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3 THE MISSING HALF OF THE SUBDUCTION FACTORY: SHIPBOARD RESULTS
4 FROM THE IZU REAR ARC, IODP EXPEDITION 350

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11

12 **ABSTRACT**

13 IODP Expedition 350 was the first to be drilled in the rear part of the Izu-Bonin,
14 although several sites had been drilled in the arc axis to fore-arc region; the scientific
15 objective was to understand the evolution of the Izu rear arc, by drilling a deepwater
16 volcanoclastic section with a long temporal record (Site U1437). The Izu rear arc is
17 dominated by a series of basaltic to dacitic seamount chains up to ~100 km long roughly
18 perpendicular to the arc front. Dredge samples from these are geochemically distinct
19 from arc front rocks, and drilling was undertaken to understand this arc asymmetry. Site
20 U1437 lies in a ~20 km-wide basin between two rear arc seamount chains, ~90 km west
21 of the arc front, and was drilled to 1804 mbsf with excellent recovery. We expected to
22 drill a volcanoclastic apron, but the section is much more mud-rich than expected (~60%),
23 and the remaining fraction of the section is much finer-grained than predicted from its

position within the Izu arc, composed half of ashes/tuffs, and half of lapilli tuffs of fine grain size (clasts <3 cm). Volcanic blocks (>6.4 cm) are only sparsely scattered through the lowermost 25% of the section, and only one igneous unit was encountered, a rhyolite peperite intrusion at ~1390 mbsf. The lowest biostratigraphic datum is at 867 mbsf (~6.5 Ma), the lowest paleomagnetic datum is at ~1300 mbsf (~9 Ma), and the rhyolite peperite at ~1390 mbsf has yielded a U-Pb zircon concordia intercept age of 13.6 +1.6/-1.7 Ma.

Both arc front and rear arc sources contributed to the fine-grained (distal) tephra of the upper 1320m, but the coarse-grained (proximal) volcanoclastics in the lowest 25% of the section are geochemically similar to the arc front, suggesting arc asymmetry is not recorded in rocks older than ~13 Ma.

Keywords: International Ocean Discovery Program, Izu-Bonin-Marianas Arc, island arcs, magmatic arcs, rear arc, Japanese volcanoes

INTRODUCTION

This paper provides an overview of shipboard results from one of three closely related International Ocean Discovery Program (IODP) expeditions carried out in sequence in the Izu-Bonin-Mariana (IBM) arc system in 2014 (Figure 1). It is meant to reach a wider audience than the scientific ocean drilling community, by presenting shipboard results in a compact and accessible manner, focusing on geologic results that will be of interest to those working in magmatic arcs on continents as well as those in the sea. More sophisticated geochemical results will be reported in future papers, using shore-based techniques; this paper focuses on geologic observations, which will not

change. on the basis We refer those seeking much greater detail to the *Proceedings of the International Ocean Discovery Program, Expedition 350*; all of the figures presented here appear in that volume, along with hundreds more (Tamura et al., 2015).

Expedition 350 was the first expedition to drill in the Izu rear arc; all previous IODP/ODP sites were drilled in or near the Izu-Bonin arc front or fore-arc (Figure 2), leading to an incomplete view of Izu arc magmatism. Thus, the main objective of Expedition 350 was to reveal the history of “the missing half” of the subduction factory (Tamura et al., 2013). The second expedition (351) focused on IBM arc origins by drilling west of the Kyushu-Palau Ridge (Figure 1), where it was inferred that the foundation, origin, and early evolution of the IBM arc are recorded (Arculus et al., 2013, 2015). The third expedition (352) examined the processes of subduction initiation, by drilling the outer IBM fore-arc (Figure 1; Pearce et al., 2013, 2015).

The goal of Expedition 350 was to core and log one site on the Izu rear arc, Site U1437 (Figure 1). This site was chosen to provide a temporal record of rear-arc magma compositions, ideally from Paleogene to Neogene time, allowing comparison with the previously drilled fore-arc magmatic record and determination of across-arc geochemical variations throughout the history of the arc system. In addition to drilling in the rear arc, Expedition 350 also drilled a 150 m deep geotechnical hole in the fore-arc (Site U1436, Figure 1) for potential deep drilling; this site was chosen partly on the basis of results gotten from ODP Site 792, which is only 1.5 to the east of site U1436 (Tamura et al., 2015a). ODP Site 792 was drilled to 886 meters below the sea floor (mbsf.) and the stratigraphy of its upper 150 m (Taylor et al., 1990) is very similar to that of Site U1436. Core from these sites yielded a rich record of Late Pleistocene explosive volcanism, but

is not discussed further here, for space considerations. This paper focuses on Site U1437, which was cored at 1776 meters below sea level (mbsl) to a depth of 1806.5 mbsf, through a volcanoclastic succession, with excellent core recovery (Holes U1437 B, D and E overall: 55%, 74% and 62%). This provided a time-integrated view of the rear arc over the past ~14 myr.

Major questions addressed by drilling the Izu rear arc include the following: (1) Izu rear arc volcanoes differ from arc front volcanoes by being more similar to averaged continental crust (i.e., enriched in alkalis, Ba, Th, U and LREE). The Izu rear arc is therefore important for understanding how arc magmas and intracrustal differentiation produces crust that is similar in composition to the “averaged continental crust.” When did this arc asymmetry develop? (2) What kinds of basins accommodated the volcanoclastic succession we drilled? (3) What eruption, transport and depositional processes are recorded in the rear arc volcanoclastic succession targeted for drilling, and what kinds of depositional environments are represented by the succession?

EVOLUTION OF THE IBM ARC SYSTEM

The IBM arc (Figure 1) formed in response to subduction of the Pacific plate over the past 52 myr (Stern et al., 2003). Subduction began as part of a hemisphere-scale foundering of old, dense lithosphere in the western Pacific (Bloomer et al., 1995; Cosca et al., 1998). During the subduction initiation stage (~52–47 Ma) investigated by Expedition 352 (Figure 1), igneous activity successively produced low-K mid-ocean-ridge basalt (MORB)-like tholeiite, boninite, and subordinate low-K rhyolite across the region that now lies in the fore-arc (cf. Reagan et al., 2015). This suggests that sinking of

the downgoing plate was rapidly followed by an episode of asthenospheric upwelling and melting, sometimes enhanced by solute-bearing water fluxes released from the downgoing plate, over a zone that was thousands of kilometers long and as wide as 200 km (Reagan et al., 2010). As subduction proceeded, hydrous mantle melting overprinted decompression mantle melting, establishing the first mature arc in Eocene to Oligocene time, referred to as the Kyushu-Palau arc (Taylor, 1992; Ishizuka et al., 2006a, 2006b, 2011), herein also referred to as the Paleogene arc.

By ~25 Ma, rifting began along the length of the Kyushu-Palau arc and opening of the Shikoku Basin isolated the rear-arc volcanoes from the arc-front volcanoes (Ishizuka et al., 2011; Figure 1), producing the Kyushu-Palau Ridge remnant arc, which has Eocene and Oligocene rear-arc rocks (see Expedition 351 site, Figure 1). Seafloor spreading of the Shikoku and Parece Vela Basins (Figure 1) at ~25–17 Ma was likely accompanied by a hiatus in arc magmatism, but the fore-arc sedimentary record shows that arc-front volcanism resumed by ~17 Ma (Stern et al., 2003), referred to as the Neogene arc, or the IBM arc (Ishizuka et al., 2011).

The Neogene IBM arc front is inferred to lie in nearly the same position as the Paleogene arc front (Ishizuka et al., 2011); however, pre-Quaternary rocks have not been recovered from the IBM arc front, perhaps because they are buried or were partly remelted and/or remobilized during the Quaternary. In contrast, the Izu rear arc (Figures, 1, 3) has not been extensively buried or modified by Quaternary magmatic processes, so Neogene rocks are well preserved; these are dominated by ~17 to 3 Ma northeast-trending rear-arc seamount chains described below. The Marianas segment of the IBM arc (Figure 1) differs from the Izu segment by lacking the rear-arc seamount chains;

instead, a new episode of arc rifting began at ~7 Ma, resulting in opening of the Mariana Trough back-arc basin by seafloor spreading at ~3–4 Ma (Yamazaki and Stern, 1997). Rifting of the Izu arc began at ~3 Ma behind the arc front (Figure 3).

We know more about the Neogene history of the IBM arc than we do about its Paleogene history; yet it is thought that most of the IBM crust was generated in the Paleogene (Eocene–Oligocene; Kodaira et al., 2008). Furthermore, silicic volcanoes of the Quaternary arc front and Miocene granitic rocks in the Izu collision zone on Honshu are inferred to have formed by melting of Eocene–Oligocene arc crust (Tamura et al., 2009, 2010). As discussed below, Neogene rhyolite volcanism may be more important in the Izu rear-arc seamount chain than previously thought and could have resulted from melting of Paleogene “arc basement.” For this reason, we will now review the evidence for Paleogene arc basement highs in the Izu arc and discuss constraints on their age and origin.

PALEOGENE ARC BASEMENT HIGHS IN THE IZU ARC

Magnetic and seismic surveys indicate that both IODP Sites U1436 and U1437 lie along buried north–south ridges that consist of magmatic crystalline rocks, which are inferred to be Oligocene–Eocene (Paleogene) in age. Three conspicuous, approximately north–south rows of long-wavelength magnetic anomalies were identified by Yamazaki and Yuasa (1998) in the Izu-Bonin arc system and attributed to loci of middle- to lower-crustal magmatic bodies (Figure 1):

- The western north–south anomaly corresponds to the Kyushu-Palau Ridge, where Eocene and Oligocene lava was dredged; these have rear-arc geochemical affinity, and

are interpreted as as rear-arc magmas rifted off the Paleogene arc during the opening of the Shikoku Basin (Ishizuka et al., 2011; Kodaira et al., 2008).

- The eastern north–south anomaly lies in the modern fore-arc near the arc front and corresponds to the Shin-Kurose Ridge (Figure 1) (Yamazaki and Yuasa, 1998), also referred to as the Izu fore-arc high (Taylor, Fujioka, et al., 1990). The Shin-Kurose Ridge/fore-arc high forms a bathymetric high in the northern Izu arc and is buried beneath Oligocene to Quaternary volcanoclastic and sedimentary rocks in the southern Izu arc, at Ocean Drilling Program (ODP) Site 792 and Site U1436. Andesite lava in the lowermost 82 m at Site 792 was referred to as “Oligocene basement,” on the basis of K/Ar ages (Taylor, Fujioka, et al., 1990; Taylor, 1992), but more recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating show these are Eocene (Ishizuka et al., 2011).

- The central north–south magnetic anomaly lies buried in the Izu rear arc (Figure 1) and is referred to as the Nishi-shichito Ridge (Figure 4) (Yamazaki and Yuasa, 1998). This basement high has not been drilled and was one of the objectives of Expedition 350. Kodaira et al. (2008) ran a wide-angle seismic profile along the length of the rear-arc Nishi-shichito Ridge and compared it to a wide-angle seismic profile made along the length of the arc front by Kodaira et al. (2007a, 2007b) (Figure 4). They divided the arc front into segments based on variations in the thickness of middle crust and did the same for the rear-arc Nishi-shichito Ridge. They concluded that although the thickness of the middle crust for each rear-arc segment is smaller than the thickness in the arc front, the bulk compositions of the crust segments are inferred to be the same, on the basis of seismic properties.. Furthermore, they used the match on middle crustal thicknesses to infer that the Nishi-shichito Ridge is a “paleo-arc” that obliquely rifted off the arc front in

an extension direction parallel to the northeast–southwest Sofugan Tectonic Line (Figure 1). The Sofugan Tectonic Line is the boundary between the Izu and Bonin arc segments (Figure 1); south of it lies the prominent Bonin Ridge and the deep fault-bounded Ogasawara Trough to the west, produced by Eocene to early Oligocene arc magmatism and back-arc extension, respectively. Both the prominent arc ridge and the fault-controlled back-arc basin are absent north of the Sofugan Tectonic Line, so we infer that the Sofugan Tectonic Line originated as an accommodation fault between a region of high extension to the south and little or no extension to the north. Kodaira et al. (2008) propose that oblique rifting of the Nishi-shichito Ridge paleoarc off the arc front occurred during the opening of the Shikoku Basin, sometime after ~30 Ma. If the oblique rifting model is correct, the crystalline basement beneath Site U1437, not reached during Expedition 350, may represent rear-arc crust but formed in a position much closer to the arc front than it is now; alternatively, it may represent arc-front crust that has become stranded in the rear arc by rifting. New seismic surveys undertaken in preparation for drilling at Site U1437, described below, also support the interpretation that the rear arc is underlain by Paleogene arc basement rocks.

NEOGENE REAR-ARC VOLCANISM, IZU ARC

We refer to all Neogene volcanic rocks behind the Izu arc front as rear-arc volcanic rocks. Rear-arc volcanic rocks (Figure 3) include (1) the ~17–3 Ma east northeast–trending basaltic to rhyolitic rear-arc seamount chains, (2) the <3 Ma bimodal back-arc knolls of the broad extensional zone, and (3) the <1.5 Ma bimodal volcanic rocks of the active rift immediately behind the arc front. Thus, Izu rear-arc volcanism

falls into two magmatic suites: the <3 Ma bimodal rift-type magmas and the ~17–3 Ma basalt to rhyolite rear-arc seamount-type magmas. Both types lie within the rear part of the arc (i.e., behind the arc front) and lie on arc crust, although the westernmost end of the rear-arc seamount chains lies on Shikoku Basin oceanic crust. The bimodal rift-type magmas differ from both the arc front and the rear-arc seamount chains in trace element and radiogenic isotopic ratios; this has been variably attributed to (1) a transition from flux to decompression mantle melting as arc rifting commences, (2) a change in the character of slab-derived flux, or (3) a change in the mantle source through mantle wedge convection (Hochstaedter et al., 1990a, 1990b, 2001; Ishizuka et al., 2003a, 2006b; Tollstrup et al., 2010).

The Izu rear-arc seamount chains are as long as ~80 km and strike N60°E (Figure 3). The tops of the Izu rear-arc volcanic chains were sampled by dredging, and their compositions range from basalt to rhyolite (Ishizuka et al., 1998, 2003b; Hochstaedter et al., 2000). Three main hypotheses have been proposed for the origin of the seamount chains:

1. They are related to compression caused by collision between the southwest Japan and Izu arcs, associated with opening of the Japan Sea (Karig and Moore, 1975a; Bandy and Hilde, 1983).

2. They formed along Shikoku Basin transform faults (Yamazaki and Yuasa, 1998).

3. They overlie diapirs in the mantle wedge, such as the “hot fingers” proposed for northeast Japan (Tamura et al., 2002), illustrated in Figure 5.

A striking characteristic of volcanic arcs is the asymmetry in geochemical characteristics with distance from the trench, which was known prior to the advent of plate tectonics (Kuno, 1959; Dickinson and Hatherton, 1967). Izu arc-front rocks are low-K, but the rear-arc type lava is medium to high-K (Gill, 1981). Similarly, arc-front volcanic rocks are strongly depleted in incompatible light rare earth elements (REEs) relative to the middle and heavy REEs, whereas lava from rear-arc seamount chains is enriched in light REEs. On both K_2O versus SiO_2 and REE plots, the composition of the rear-arc seamount chain magmas is more similar to the continental crust composition than the arc-front magmas. Thus, the Izu rear-arc magmatism and crust formation appears to be a better analog to generate continental crust than the arc front (Tamura et al., 2013).

Site U1437 lies in a ~20 km wide basin in the low area between two major constructional volcanic ridges: the Manji and Enpo rear-arc seamount chains (Figure 3). It is therefore classified as a volcano-bounded intra-arc basin, using the criteria elucidated by Smith and Landis (1995) (Figure 6). In contrast, the active rift to the east of Site U1437 (Figure 3) is a fault-bounded intra-arc basin, using the terminology of Smith and Landis (1995) (Figure 6). For simplicity, the volcano-bounded basin bounded by the Enpo and Manji rear-arc seamount chains (Figure 7) is referred to as the Enpo-Manji volcano-bounded basin (Figure 8C, 8D). Similarly, we propose that future workers refer to other basins between rear-arc seamount chains by the names of the chains that bound them (e.g., Genroku-Enpo Basin and Manji-Kan'ei Basin, Figure 3).

NEW DESCRIPTIVE SCHEME FOR VOLCANICLASTIC ROCKS

Expedition 350 devised a new scheme for describing volcanoclastic and associated nonvolcanoclastic sediments, described in detail by Tamura et al. (2015b). The new scheme was devised to improve description of volcanoclastic sediments and their mixtures with nonvolcanic (siliciclastic, chemical, and biogenic) sediments but maintain the usefulness of prior schemes for describing nonvolcanic sediments. The new scheme was devised to facilitate the understanding of volcano-sedimentary processes by making reproducible and quantifiable observations of volcanic input to the sedimentary record. Previous core descriptions (e.g. ODP Leg 126) obscured the importance of volcanic input by referring to volcanic material (e.g. ashes/tuffs) as siliclastic material (e.g. sands/sandstone or tuffaceous sands/sandstones). The new classification scheme is based entirely on observations that can be made by any scientist at the macroscopic and microscopic level, making the data more reproducible from user to user. Genetic inferences are not part of the descriptive scheme but can be added as comments to descriptive records if so desired. A very brief description of the scheme is presented here to allow the reader to understand our rock descriptions.

Four sedimentary lithologic classes were defined, including: 1. Volcanic lithologic class, defined as >75% volcanic particles. 2. Tuffaceous lithologic class, containing 25%–75% volcanic-derived particles mixed with nonvolcanic particles. 3. Nonvolcanic siliciclastic lithologic class, containing <25% volcanic siliciclastic particles, where nonvolcanic siliciclastic particles dominate chemical and biogenic particles. 4. Biogenic lithologic class, containing <25% volcanic and nonvolcanoclastic siliciclastic and chemical particles. The principal name for sediments and sedimentary rocks is based on grain size and is purely descriptive; it does not depend on interpretations of

fragmentation, transport, or depositional or alteration processes. The sedimentary grain size classes of Wentworth (1922) are used for the nonvolcanic siliciclastic and tuffaceous lithologic classes, whereas the grain size classes of Fisher and Schmincke (1984) are used for the volcanic lithologic class. The prefix “monomict” was applied where clast compositions were restricted to a single type and “polymict” was applied where clast compositions of multiple types were present. We adopted a new method to estimate the compositional range of volcanic clasts using three entries: “mafic,” “evolved” and a mixture of the two, termed “bimodal.” In our macroscopic analyses, mafic versus evolved intervals were defined by the grayscale index of the main particle component, with mafic grains and clasts usually ranging from black to dark gray and evolved grains and clasts ranging from dark gray to white. Microscopic examination further aided in assigning the prefix “mafic” or “evolved”, using glass shard color and mineralogy. Intervals we described as mafic are inferred to be basalt and basaltic andesite, and intervals we described as evolved were inferred to be intermediate and silicic in composition; however, precise determination of bulk composition requires chemical analysis.

In summary, the new volcanoclastic descriptive scheme applied during Expedition 350 uses a more nongenetic approach than proposed by previous authors because the sediments and rocks are named based on materials that are visible macroscopically and microscopically and not on the basis of inferred fragmentation, transport, and depositional processes (i.e., pyroclasts, autoclats, hydroclasts, epiclasts, and reworked volcanic clasts [Fisher and Schmincke, 1984; Cas and Wright, 1987; McPhie et al., 1993]).

IODP SITE U1437

Site U1437 is located in the Izu rear arc and is ~330 km west of the axis of the Izu-Bonin Trench (Figures 1, 2) and ~90 km west of the arc-front volcanoes Myojinsho and Myojin Knoll (Figure 3) at 2117 meters below sea level between the Manji and Enpo seamount chains (Figure 7). The stratigraphic section shown in Figure 9 is a composite from three holes drilled a few tens of meters apart using different techniques. The shallowest and least consolidated material was penetrated at Hole U1437B (drilled using Advanced Piston Coring (APC), Half-Length Advanced Piston Corer (HLAPC), and Extended Core Barrel (XCB). Deeper, more consolidated units were drilled at Holes U1437D and U1437E using the Rotary Core Barrel (RCB) (see <http://iodp.tamu.edu/tools/> for details about these tools). These different drilling techniques resulted in partial sampling of the section: In Hole U1437B we cored 439.1 m and recovered 242.6 m (55% recovery). In Hole U1437D we cored 677.4 m, with 503.8 m recovered (74%). In Hole U1437E we cored 702.5 m and recovered 387.45 m (55% recovery). Incomplete and disturbed cores are unfortunate but expected; to ensure a more uniform perspective on the section (including intervals that are not recovered in cores), downhole logging was carried out before the hole is cased. Combined studies of cores and well logs allowed the entire sequence to be interrogated. Most of the unconsolidated stratigraphy in Hole U1437B is well preserved and few coring disturbances (Jutzeler et al. 2014) occur, allowing very good stratigraphic continuity. Drilling disturbances are present in Holes U1437D and U1437E, and vary depending on rock type and consolidation.

Seismic Surveys

Seismic surveys for Site U1437 are summarized briefly here. Numerous lines were shot in two different campaigns (Yamashita et al., 2017); parts of three seismic sections that cross at Site U1437 are plotted on Figure 7C and shown in Figure 8. Line IBr5 (Figure 8A) is the longest seismic line, running east–west from the Manji rear-arc seamount chain across the Enpo seamount chain to the arc front; it was shot both by wide-angle ocean-bottom seismometer (OBS, Figure 8A) and by multichannel seismic (MCS, Figure 8B). The wide-angle OBS survey shows the velocity structure of the upper ~10 km, and the MCS line shows the upper ~5 km. Generally, the velocity transition to >5 km/s is thought to represent the transition to igneous rocks, perhaps representing arc upper crust lava or crystalline rocks, and the velocity transition to 6 km/s is generally thought to represent the transition to middle crust (see boundaries picked in Figure 8B). Tamura et al. (2013) estimated the 5 km/s iso-velocity contour to lie at ~2100 mbsf at Site U1437 and suggested that these rocks could be Oligocene–Eocene “igneous basement,” consisting of lava and/or intrusions. Line IBM3-NW5 (Figure 8C) clearly shows that Site U1437 lies in a volcano-bounded basin between the Enpo and Manji rear-arc seamount chains.

Age Model

Site U1437 was drilled to a depth of 1804 mbsf in three holes (U1437B, U1437D, and U1437E), which we divide into seven lithostratigraphic units and one igneous unit (Figures 9 and 10). The biochronology for Site U1437 was established based on planktonic foraminifers and calcareous nannofossils (Figure 9). Both fossil groups show

that the upper 1403 m of the succession spans from the lower Pleistocene to the upper Miocene (maximum age detectable was ~11–12 Ma), and the timing of bioevents agrees well with magnetostratigraphic data. Deeper than 1403 mbsf, bioevents were difficult to establish because of poor preservation and low microfossil abundance (Figure 9), corresponding to a lithologic change from a succession dominated by tuffaceous mud/mudstone to one dominated by volcanic material (Figure 10).

We infer that a normal fault at the base of Hole U1437D was responsible for drilling problems there, including low recovery and more fractured rock. This forced us to drill a new hole (Hole U1437E) which started at the same subbottom depth as the base of Hole U1437D.; the first core was also fractured but cores below that were not. The fault is not obvious in the seismic section (Figure 8C, 8D) but it is not excluded either. On the basis of paleomagnetic results (Tamura et al. 2015a), this normal fault is inferred to have caused a loss of section between the two holes (Figure 9). Magnetostratigraphy could then be followed down as far as the top of Chron C4An (8.771 Ma) at 1302 mbsf (Unit V, Figure 9). The age model does not extend into Units VI and VII (Figure 9) because magnetostratigraphy was impossible to recognize, with the exception of reversed polarity seen at 1389.35 mbsf in igneous Unit 1, which indicated that coring had proceeded below the base of normal Chron C5n.2n (9.984–11.056 Ma; Tamura et al. 2015a) spanning the upper part of the lowest nannofossil age range. One additional age control point was added immediately postcruise: Igneous Unit 1 is a rhyolite intrusive sheet with peperite margins (at 1389 – 1390 mbsf, Figure 10), described further below, which indicate that it is penecontemporaneous with the volcanoclastic section that encloses it (Unit VI, Figure 10). In-situ measurement of zircons within magnetite crystals

in the rhyolite intrusion yielded a preliminary U-Pb age of 13.6 Ma $\pm$ 1.7 ($n = 9$) (Schmitt, pers. comm., 2014; Andrews et al., 2015; Konrad et al., 2016). Thus, we tentatively infer that the age of units VI and VII is ca. 9 – 14 Ma.

Description and Interpretation of Lithostratigraphic Units

Lithostratigraphic Units I–VII (Figure 10) are distinguished from each other based on the proportion and characteristics of tuffaceous mud/mudstone and interbedded tuff, lapilli-tuff, and tuff-breccia. Visual description of core was supplemented by 13 smear slides from Hole U1437B, and thin sections from Holes U1437B, U1437D, U1437E (5, 63 and 93, respectively). Mineralogy was done by macroscopic and microscopic description; the shipboard XRD unit was not working so more detailed clay mineralogy was not done. The tuffaceous mud/mudstone is strongly to intensely bioturbated. Alteration becomes more pervasive and increases in intensity downhole; it is initially predominantly glauconitic–smectitic and eventually becomes more chloritic. The transition from unconsolidated to lithified rocks occurred progressively; however, the change to RCB drilling provides a useful approximation of the transition between unconsolidated sediment and sedimentary rock; on this basis the transition lies at 427 mbsf (bottom of Hole U1437B and top of Hole U1437D). Exact positions of the contacts between lithostratigraphic units are given in Tamura et al. (2015a, 2015d).

Lithostratigraphic Unit I (0 to 682.12 mbsf)

Unit I is 0 to ~4.3 Ma in age (Figure 9), is 682.12 m thick, and consists largely (88%) of mud/mudstone with 25%–75% dispersed ash, referred to as tuffaceous mud or

mudstone (depending on whether or not it is lithified; Figures 10, 11). The tuffaceous mud/mudstone contains abundant fine colorless glass shards and rare crystals, plus carbonate materials such as foraminifers. The rest of Unit I (12%) consists of ash or tuff intervals (again depending on whether or not it is lithified), except for very rare (1.2%) lapilli-ash/lapilli tuff and lapillistone intervals with pumice or scoria <1 cm in size. The ash/tuff lithofacies was mainly differentiated into two types, evolved (white to dark gray, probably intermediate to silicic composition), or mafic (black, with brownish shards). A small number of intervals were described as bimodal because they have both colorless and brown-colored glass. The ashes/tuffs are mainly composed of glass shards (i.e., they are vitric tuffs), although some are graded, with crystal-rich basal layers, commonly plagioclase and pyroxene (Figure 11). Sedimentary structures include lamination and bioturbation (Figure 11). Evolved ash/tuff intervals are four times as common as the mafic ash/tuff intervals. Hornblende-bearing evolved ashes/tuffs, while rare (7%), have elevated K_2O contents relative to most of the other ash/tuff intervals (geochemical methods described in Tamura et al., 2015b); we suggest these record rear-arc seamount volcanism rather than arc front or rift volcanism (geochemistry discussed further below). Unit I has an unusually high sedimentation rate for fine-grained deep marine sediment far from a continental margin and not associated with a deep-sea fan system; it is ~118 m/myr in the upper 230 m (0~2 Ma), and ~200 m/myr in the lower 450 m (2~4.3 Ma).

For more than 4 myr, this part of the Enpo-Manji basin collected mud with a high ash component at a high rate, with volcanoclastic intervals consisting almost entirely of ash/tuff limited to only 12% of the section. The sparseness, thinness, and fine grain size of discrete volcanoclastic layers in lithostratigraphic Unit I is enigmatic, given that it

accumulated in close proximity to volcanoes of the active rift and back-arc knolls extensional zone (<3 Ma) and rear-arc seamount chains (>3 Ma), in addition to lying within 90 km of the arc front (Figures 1 and 3). The lateral continuity of reflectors in Lithostratigraphic Unit I on the seismic section that lies transverse to the Enpo-Manji basin (Figure 8C) is typical of fine-grained basinal deposits far from volcanic sources. Based on features of the volcanoclastic intervals (evolved ash/tuff and mafic ash/tuff), including sharp basal contacts, good sorting, and normal grading, we suggest deposition by suspension settling through water, or by seafloor-hugging density currents, or some combination (e.g., vertical density currents that transition into lateral density currents when they reach the seafloor, in a manner envisioned by Carey [1997] and Manville and Wilson [2004]). Thus, the ash/tuff intervals may represent ash falls from relatively distal subaerial eruptions, which settled through water, and perhaps in some cases flowed along the bottom as dilute density currents, and escaped reworking by bottom currents before burial. The depositional process for the tuffaceous mud/mudstone that make up 88% of Unit I is less well understood; it may be hemipelagic rain, dilute turbid flow, sediment drift, or some combination thereof.

Lithostratigraphic Unit II (682.12 – 726.50 mbsf)

Unit II is ~4.3 – 4.4 Ma in age and is only 44.38 m thick (Figures 9, 10), but it makes bright reflectors on the seismic profiles (Figure 8C, 8D). This is because it has much more abundant volcanoclastics (~75%) and much less tuffaceous mudstone (~25%) than is present in Units I or III. Additionally, the volcanoclastics in Unit II are coarser grained than those in adjacent Units I and III (Figure 12), with pumice lapilli-tuff and

pumice lapillistone forming slightly more than half of the thickness, and tuff forming slightly less than half. The volcaniclastics in Unit II also differ from those of Units I and III by being entirely evolved (no mafic volcaniclastics present). The volcaniclastic intervals are planar bedded or cross bedded, and commonly show normal grading (Figure 12). They contain plagioclase, clinopyroxene, orthopyroxene and amphibole crystals in varying proportions. The tuffaceous mudstone is like that of Unit I but more lithified and altered to green clay minerals.

Unit II is dominated by monomictic pumice lapilli-tuff and lapillistone that is relatively well sorted, with abundant interstratified well-sorted crystal and vitric tuff, and is stratified, with planar and cross lamination, sharp bases, and graded bioturbated tops (Figure 12). We interpret it to represent the deposits of density current deposits, and the monomictic composition may indicate that at least some were eruption fed.

Lithostratigraphic Unit III (726.50 – 1017.88 mbsf)

Unit III is ~4.4 – 6.2 Ma in age (Figure 9), is 291.38 m thick, and is dominated by tuffaceous mudstone (~64%) and lesser tuff (~35%) (Figures 10, 13). Lapilli-tuff represents only ~1% of the unit. All intervals of tuff, and the rare lapilli-tuff, are compositionally evolved. Unit III shows an increase in fine-grained tuff (relative to tuffaceous mudstone) in its basal ~80 m; above that, Unit III is similar to Unit I, except that it lacks the mafic tuff that makes up ~20% of the tuff in Unit I. The tuffaceous mudstone intervals in Unit III have abundant bioturbation (Figure 13). The evolved tuffs of Unit III are of two main types: (1) dark gray tuffs identical to those of Units I and II, and not described further here; and (2) intercalated white to gray-green tuff, which is

much finer grained and better sorted, in places appearing chert-like, i.e. a dense very fine-grained siliceous material (Figure 13). This fine-grained tuff has laminations produced by alternation of glass shard-rich layers (white) and layers of mixed shards, pumice, and crystal fragments (gray-green), repeated over intervals up to several meters thick, with no bioturbation or tuffaceous mudstone interbeds. Thus, the intervals seem to record fairly continuous but pulsating sedimentation, probably from unsteady density currents, over a relatively short period of time for each interval (possibly days or weeks). The laminations commonly show soft-sediment deformation (Figure 13), supporting the interpretation that the intervals were deposited rapidly. Intercalated white to gray-green evolved tuff intervals form much of the volcaniclastics in the lower part of Unit III, where the volcaniclastic content is highest for this unit. The very large quantity of very fine glass shards in this facies suggests phreatomagmatic eruption, typified by extremely efficient glass fragmentation due to enhanced explosivity (Fisher and Schmincke, 1984). This lithofacies also occurs in Units IV and V.

Unit III also contains one distinctive interval (1.91 m thick) with deformed tuffaceous mudstone intraclasts (up to ~20 cm in size) and clasts of scoria and pumice (up to 5 cm) supported in a deformed tuffaceous mudstone matrix; this is interpreted to represent a disaggregated slump or submarine debris flow deposit.

Lithostratigraphic Unit IV (1017.88 – 1120.11 mbsf)

Unit IV is ~6.2– 7.5 Ma in age (Figure 9), and is 102.23 m thick (Figure 10). It contrasts with the tuffaceous mudstone-dominated Units III and V, and consists of four lithofacies, in order of abundance: (1) normally-graded polyimictic lapilli-tuff and

lapillistone (Figure 14). Lapilli are small (average 3-5 mm), and volcanic lithic clasts dominate over pumice, and are plagioclase-pyroxene andesites (Figure 14), that is, they are evolved. Shell fragments are also present, indicating that at least some of the material was sourced from shallow water. (2) intercalated white to gray-green evolved tuff, identical to that in Unit III (compare Figure 14C- with Figure 13B). Similarly, it forms multi-meter thick, non-bioturbated intervals with planar lamination or soft-sediment deformation. (3) dark gray evolved tuff, like that described in Units I, II and III, with plagioclase, pyroxene and pumice. (4) tuffaceous mudstone, like that described in Units I, II and III. For interpretation of the second through fourth lithofacies, see above. The first lithofacies (polymictic, evolved lapilli-tuff and lapillistone) occurs as very thick (multimeter) relatively well-sorted intervals with no internal stratification, composed of volcanic clasts of a variety of evolved types (Figures 14A, 14B). These characteristics suggest deposition from high-concentration density currents, probably by mass wasting or resedimentation from one or more volcanoes; alternatively, this facies could be products from pyroclastic eruptions that mobilized large volumes of lithic clasts. This lithofacies is also abundant in Unit V.

Lithostratigraphic Unit V 1120.11 to 1320.00 mbsf)

Lithostratigraphic Unit V is ~7.5 – 9 Ma in age (Figure 9), and is 199.89 m thick (Figure 10). It is distinguished largely on the basis of its intervals of monomictic reversely graded pumice lapilli-tuff (Figure 15A); these distinctive beds, with their flattened pumice and nonflattened pumice dispersed in a tuff matrix, contrast with the polymictic, dominantly lithic lapilli-tuff of the overlying and underlying units (IV and

VI). The flattened pumice is referred to as “fiamme” with no connotation of welding compaction; in fact most or all of the pumices were probably flattened during diagenesis. Each monomictic reversely graded pumice lapilli-tuff in Unit V has (Figure 15A): (1) a sharp base, typically eroded into the underlying tuffaceous mudstone, overlain by (2) evolved tuff with abundant glass shards and grains of pumice, in turn grading upward into (3) pumice lapilli-tuff with flattened or non-flattened pumices that become progressively coarser upward (i.e., reversely graded); this passes upward into (4) tuffaceous mudstone. This lithofacies is thus composed almost entirely of vitric material (glass shards and pumice). This monomictic tuff with pumice and fiamme makes up 13% of Unit V and recurs throughout. We interpret this lithofacies to represent density current deposits, based on (a) basal scours; (b) poor sorting with ash-sized material with pumice lapilli or fiamme that become more abundant upward in each bed, indicating density grading; and (c) the increase in tuffaceous mudstone at the top of each bed. The monomict composition and the presence of abundant evolved glass shards, pumice, and broken crystals indicate that these were fed from pyroclastic eruptions.

Similar to Units I, III, and IV, Unit V also has tuffaceous mudstone (69%); evolved tuff (15%), some with soft-sediment faulting (Figure 15B); and lapilli-tuff and lapillistone (3%) with lithic and volcanic rock fragments (Figure 15C).

Lithostratigraphic Unit VI (1320.00 to 1459.80 mbsf)

Lithostratigraphic Unit VI is older than ~9 Ma (Figure 9) and extends to at least 10.97-11.85 Ma in age, and is 139.80 m thick (Figure 10). It is characterized by an abundance of polymictic lapilli-tuff with pumice and lithic clasts (Figure 16A, 16B), although it also

contains monomictic pumice lapilli-tuff (Figures 16C, 16D). The top of lithostratigraphic Unit VI is marked by the first appearance of multiple intervals of polymictic lapilli-tuff, and its base is marked by the top of a very distinctive black monomictic glassy lapillistone and lapilli-tuff in the upper part of Unit VII.

The polymictic lapilli-tuff and lapillistone forms very thick beds (>1.5 m, the length of a core section, or up to 2.8 m thick assuming complete recovery between core sections). Tuff and tuffaceous mudstone intervals are interbedded. Polymictic lapilli-tuff with pumice and lithic clasts is four times more abundant than monomictic pumice lapilli-tuff in Unit VI; monomictic varieties contain only pumice, whereas polymictic varieties have evolved and lesser mafic volcanic lithic clast types as well as pumice clasts (Figures 16A, 16B). The polymictic lapilli-tuff with lithic clasts and pumice shows a complete gradation from clast-supported (Figure 16E), to matrix-supported (Figure 16F) whereas the monomictic pumice lapilli-tuff is entirely matrix-supported.

Lithic lapilli in Unit VI are dominantly:

- Porphyritic andesite with plagioclase and clinopyroxene (Figures 16G, 16H, 16I). Clasts of this type also occur as scattered small blocks (>6.4 cm in size) in the polymictic lapilli-tuff.
- Rhyolite-dacite, which becomes more common near the rhyolite intrusive sheet with peperitic boundaries, described as igneous Unit 1 below. These include crystal-poor and porphyritic varieties, with amphibole, plagioclase, and quartz.

Pumice lapilli clasts in Unit VI are light to dark green and commonly flattened by compaction and lithification into fiamme (Figures 16C, 16D). Red to brown tuffaceous mudstone clasts are also present in Unit VI (Figure 16B).

In summary, Unit VI is dominated by lapilli-tuff and lapillistone in very thick (multimeter) beds with no internal stratification, composed of volcanic clasts of a variety of evolved types (Figures 16A, 16B); this was deposited from high-concentration density currents, probably by mass wasting or resedimentation from one or more volcanoes. Additionally, Unit VI has matrix-supported monomictic pumice lapilli tuff that may have had been fed from pyroclastic eruptions.

Igneous Unit 1 (1388.86 to 1390.07 mbsf)

The only igneous unit at Site U1437 consists of a single rhyolite intrusion, which lies within lithostratigraphic Unit VI (Figure 10). As noted above, igneous Unit 1 yielded a U-Pb zircon age of 13.6 Ma $\pm$ 1.7 in shore-based work immediately following the expedition, described by Konrad et al. (2016). Core recovery is much lower in igneous Unit 1 (~45%) than its host volcanoclastic rock (~94%), and the recovered igneous Unit 1 core material is fractured by drilling disturbance (Figure 17), probably due to greater competency of the rhyolite intrusion compared to the surrounding volcanoclastic host. Therefore, although only 1.21 m thickness was described for igneous Unit 1 (Figure 17), its maximum thickness is estimated at 6.50 m assuming all the material not recovered from this interval was part of igneous Unit 1.

Shipboard geochemical analysis (discussed below) shows that igneous Unit 1 is a rhyolite with 74.5% SiO₂. It has sieve-textured subhedral plagioclase (up to 4 mm, ~7%), euhedral hornblende (up to 0.5 mm, ~3%), large anhedral to subhedral quartz (up to 8 mm, ~1%) with fresh glassy melt inclusions, some opaque minerals, and rare zircon (<30 μ m in size). Flow banding is observed across the entire unit in various orientations

(Figure 17B). The groundmass varies from cryptocrystalline near the upper and lower contacts to fine grained in the center of the unit (Figure 17B). Paleomagnetic data on igneous Unit 1 show a consistent, single component demagnetization and normal polarity with appropriate inclination of the characteristic remanent magnetization, supporting the interpretation that igneous Unit 1 is an intrusion, rather than simply a large clast. The upper margin of the intrusion is chilled, and the overlying lapilli-tuff is baked (Figure 17B), also indicating that igneous Unit 1 is an intrusion rather than a clast or lava. The lower contact of igneous Unit 1 is peperitic, defined as a magma-wet sediment mixture (Busby-Spera and White, 1987); the contact shows complex mingling between the intrusion and the host, including crenulated lobate margins on the intrusion and dispersal of the magma into the host on the microscopic scale (Figure 17C). Peperite is considered penecontemporaneous with the section it intrudes (Busby-Spera and White, 1987). Blocks of similar material occur in the host, Unit VI (rhyolite-dacite blocks, described above), indicating that the body locally vented onto the surface during accumulation of Unit VI.

Lithostratigraphic Unit VII (1459.80 to 1806.50 mbsf)

Unit VII is older than 10.97 – 11.85 Ma and is 346.70 m thick (Figure 10). It is ~90% extremely thick bedded, nongraded, nonstratified, poorly sorted, coarse-grained angular andesitic lapilli-tuff, in places with blocks tens of centimeters in size (Figure 18). Some of these blocks have quenched margins, jigsaw-fit textures, intricate fluidal margins, or peperitic margins, described in detail below. These features indicate that the blocks were emplaced hot, so the blocks could have originated as hot clasts, lava, and/or

574 intrusions. Thus Unit VII is interpreted to be a near-vent deposit. Unit VII is divided into
575 upper and lower parts (shallower and deeper than 1643.73 mbsf).

576 *Upper Part of Unit VII: Black glassy lapillistone and lapilli-tuff*

577 The upper part of Unit VII consists of one massive (nonstratified) ~184-m thick
578 deposit of homogeneous, nonvesicular glassy black lapillistone and lapilli-tuff. The glass
579 clasts are unaltered and angular, with abundant large clinopyroxene glomerocrysts and
580 plagioclase glomerocrysts (Figure 18A). The glass is isotropic and nonvesicular, and
581 bubble-wall shards or broken crystals are absent (Figures 18B, 18C). Only a few volcanic
582 lithic clasts are present, some with quenched margins, and a few red oxidized clasts also
583 occur. The black glassy lapillistone and lapilli-tuff lithofacies lacks stratification
584 completely, except for one thin (~25 cm thick) interval of crudely stratified ash. The
585 angular, glassy, nonvesicular, monomict character of the clasts, together with the lack of
586 bubble-wall shard or broken crystals, indicates fragmentation by autobrecciation and
587 quenching of lava in a submarine environment (i.e., hyaloclastite). The few nonglassy
588 clasts in the deposit suggest minor accidental incorporation of clasts during transport, but
589 most of the unit is monomictic and nonstratified, indicating minimal resedimentation. A
590 lack of tuffaceous mudstone interbeds indicates rapid accumulation.

591 *Lower Part of Unit VII: Coarse-grained massive lapilli-tuff with in situ quench-*
592 *fragmented blocks*

593 The lower part of Unit VII (~157 m thick) is dominated by a lithofacies of green
594 (i.e., altered) angular andesite lithic lapilli-tuff, in places with blocks up to 53 cm in size
595 (tuff breccia) (see Figures 18F, 18G). Like the black glassy lapillistone and lapilli-tuff

unit that forms the upper part of lithostratigraphic Unit VII, these lithic lapilli-tuff and tuff-breccia intervals are massive, forming extremely thick intervals of nonstratified, very poorly sorted monomictic andesite lapilli-tuff with blocks, but unlike the upper part of Unit VII, the lower part has intercalated stratified lithic lapilli-tuff and tuff (also altered green). Clasts in the extremely thick nonstratified intervals are angular or have very irregular shapes, including jig-saw fit clasts (Figures 18D, 18E), indicating very minimal transport. Many intervals contain glassy blocks and coarse lapilli, and some have glassy rims and poorly inflated breadcrust or cauliflower texture, indicating that clasts came to rest at high temperatures (Figures 18F, 18G). In at least one case, a clast appears to be surrounded by sediment with a baked margin. Additionally, there are no clasts with broken chilled margins as would be expected if the clasts were transported and deposited after they cooled. In some intervals, very angular, jigsaw-fit hyaloclasts (formed of quenched glass) indicate in situ mixing of hot clasts and/or intrusions with the host hyaloclastic tuff-breccia, all of the same andesitic composition. On the basis of the core, it is not possible to determine whether all of these features formed on hot clasts or if some of these features formed on the complexly embayed margins of small intrusive bodies or lava. Further support of hot emplacement is provided by paleomagnetic inclinations from two of the clasts; despite multidomain overprinting, the demagnetization analyses of these two individual clasts resolved the characteristic reversed polarity expected for hot emplacement (for more details see Tamura et al., 2015a). Some intervals have more heterogeneous andesite lithic clast types, with variable plagioclase and pyroxene contents, and ranging from nonvesicular to moderately vesicular, indicating resedimentation.

Petrophysical data from cores and downhole logging

We collected petrophysical data from all cores, including density and porosity, sonic velocity, magnetic susceptibility and natural gamma radiation (Figure 19). In addition, we conducted downhole logging operations in Hole U1437D, from 92 to ~960 mbsf. The logging parameters included those measured on Figure 19, plus bulk resistivity, and micro-resistivity imaging (not presented here). The top 92 m could not be logged because the drill pipe extended to that depth for operational and safety reasons. The logs extend to ~960 mbsf because 980 mbsf was the depth of the hole when the drill string had to be retrieved for a bit change and it seemed prudent to conduct a first set of downhole measurements at that time. After logging was completed, Hole U1437D was deepened from 980 to 1105 mbsf, where drilling difficulties were encountered and the hole had to be terminated. We drilled a new Hole U1437E to that depth without coring, deployed a 1086-m long casing string, and cored from 1104 to 1806 mbsf. At that time a technical problem precluded re-entry and we could not log Hole 1437E. Fortunately the onboard petrophysical measurements were unaffected (Figure 19). The two shallowest logging unit boundaries, between 1 and 2 and between 2 and 3, correspond to the lower boundaries of sharp resistivity anomalies at 310 m and 612 m, respectively, and both lie within lithologic Unit I. Logging unit boundary 3 to 4 corresponds to lithologic unit boundary I/II at 680 m. The lower boundary of the conspicuous lithologic Unit II was not defined in the logging data, although it can be clearly recognized in the resistivity log. The deepest logging unit boundary 4/5 at 789 m corresponds to an increase in natural gamma radiation and resistivity and lies within lithologic Unit III (Figure 19).

The first order trends in physical properties are indicated by density, porosity, resistivity and p-wave velocity. These all change rapidly with depth in the interval ~700-950 mbsf, which corresponds to lithologic Unit II and most of Unit III. The trends above and below this interval have similar and lower rates of change with depth; the range of values is significantly larger below 950 mbsf.

The higher rate of downhole increase in density and sonic velocity, and the corresponding decrease in porosity, in the interval 700-950 mbsf, are the result of compaction and cementation by incipient diagenesis in the volcanoclastics and tuffaceous mudstone of lithologic Units II and III. These trends are accompanied by significant changes in the magnetic susceptibility (MS) and natural gamma radiation (NGR), which are compositional proxies. MS is low in the upper 700 m at Site U1437, increases two to threefold in the interval 700-950 mbsf, and below 950 mbsf shows a cyclic pattern with values ranging from lowest to highest in the entire section. MS variations most likely reflect oxide concentration, particularly magnetite. NGR, in contrast, has generally higher values above 1000 mbsf and lower values below, suggesting first-order changes in sediment provenance above and below that depth; this lies at the Unit III/IV boundary at ~6.2 Ma (Figure 19).

The interval at 290-312 mbsf (logging depth, within Unit I, Figure 19) shows a sharp resistivity increase to twice the local baseline value. In the Formation MicroScanner (FMS) micro-resistivity images, this interval appears slightly less layered (more granular or chaotic?) than the overlying and underlying intervals. In this same high-resistivity interval, MS values triple, and natural gamma radiation drops to local minimum values. The corresponding interval in the cores (at coring depth scale) had

almost no recovery: Core U1437B-40X (291.1-300.8 mbsf) had 1.8 m recovery (12%) and the recovered tuffaceous mud and ash layers are indistinguishable from overlying sediments. Cored intervals 41-42X (300.8-320.2 mbsf) had zero recovery. Furthermore, when we attempted to drill Hole U1437C to 425 mbsf without coring, circulation and rotation were lost at 309.7 mbsf. The bit had to be dropped and the stuck pipe had to be worked for several hours before it became free and could be retrieved, at which point Hole U1437C was abandoned. The drilling problems in this interval suggests loose or fractured material, however, that would not explain higher resistivity, which may indicate less porosity (cementation, remolding) or less saline pore water. The high-resistivity interval corresponds to the sequence boundary between seismic layers L2 and L3 (Figure 8), a boundary that may reflect a period of non-deposition, erosion and/or deposition by mass wasting, and/or lateral fluid flow. The MS and NGR signals could indicate a primary compositional change or alteration associated with fluid flow. At this time we simply don't know what this mystery interval represents. An interval with similar log signature at 607.3-614.6 m (logging depth) has also lower, but reasonably good core recovery (~60%, compared to ~82% in 50 m above and ~97% in 50 m below). The recovered material from this interval is tuffaceous mudstone with intercalations of tuff and shows no obvious characteristics that would differentiate it macroscopically from the overlying and underling intervals.

Over the entire section at Site U1437, both MS and NGR records show high-amplitude variations at the decimeter to meter depth scale that can be linked to lithologic and compositional changes. These relationships cannot be elaborated or illustrated within the scope of this overview and are subject to ongoing studies.

Interpretation of Depositional Environment at Site U1437: Deepwater Basinal Succession

As noted above, the section drilled at Site U1437 accumulated in a deepwater volcano-bounded basin between the Manji and Enpo seamount chains. We now present evidence that the section is best described as a deepwater basinal succession, characterized by fine-grained well-stratified, laterally continuous deposits in the upper 75% of the section; this passes downward into proximal volcanoclastic deposits in the lower 25% of the section, which we infer records eruption and sedimentation from nearby volcanoes and localized venting within the deepwater basinal setting.

Upper 75% of the section drilled at Site U1437

This part of the section (Units I through V; 0–1320 mbsf; ca. 0–7.5 Ma) has the following characteristics:

- It is mostly tuffaceous mudstone (~60%) deposited from hemipelagic rain, dilute turbid flows, bottom currents/sediment drift, or some combination thereof.
- The grain size of volcanic clasts in the discrete volcanoclastic layers is small: about half ash and half fine-grained lapilli.
- Lack of block-sized clasts.
- Little evidence for density current deposits, except in Unit II, which is thin; most of the volcanoclastics could represent suspension fallout from distal eruptions.
- There is no geomorphic or seismic stratigraphic evidence for fan- or wedge-shaped sediment bodies or of chaotic facies; instead, the seismic reflection images show laterally

711 persistent tabular stratification, consistent with the fine grained character of the section
712 drilled.

713 In summary, from 0 Ma to ca. 7.5 Ma, hemipelagic sedimentation dominated the
714 basin, with ash regularly deposited in the area and variably mixed with mud of uncertain
715 origin (possible origins of the mud discussed below). Lapilli-sized fragments (albeit fine-
716 grained) were only provided to the basin in one brief episode at 4.3 Ma, represented by
717 Unit II, and it is dominated by evolved pumice lapilli indicative of an explosive volcanic
718 event; however the fine grain size of the lapilli could indicate that the eruption was
719 relatively distal, and this unit only represents 3% of the drilled section. Two aspects of
720 the upper 75% of the section are difficult to explain: (1) The section is much more mud-
721 rich than expected for an arc-proximal sedimentary succession, and (2) the grain size of
722 the volcanoclastics is much smaller than expected for an intra-arc basin surrounded by
723 volcanoes.

724
725 Lower 25% of the section drilled at Site U1437

726 This part of the section (Unit VI, igneous Unit 1, and Unit VII; 1320-1804 mbsf; ca. 9
727 -14 Ma) differs from the upper 75% in the following ways:

- 728 • Tuffaceous mudstone is minor (10% of Unit VI) to absent (Unit VII).
- 729 • The grain size of volcanic clasts increases dramatically, with coarse-grained lapilli
730 dominating the section, and blocks occurring in Unit VII.
- 731 • Lapilli-sized volcanoclastics of unit VI are polymictic and formed thick massive beds,
732 some graded; these were deposited from density currents carrying detritus from

seamounts surrounding the Enpo-Manji Basin. Intervening minor tuffaceous mudstone record background hemipelagic sedimentation between density current events.

- Andesite lapilli tuff and tuff breccia of Unit VII are monomictic, and show macroscopic textural evidence of quench fragmentation and paleomagnetic evidence of emplacement at high temperatures. The absence of background sediment (tuffaceous mudstone) indicates high/steady volcanic input. Unit VII is a vent-proximal deposit.

- Unit VI was intruded by a quartz-phyric rhyolite-dacite sheet dated at $13.6 \pm 1.6/-1.7$ Ma (igneous Unit 1); this intrusion is a peperite (formed by mixing of magma and wet sediment), indicating that it formed contemporaneously with the section it intrudes; furthermore, blocks of igneous Unit I are scattered through the section above and below, indicating its contemporaneity with Unit VI.

In summary, from ~9 to 14 Ma, coarse-grained volcanoclastic sedimentation dominated the area of Site U1437, with polymictic material derived from adjacent volcanoes (Unit VI), and monomictic material produced by local eruptions (Unit VII) and peperite intrusions (igneous Unit 1), with little to no evidence for resedimentation, i.e., dominantly in situ.

Shipboard Igneous Geochemistry

This section is brief, because shore-based micro-analytical igneous geochemical studies (in progress) are expected to be much more revealing than the ship-based studies. This is because:

- The fine grain size of the upper 75% of the section largely precluded analysis of individual clasts by shipboard techniques, requiring us to analyze bulk samples, referred

to as “volcaniclastic samples” (Figures 20, 21), taken from different parts of lapilli-tuff or tuff beds, some of which are graded. Shipboard analyses of individual clasts are restricted to: (1) a single dacite pumice clast from Unit II, (2) a single andesitic lithic clast from Unit IV. These two clasts, along with igneous Unit I, are referred to as “igneous samples”. Shore-based microanalytical techniques will allow analysis of individual clasts that are lapilli- to ash-sized.

- Due to alteration, shipboard analyses relied largely on Zr, Zr/Y and Zr/Y vs. SiO₂ plots for distinguishing defining geochemical units (Figures 20, 21). We focused on Zr and Y because they are relatively fluid immobile and remain robust during alteration (Gill et al., 1994). We used shipboard Zr/Y analyses as an indicator for magmatic provenance and to distinguish between rear-arc and arc-front sources. Micro-analytical techniques will be more successful at exploiting relict glass domains, and will be used to determine the chemistry of minerals, which are less altered than the glass.

Downhole geochemical variations in Units I–V generally reflect the relative proportions of distal arc-front and proximal rear-arc volcanic sources (Figure 21). As a general trend, coarse-grained volcaniclastics from Units II and IV show stronger rear-arc affinity compared to fine-grained tuff from Units I, III, and V. Complications for provenance arise from mixing evident by mafic and evolved glass shards in fine-grained volcaniclastic samples. Also, alteration is pervasive in Units III and V. The predominance of ash layers from Unit I containing low K₂O relative to SiO₂ indicates a likely arc front or active rift (<1s Ma) provenance. Volcaniclastics in Unit I with high Zr/Y could be mixtures of mafic ash from arc front basalt-dominated island volcanoes, and evolved ash from the rhyolite-dominated submarine calderas (R2 rhyolites), which have high Zr/Y;

however, this cannot be confirmed without onshore in situ analyses of glass. The coarse-grained deposits from Units II and IV indicate proximal sources. Active Manji seamount chain volcanoes around the time of deposition of Unit II (4.2–4.3 Ma) were the Meireki Seamount (3.76 Ma; Ishizuka et al., 1998) ~20 km to the north and the Daigo-Nishi-Aogashima Knoll (5.05 Ma; Ishizuka et al., 2003b) ~40 km to the northeast of Site U1437 (Figure 7). Both are rhyolite volcanoes with similar SiO₂ contents (72–76 wt%), whereas Meireki Seamount volcanic rocks have higher K₂O (~3 wt%) but lower Zr/Y (~2.8) compared to the Daigo-Nishi-Aogashima Knoll (K₂O = ~1.5 wt%; Zr/Y = ~4.4) (Hochstaedter et al., 2001). Although the limited data (5 analyses in total) available for both seamounts preclude reliable geochemical matching with Unit II volcanoclastics, they are potential sources for lapilli in Unit II considering their geographic locations, ages, and chemical composition. Similarly, single clast compositions of Unit IV can be tentatively matched to available data for Manji Seamount volcanic rocks (Figure 7; ~6.5–6.9 Ma; Ishizuka et al., 2002). Two high-K₂O volcanoclastics resemble the high-K Manji Seamount rocks with potassic alteration, whereas most volcanoclastics from Unit IV follow the trend for altered Manji Seamount rocks (Ishizuka et al., 2002), including depletions in CaO with increasing SiO₂ (see Figure F44 of Tamura et al., 2015a). Unit V is primarily tuffaceous mudstone, and given the pervasive alteration throughout this unit, it is difficult to provide an accurate provenance for its volcanoclastic intervals.

The geochemistry of samples from Units VI and VII and igneous Unit 1 does not fall neatly into the rear-arc field, but instead spans both fields (Figure 20), even though a rear-arc source is demanded by the vent-proximal nature of the deposits (described above). One of the goals of Expedition 350 (Tamura et al., 2013) was to determine the

timing of development of geochemical asymmetry between the arc front and rear arc. This is important because dredge samples that were already in hand from Neogene volcanoes of the rear arc were more “continental” in chemical composition than dredge and drill core samples from the arc front, therefore making the rear arc more suitable as a possible building block for continental crust. We presented two models for the development of arc asymmetry: “from the beginning” and “from the middle” (Tamura et al., 2013). The “from the beginning” hypothesis stipulated that arc asymmetry was established at Eocene arc inception and persisted through the Neogene. The “from the middle” hypothesis stipulated that the asymmetry developed during an arc hiatus associated with opening of the Shikoku backarc basin at 27-17 Ma. On the basis of seismic stratigraphy, we expected to reach Oligocene (>23 Ma) strata at 1250 mbsf, to determine which hypothesis was correct, but instead those strata are 9 Ma (Late Miocene; lower part of Unit V), so the chemistry of the Paleogene rear arc remains unknown. However, the compositional heterogeneity of Units VI and VII suggests that arc asymmetry did not develop until after ~13 Ma (Middle Miocene), which is *during* the Neogene, that is, neither “from the beginning” nor “from the middle”.

Depositional Model

The biggest surprise of the expedition was the predominance of tuffaceous mud and the fine grain size of the volcanoclastics at Site U1437. We expected to drill into a volcanoclastic apron (see Scientific Prospectus; Tamura et al., 2013), with abundant large lapilli- to block-sized volcanic clasts that could be geochemically analyzed individually on the ship. This is not what we encountered, but before presenting the depositional

model, it is necessary to define the term “volcaniclastic apron” in order to show how the depositional model for Site U1437 differs from models for volcaniclastic aprons.

Although some may use the term “volcaniclastic apron” to loosely refer to any accumulation of sediment around a volcano or chain of volcanoes, the term has been used in a much more rigorous sense by sedimentologists over the past 40 years (Karig and Moore, 1975b; Sample and Karig, 1982; Carey and Sigurdsson, 1984; Farquharson et al., 1984; Fisher, 1984; Busby-Spera, 1985, 1988; Cas and Wright, 1987; Smith, 1987; White and Busby-Spera, 1987; Houghton and Landis, 1989; Palmer and Walton, 1990; Fisher and Smith, 1991; Fisher and Schmincke, 1994; Smith and Landis, 1995; Orton, 1996; Wright, 1996; Mitchell, 2000; Carey, 2000; Gamberi, 2001; Karátson and Németh, 2001; Allen et al., 2006; Casalbore et al., 2010; Carey and Schneider, 2011). In these papers, a volcaniclastic apron is defined as a thick accumulation of coarse volcanic debris that fringes a volcano or a chain of volcanoes and builds outward from them; volcaniclastic aprons are typically fan shaped or are composed of coalescing fans that form a wedge. They are steep in their proximal reaches, with abundant large lithic blocks and slumps, passing smoothly into medial to distal reaches that have gentler slopes, formed of debris flow and coarse-grained pyroclastic density current deposits. For example, the “volcanic apron” of Gran Canaria (Shipboard Scientific Party, 1995) is a volcaniclastic apron (Funck et al., 1996), consisting of volcano-flank seismically chaotic pillow breccia and hyaloclastite and poorly stratified debris flow deposits, which pass basinward into crudely stratified slump, debris flow, and turbidity current deposits. The submarine flanks of Anahatan Volcano and Northeast Anahatan Volcano (Mariana Arc) are largely mantled with volcaniclastic aprons, which extend 5-20 km from the island of Anahatan;

these have slopes decreasing from 15-25° to 5° with distance, and their outer edge is marked by a distinct break in slope, with abyssal sediment beyond (Chadwick et al., 2005). Volcaniclastic aprons form in both nonmarine and marine environments, and they commonly prograde into basins with time, producing an overall upward-coarsening sequence.

The depositional model for Site U1437 must take account of the fact that it is an entirely deepwater deposit, and using the criteria above, it clearly does not represent a volcaniclastic apron. The depositional model may instead be based on analogies with the other major type of deepwater depositional system, the submarine fans and aprons of siliciclastic deepwater systems. Submarine fans and aprons are relatively coarse grained constructional features, whereas the basin plain beyond is flat and fine grained with laterally continuous deposits (Reading and Richards, 1994; Stow et al., 1996; Richards, 2009). The upper 75% of the section drilled at Site U1437 is analogous to the basin plain; it is a fine-grained, well-stratified sequence with laterally continuous layers. For this reason we refer to it as a deepwater basinal succession, not a volcaniclastic apron.

The lower 25% of the section, in contrast, consists largely of blocky hyaloclastic deposits (Unit VII, 347 m) that cooled in situ with very limited remobilization and thus represent near-vent deposits. It also includes lesser polymict lapilli tuffs (Unit VI, 140 m) sourced from nearby volcanoes but also with rhyolite blocks locally derived from igneous Unit 1 (within Unit VI). Therefore, the lower 25% of the section is dominated by localized vent-related deposits within the deepwater basinal succession. As discussed above, the geochemistry of the lower 25% also differs from the upper 75% of the section.

CONCLUSION: SURPRISES, AND QUESTIONS TO BE ADDRESSED IN SHORE-BASED INVESTIGATIONS

Four surprises resulted from drilling at U1437 that led to questions for ongoing (shore-based) investigation, to be summarized in future papers.

The first surprise is that the section is much more mud-rich than expected for an arc-proximal sedimentary succession. The section as a whole is 60% tuffaceous mudstone, with 89% in the uppermost 433 m, and with high sedimentation rates of 100-260 m/my for the upper 1300 m. What was the source of all that mud, and how was it deposited?

The second surprise is that the grain size of the volcanoclastics is much smaller than expected for an arc-proximal sedimentary succession, composed of half ash/tuff and half fine-grained lapilli tuff. No volcanic blocks are present in the upper 75% of the section. Yet Site U1437 lies downslope, within kms to tens of km, of seamounts dated at 6.86 – 6.53 (Manji), 3.76 Ma (Meoreki) and 5.05 Ma and 0.55 Ma (Daigo-Nishi-Aogashima Knoll) from dredged samples, as shown on Figure 7. This may indicate that most <7 Ma eruptions from the seamounts were small-volume effusions that did not produce much volcanoclastic material. Alternatively, the dredged samples represent late-stage, small volume eruptions that mantle the surfaces on the seamounts, and they were largely built before ~9 Ma.

The third surprise is that the section is much younger than predicted from seismic stratigraphy. For example, Oligocene (>23 Ma) strata were predicted at 1250 mbsf, but instead those strata are 9 Ma (Miocene).

Fourth, it was predicted that compositional divergence between arc-front and rear-arc magmas developed during a volcanic hiatus associated with opening of the backarc basin at 27-17 Ma, if it did not already exist from the time of arc inception in the Eocene (~45 Ma); however, preliminary data presented here suggest that this divergence only fully developed after ~13-14 Ma (Middle Miocene). The cause is not known.

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1322 CAPTIONS

1323 Figure 1 – Tectonic setting of IBM arc (from Taylor, 1992; Tamura and Tatsumi, 2002).
 1324 The IBM arc-trench system forms the convergent margin between the Pacific and
 1325 Philippine Sea plates. Shown here are bathymetric features of the eastern Philippine Sea,
 1326 IBM arc system, and Expedition 350 (Site U1436 in fore-arc and Site U1437 in rear arc)

and Expedition 351 and 352 site locations (EXP). Dashed lines = wide-angle seismic profiles; the north–south seismic profiles (along the present-day arc front and rear arc ~150 km west of the arc front) are shown in Figure 4. Lines of circles = conspicuous north–south rows of long-wavelength magnetic anomalies, attributed to loci of Oligocene magmatic centers by Yamazaki and Yuasa (1998). Site U1436 is on the fore-arc anomaly (fore-arc high/Shin-Kurose Ridge); Site U1437 is on the rear-arc anomaly (Nishi-shichito Ridge). The boundary between the Izu arc and the Bonin arc lies at the Sofugan Tectonic Line, discussed further in Figure 4.

Figure 2 - Wide-angle seismic profile across the Izu arc, with *P*-wave velocities for upper, middle, and lower crust (greens) and for mantle (blues) (Suyehiro et al., 1996). ODP (black) and IODP (red) sites are projected onto this line of section. Site U1437 is the first site drilled in the broad region of long-lived rear-arc seamount chains (shown on Figure 3). ODP Site 791 is also in the rear arc, but it is located in the narrow, young, and active Sumisu rift. Site U1436 and ODP Sites 792, 793, and 786 are in the modern fore-arc basin. BON = boninite, FAB = fore-arc basalt.

Figure 3 - Volcano-tectonic domains within Izu arc. The well-defined arc front is formed by a ~north-south chain of island volcanoes, the largest of which are named here. Arc crust underlies the rear arc, whereas the Shikoku Basin (Figure 1), which forms the western boundary of the rear arc, is floored by oceanic crust. The rear arc is divided into two tectonic zones, from west to east (also oldest to youngest): (1) rear-arc seamount chains (~100 km long; ~17-3 Ma) which trend at a high angle to the arc front and span

the compositional range from basalt to rhyolite, and (2) extensional zone (~100 km wide, <3 Ma), overlapping the eastern half of the rear-arc seamount chains, and characterized by ~north-south normal faults with small bimodal volcanoes (backarc knolls). Along the eastern margin of the extensional zone, immediately behind the arc front, lies a narrow active rift (<1 Ma), with north-south rift basins and bimodal volcanism. Volcanic rocks in the extensional zone and the active rift are referred to as rift-type magmas, and those in the rear-arc seamount chains are referred to as rear-arc seamount chain-type magmas. White stars = Site U1436 (fore-arc) and Site U1437 (rear arc). Box = area of Figure 7.

Figure 4 - Wide-angle seismic profiles (Kodaira et al., 2008) showing middle-crust thickness variations in two transects: one along the arc front and one along the rear-arc Nishi-shichito Ridge; the positions of these lines are shown as lines of circles on Figure 1. The 6.0–6.8, 7.1–7.3, and 7.8 km/s layers (see P wave velocity on key) correspond to middle crust, lower crust, and upper mantle, respectively. Based on variations in middle-crust thickness in these profiles, Kodaira et al. (2008) infer that rear-arc crust was obliquely rifted off the arc front, probably during the opening of the Shikoku and Parece Vela Basins (~25 Ma; Figure 1). Quaternary basalt-dominant island volcanoes on the arc front: Mi = Miyakejima, Ha = Hachijojima, Ao = Aogashima, Su = Sumisu Caldera, To = Torishima; andesite Oligocene volcano east of arc front: Om = Omachi Seamount. ODP Sites 787, 792, and 793 also shown.

Figure 5 - Hot fingers hypothesis of Tamura et al. (2002) proposed for northeast Japan and adapted here for the origin of Izu rear-arc seamount chains. Hypothetically, mantle

convection above the subducting slab produces fingerlike hot regions in the mantle wedge below the rear-arc plate. These hot regions extend toward the arc front with time, suggesting younging of rear-arc seamounts from west to east.

Figure 6 - Two main basin types recognized within arcs, as defined by Smith and Landis (1995). A. Volcano-bounded basin: small, irregular basins between individual volcanoes; larger linear troughs between volcanic chains; and thick basin fill preserved only in oceanic arcs, below sea level. Low areas between the series of rear-arc seamount chains shown on Figure 3 are volcano-bounded basins formed during growth of the chains between ~17 and 3 Ma. Site U1437 is located in one of these volcano-bounded basins, which we refer to as the Enpo-Manji Basin (Figures 7, 8C, 8D). B. Fault-bounded basin: rapidly subsiding basins that are deep (up to 10 km) and have very high sediment accumulation rates (~1 km/My); they are found in continental and oceanic arcs. A fault-bounded basin is currently forming in the <1 Ma active rift west of the Izu arc front (Figure 3). Although the broader zone of extension (<3 Ma) produced faults within the eastern halves of the volcano-bounded basins between the rear-arc seamount chains, including the basin drilled at Site U1437 (some visible on Figures 8C, 8D), the bounding volcanic chains (and not the <3 Ma extensional zone faults) primarily controlled accommodation (Figure 8C).

Figure 7 - Bathymetric maps of rear-arc region behind the arc-front volcanoes (location on Figure 3). (A) Unannotated and annotated bathymetric maps, showing named volcanoes and $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar ages in Ma from Ishizuka et al. (2003b). Age groups:

1396 ~12.5–3 Ma rear-arc basalt to rhyolite seamount volcanoes, <3 Ma bimodal volcanic
1397 rocks in extension zone that overlaps eastern half of the rear-arc seamount chains, and <1
1398 Ma bimodal volcanic rocks of the narrow active rift (Figure 3). Site U1437 lies in a
1399 volcano-bounded basin (Figure 6A) between the Manji and Enpo rear-arc seamount
1400 chains at the foot of flat-topped Manji Volcano, presumably planed by wave action. (B)
1401 Positions of JAMSTEC surveys (Yamashita et al., 2015) shown in Figure 8.

1402

1403 Figures 8 – Three seismic lines, crossing at Site U1437 (Yamashita et al., 2008);
1404 positions plotted on Figure 7B. Line IBr5 is the longest, an ~E-W line that runs from the
1405 Manji rear-arc seamount chain in the west to the arc front in the east. This is shown as:
1406 (A) Line IBr5 OBS: seismic velocity image obtained from wide-angle OBS data, with
1407 OBSs deployed every 5 km along Line IBr5, and (B) Line IBr5 MCS, depth-converted
1408 MCS reflection profile; dashed yellow lines = iso-velocity contours of 5 and 6 km/s
1409 obtained from seismic velocity image in (A), which are interpreted as the depth to
1410 igneous basement (upper crust) and middle crust, respectively. Seismic lines with
1411 interpreted seismic layers are shown in (C) and (D), running transverse to the Enpo-Manji
1412 volcano-bounded basin (C) and along the axis of the basin (D). On (C), the Manji
1413 volcano lies on the northwest, with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 6.86 and 6.53 Ma, and an unnamed
1414 volcano lies on the southeast, with an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 1.96 Ma (see Figure 7). On (D), an
1415 unnamed volcano lies on the southwest, with an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 12.35 Ma; minor
1416 north-northwest faults lie transverse to the volcano-bounded basin, parallel to normal
1417 faults in the broad extensional zone to the east (Figure 3). The north-northwest faults

appear to have been active prior to the deposition of Layer L3 but do not provide the primary accommodation.

Figure 9 – Age-depth model for Site U1437. Shown are shipboard biostratigraphic and magnetostratigraphic datums, and LSR (linear sedimentation rates)/MAR (mass accumulation rates). MARs are calculated using LSR derived from the age-depth model and dry bulk density calculated from shipboard moisture and density (MAD) analyses. MARs of carbonate (CAR) and noncarbonated (nCAR) are calculated by multiplying the MAR by carbonate weight percent, calculated from shipboard coulometry measurements of inorganic carbon weight percent. T = top, B = bottom, X = crossover.

Figure 10 - Summary lithostratigraphic log for Site U1437. The boundary between coarse- and fine-grained volcanoclastics is 2 mm (corresponding to the boundary between ash and lapilli-sized particles). Representative core photos for Lithostratigraphic Units I through VI and Igneous Unit 1 are shown in Figures 11 to 18.

Figure 11 – Unit I, representative core photos and interpretations: (Left pair) 5–10 cm mafic ash intervals with sharp bases and tops grading upward into tuffaceous mud, with mafic ash pods. (Right pair) Evolved tuff intervals grading upward into tuffaceous mud and bioturbation.

Figure 12 – Unit II, core photos and line drawings of closely intercalated monomictic tuff, lapilli-tuff, and lapillistone, showing stratification, cross stratification, and normal

1441 grading. Crystal-rich tuff (1), lapilli-tuff (2), and lapillistone (3) in planar and cross-
1442 bedded intervals.

1443

1444 Figure 13 - Unit III, core photos: (a) Alternating intervals of tuffaceous mudstone,
1445 evolved tuff, and evolved lapilli-tuff. (b) Intercalated white to gray-green evolved tuff,
1446 including soft-sediment deformation. (c) Crystal-rich stratified interval. (d) Fiamme-rich
1447 (with flattened pumice) and (nonflattened) pumice-rich intercalated layers.

1448

1449 Figure 14 - Unit IV: (a) Line scan and schematic drawing showing tuff, clast-supported
1450 polymictic lapilli-tuff, and fine-grained light green tuff lithofacies. (b) Line scan and
1451 schematic drawing of tuff and clast-supported polymictic lapilli-tuff lithofacies. (c) Fine-
1452 grained light green tuff, including: 1. sand-sized tuff with planar stratification, and 2. silt-
1453 sized vitric light green tuff with convolute bedding. (d) Photomicrographs of lapillistone
1454 and lapilli-tuff (plane-polarized light): 1. Lapillistone dominated by plagioclase-phyric
1455 andesite clasts with minor pumice clasts. 2. Lapilli-tuff with pumice clasts and fiamme.

1456

1457 Figure 15 - Unit V: (a) Monomictic reversely graded lapilli-tuff with tuffaceous
1458 mudstone. The lapilli are made of flattened pumice (fiamme) or nonflattened pumice.
1459 Note the erosive base and reverse coarse-tail grading of lapilli, with upward-increasing
1460 tuffaceous mudstone. (b) Annotated line scan of soft-sediment faulting in tuff, Unit V. (c)
1461 Lapilli-tuff and lapillistone: 1. White to light gray lapilli-tuff with large pumice lapillus.
1462 The matrix is composed of glass shards, smaller pumice lapilli, and plagioclase; 2. Clast-
1463 supported dark gray-green lapilli-tuff showing pumice lapilli and volcanic lithic clasts,

plagioclase, and opaques; 3. Clast-supported dark gray-green lapilli-tuff with crystals of pyroxene, plagioclase, and opaques; the large feldspars have visible melt inclusions.

Figure 16 - Unit VI: (a) Clast-supported polymictic lapilli-tuff with subrounded pumice and lithic clasts of rounded mafic and evolved volcanics. (b) Clast-supported polymictic lapillistone with pumice and lithic clasts of subrounded tuffaceous mudstone and evolved volcanics. (c) Stratification in a tuff layer with subordinate fiamme, in macroscopic view, and (d) in microscopic view. (e) Microscopic view of clast-supported polymictic lapilli-tuff. (f) Microscopic view of matrix-supported polymictic lapilli-tuff. (g) Andesite clast with plagioclase, clinopyroxene, and opaques (plane-polarized light). Red box = location of photomicrographs shown in (h) plane-polarized light and (i) cross-polarized light.

Figure 17 - Igneous Unit 1 intrusive rhyolite: (a) Igneous Unit 1 and its intrusive relationship with Unit VI. Only 1.21 m was recovered but its true thickness may be up to 6.50 m (see text). A second interval of similar material lower in the core (labeled “?”) is only 5 cm thick and has no recovered contacts; it was therefore described as a clast (note that similar clasts are described from the host Unit VI). Continued on next page: (b) Upper contact on igneous Unit 1 intrusive rhyolite and relationship with its Unit VI host; for discussion, see text. Photomicrographs of the (1, 2) margin and (3, 4) interior show the chilled upper margin of igneous Unit 1. (c) Peperitic lower contact on igneous Unit 1 intrusive rhyolite.

Figure 18 - Unit VII: (a) Representative photo of 84 m thick nongraded, nonstratified, black glassy lapillistone and lapilli tuff: consists of nonvesicular glass particles with plagioclase and pyroxene phenocrysts and glomerocrysts, with no bubble-wall shards or broken crystals. (b) Plane-polarized light and (c) cross-polarized light photomicrograph of andesite clast containing plagioclase (Plag) and clinopyroxene (Cpx) in a glass groundmass. (d) Plane-polarized light and (e) cross-polarized light photomicrograph of jigsaw-fit and randomly distributed andesite glassy clasts with poorly inflated breadcrust textures. (f) Matrix-supported lapilli-tuff showing clasts with quenched margins and breadcrust texture. (g) Chilled margin around amygdaloidal andesite lithic clast surrounded by lapilli-tuff.

Figure 19 - Petrophysical data from cores (whole-round core section logging, black dots; section half measurements, green crosses; discrete samples, blue crosses) and from downhole logging (red lines). Three holes were cored at Site U1437 (B, D, E) with core recovery shown in the left-most column (black = recovered, white = not recovered). GRA = Gamma Ray Attenuation method. PWC = P-Wave Caliper method. MAD = Moisture And Density method. Log RT = “True resistivity” from downhole logging. Mag. Susc. = magnetic susceptibility. Bulk density estimates from the MAD method used on cores match very well the values obtained with the GRA method in downhole logs. Density values using GRA on cores (black dots) are underestimated because (1) calibration is routinely performed for 66 mm diameter cores (as in Hole U1437B) and not the 58 mm diameter cores of Holes U1437D and E; and (2) core disturbance (gaps, cracks, washouts) result in even lower values. These data are useful for the detection of core

disturbance and they can be partially corrected for a high-resolution density record with some effort. Porosity and P-wave velocity values obtained from cores and from logs match well despite the different methods, tools and scales employed. Magnetic susceptibility values are arbitrary instrument units from both core and downhole detectors and we bring the values to the same scale by multiplying the log values with 10^5 and adding 30. Natural gamma radiation values from cores are in instrument-specific counts/s unit, whereas those from downhole logs are calibrated according to the American Petroleum Institute (API) standard and expressed as gAPI. We chose to bring the core and log records to the same scale by multiplying the core data by 1.4 and adding 8. Technical difficulties prohibited downhole logging in Hole U1437E. Gray lines delineate lithologic unit boundaries (Roman numerals in Lith. Units column). Purple lines (appear as one line) represent the nominally 1.2-m thick igneous unit 1.

Figure 20 - Zr/Y vs. SiO₂ for volcanoclastic and igneous samples from sedimentary Units I–VII and igneous Unit 1 (Site U1437) (below), compared to literature data from Izu arc and from the Izu arc (above). Literature data include: rear arc volcanoes, shown in blue; arc front basalt-dominated island volcanoes with small volumes of rhyolite (R1 type rhyolite), shown in red; and arc front rhyolite-dominant submarine calderas (R2 type rhyolite), shown in black. R1 and R2 rhyolites defined by Tamura et al. (2009). Literature data sources: Tamura et al. (2009), Gill et al. (1994), Bryant et al. (2003), Straub et al. (2003, 2010), Hochstaedter et al. (2001), Ishizuka et al. (2002, 2003a, 2003b, 2006a, 2006b), Machida et al. (2003, 2008), Tollstrup et al. (2010). Samples from Units I through V (upper 1320 m) lie in both the arc front and rear arc fields, consistent with

their fine grain size, which may be distal from sources. In contrast, Units VI and VII (lower 25% of section) are coarse-grained, vent-proximal deposits (see text), and igneous Unit 1 is an intrusion and thus also vent-proximal; however, these plot mainly in the arc front field, despite their position in the rear arc. This suggests that rear arc magmas only fully compositionally diverged after ca. 13 Ma. (Note: One outlier contains anomalously high Zr/Y and is not included in the fields).

Figure 21 - Zr and Zr/Y analyzed by pXRF and ICP-AES for volcanoclastic and igneous samples, Site U1437. Probability curves below depth panels show the relative distribution of Zr and Zr/Y in basalt-dominant island volcanoes from the arc front (including R1 rhyolites), rhyolite-dominant submarine calderas in the arc front (R2 rhyolites), and rear-arc volcanic rocks. Vertical lines = composition of the peaks in the literature data distributions. Ig1 = igneous Unit 1. Data sources: Tamura et al. (2009), Gill et al. (1994), Bryant et al. (2003), Straub et al. (2003, 2010), Hochstaedter et al. (2001), Ishizuka et al. (2002, 2003a, 2003b, 2006a, 2006b), Machida et al. (2003, 2008), Tollstrup et al. (2010).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8A, 8B

Figure 8C, 8D

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

a.

Figure 17 - 1

Figure 17 - 2

a.

f.

Matrix-supported lapilli-tuff and lapillistone

g.

Figure 18

Figure
19

Figure 20

Figure 21