The earliest stage of Izu rear-arc volcanism revealed by drilling at Site U1437, International Ocean Discovery Program Expedition 350

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Abstract
The International Ocean Discovery Program Expedition 350 drilled between two Izu rear-arc seamount chains at Site U1437 and recovered the first complete succession of rear-arc rocks. The drilling reached 1806.5 m below seafloor. In situ hyaloclastites, which had erupted before the rear-arc seamounts came into existence at this site, were recovered in the deepest part of the hole (~15–16 Ma). Here it is found that the composition of the oldest rocks recovered does not have rear-arc seamount chain geochemical signatures, but instead shows affinities with volcanic front or some of the extensional zone basalts between the present volcanic front and the rear-arc seamount chains. It is suggested that following the opening of the Shikoku back-arc Basin, Site U1437 was a volcanic rift zone just behind the volcanic front, and was followed at ~9 Ma by the start of rear-arc seamount chains volcanism. This geochemical change records variations in the subduction components with time, which might have followed eastward moving of hot fingers in the mantle wedge and deepening of the subducting slab below Site U1437 after the cessation of Shikoku back-arc Basin opening.

KEYWORDS
andesite, basalt, IODP, Izu-Ogasawara arc, Miocene, oceanic arc, Pacific plate, rear-arc, slab depth, subduction

1 | INTRODUCTION

The Izu arc (Figure 1a) is a classic oceanic arc characterized by two types of basalt magmas (Tamura et al., 2005, 2007) and bimodal volcanism that produces basalt and rhyolite magmas (Shukuno et al., 2006; Tamura & Tatsumi, 2002), and magma types have been correlated to crustal structures (Kodaira, Sato, Takahashi, Ito et al., 2007; Kodaira, Sato, Takahashi, Miura, et al., 2007; Tamura et al., 2009; Tamura, Sato, Fujiwara, Kodaira, & Nichols, 2016). The Izu arc is also characterized by Miocene rear-arc seamount chains developed at high angle to the arc (Ishizuka, Uto, & Yuasa, 2003; Kodaira et al., 2008; Figure 1b). Despite extensive research carried out in the Izu rear-arc through multiple dredging and remotely operated vehicle sampling expeditions, its magmatic history is poorly known, and it is unclear how and when the Izu rear-arc acquired its continental crust-like composition in terms of trace elements, such as light rare earth element (LREE)-enriched patterns (Tamura et al., 2015b). The rear-arc seamount chain volcanism was active from 12 to 3 Ma (Ishizuka, Uto, & Yuasa, 2003) and one older andesite (17 Ma) has been found in the westernmost Kan'e chain (Ishizuka, Uto, & Yuasa, 2003).
Site U1437 of the International Ocean Discovery Program (IODP) Expedition 350 is located between the Manji and Enpo rear-arc seamount chains. At this site, the recovery of an in situ volcanic succession subsequently covered by > 1400 m of sediments provides the first information on the magmatism before the formation of the rear-arc seamount chains. In this study, we present whole rock chemical compositions collected from the deepest part of the drilling site, which we interpret as not derived from the Izu rear-arc volcanism in its current form. This study thus reveals important information on the previous stage of Izu rear-arc volcanism and on the complexity of arc and rear-arc magmatism.

1.1 Background

The Izu-Ogasawara (or Izu-Bonin) arc crust, south of Honshu Island, Japan, has been formed by arc magmatism related to the subduction of the Pacific plate beneath the Philippine Sea plate. It is an excellent example of the possible formation of juvenile continental crust in an intra-oceanic convergent margin system (Kodaira et al., 2008; Suyehrio, Takahashi, Ariie, & Yokoi, 1996; Tamura et al., 2016; Tamura, Ishizuka, Sato, & Nichols, 2019). Figure 1b shows the present Izu arc system, which consists of three types of volcanic environments: (i) Quaternary arc-front volcanoes that are parallel to the Izu-Ogasawara trench (volcanic front); (ii) Miocene–Pliocene rear-arc seamount chains consisting of volcanoes lying at a high angle (60–70°) to the arc; and (iii) < 2.8 Ma (Ishizuka, Uto, & Yuasa, 2003; Ishizuka, Uto, Yuasa, & Hochstaedter, 1998) bimodal rift-type volcanoes in the extensional zone between the volcanic front and rear-arc seamount chains.

The rear-arc seamount chains have been interpreted to have formed after cessation of seafloor spreading in the Shikoku back-arc Basin at ~ 15 Ma (Okino, Ohara, Kasuga, & Kato, 1999). The seamount chains show a trend toward becoming younger from west to east (Ishizuka, Uto, & Yuasa, 2003). The formation of the seamounts...
chains might be related to compression caused by collision between the southwest Japan and Izu arcs associated with the Japan Sea opening (Bandy & Hilde, 1983; Karig & Moore, 1975), or they might overlie Shikoku Basin transform faults (Yamazaki & Yuasa, 1998). Kodaira et al. (2008) showed that the north–south spacing of rear-arc volcanoes is not linked to the underlying undulating thick and thin crustal structure, suggesting that thick parts of rear-arc crust had been produced in Oligocene before the formation of the Shikoku Basin (25–15 Ma). Another possible hypothesis is that the seamount chains overlie hot regions in the mantle wedge, such as the hot fingers proposed for northeast Japan that intruded into the mantle wedge from west to east (Honda, Yoshida, & Aoi, 2007; Tamura, Tatsumi, Zhao, Kido, & Shukuno, 2002).

IODP Expedition Site U1437 is located in a volcano-bounded basin between the Manji and Enpo rear-arc seamount chains at a depth of 2117 m below sea level, and ~ 90 km west of the arc-front volcano Myojinsho (Figure 1b). Figure 2 shows the age-depth diagram of Site U1437. A seismic reflection profile, showing the nature of the studied units, is presented in Yamashita, Takahashi, Tamura, Miura, and Kodaira (2018). Drilling at Site U1437 reached 1806.5 m below seafloor (mbsf). During the expedition, the recovered rocks were divided into seven lithostratigraphic units from Unit I to Unit VII and one igneous unit (Igneous Unit 1) within lithostratigraphic Unit VI that consists of a peperitic rhyolite intrusion (Tamura et al., 2015b). Overlying volcaniclastic sediments (Units I to Unit VI) were derived from nearby rear-arc and/or distal volcanic front volcanoes (Tamura et al., 2015b; Gill et al., 2018). Magnetic stratigraphy derived from polarity reversals was used down to 1300 mbsf at the base of Unit V, suggesting ~ 9 Ma (Tamura et al., 2015b).

Secondary ion mass spectrometry U–Pb zircon ages obtained from Igneous Unit 1 and Unit VII are (13.9 ±0.2) Ma and (15.4 ±0.8) Ma, respectively (Schmitt et al., 2018). Unit VII records the oldest magmatism discovered during Expedition 350, and it occurred after the end of the adjacent Shikoku back-arc Basin spreading.

2 | MATERIAL AND METHOD

2.1 | Provenance of Unit VII

Unit VII is the deepest portion of Site U1437 from 1460 to 1806 mbsf (Figure 2), and consists of ~ 350 m of relatively homogeneous, coarse-grained, hyaloclastite units. Most hyaloclastites have framework-supported lapilli-size clasts with a wide range in vesicularity (0–80 vol %) and crystallinity (glassy to porphyritic).

Parts of Unit VII are thick monomictic breccia interpreted to be hyaloclastite deposits showing macroscopic textural evidence of quench fragmentation (e.g., quenched concave margins, and emplacement at high temperature). In the lower part of Unit VII, Core Section 70R2 (1721 mbsf) is made of metric domains of very angular, moderately vesicular lava surrounded by jigsaw fit breccia of the same composition, in which alteration pipes occur, all attesting to in situ hyaloclastite. Alteration pipes in Core Section 68R3 (1703 mbsf) suggest another in situ facies. Core Section 59R2 (1623 mbsf) contains numerous coarse, poorly vesicular lava clasts with delicate quench margins, and may also represent in situ facies. Cores 42R to 54R consist of a > 100 m-thick, black, framework-supported, hyaloclastite breccia that broadly grades from being dense clast-dominated to pumice clast-dominated. With the exception of some hydrothermally altered red clasts, the breccia is very homogeneous in type of components and grain size, and is considered monomictic overall. Most of the unit is nonstratified, although its top includes normally graded beds. The presence of stratification attests to at least partial resedimentation, but the overall homogeneity indicates that it is a proximal hyaloclastite facies, with minimal resedimentation involved. These lines of evidence suggest that these are near-vent facies and, therefore, representing magmas emplaced at or at close distance from the drill site.
| Unit: Unit IV | Unit V | Unit VI |
|--------------|--------|--------|
| Sample ID: 6R3W-100/102 | 17R2W-125/127 | 25R3W-54/56 |
| Depth (mbsf): 1119.90 | 1215.99 | 1391.63 |
| Lithology: Lapilli tuff | Lapilli stone | Lapilli |
| Host rock: — | — | Lapilli stone |
| Major element (wt%) by XRF | | |
| SiO₂ | 54.41 | 52.38 | 71.62 |
| TiO₂ | 0.99 | 1.21 | 0.25 |
| Al₂O₃ | 17.00 | 10.27 | 5.03 |
| Fe₂O₃ | 11.66 | 10.42 | 4.95 |
| MnO | 0.18 | 0.13 | 4.50 |
| MgO | 5.03 | 4.95 | 4.25 |
| CaO | 7.46 | 8.50 | 2.97 |
| Na₂O | 1.49 | 1.28 | 1.07 |
| K₂O | 1.63 | 1.24 | 1.07 |
| P₂O₅ | 0.11 | 0.16 | 0.13 |
| Total | 99.95 | 99.74 | 99.82 |
| LOI | 8.10 | 5.95 | 3.42 |
| Trace element (ppm) by XRF | | |
| Ba | 237.3 | 114.1 | 133.7 |
| Ni | 13.2 | 27.9 | 6.4 |
| Cu | 126.3 | 102.5 | 21.6 |
| Zn | 111.8 | 2.9 | 8.2 |
| Pb | 2.9 | 2.8 | 6.5 |
| Rb | 14.0 | 6.6 | 2.1 |
| Sr | 507.4 | 373.0 | 316.3 |
| Y | 24.4 | 26.6 | 16.6 |
| Zr | 57.1 | 113.7 | 316.3 |
| Nb | 0.7 | 2.6 | 11.6 |
| Cr | 13.8 | 21.6 | 6.5 |
| V | 337.8 | 295.2 | 26.6 |
| Trace element (ppm) by ICP-MS | | |
| Sc | — | — | 24.7 |
| Co | — | — | 33.4 |
| Ni | — | — | 27.8 |
| Cu | — | — | 42.9 |
| Rb | — | — | 10.9 |
| Sr | — | — | 359 |
| Y | — | — | 23.3 |
| Zr | — | — | 65.4 |
| Nb | — | — | 2.47 |
| Cs | — | — | 0.21 |
| Ba | — | — | 156 |
| La | — | — | 7.33 |
| Ce | — | — | 17.4 |
| Pr | — | — | 2.39 |
| Nd | — | — | 10.8 |

(Continues)
TABLE 1 (Continued)

| Unit: | Unit IV | Unit V | Unit VI |
|-------|---------|--------|---------|
| Sample ID: | 6R3W-100/102 | 17R2W-125/127 | 21R6W-43/44 |
| Depth (mbsf): | 1119.90 | 1215.99 | 1293.87 |
| Lithology: | Lapilli tuff | Lapilli stone | Lapilli tuff |
| Host rock: | — | — | — |
| Sm | — | 2.85 | — |
| Eu | — | 0.971 | — |
| Gd | — | 3.33 | 4.66 |
| Tb | — | 0.573 | 0.790 |
| Dy | — | 3.83 | 5.14 |
| Ho | — | 0.856 | 1.12 |
| Er | — | 2.65 | 3.40 |
| Tm | — | 0.386 | 0.500 |
| Yb | — | 2.51 | 3.38 |
| Lu | — | 0.386 | 0.521 |
| Hf | — | 1.79 | 2.38 |
| Ta | — | 0.189 | 0.169 |
| Ti | — | 0.192 | 0.074 |
| Pb | — | 9.24 | 5.03 |
| Th | — | 1.410 | 1.300 |
| U | — | 0.528 | 0.519 |

| Unit: | Unit VII |
|-------|---------|
| Sample ID: | 41R4W-129/133 |
| Depth (mbsf): | 1452.11 |
| Lithology: | Lapilli tuff |
| Host rock: | — |
| Major element (wt%) by XRF |
| SiO₂ | 53.22 |
| TiO₂ | 0.97 |
| Al₂O₃ | 18.22 |
| Fe₂O₃ | 10.42 |
| MnO | 0.23 |
| MgO | 7.24 |
| CaO | 7.65 |
| Na₂O | 1.24 |
| K₂O | 0.72 |
| P₂O₅ | 0.16 |
| Total | 100.07 |
| LOI | 6.08 |
| Trace element (ppm) by XRF |
| Ba | n.d. |
| Ni | 40.9 |
| Cu | 118.5 |
| Zn | 108.2 |

(Continues)
| Unit: | Unit VI | Unit VII |
|-------|---------|----------|
| Sample ID: | 41R4W-129/133 | 43R2W-106/112 |
| Depth (mbsf): | 1452.11 | 1461.68 |
| Lithology: | Lapilli tuff | Volcanic block |
| Host rock: | — | Lapilli stone |
| Pb | 6.4 | 2.1 |
| Rb | 8.5 | 2.3 |
| Sr | 161.2 | 208.0 |
| Y | 25.2 | 19.0 |
| Zr | 63.2 | 52.5 |
| Nb | 31.0 | 0.7 |
| Cr | 53.4 | 16.7 |
| V | 283.0 | 342.0 |
| Trace element (ppm) by ICP-MS |
| Sc | — | 22.3 |
| Co | — | 19.6 |
| Ni | — | 9.64 |
| Cu | — | 57.4 |
| Rb | — | 1.34 |
| Sr | — | 190 |
| Y | — | 17.2 |
| Zr | — | 49.6 |
| Nb | — | 0.63 |
| Cs | — | 0.06 |
| Ba | — | 13.3 |
| La | — | 2.94 |
| Ce | — | 8.07 |
| Pr | — | 1.30 |
| Nd | — | 6.74 |
| Sm | — | 2.13 |
| Eu | — | 0.791 |
| Gd | — | 2.77 |
| Tb | — | 0.486 |
| Dy | — | 3.22 |
| Ho | — | 0.692 |
| Er | — | 2.08 |
| Tm | — | 0.303 |
| Yb | — | 2.00 |
| Lu | — | 0.303 |
| Hf | — | 1.49 |
| Ta | — | 0.043 |
| Tl | — | 0.015 |
| Pb | — | 1.88 |
| Th | — | 0.326 |
| U | — | 0.222 |

TABLE 1 (Continued)
| Unit          | Sample ID: Depth (mbsf) | Lithology:                          | Host rock:                          | Major element (wt%) by XRF | Trace element (ppm) by XRF | Trace element (ppm) by ICP-MS |
|--------------|------------------------|-------------------------------------|-------------------------------------|-----------------------------|----------------------------|-----------------------------|
|              | 57R1W-71/75 1603.10    | 1612.25 Volcanic block              | Lapilli stone                       | SiO₂ 52.04                  | Ba 96.0                    | Sc —                         |
|              | 58R1W-34/36 1613.70    | Lapilli                             | Tuff breccia                        | TiO₂ 1.13                   | Ni 21.9                    | Co —                         |
|              | 58R2W-36/38 1623.68    | Lapilli                             | Tuff breccia                        | Al₂O₃ 19.75                  | Cu 85.3                    | Ni —                         |
|              | 59R2W-60/64 1633.42    | Lapilli                             | Lapilli tuff                        | Fe₂O₃ 8.72                   | Zn 110.3                   | Cu —                         |
|              | 60R2W-60/66 1641.22    | Lapilli                             | Tuff breccia                        | MnO 0.15                    | Pb 2.0                     | Rb —                         |
|              | 61R1W-10/14 1695.05    | Volcanic block and lapilli tuff     | Tuff breccia                        | MgO 3.95                    | Rb —                       | Sr —                         |
|              | 66R4W-101/103         |                                     |                                     | CaO 9.50                    | Cr 73.8                    | Y —                          |

(Continues)
### TABLE 1 (Continued)

| Unit:             | Unit VII |
|-------------------|----------|
| Sample ID:        | 57R1W-71/75 | 58R1W-34/36 | 58R2W-36/38 | 59R2W-60/64 | 60R2W-60/66 | 61R1W-10/14 | 66R4W-101/103 |
| Depth (mbsf):     | 1603.10 | 1612.25 | 1613.70 | 1623.68 | 1633.42 | 1641.22 | 1695.05 |
| Lithology:        | Lapilli | Volcanic block | Volcanic block | Lapilli | Lapilli | Lapilli tuff | Volcanic block and lapilli tuff |
| Host rock:        | Lapilli stone | Tuff breccia | Tuff breccia | Lapilli tuff | Tuff breccia | - | - |
| Pr                | —       | —       | 1.38    | —       | 4.00      | —       | —       |
| Nd                | —       | —       | 7.04    | —       | 19.80     | —       | —       |
| Sm                | —       | —       | 2.19    | —       | 5.58      | —       | —       |
| Eu                | —       | —       | 0.805   | —       | 1.87      | —       | —       |
| Gd                | —       | —       | 2.83    | —       | 7.83      | —       | —       |
| Tb                | —       | —       | 0.498   | —       | 1.34      | —       | —       |
| Dy                | —       | —       | 3.26    | —       | 9.33      | —       | —       |
| Ho                | —       | —       | 0.704   | —       | 2.18      | —       | —       |
| Er                | —       | —       | 2.10    | —       | 6.85      | —       | —       |
| Tb                | —       | —       | 0.298   | —       | 0.993     | —       | —       |
| Yb                | —       | —       | 2.03    | —       | 6.49      | —       | —       |
| Lu                | —       | —       | 0.309   | —       | 1.02      | —       | —       |
| Hf                | —       | —       | 1.50    | —       | 2.23      | —       | —       |
| Ta                | —       | —       | 0.044   | —       | 0.079     | —       | —       |
| Tl                | —       | —       | 0.005   | —       | 0.079     | —       | —       |
| Pb                | —       | —       | 1.51    | —       | 1.69      | —       | —       |
| Th                | —       | —       | 0.336   | —       | 0.565     | —       | —       |
| U                 | —       | —       | 0.123   | —       | 0.23      | —       | —       |

### Major element (wt%) by XRF

|          | 57R1W-71/75 | 58R1W-34/36 | 58R2W-36/38 | 59R2W-60/64 | 60R2W-60/66 | 61R1W-10/14 | 66R4W-101/103 |
|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| SiO₂     | 56.87       | 53.32       | 55.91       | 52.94       | 51.34       | 56.49       | 52.44       |
| TiO₂     | 0.95        | 1.09        | 0.96        | 1.05        | 1.30        | 1.07        | 1.14        |
| Al₂O₃    | 16.79       | 18.99       | 18.99       | 21.14       | 19.62       | 18.20       | 19.67       |
| Fe₂O₃    | 9.35        | 9.32        | 8.39        | 7.35        | 10.04       | 8.26        | 9.31        |
| MnO      | 0.22        | 0.20        | 0.20        | 0.16        | 0.21        | 0.22        | 0.17        |
| MgO      | 3.93        | 4.62        | 3.42        | 3.39        | 4.77        | 2.85        | 4.00        |
| CaO      | 5.69        | 6.81        | 7.25        | 9.09        | 8.16        | 7.47        | 9.03        |
| Na₂O     | 5.47        | 5.15        | 4.23        | 4.34        | 4.25        | 4.42        | 3.68        |
| K₂O      | 0.64        | 0.53        | 0.83        | 0.63        | 0.59        | 0.87        | 0.48        |
| P₂O₅     | 0.19        | 0.23        | 0.21        | 0.21        | 0.20        | 0.19        | 0.23        |
| Total    | 100.10      | 100.25      | 100.40      | 100.29      | 100.46      | 100.03      | 100.14      |
| LOI      | 2.49        | 2.64        | 2.30        | 1.51        | 2.55        | 1.68        | 2.33        |

### Trace element (ppm) by XRF

|          | 57R1W-71/75 | 58R1W-34/36 | 58R2W-36/38 | 59R2W-60/64 | 60R2W-60/66 | 61R1W-10/14 | 66R4W-101/103 |
|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Ba       | 86.0        | 108.6       | 79.1        | 61.0        | 98.5        | 123         | 77.0        |
| Ni       | 21.7        | 13.7        | 9.4         | 18.8        | 14.5        | 11          | 10.8        |

(Continues)
| Unit: Sample ID: Depth (mbsf): Lithology: Host rock: | Unit VII |
|---------------------------------------------------|----------|
| 66R5W-97/99 1696.52 | 69R3W-9/11 1712.27 | 70R2W-101/105 1721.42 | 70R4W-129/131 1724.49 | 70R6W-35/37 1726.50 | 71R2W-13/15 1729.91 | 71R2W-69/71 1730.47 |
| Volcanic block Tuff breccia | Volcanic block Tuff breccia | Volcanic block Volcanic breccia | Lapilli Lapilli stone | Lapilli Lapilli tuff | Volcanic block Not recovered | Volcanic block Not recovered |
| Cu | 33.3 | 40.0 | 32.3 | 53.5 | 41.9 | 25.8 | 38.4 |
| Zn | 92.8 | 96.3 | 95.2 | 88.3 | 118.8 | 98 | 89.8 |
| Pb | 2.9 | 3.2 | 1.9 | 3.3 | 1.7 | 1.6 | 3.0 |
| Rb | 8.2 | 5.8 | 8.5 | 6.8 | 6.6 | 8.8 | 5.0 |
| Sr | 220.6 | 262.5 | 276.1 | 296.9 | 280.1 | 257.1 | 338.4 |
| Y | 27.9 | 35.9 | 34.0 | 33.8 | 35.5 | 29.9 | 32.1 |
| Zr | 88.9 | 102.9 | 89.2 | 92.0 | 94.2 | 84.1 | 92.4 |
| Nb | (1.4) | (1.5) | (0.9) | (1.1) | (1.2) | (1.1) | (1.0) |
| Cr | 45.3 | 25.6 | 12.3 | 29.8 | 395.9 | 316.4 | 325.5 |
| V | 234.5 | 278.0 | 251.8 | 296.3 | 39.1 | 35.1 | 35.1 |

Trace element (ppm) by ICP-MS

| Element | Unit VII |
|---------|----------|
| Sc | 26.8 |
| Co | 18.8 |
| Ni | 11.2 |
| Cu | 37.5 |
| Rb | 4.66 |
| Sr | 242 |
| Y | 34.2 |
| Zr | 102 |
| Nb | 1.20 |
| Cs | 0.14 |
| Ba | 116 |
| La | 5.92 |
| Ce | 17.8 |
| Pr | 2.80 |
| Nd | 14.1 |
| Sm | 4.20 |
| Eu | 1.340 |
| Gd | 5.18 |
| Tb | 0.898 |
| Dy | 5.86 |
| Ho | 1.270 |
| Er | 3.83 |
| Tm | 0.568 |
| Yb | 3.80 |
| Lu | 0.582 |
| Hf | 2.96 |
| Ta | 0.085 |
| Ti | 0.041 |
| Pb | 2.89 |

(Continues)
Table 1 (Continued)

| Unit: Unit VII | Sample ID: | Depth (mbsf): | Lithology: | Host rock: |
|---------------|------------|---------------|------------|------------|
|               | 66R5W-97/99| 1696.52       | Volcanic block | Tuff breccia |
|               | 69R3W-9/11 | 1712.27       | Volcanic block | Tuff breccia |
|               | 70R2W-101/105 | 1721.42      | Volcanic block | Breccia |
|               | 70R4W-129/131 | 1724.49      | Lapilli stone | Not recovered |
|               | 70R6W-35/37 | 1726.50       | Lapilli stone | Not recovered |
|               | 71R2W-13/15 | 1729.91       | Lapilli stone | Not recovered |
|               | 71R2W-69/71 | 1730.47       | Lapilli stone | Not recovered |
| Sample ID:    | 72R2W-109/112 | 1740.62      | Volcanic block | Not recovered |
|               | 75R3W-70/72 | 1770.72       | Lapilli stone | Lapilli stone |
| Lithology:    | 1793.60    | 1797.27       | Lapilli stone | Not recovered |
| Host rock:    | 35R1W-123/125 | 1389.34      | Sheet Lapilli tuff, Lapilli stone | Lapilli stone |
|               | 35R2W-44/46 | 1389.97       | Sheet Lapilli tuff, Lapilli stone | Lapilli stone |

Major element (wt%) by XRF

|               | SiO2  | TiO2  | Al2O3 | Fe2O3 | MnO   | MgO   | CaO   | Na2O  | K2O   | P2O5  | Total | LOI   |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sample ID:    |       |       |       |       |       |       |       |       |       |       |       |       |
| Depth (mbsf): |       |       |       |       |       |       |       |       |       |       |       |       |
| Lithology:    |       |       |       |       |       |       |       |       |       |       |       |       |
| Host rock:    |       |       |       |       |       |       |       |       |       |       |       |       |

Trace element (ppm) by XRF

|               | Ba    | Ni    | Cu    | Zn    | Pb    | Rb    | Sr    | Y     | Zr    | Nb    | Cr    | V     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sample ID:    |       |       |       |       |       |       |       |       |       |       |       |       |
| Depth (mbsf): |       |       |       |       |       |       |       |       |       |       |       |       |
| Lithology:    |       |       |       |       |       |       |       |       |       |       |       |       |
| Host rock:    |       |       |       |       |       |       |       |       |       |       |       |       |

Trace element (ppm) by ICP-MS

|               | Sc    | Co    | Ni    | Cu    | Rb    |       |       |       |       |       |       |       |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sample ID:    |       |       |       |       |       |       |       |       |       |       |       |       |
| Depth (mbsf): |       |       |       |       |       |       |       |       |       |       |       |       |
| Lithology:    |       |       |       |       |       |       |       |       |       |       |       |       |
| Host rock:    |       |       |       |       |       |       |       |       |       |       |       |       |

(Continues)
How much transport affected the rest of Unit VII is more ambiguous. Some intervals are clearly graded, stratified, and/or polymictic, attesting to lateral transport and accidental pick-up from the substrate. The provenance of other intervals cannot be assessed with confidence because of poor core recovery. Nevertheless, apart from a few fine-grained intervals, most of Unit VII is made of thick beds of angular, coarse ash-size to lapilli-size hyaloclasts and lava clasts, strongly suggesting that they are derived from sources less than a few hundred meters away, thus not associated with long-distance transport. Most of the analyzed clasts are atypically large (2–42 cm) and dense (non- to moderately vesicular). The provenance of these coarse clasts may be linked to accidental pick-up from the substrate during local avalanching of the hyaloclastites, or they may represent in situ subsurface intrusive hyaloclasts. The large range in textures shown in these clasts therefore makes them representative of a broader region upslope (hundreds of meters to a few kilometers), and not only derived from a single locality or vent. Large chemical variations of clasts from Unit VII are consistent with this provenance model.

2.2 | Samples and methods

Samples were selected from Unit IV to Unit VII of Site U1437 (Figure 2; Table 1). The cores are overall green in color, suggesting low-grade burial metamorphism (Tamura et al., 2015b). Samples from Unit VII
were collected between 1461 and 1799 mbsf. Two samples (42R4W-106/112 and 61R1W-10/14) are lapilli tuff in grain size, following the onboard classification (Tamura et al., 2015a). The other 23 samples are made of individual volcanic clasts (lapilli to block in size); the single dense clasts are part of clast-supported or matrix-supported, polymictic (lava and fiamme) breccia. Most clasts have phenocrysts of pyroxene and/or feldspar; three (58R1W-34/36, 58R2W-36/38, and 69R3W-9/11) have additional amphibole as phenocrysts. Samples from Unit VI were collected between 1391 and 1453 mbsf. One (41R4W-129/133) is lapilli tuff in grain size (Tamura et al., 2015a), and others are individual volcanic clasts (lapilli in size). Igneous Unit 1 is a peperitic rhyolite intrusion, and samples were collected for analyses from 1389.34 and 1389.97 mbsf. Samples from Unit V were collected between 1215 and 1294 mbsf. One (17R2W-125/127) is a lapilli stone in grain size, and other three are lapilli tuff (Tamura et al., 2015a). Sample from Unit IV is a lapilli tuff collected from 1119.9 mbsf.

### 2.3 Sample preparation

Rocks were sawn and polished to extract individual clasts. These clasts were crushed into pebble sizes (5–10 mm) and soaked in plenty of water. The water was allowed to percolate through the rock samples for several days before being filtered and analyzed. The results of these analyses are summarized in Table 2.

### Table 2 Result for standard rock (JB-2) compositions

| Element | This study (XRF, n = 2) | This study (ICP-MS, n = 2) | Imai et al. (1995) | Chang et al. (2003) |
|---------|-------------------------|-----------------------------|--------------------|--------------------|
| Zn      | 114.3                   | 108                         | —                  | —                  |
| Cr      | 24.2                    | 28.1                        | —                  | —                  |
| V       | 589.7                   | 575                         | —                  | —                  |
| Sc      | —                       | 51.2                        | 53.5               | —                  |
| Co      | —                       | 36.7                        | 38                 | —                  |
| Ni      | 12.8                    | 14.0                        | 16.6               | —                  |
| Cu      | 225.6                   | 220.3                       | 225                | —                  |
| Rb      | 7.4                     | 6.11                        | 7.37               | 6.91               |
| Sr      | 174.6                   | 169                         | 178                | 182.6              |
| Y       | 21.2                    | 21.5                        | 24.9               | 23.3               |
| Zr      | 43.5                    | 45.8                        | 51.2               | 49.8               |
| Nb      | 0.5                     | 0.46                        | 1.58               | 0.510              |
| Cs      | —                       | 0.77                        | 0.85               | —                  |
| Ba      | 206.9                   | 213.0                       | 222                | 215.5              |
| La      | —                       | 2.15                        | 2.35               | 2.14               |
| Ce      | —                       | 6.28                        | 6.76               | 6.37               |
| Pr      | —                       | 1.10                        | 1.01               | 1.09               |
| Nd      | —                       | 6.1                         | 6.63               | 6.13               |
| Sm      | —                       | 2.16                        | 2.31               | 2.21               |
| Eu      | —                       | 0.784                       | 0.86               | 0.803              |
| Gd      | —                       | 3.09                        | 3.28               | 3.06               |
| Tb      | —                       | 0.562                       | 0.6                | 0.557              |
| Dy      | —                       | 3.83                        | 3.73               | 3.83               |
| Ho      | —                       | 0.835                       | 0.75               | 0.832              |
| Er      | —                       | 2.51                        | 2.6                | 2.53               |
| Tm      | —                       | 0.364                       | 0.41               | 0.368              |
| Yb      | —                       | 2.43                        | 2.62               | 2.49               |
| Lu      | —                       | 0.371                       | 0.4                | 0.376              |
| Hf      | —                       | 1.48                        | 1.49               | 1.50               |
| Ta      | —                       | 0.029                       | 0.13               | 0.043              |
| Tl      | —                       | 0.031                       | 0.042              | —                  |
| Pb      | 4.65                    | 4.98                        | 5.36               | 5.48               |
| Th      | —                       | 0.249                       | 0.35               | 0.282              |
| U       | —                       | 0.150                       | 0.18               | 0.163              |

Abbreviations: —, no data; ICP-MS, inductively coupled plasma-mass spectrometry.
of slowly flooded hot water of ~ 40 °C for 2 weeks. Then, these clasts were put into a glass beaker with distilled water, which was boiled in a microwave oven. The addition of fresh distilled water and boiling were repeated until an addition of silver nitrate solution stops to precipitate silver chloride. After the desalinization, all samples were washed with pure water and acetone using an ultrasonic cleaner. Coarse samples were pounded in an iron mortar, and altered pieces were removed by hand picking as much as possible. All samples were pulverized using a polycarbonate tube and alumina rod.

### 2.4 | Major and trace element analyses

For analysis of major elements, a mixture of 0.4 g of sample powder and 4 g of Li2B4O7 was fused and vitrified. This glass bead was analyzed using a Rigaku Simultix 12, X-ray fluorescence (XRF) analyzer, following the method of Tani, Kawabata, Chang, Sato, and Tatsumi (2006). Accuracy and reproducibility for major elements are better than 1 % and better than 2 % relative standard deviation (2 standard deviation), respectively.

The concentrations of Ba, Ni, Cu, Zn, Pb, Rb, Sr, Y, Zr, Nb, Cr, and V were measured using pressed powder pellets and a Rigaku RIX3000 (XRF), following the method of Goto and Tatsumi (1996). For selected seven samples from Unit VII, Unit V, and Igneous Unit 1, the concentrations of 31 trace elements (including rare earth element [REE]) were determined by inductively coupled plasma-mass spectrometry (ICP-MS) using an Agilent 7500ce (Agilent Technologies, Santa Clara, California). Rock powders were digested in a HClO4/HF mixture. After reaching dryness, the samples were dissolved in 2 % HNO3 with trace HF. Indium and bismuth were added as internal standards (Chang, Shibata, Shinotsuka, Yoshikawa, & Tatsumi, 2003). Oxide and hydroxide interferences were subtracted from the peaks of Eu and Gd. The concentrations of Y, Zr, Ho, Er, Tm, Yb, Lu, Hf, and Th from the sample of Igneous Unit 1 were measured using alkali fusion for decomposition because of the presence of zircon (Senda, Kimura, & Chang, 2014). The analytical results of well-established reference standard (JB-2) agreed very well with recommended values by Imai, Terashima, Itoh, and Ando (1995) and Chang et al. (2003), demonstrating that trace element determinations had high accuracy. Results for standard
rock sample (JB-2) are presented in Table 2. We focus mainly on Units VII and V, in the following chapters.

3 | RESULTS

Major and trace element concentrations in the samples from Unit IV to Unit VII (Figure 2) are presented in Table 1 and shown in Figures 3–6. Several samples of Unit VII had anomalously high MnO and/or P2O5, indicating the possibility of secondary alteration; therefore, in the following discussion of major elements, we excluded the samples with more than 0.3 wt% of MnO and/or 0.4 wt% of P2O5 (43R2W-98/101, 59R2W-60/64, 60R2W-60/66, 75R3W-70/72, and 78R1W-129/131). Major elements in the following discussion have been normalized to 100 % on a volatile-free basis with total iron calculated as FeO.

Variation diagrams of wt% SiO2 vs major element oxides (wt%), total alkali, Mg values (100 Mg/[Mg + ΣFe]), and Zr/Y ratio are shown in Figure 3. All but three with rhyolitic composition show a broad trend, with a narrow SiO2 (49–58 wt%), mostly ranging from basalts to andesites but having three basaltic trachyandesites and two trachyandesites in the SiO2 vs (Na2O + K2O) plot after Le Maitre (2002) (Figure 3). These samples also plot in low- to medium-K fields in the SiO2 vs K2O plot of Gill (1981) (Figure 3). Many of Unit VII samples are low-K basalts and andesites, which are different from medium-K rocks of rear-arc seamount chains. Mg numbers of basalts and andesites range from 31 to 59, and they are plotted both in the calc-alkaline and tholeiitic fields of Miyashiro (1974) (Figure 3). Four samples from Unit V are plotted in the tholeiitic field, but samples from Unit VII range from tholeiitic to calc-alkaline fields, which variation is often observed in the respective arc volcanoes. Many samples from Unit VII have higher Al2O3 and lower FeO* than four samples of Unit V, and these characteristics are similar to volcanoes of the Oligocene volcanic front (Tamura et al., 2010).

Two samples from Unit V have high K2O contents (1.26 and 1.38 wt%) and have LREE-enriched patterns similar to those of the rear-arc seamount chain basalts (Figure 4a). REE patterns of selected eight samples from Unit VII are flat or concave with a maximum at Nd, and are neither similar to the LREE-enriched rear-arc seamount chains, nor to the LREE-depleted Quaternary volcanic front basalts (Figure 4b). Kinan Escarpment basalts, which had erupted at the Shikoku Basin, southwest of the Izu arc (Figure 1a), have distinctive Ce anomalies (Figure 4b), which are also different from that of Unit VII. Recent extensional zone basalts have relatively gently sloped patterns but are more enriched in LREE compared to heavy rare earth element (HREE) and are different from those of Unit VII (Figure 4b).

Figure 5 shows N-mid-ocean ridge basalt normalized incompatible element patterns for Unit V, Igneous Unit 1, and Unit VII. The differences between Unit V and Unit VII are clearly shown in these trace element patterns. HREE contents of Unit V overlap those of Unit VII, but Nb and Ta contents are much more depleted in Unit VII than in Unit V. Such strong and weak depletions of Nb and Ta were observed in Pagan volcano of Mariana volcanic front and northwest Rota-1 volcano.
of Mariana rear-arc, respectively (Tamura et al., 2014). Thus, in terms of the negative anomalies of Nb and Ta, Unit VII and Unit V are similar to the volcanic front and the rear-arc, respectively. Interestingly, Igneous Unit 1 is rhyolitic in composition, and its incompatible elements are generally lower than in basalts and basaltic andesites of Units V and VII. Igneous Unit 1 is highly depleted in Sr and Ti in particular (Figure 5).

4 | DISCUSSION

4.1 | Volcanic front vs rear-arc

The geochemical differences between volcanic front and rear-arc volcanoes could be related to spatial variations in subduction components within the subducting plate, which were added at different depths in the overlying mantle wedge during subduction before or during its melting (Ishizuka et al., 2006; Ishizuka, Taylor, Milton, & Nesbitt, 2003; Tamura et al., 2007; Tamura et al., 2014). The mantle...
wedge might also have variations resulting from hot and low-velocity mantle materials (hot fingers; Tamura et al., 2002) intruding into the mantle wedge. In this scenario, the magma is first extracted beneath the rear-arc and then extracted again as the depleted mantle moves toward the volcanic front where it is fluxed by fluids from the slab (Hochstaedter et al., 2000; Hochstaedter et al., 2001). The geochemical signature of the generated magmas reflects the subduction components and the original mantle wedge (Hochstaedter et al., 2001; Straub, Woodhead, & Arculus, 2015; Tollstrup et al., 2010). Tamura et al. (2014) found that these distinct subduction components generate two primary magmas at the single volcanic front volcano of Pagan, Mariana arc, and suggested that these two subduction components can exist separately, because the hydrous fluid is a hydrous carbonate, which is immiscible with a silicate melt (sediment melt) (Tamura et al., 2014).

In summary, the volcanic front and rear-arc magmas are generated through partial melting of the underlying mantle wedge that contains different subduction components from the subducting slab. The dominant subduction component beneath the volcanic front is a hydrous fluid, whereas it is a sediment melt beneath rear-arc volcanoes. However, as mentioned above, a sediment melt could also coexist with a hydrous fluid beneath the volcanic front. In that case, the subduction component at the volcanic front could be characterized by diverse proportions of silicate melts and hydrous fluids derived from the subducting plate, whereas the hydrous fluids are seldom in the rear-arc.

Diagrams a, b, and c in Figure 6 show Ba/La vs La/Sm, Th/Yb vs Nb/Yb, and Ba/Th vs Th/Nb of selected Unit V and Unit VII samples. Ba/La and Ba/Th, and La/Sm and Th/Yb are proxies of subduction components that could represent H2O-dominant fluids and sediment melts, respectively (Hochstaedter et al., 2001; Pearce, 2008). Samples from the Quaternary volcanic front (< 55 wt% SiO2) have high Ba/La and Ba/Th ratios, suggesting that their subduction components are fluid dominated. Lavas from the rear-arc seamount chains (< 55 wt% SiO2) have relatively higher La/Sm and Th/Yb and lower Ba/La and Ba/Th ratios, suggesting subduction components that are dominated by sediment melts. REE patterns of the volcanic front and the rear-arc are consistent with this (Figure 4a); the LREE-enriched patterns of the rear-arc partly reflect sediment melts that can transport REE. Unit V samples show a rear-arc affinity, but Unit VII samples show a wide range of Ba/La and Ba/Th and La/Sm are higher than Quaternary volcanic front. La/Sm values of Unit VII are similar to values of Oligocene volcanic front (Tamura et al., 2010), and the strong depletion of Nb and Ta compared to heavy REE in Unit VII are also similar to the volcanic front (Tamura et al., 2010).

4.2 Geochemical comparison with other volcanic areas near Site U1437

Samples from Site U1437 are compared to volcanic rocks from the middle part of the Izu arc in Figures 4 and 6. Selected Unit V lapilli tuff have REE patterns and subduction components that are similar to the rear-arc seamount chains (Figures 4a and 6), and the ~8 Ma stratigraphic age of these samples (Figure 2) corresponds to the radiometric age of nearby rear-arc seamount chain volcanoes (Ishizuka, Uto, & Yuasa, 2003). This indicates that these Unit V samples have been reworked from neighboring rear-arc seamounts at ~8 Ma.

Unit VII samples have flat patterns or concave REE patterns with a maximum at Nd (Figure 4b). Some of the extensional zone basalts (Tollstrup et al., 2010) between the volcanic front and the rear-arc seamount chains have concave REE patterns with a maximum at Nd (Figure 4c). Their low Ba/La and La/Sm ratios also are similar to some of Unit VII (Figure 6). Extensional zone basalts are related to rifting within the Izu arc. They have been influenced by subduction components depending on the distance from the volcanic front (Hochstaedter et al., 2001).

The Kinan Escarpment is the boundary between the central part (19–15 Ma) and the eastern part (23–19 Ma) of the Shikoku Basin recognized by magmatic anomalies (Okino, Shimakawa, & Nagaoka, 1994). Kasuga and Ohara (1997) propose that this escarpment is a large normal fault that formed soon after the back-arc spreading ceased (15.69–11.8 Ma; Ishizuka, Yuasa, Taylor, & Sakamoto, 2009). Kinan Escarpment basalts (Ishizuka et al., 2009) have negative Ce anomalies (Figure 4d), which are different from Units V and VII. In the eastern part of the Shikoku Basin, there is additional post-spreading volcanism, that is, the East Shikoku Basin seamounts (14.39–11.04 Ma; Ishizuka et al., 2009). Ishizuka et al. (2009) show that these seamounts have a slab signature similar to that of the rear-arc seamount chains.

The wide variations in Ba/La and Ba/Th in Unit VII lavas (Figure 6) suggest the transient nature of fluid addition from the subducting plate, which might represent a prologue to a renaissance of active arc volcanism in the Izu-Ogasawara arc.

4.3 The early Izu rear-arc magmatism

The rear-arc seamount chain-type volcanism occurred at about 17–8 Ma in the western part of this broader zone (i.e. East Shikoku Basin seamounts and the westernmost seamounts of the chains), and migrated to the eastern part of the chains over time during 8–3 Ma (Ishizuka et al., 1998; Ishizuka et al., 2009; Ishizuka, Uto, & Yuasa, 2003). Ishizuka et al. (2009) propose that this migration was caused by steepening of the subducting slab. At Site U1437, volcanic front and/or rift-type magmatism (Unit VII) is overlain by sediments from the rear-arc seamount chain-type magmatism (Unit V). The difference between Units VII and V indicates a temporal change of the subduction components, and supports the slab steepening hypothesis. Moreover, intrusions of hot fingers into the mantle wedge could play an important role in the genesis of arc volcanoes (Tamura, 2003; Tamura et al., 2002). It may be possible that eastward intrusions of hot fingers into the Izu-Ogasawara arc mantle wedge at about 17–15 Ma had restarted arc volcanism after the vigorous volcanism that accompanied the opening of the Shikoku and Parece Vera Basins. The subducting slab might have been shallower immediately after the cessation of the Shikoku
Basin opening (Figure 7a), and followed by intrusion of hot fingers into the mantle wedge. The slab steepened with time, resulting in a trench-ward migration of the volcanic front, accompanied by extensional zone volcanism and rear-arc seamount chain-type volcanism (Figure 7b).

5 | CONCLUSIONS

Drilling at Site U1437 in the IODP Expedition 350 has revealed temporal and spatial changes of magmatism in the Izu rear-arc. The geochemical characteristics of the hyaloclastites in Unit VII, the deepest part of the hole, represent the early arc magmatism (16–15 Ma) after the opening of the Shikoku Basin. These hyaloclastites reflect proximal submarine vents facies. Unit VII does not contain a rear-arc signature in terms of major element compositions and REE patterns. Instead, strong Nb and Ta depletions are similar to the composition of the volcanic front. The composition of Unit VII is similar to the Oligocene volcanic front in terms of major elements, and/or Pliocene to recent extensional zone basalts. The difference in rock composition between Units VII and V suggests intrusion of hot fingers in the mantle wedge and steepening of the subducting slab below Site U1437 after the formation of the Shikoku Basin.

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