 g/cm^3; (3) high porosity (>80%); and (4) low magnetic susceptibility, resistivity, velocity and self potential values. The second interval (160–300 mbsf) corresponds to lithostratigraphic Unit II. This interval is characterized by an overall increase in velocity, magnetic susceptibility, density and self-potential. Gamma ray radiation becomes weak. Thorium and uranium reach concentration values smaller than 1 ppm. Porosity decreases slightly; however, this may also be due to changes in borehole diameter.

The last major interval (300–1200 mbsf) can also be divided into subunits. Overall, this unit is characterized by (1) a decrease of porosity from 80–50%; (2) an important decrease in self-potential; (3) low values of gamma ray (around 20 gAPI with a slight increase at 500 mbsf); (4) a large increase in resistivity data (1–3.5 Ωm); (5) an increase to velocity values around 2500 m/s and; (6) a large increase in magnetic susceptibility values.

The logging data correlate well with the lithostratigraphic units described from the core material. Therefore, it is reasonable that the logging data can provide information where core recovery is <100%. For example, the FMS images display bedding features that can be reorientated to help characterize the source of mass wasting deposits observed in the cores. Additionally, the good record of sonic velocity and its agreement with core measurements will allow the construction of a strong time-depth relationship for Site U1438 and thus provide characterization of seismic boundaries. Ultimately, this correlation will help understand the nature of the arc structure as well as the velocity structure of the IBM system.