4D volcanic geology of Hachijo-jima islet, Izu-Bonin arc

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ABSTRACT
This study combines detailed geologic mapping, tephrochronology, U-Pb zircon dating, and published drill core data to evaluate the time transgressive 3-dimensional (thus 4-dimensional) structure and evolution of the two volcanoes on Hachijo-jima of the juvenile Izu-Bonin intra oceanic arc. The regional Ata-Torihama tephra (Ata-Th; 0.24 Ma) and Kikai-Tozurahara tephra (K-Tz; 0.095 Ma) from Kyushu are intercalated within the voluminous proximal volcanic products. The silicic tuff cover of some supra-subduction zone ophiolites, that formed in a nascent arc setting, may be ancient analogs of the regional tephra derived from the adjacent but mature volcanic arc. The volcanic succession comprises submarine volcanic basement, marine volcaniclastic rocks, and terrestrial tuff intercalated with tholeiitic basalt and the exotic calc-alkaline tephra layers. The undissected Hachijo-Fuji stratovolcano (tholeiitic basalt) overlies marine volcaniclastics abutting the northwestern paleo sea cliffs of the older dissected volcano, Mihara-yama. Newly-described folding and normal faulting of the marine and overlying terrestrial volcaniclastic rocks record NW-SE shortening that may be associated with the collision of the Izu-Bonin arc with the Honshu arc, analogous to the NNE-SSW shortening observed for the Troodos ophiolite. The proto Hachijo-jima volcano emerged above the sea >0.24 Ma, and this date can be applied as a molecular biological calibration date for organisms on this island.

1 Introduction
Volcanic arcs are among the fundamental geotectonic environments on Earth, and studies of them provide information on plate tectonic mechanisms and history, as well as igneous processes. Whereas most research of volcanic arc geology has focused on petrology, geochemistry, and geochronology of the igneous rocks (e.g. Ewart et al. 1998), important new insights into tectonic and igneous processes can be gained by analytical research integrated with detailed geologic mapping (e.g. Buchs et al. 2010; Nye et al. 2017; Farris et al. 2017; Busby et al. 2018).

Detailed geologic mapping where available and subsurface data provide a necessary foundation for geochemical and geochemical studies of volcanic arcs. Details of volcanic arc evolution allow assessment of fundamental geologic features and tectonic processes, such as volcanostratigraphy and structural evolution of volcanic arcs approaching arc-arc collisions (e.g. Montes et al. 2012, 2015). Detailed field-based studies of modern oceanic volcanic island arcs also provide guidance for interpretation of island arc rocks in orogenic belts, including ophiolites interpreted as having formed in arc settings primarily on the basis of geochemical and petrologic data (supra-subduction zone ophiolites, e.g. Stern and Bloomer 1992; Shervais 2001; Pearce 2003; Meffre et al. 2012; Whattam et al. 2020). This specific research also provides information on emergence time of intra oceanic volcanic islands, which is useful for studies of evolution of endemic species that populate such islands by dispersal, including the South Aegean volcanic arc and the other Aegean islands behind the non-volcanic Hellenic arc (Papadopoulo et al. 2010; Note that their calibration date of Miocene should be revised to the Quaternary date following Guillon et al. 2014), the Hawaii hotspot islands (e.g. Bacon et al. 2012), and the Galápagos hotspot after 139 Ma (Heads and Grehan 2021). Although the present survey is only for a single island, there are few global examples for which the ages of physical emergence or isolation of environments have been geologically determined (Ryukyu continental arc, Osozawa et al. 2012a, Osozawa et al. 2015, 2017a; -2017c, 2021.

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and others; Panama continental arc; Buchs et al. 2019), so just a single age of this sort is of potential global importance.

2. Regional setting and background

From east to west, Izu-Bonin oceanic arc consists of the Bonin ridge that constitutes a fore-arc high, the Ogasawara trough that forms a fore-arc or intra-arc basin, the Izu volcanic arc, and the Shikoku back-arc basin (Tamura et al. 2015; Figure 1a). The Izu volcanic arc is a Quaternary volcanic island chain lying largely below sea level, with some subaerial volcanoes, including some that have produced historic eruptions, such as the recent Nishino-shima eruptions (Tamura et al. 2016, 2019; websites Japan Coast Guard: https://www1.kaiho.mlit.go.jp/GIJUTSUOKOKUSAI/kaikiIDB/kaiyo18-e1.htm). Because of the extremely low K content of tholeiitic basalt and young age, reliable K-Ar and Ar-Ar dates have been difficult to obtain for the young volcanoes of this arc, so the age of much of the volcanic rocks making up this arc has remained uncertain.

The Izu-Bonin arc has long been considered a modern analog for various components of orogenic belts, including ophiolites with arc petrologic-geochemical signatures (e.g. Stern and Bloomer 1992; Shervais 2001; Pearce 2003; Whattam and Stern 2011; Ishizuka et al. 2006, 2011; c.f., Tamura et al. 2016). Osozawa et al. (2012b) showed that the trace element and REE patterns of tholeiitic basalt from the well-known Troodos ophiolite of Cyprus overlaps arc tholeiite of the O-shima basalt locality JB-2 (O-shima location in Figure 1a) of the Izu-Bonin arc, and the Troodos ophiolite boninite is comparable to the type boninite of the Bonin islands. Whereas petrologic and geochemical studies have contributed much to knowledge of the Izu-Bonin island arcs, detailed field studies are also important to understand both the evolution of this specific arc and to provide more robust comparisons to field relationships observed in ancient orogenic belts.

The trench-trench-trench triple junction exists to the east of the northern Izu volcanic arc (Figure 1a), and the Izu arc is presently with the central Japan arc at the triple junction. This collision formed the post-15 Ma southern Fossa Magna outboard (trench ward and SSE ward) of the pre 15 Ma Shimanto accretionary prism shortly after the back-arc spreading of the Japan Sea and the Shikoku basin (Osozawa 1988). Uplift resulting from the collision built the Japan Alps, uplifted an ENE edge of the Nankai trench above sea level, accreted volcanic materials that form the Izu Peninsula (proto volcanic island; Hoshi 2018, Figure 1), and generated the Zenisu ridge as a zone of NNW-SSE intra-plate shortening (Le Pichon et al. 1987; Figure 1a).

In addition, the Izu-Bonin oceanic islands provide important information constraining dispersal time and the consequent vicariant speciation of various animals and plants that inhabit them. Any terrestrial species on such islands must have originally arrived from other land masses through flight or rafting, so the emergence date of the island is critical to calibrate their phylogeny and evolution (Osozawa et al. 2016). Until this study, information on the emergence ages of volcanic islands in the Izu-Bonin arc have been lacking. We have successfully applied the presently obtained emergence date (start of vicariance) of $>$0.25 Ma to the phylogeny of endemic cicadas on the Izu-Bonin oceanic islands (Osozawa et al. 2021).

Our study focuses on the geology of the Hachijo-jima volcanic island, of the northern Izu volcanic arc (Figure 1b; Figure 2). The island consists of a dissected older Mihara-yama volcano (Figure 1d–d') and a younger, non-dissected Hachijo-Fuji volcano (Figure 1c–c'). The non-dissected Hachijo-kojima (kojima = small island) volcano lies offshore and west to the Hachijo-Fuji volcano (Figure 1b). Although dissection of the Mihara-yama volcano is extensive (Figure 1 d–d'), previous studies on this volcano (Isshiki 1959; Tsukui et al. 1991, 1993; Suga 1994, 1998; Suga et al. 1997; Sugihara 1998) were based primarily on aerial photo interpretation. The geological map by Sugihara and Shimada (1998) for the younger Hachijo-Fuji volcano appears to be inconsistent with field relationships recorded by detailed geologic mapping of the outcrops. In addition, the recently published geological map by the Geological Survey of Japan (Ishizuka and Geshi 2018) is a compilation of the above-referenced studies, so it also lacks a detailed field geologic foundation such as sample locations, photo locations, outcrop descriptions, modes of occurrence (of volcanic rocks), strike and dips of volcanic strata, and stratigraphic relationships.

The dissection of Mihara-yama volcano (Figure 1d–d') allows evaluation of internal structure and surface geologic relationships. In contrast, internal structure of a young active volcano such as Hachijo-Fuji volcano (Figure 1c–c') cannot be observed in surface geologic investigations alone. Core data from kilometer-deep eight borings (Figures 2 and Figures 3) are available as a result of extensive investigations for geothermal potential reported by NEDO (1993). Such subsurface data is seldom available for a volcano, and the data facilitates characterization of the three-dimensional (3D) structure of the stratovolcano. This structure and stratigraphy is tied to time by K-Ar ages of 2.27 ± 4.07 Ma.
Figure 1. (a) Index map of the Izu-Bonin arc (base map from Vector Map Level 0, National Geospatial-Intelligence Agency). (b) Vector map of Hachijo-jima (base map from Search by Map Area, Gateway to Astronaut Photography of Earth – NASA). (c–c’) Paired aerial photo of the Hachijo-Fuji volcano, not dissected. (d–d’) Aerial photo of the Mihara-yama volcano, severely dissected by post-eruptive erosion. Note that U-shaped deep valley and ridge is not a normal fault scarp of caldera, and the northeastern ridge is not a somma. The original volcanic geomorphology (stratovolcano) is not preserved as a result of significant erosion. Digital images of c–d’ from the Geospatial Information Authority of Japan.
Figure 2. Geological map of Hachijo-jima. Numbered sites: bore holes by NEDO (1993). A-B-C, D-E, F-G: cross sections. Background: Digital topographic maps of 1: 25,000 scale, the Geospatial Information Authority of Japan.
from the submarine basement basalt and $0.22 \pm 0.06 \text{ Ma}$ from a terrestrial marker basalt horizon (NEDO 1993), and $2.12 \text{ Ma}$ from a fragment in marine volcaniclastic rocks derived from the submarine basement basalt (Kaneoka, 1970), and marine micropaleontological data giving biostratigraphic ages of $<1.8 \text{ Ma}$ for marine volcaniclastic rocks above the submarine basement (beneath the terrestrial tuff), and $<0.26 \text{ Ma}$ for marine volcaniclastic rocks of the Hachijo Fuji basement (NEDO 1993) (see compilation ages in Figure 3).

The NNW-SSE trending Izu-Bonin arc intersects the ENE-WSW trending southwest Japan arc as a consequence of arc-arc collision, and the prevailing west winds (westerlies) can transport volcanic ashes from the supervolcanoes in Kyushu (Japan arc) toward the Hachijo-jima volcanic island of the northern Izu-Bonin arc. A regional tephra interpreted as the 0.0275 Ma Aira-Tn tephra from the Aira caldera, southern Kyushu (Machida and Arai 2003; See relevant regional tephra list in Supp.Table 1) was reported from the Mihara-yama succession with multiple $^{14}$C dates younger than 0.03 Ma (Sugihara 1998). This finding by Sugihara (1998) was attractive, but the senior author was skeptical that regional silicic tephra derived from 900-km-away was intercalated in the proximal volcanic successions including voluminous and visually similar silicic pumice fragments derived from the Mihara-yama volcano. In addition, preliminary field observations showed that the tephra clearly constituted two distinct layers at two distinct stratigraphic horizons instead a single layer within the Mihara-yama scoria-pumice tuff successions as previously stated by Sugihara (1998). We conducted detailed geological analyses to better constrain stratigraphic relationships including tephra(s) (Figure 1b); such analysis was lacking in Sugihara (1998).

Regional tephras in Japan were documented by Machida and Arai (2003), including the distribution and source caldera, shape of glass shards, refractive index, and mineral composition (Supp.Table 1). Note that the Aira-Tn (AT) tephra was named on the basis of its origin from the Aira caldera and the type locality of the tephra Tn (Tanzawa mountains) for example (Supp.Table 1), although this ‘dual’ naming by Machida and Arai (2003; in Japanese) does not follow the International Stratigraphic Guide. A data table summarizing the regional tephras that potentially correlate to those on Hachijo-jima (Supp.Table 1) was constructed combining fission track dating (Danhara 1995), drill core descriptions (Yoshikawa and Inouchi 1993), correlation to the oxygen isotopic curve (Ikehara et al. 2006) and other data. Such regional data, however, should be continually updated with geochronological and other data. We conducted laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) U-Pb dating on zircons from the glassy tuffs (tephras) intercalated in the terrestrial strata of the Mihara-yama volcano to provide more robust chronologic correlations.

3. Methods
3.1. Morphological and volcanic geological survey

The three-dimensional (3D) characteristics of the topographic surface can be evaluated with 1:25,000 scale topographic maps (Figure 2 background) and aerial photos (Figure 1c–d) offered by the Geospatial Information Authority of Japan. The relative time relationships of topographic evolution and volcanic deposition, including volcanic development of the Mihara-yama and Hachijo-Fuji volcanoes can be observed by dual examination of the topography and imagery.
The Mihara-yama volcano has been severely dissected significantly altering the geomorphology of the original edifice (cf., Isshiki 1959; Sugihara 1998; Suga 1998). Whereas this erosional dissection destroyed the original edifice shape (Figure 1d–d'), it facilitates detailed field geologic investigation because of the 3D exposures afforded by the deep gullies into the volcano.

Field geologic mapping was conducted in the traditional way, integrating field identification of rocks and their position with outcrop photography, sketching volcanic-stratigraphic relationships, measuring contact and fault-fold orientations with a compass, and identifying marker stratigraphic horizons, to produce a new geologic map for the volcanoes (Figure 2). The drill core data of NEDO (1993) provides subsurface information to integrate with the geologic map data and generate more accurate cross sections (Figure 3).

Previous mapping of the island misidentified some rock types, and distribution and orientations of inclined strata were not given. As for the Aira-Tn tephra proposed by Sugihara (1998), sample locations and the map distributions were not shown, so the field occurrences could not be reliably reproduced. Through geological mapping, we identified and mapped two distinct tephra (glassy tuff) layers (Figures 1b, Figures 2, Figures 3), and did mineralogical and chronological analyses presented below.

### 3.2. Mineralogy

Minerals including those in the glassy tuffs were observed under stereoscopic microscope and by polarized light microscopy, and identified as well as possible by those methods. Mineral compositions in tephras and pumice (+ obsidian) were analyzed by energy-dispersive spectrometer (EDS) attached to a scanning electron microscope (Oxford Link ISIS3001 and JEOL JSM-5800LV; the same instruments used by Asaki and Yoshida 1999; Osozawa et al. 2009; Osozawa and Wakabayashi 2017) at Tohoku University. Sample sites are shown on Figures 2, Figures 5, and Figures 6e, f. Our primary objective was a compositional comparison of a white glassy tuff with yellow pumices and an obsidian in an outcrop of Figure 5 (HAC-Ata-Th vs HAC-UP, HAC-LP, and HAC-OBC), conducted with the same instrument. Note that Supp.Table 2 contains published data of regional tephras Glass shards in the glassy tuffs were morphologically classified as H (no to few bubbles), C (an intermediate amount of bubbles), and T (many bubbles) types following Yoshikawa (1976). The H type was further classified into Ha (no bubbles) and Hb (with scattered bubbles), and C and T types were further classified into Ca and Ta (with globular bubbles) andCb and Tb (with tubular bubbles).

The refractive index of glass shards included in the lower and upper glassy tuffs, as well as that of hornblends included in the lower glassy tuff, was measured by a Measuring Actual Immersion Oil Temperature refractometer (Furusawa 1995) at the National Agriculture and Food Research Organization.

### 3.3. U-Pb dating

Glassy tuffs originally correlated to the Aira-Tn tephra by Sugihara (1998) have zircons, allowing dating by U-Pb methods. Samples were collected from the lower and upper glassy tuffs (HAC-Ata-Th and HAC-K-Tz), and sample sites are shown on Figures 2, Figures 5, and Figures 6e, f. In addition to zircons from these tephras, we analyzed zircons of Plešovice (Sláma et al. 2008), Fish Canyon Tuff (Schmitz and Bowring 2001), and Bishop Tuff (Crowley et al. 2007) as secondary standards, and the U-Pb ages obtained were in accordance with the reference values (Supp.Table 3).

LA-ICP-MS U-Pb dating of zircon has been widely used in recent Quaternary tephostechnology studies (e.g. Guillong et al. 2014). Ito (2014) successfully obtained a U-Pb age of the Toya tephra of 0.1 Ma, demonstrating that a U-Pb age by LA-ICP-MS can be obtained for samples as young as ~0.1 Ma under favorable conditions. Determination of the age of eruption from U-Pb zircon dates for such young volcanic rocks is not straightforward because zircon growth may significantly precede eruption. U-Pb dating combined with (U-Th)/He dating suggests protracted periods of zircon crystallization (100’s of k.y.) prior to eruption for the Quaternary Omachi tephra of central Japan (Ito and Danišík 2020), and a weighted mean U-Pb age of 0.17 ± 0.05 Ma obtained for the Kikai-Tozurahara tephra in Yaku-shima island (Ito et al. 2017b) was ~70 kyr older than its estimated eruption age of 0.095 Ma (Supp.Table 1; Danhara et al. 2010).

LA-ICP-MS U-Pb dating was performed at the Central Research Institute of Electric Power Industry (CRIEPI), using a Thermo Fisher Scientific ELEMENT XR magnetic sector-field ICP-MS coupled to a New Wave Research UP-213 Nd-YAG laser. Data reduction procedures included a Th/U disequilibrium correction assuming a Th/U of magma at 4.0 ± 2.0, and data with high (>75%) common Pb contamination were excluded for further U-Pb analyses. U-Pb ages were calculated following methodology of Sakata (2018). See details of the method in Ito (2014) and Ito and Danišík (2020).
Figure 4. Outcrop photos. Photo localities are shown in Figure 2. (a) stratified scoriaceous tuff. (b) marker lava flow. Haematite was formed in the scoriaceous tuffs. (c) A marker basaltic lava flow along the sea cliff. Black key scoria tuff is visible at the base. Note that the dip is lower than that of the coastal slope. Another lava at the higher stratigraphic position than the cliff lava crops out within the vegetation, although Ishiki (1987) and Ishizuka and Geshi (2018) interpreted these as single lava flow that extended far inland. Ruins of human habitation were found, but these lack a systematic description of the occurrence of items as human bones, earthenware, and stone implements. The correlation to the 0.0073 Ma Kikai-Akahoya tephra (K-Ah; Sugihara 1998; lacking descriptions relative to the ruins) is doubtful based on the age-stratigraphic information presented in this paper. (d) The strata top of the cliff is light coloured, but basaltic lava (marker horizon), below: black scoriaceous tuff (marker horizon) of 10 m in thickness (extending from Figure 4c), and below: asymmetrically folded and light coloured bedded silicic and scoriaceous tuffs (marker). These strata are cut by a basaltic intrusion (right side). The intrusion contact of the strata has an orientation of N10W 60NE and is reddish because of haematite growth. Ishiki (1987) and Ishizuka and Geshi (2018) described the dike as a lava flow originating inland. (e) Black scoriaceous tuff (marker horizon) of 10 m in thickness, and below: bedded silicic (marker horizon) and scoriaceous tuffs, eastern coast of the peninsula. Asymmetric folds are visible, as Figure 4d. (f) Close up of bedded silicic and scoriaceous tuffs and SSE vergent asymmetric folds. (g) Close up, a grading from silicic tuff below to scoriaceous tuff above is visible, and the tuff contains obsidian. A haematite-rich tuff layer is intercalated. The white silicic tuff contained no zircon, so U-Pb dating of it was not possible. H: normal fault between tuff breccia (debris flow; hanging wall; left) and interbedded lava and tuff (foot wall; right). I: conjugate sets of normal faults in the hanging wall of a major normal fault (‘main’ fault). Orientation(s) of main fault: N30W 65SW; associated faults: N30W 55SW vs N30W 50NE, N10W 80SW, N10W 75SW (photo), three faults of N10W 60SW.

4. Results
4.1. Morphology

The deep dissection of the Mihara-yama volcano observed in aerial photographs (Figure 1d–d’) obscures the original volcanic landforms such as calderas and sommas (cf., Ishiki 1987; Tsukui et al. 1991, 1993; Suga 1994, 1998; Suga et al. 1997; Sugihara 1998). The ‘Koiwato’ peninsula with the Koiwatoga-hana cape projects southeastward from the main Mihara-yama volcano without a change in geomorphological character relative to the main island (Figures 1 and Figures 2).
Figure 5. Columnar section and photos including the lower glassy tuff directly east of the Ishizumi-hana cape. HAC-Ata-Th of the glassy tuff specimen contains zircons of 50 to 200 μm, but HAC-UP and HAC-LP of pumice fragments contain no zircon. Both were geochemically analysed including an obsidian fragment of HAC-OBC.
Sea cliffs surrounding the Mihara-yama volcano are well developed, including those around the Koiwato peninsula, the southernmost part of the island (Figures 1b and Figures 2). Based on geomorphic-volcanostratigraphic relationships, the cliff at the northwestern base of the volcanic edifice is an old sea cliff of an island, and this paleo sea cliff was later buried by lavas from the Hachijo-Fuji stratovolcano (‘former sea cliff’ on Figure 2). The Hachijo-jima airport and Hachijo town area on the island were constructed on these subhorizontal younger lava flows northwest of the paleo sea cliff. Small hills surrounded by the Hachijo-Fuji lava flows represent islets offshore the original Mihara-yama main island (Figure 2). Mt. Kando-yama (Figure 2; tuff cone, see below) on the southeastern flank of Hachijo-Fuji was such an islet, but it was reactivated as a tuff cone and then uplifted.

In contrast to the older eroded Mihara-yama volcano, the younger Hachijo-Fuji volcano lacks erosional dissection and each lava flow radially spreads from the 500-m-diameter crater (Figure 1c-c'; cf., Sugihara 1998; Ishizuka and Geshi 2018). The present sea cliff at the base of this volcano is composed of the younger volcanic materials and is much lower (>5m) compared to those associated the older Mihara-yama coast (Figure 1d-d' and Figure 2).

4.2. Stratigraphy and structure of the Mihara-yama volcano

The Mihara-yama volcano represents a single severely dissected stratovolcano, and associated a scoria cone. Scoriaceous tuffs of the main Mihara-yama edifice are well bedded, reach 50 cm in thickness (Figure 4a), and dip to oceanward from the summit of the Mihara-yama up to 30°. The strike lines are concentric around the summit, a typical structure of a stratovolcano. Everywhere on the Mihara-yama edifice, the surface slopes are steeper than the dip of the strata, so stratigraphically higher horizons crop out near the summit whereas stratigraphically lower horizons are exposed in the sea cliffs (Figures 2 and Figures 3).

Basaltic lavas comprising one to three layers of about 10 m in thickness make up the stratigraphically lowest horizons of the main part of the Mihara-yama volcano, and are exposed in most of the sea cliffs (Figure 2). The basaltic lava flows represent a marker horizon that can be mapped around the island (Figure 2). Outcrops of the marker basaltic lava are shown on Figure 4b–d and Figure 6a–d, g.

Drill holes No. 2 to No. 8 provide subsurface data from the southern half of the Mihara-yama volcano (Figure 2; NEDO 1993). Based on the concentric structure of stratovolcano determined from surface geologic mapping, the contact locations in the subsurface can be projected to the section line B-C of cross section of Figure 3. Figure 3 shows that the basalt thickens from C (SE coast, Koiwato Peninsula) to B (summit).

A WSW-ENE trending syncline at the base of the Koiwato peninsula is defined by NWN ward (landward) dipping volcanic strata on the peninsula in contrast to the SES ward (seaward) dipping strata on the main island, and the marker basaltic lava is traceable to the peninsula cliff (Figure 2). On this peninsula the lowest subaerial stratigraphic levels crop out below the marker basalt layers. These lowest subaerial horizons, that are not observed on the main volcanic edifice, are, from top to bottom, a black scoria tuff of 10 m in thickness directly beneath the marker basalt, marine volcanioclastic rocks (with cross laminations and with fragments of altered volcanic rocks) including stratified pale yellowish silicic tuffs, and interbedded lavas and tuffs at the base of the sea cliff (Figures 2 and Figures 3; Figure 4d–h). These three stratigraphic packages are traceable from the Shioma coast on the NE side of the island, to the Koiwato-hana cape (apex of the Koiwto peninsula), to the Aigae coast of the SW coastline, and constitute marker stratigraphic horizons (Figure 2). The silicic tuffs are asymmetrically folded with SSE vergence, and the folds are observed on opposing coastlines (Shioma and Aigae coasts) (Figure 4d–g). Along the Aigae coast, NNW-SSE-striking normal faults are observed, mostly as conjugate sets (Figure 2; Figure 4h, i). Isshiki (1959) described a normal fault at the Aigae coast, but mistook the main fault for a sedimentary contact of the base of the recent terrace deposits. A basaltic dike has intruded along the normal fault (Figure 4d).

Drill holes No. 3 and No. 6 penetrated marine volcanioclastic rocks that correspond to the above-mentioned marine strata in the lowest stratigraphic horizon exposed above sea level (Figure 3). Below this horizon, the borings recovered the altered volcanic basement (mostly andesitic and likely marine, based on amygdaloidal texture), but those rocks are not subaerially exposed (Figure 3). Such basement is directly overlain by the marker basalt in drill hole No. 2, 4, 5, 7, and 8, showing that the marine volcanioclastic rocks have pinched out in that area (Figure 3). All lithological contacts are conformable and there was no evidence of unconformities observed in the cores (NEDO 1993; core recovery rate was close to 100% except near the surface), but there is an onlap relationship of marine and overlying terrestrial strata onto the old volcanic basement (Figure 3).

Overlying the marker basaltic lava is a thick terrestrial accumulation of stratified scoriaceous and pumice tuffs. Sporadic intercalations of basaltic lava are shown on the
geological map (Figure 2). The stratified tuffs (tuff/lapilli tuff/tuff breccia following Fisher 1961) consist of scoria and some pumice fragments. Pumice is locally predominant and up to boulder size. Normal grading is commonly observed. These deposits appear to have been deposited as pyroclastic flows, but some horizons appear to have been deposited as debris flows (volcanic sandstone or conglomerate) associated with apparent ash fall from the summit.

Two layers of white glassy tuffs are observed, both of which were previously considered a single layer of the Aira-Tn tephra derived from the Aira caldera, southern Kyushu (Sugihara 1998). The lower glassy tuff crops out directly above the marker basaltic flows in the sea cliff at the cape Ishizumihana, along the southeastern coast of the island, where it is 5 cm thick, and in the frontal cliff of the Sokodo (Kando) port where it attains 2 m in thickness (Figure 2). A columnar section and outcrop photos including the lower glassy tuff at the Ishizumihana cape are shown in Figure 5. The glassy tuff is intercalated in pumice-dominant tuff layers (pumice flows; Figure 5). Additional photos of the lower glassy tuff at the Ishizumihana cape are shown in Figure 6a, b, and photos at the Sokodo port are shown in Figure 6c, d. The upper glassy tuff is observed at 170 m in altitude (Figures 2 and Figures 3), and stratigraphically overlies the lower glassy tuff by approximately ~170 m thickness, taking into account the dip of ~10 degrees. Photos of the upper glassy tuff are shown in Figure 6e, f, and the tuff is also intercalated in pumice-rich tuff but with volcanic fragments. These tuffs are locally asymmetrically folded with NW vergence and displaced by a thrust fault (right side of Figure 6e).

In Figure 6e, pumice tuff/tuff breccia is weathered and soft, but hard fresh tuff is exposed near the valley, so that the original fresh rock is not a soft and unconsolidated sediment composed of airfall pumice. Stream potholes are eroded into the resistant black scoria and glassy tuff and this geomorphology reflects the high resistance of these lithologies (Figures 2 and Figures 7). In thin section, the matrix is glass, and plagioclase and pyroxene are anhedral (Figure 7), in contrast to euhedral crystals in basaltic lava cropping out to the NE (Figure 2). The tuff lacks welded texture (Figure 7). The type Aira-Tn tephra is an unconsolidated loam (e.g. Kosaka et al. 2014), and potholes cannot form in such unconsolidated deposits; they can only form in erosionally resistant rock.

4.3. Scoria cone and tuff cone

The Kurozuna scoria cone is on the rim of the SW sea cliff of the Mihara-yama volcano (Figure 2). ‘Kurozuna’ in Japanese means black sands, and consists of unconsolidated scoria of granule to pebble size. This vent is close to the sea cliff edge, so colluvial sand covers the top of the sea cliff that consists of the marker basaltic lavas and tuffs (Figure 6g). ‘Kurozuna’ is frequented by sightseers but is dangerous owing to the loose material perched on the cliff edge (Figure 6g). In spite of its popularity with tourists it was only recently documented in the geologic literature (Ishizuka and Geshi 2018).

Mt. Kando-yama, on the southeastern flank of the Hachijo-Fuji volcano, consists of shallow to moderately-dipping bedded scoriaceous tuffs, and the lithology is the same as the terrestrial scoriaceous tuffs widespread on the southeastern Mihara-yama volcano (Figure 2). Two circular depressions representing two craters are observed at the NE-SW trending anticlinal core (Figure 2), and these are filled by unconsolidated scoria of granule to pebble size. The scoria overlies unconsolidated talus deposits (Figure 6h), and underlies the Hachijo-Fuji lava (at this outcrop, the scorias are associated with lava breccia).

4.4. Stratigraphy and structure of the Hachijo-Fuji volcano

Hachijo-Fuji volcano has a crater of 500 m in diameter, with lavas making up the crater walls and the flanks of the volcano. Basaltic lavas are mostly pahoehoe (Figure 6i). Lavas are best observed in sea cliff on the NW side of the Hachijo-Fuji volcano, and the strata dip gently seaward, similar to the Mihara-yama volcano, but the dip angle is the same as the slope angle for Hachijo-Fuji. Lavas along the SE flank have horizontal dip, buried a paleo shallow sea, and reached the NW sea cliff of the Mihara-yama volcano. As noted, the airport, town area, and also the NE side Sokodo port and the SW side Yaene port were built on these relatively flat lava flows (Figure 2).

Drill hole No. 1 near the airport (Figure 2) penetrated the Hachijo-Fuji basalt, then terrestrial volcanioclastics beneath the lava flows, marine unconsolidated volcanioclastics, and marine consolidated volcanioclastic rocks probably correlated to those of the Shioma coast, SE of the Mihara-yama volcano (Figure 3; NEDO 1993).

4.5. Compositions and geochemistry of glassy tuffs (Supp. Table 2)

Stereoscopic microscopic examination shows that both the lower and upper glassy tuffs consist primarily of glass shards. Bubbles in glass shards are not common, and Ha and Hb>Cb>Tb. The upper glassy tuff contains high quartz (β-quartz) as well as plagioclase fragments, but the lower glassy tuff does not contain quartz, and both tuffs contain mafic minerals.
The glass composition for the lower glassy tuff (HAC-Ata-Th) is 77–78% SiO₂, 1.2–1.5% FeO, 0.12–0.16% MgO, and 3.4–3.6% K₂O. The glass composition for the upper glassy tuff (HAC-K-Tz) is 78% SiO₂, 1.2–1.5% FeO, and 0.12–0.18% MgO, and 3.3–3.5% K₂O similar to HAC-Ata-Th.

Glass composition for pumice and obsidian (HAC-LP-pumice, HAC-UP-pumice, HAC-OBC-obsidian) is 73–75% SiO₂, 4.1–5.2% FeO, 0.47–0.75% MgO, and 0.95–1.05% K₂O distinct from that of the upper and lower glassy tuffs. High quartz (β-quartz) is observed in HAC-LP-pumice and HAC-UP-pumice; some is visible macroscopically.

These glass composition data combined with published tephra data were plotted on a SiO₂-K₂O diagram (Figure 8). Data of the Ata-Th and K-Tz tephras plot within calc-alkaline series, and those of HAC-LP-pumice, HAC-UP-pumice, HAC-OBC-obsidian plot within tholeiite series.

**Figure 6.** Outcrop photos. Photo localities are shown in Figure 2. (a) Lower glassy tuff (arrow) at the Ishizumi-hana cape, west of the cape (opposite side of Figure 5) and directly above the marker basaltic lava. To the NE on the cliff, the basaltic lava (marker horizon) with haematite-rich base is continuously exposed. (b) close up. Arrow: glassy tuff. (c) Lower silicic tuff (arrow) opposite side of the Sokodo port, directly above the basaltic lava (marker horizon) at the base of sea cliff. To the west (right and frontal side), the young, horizontally-oriented Hachijo-juji lava abuts the Mihara-yama basaltic lava (marker horizon). (d) close up of Figure 4c. The white silicic tuff is very thick (2 m). (e) The upper glassy tuff (arrow; HAC-K-Tz). Note that the strata dip to the SE (oceanward; to the right), and fresh hard tuff breccia located adjacent to the bridge southwest of the valley. The upper white line is a thrust fault associated with NW-vergence asymmetric fold to the right (SE side of the photo; not shown). The sign placed by the Board of Education in Hachijo-jima explains that the glassy tuff is the 0.02 Ma Aira-Tn tephra (which is incorrect; see text) intercalated in the unconsolidated (incorrect, see text) pumice falls from the Mihara-yama, and that the upper white line is an unconformity (incorrect as noted above). (f) close up of Figure 4e. (g) Scoria cone (black) at the top of the sea cliff. 'Kurosuna' (black sands) sightseeing locality. (h) The Kando-yama scoria covers talus deposits. Tuff cone consists of tilted scoriaceous tuff derived from the Mihara-yama volcano, not from the Hachijo-Fuji volcano. (i) Pahoehoe lava of the Hachijo-Fuji volcano tilted oceanward.
The mafic mineral(s) is (are) hornblende (HAC-Ata-Th-hornblende) in the lower glassy tuff, and orthopyroxene (HAC-K-Tz-orthopyroxene) and clinopyroxene (HAC-K-Tz-clinopyroxene) in the upper glassy tuff.

We obtained similar range of refractive index of glass shards of the lower and upper glassy tuffs (HAC-Ata-Th-glass, HAC-K-Tz-glass), and the refractive index of hornblende of the lower glassy tuff (HAC-Ata-Th-hornblende).

**4.6. U-Pb age (Supp.Table 3)**

We obtained U-Pb ages from zircons of the lower and upper glassy tuffs (HAC-Ata-Th and HAC-K-tz). The HAC-LP-pumice, HAC-UP-pumice, and silicic tuff of Figure 4g contain no zircon.

U-Pb dates from the lower glassy tuff zircons (HAC-Ata-Th) were mostly < 4 Ma with some xenocrystic > 15 Ma zircons (Supp.Table 3). Taking a weighted mean age of all < 4 Ma zircons yields an age of 0.88 ± 0.21 Ma (95% confidence; n = 15; MSWD = 10.3) (Figure 9). The large MSWD indicates that these zircons may contain xenocrysts and/or antecrysts (Miller et al. 2007). In this case, age of the youngest zircons are closest to the eruption date, although they still should be regarded as slightly older than the eruption age (i.e. maximum eruption age) owing to the likelihood of zircon growth prior to eruption indicated earlier. We selected the youngest 3 zircons to represent the maximum eruptive age, giving a weighted mean age of 0.46 ± 0.12 Ma (MSWD = 0.44). Although an age of 0.36 (+0.16, −0.19) Ma was calculated by the ‘youngest detrital zircon’ routine in Isoplot program (Ludwig 2012), we assume that the lower glassy tuff erupted at 0.46 ± 0.12 Ma.

The upper glassy tuff zircons (HAC-K-tz) yielded predominantly ages of < 3 Ma with one ~14 Ma (Supp. Table 3). A weighted mean age of all < 3 Ma zircons is calculated as 0.41 ± 0.33 Ma (n = 10; MSWD = 13). Because of a large MSWD value, we selected the youngest 4 zircons, which yielded a weighted mean age of

**Figure 7.** Route map of erosional streambed pot holes and associated field photos that illustrate the erosional resistance of the glassy tuffs; unconsolidated ash cannot form such erosional features. In addition, photomicrographs are presented with plane polarized and cross polarized views that show no welded structure. The pot hole transect area is shown in Figure 2. Holes are numbered 0 at the bridge to 50 upstream of it, and downstream of it to −14.
0.24 ± 0.09 Ma (MSWD = 0.48). Although an age of 0.08 (+0.16, 0.9) Ma is calculated by the ‘youngest detrital zircon’ routine in Isoplot program (Ludwig 2012), we tentatively assume a maximum eruptive age for the upper glassy tuff of 0.24 ± 0.09 Ma.

5. Discussion

5.1 Correlation to the regional tephras

Both the lower and upper tuffs mostly consist of glass shards associated with variable bubbles, and should have originated from subaerial ash falls derived from some of the giant calderas of western Japan. As noted, winds blowing from the west prevail in the middle latitudes of northern hemisphere, including Japan and Hachijo-jima island. Pumice and obsidian (HAC-UP, HAC-LP, HAVC-OBC) have lower and distinct K2O contents than the glass shards of the white colored lower and upper glassy tuffs (HAC-Ata-Th, HAC-K-Tz), and were directly derived from the Mihara-yama volcano, in contrast to the ‘exotic’ glass shards in regional tephras (HAC-Ata-Th, HAC-K-Tz). Pumice and obsidian (HAC-UP, HAC-LP, HAVC-OBC) are tholeiitic (Figure 8) as are the Mihara-yama lavas (Tsukui et al. 1993; Suga et al. 1997) and the Hachijo-Fuji lavas (Nakano et al. 1991; Tsukui and Hoshino 2002). In contrast, the glass shards of the lower and upper tuffs including HAC-Ata-Th and HAC-K-Tz are calc-alkaline (Figure 8). Note that most lavas of the northern Izu volcanic arc are tholeiitic (Tamura et al. 2016) including the O-shima lavas (e.g. Osozawa et al. 2012b; Figure 1a).

The Izu-Bonin volcanic arc initiated activity at ca. 48 Ma at Chichi-jima island (Ar-Ar dating; Ishizuka et al. 2006) and ca. 51 Ma at the Bonin Ridge (Ar-Ar dating; Ishizuka et al. 2011), and was a juvenile arc at that time (Stern and Scholl 2010; c.f., Taira et al. 1998; Tamura et al. 2016). Zircon xenocrysts as old as 200 Ma obtained from the glassy tuffs (Supp.Table 3) are not expected for the relatively young Izu-Bonin arc (although dredged basalts yielded rare Ar-Ar ages of 159 Ma; Ishizuka et al. 2011). In contrast, eruption with old xenocrystic zircons would be expected from volcanoes in the Japan-Ryukyu mature arc (Stern and Scholl 2010), which has old continental basement. Note that zircon of any sort was lacking in pumice (HAC-UP and HAC-LP in 5) and silicic tuff (Figure 4g) from the Miharayama volcano, Hachijo-jima, Izu-Bonin volcanic arc.

The lower and upper tuffs should be correlated with two distinct regional tephras whose ages should be younger than 0.46 ± 0.12 Ma (weighted mean age of the lower glassy tuff; Figure 9). Machida and Arai (2003) studied and compiled regional tephras from the Kyushu giant calderas (Supp.Table 1), and the Kakuto (0.335 Ma), Aso-1 (0.26 Ma), Ata-Torihama (0.24 Ma), Ata (0.107 Ma), Kikai-Tozurahara (0.095 Ma), Aso-4 (0.0875 Ma), Aira-Tn (Aira-Tanzawa; 0.0275 Ma), and Kikai-Ah (Kikai-Akahoya; 0.0073 Ma) tephras are viable candidates based on age (ages after Danhara et al. 2010). Mt. Sanbe (alkaline), Daisein (alkaline), Tateyama (calc-alkaline), Ontake (calc-alkaline), and Fuji (tholeiite) and Hakone (calc-alkaline) (Figure 10) are not candidates because of the prevailing west winds (westerlies) would not carry tephra to Hachijo-jima.

Discrimination between alternative tephras is relatively easy, because hornblende as the only mafic mineral is a characteristic of only the Ata-Torihama tephra (hornblende refractive index is also similar; see Supp.Table 2), and high quartz (β-quartz) inclusions are a characteristic of the Kikai-Tozurahara tephra (Machida and Arai 2003). Accordingly, we correlate the lower glassy tuff to the Ata-Torihama tephra and the upper glassy tuff to the Kikai-Tozurahara tephra, although glass compositions of such as SiO2 and K2O are similar among various tephras and glassy tuffs, including the Aira-Tn tephra (Supp.Table 2; Figure 8). Note that although major element geochemical data are not distinctive among the Ata-Torihama, Kikai-Tozurahara, and Aira-Tn tephras, the Kakuto, Ata, and Aso-4 tephras have distinct compositions (Supp.Table 2; Figure 8). In addition, the refractive index of glass is similar among these tephras and glassy tuffs including the Aira-Tn tephra (Supp. Table 2) and hence does not distinguish these tephras, although it is distinct for the Kakuto, Ata, and Aso-4 tephras (Supp.Table 2). A glass refractive index was reported in Sugihara (1998; no sample location data) and a glass chemical composition was given in Tsukui et al. (1991; no sample location data), which misled these authors to correlate the glassy tuff(s) with the Aira-Tn tephra. Refractive index of HAC-Ata-Th-hornblende from the lower glassy tuff was also similar to those of the Ata-Th tephra from other localities (Supp.Table 2).

5.2. Tephrochronology combined with the present U-Pb dating

Ages of the correlated regional tephras of Ata-Torihama (0.24 Ma) and the Kikai-Tozurahara (0.095 Ma) may be applied to the ages of the lower and upper glassy tuffs (HAC-Ata-Th, HAC-K-Tz) intercalated in the terrestrial stratigraphy of the Mihara-yama volcano. The age estimation of these regional tephras was done combining radioisotopic dates with oxygen isotopic stratigraphy, estimate of sedimentation rate, and marine micropaleontology (Yoshikawa and Inouchi 1993; Nagahashi
The above age estimates for specific tephras, however, primarily rely on the zircon fission track ages of 0.24 ± 0.04 Ma for the Ata-Torihama tephra and 0.098 ± 0.026 Ma (later modified to 0.095 Ma in Danhara et al. 2010) for the Kikai-Tozurahara tephra (Danhara 1995). Danhara (1995) noted that for the Kikai-Tozurahara tephra, the total numbers of zircons with fission tracks were only 14 of 144 zircons, with 130 zircons lacking fission tracks.

Ito (2014), Ito et al. (2017a, 2017b), and Ito and Danišík (2020) attempted to estimate more reliable U-Pb ages of <1 Ma regional tephras in Japan. Whereas Sugihara (1998) misinterpreted the glassy tuffs as the Aira-Tn tephra (0.0275 Ma), he presented many radiocarbon ages for lignite fragments contained in the Mihara-yama strata (a dated lignite sample may be from that near HAC-UP in Figure 5), but his data are difficult to interpret due to a lack of field stratigraphic context.

Our zircon analyses obtained a weighted mean U-Pb age of the lower glassy tuff (HAC-Ata-Th) at 0.46 ± 0.12 Ma, which is older than the widely-accepted Ata-Torihama age of 0.24 Ma, but this is expected owing to the probable growth of zircon prior to eruption (Ito and Danišík 2020). The U-Pb age is useful, however, because it constrains the tephra to be younger than ~0.5 Ma which facilitates application of the other correlation criteria which we applied.

A weighted mean zircon U-Pb age of the upper glassy tuff (HAC-K-Tz) was obtained at 0.24 ± 0.09 Ma, younger than the lower glassy tuff. From mineralogical perspectives as mentioned above, we correlate this tephra the Kikai-Tozurahara. Ito et al. (2017b) obtained a zircon age of 0.24 ± 0.09 Ma for the Kikai-Tozurahara tephra, consistent with our results.
Figure 9. Zircon U-Pb ages (2σ analytical uncertainties) for the lower and upper glassy tuffs. Individual U-Pb grain ages are arranged from young to old. Also shown are photos of a typical zircon from each tuff. White dashed circles of 30 μm diameter represent the positions of laser ablation.
U-Pb age of 0.17 ± 0.05 Ma from the Kikai-Tozurahara tephra in the Yaku-shima island, Kyushu, concordant with the present result.

5.3. 4D volcanic geology (Figure 3)

The evolution of the Hachijo-jima volcanoes in relative time is illustrated by the cross-sections that show the 3D stratigraphic relationships. Structure and succession of the Mihara-yama volcano is symmetric relative to the section, as illustrated by the concentric strike lines around the summit, constituting a typical radial structure of a stratovolcano. The 3D relationships tied to the ages of strata allow analysis of the 4D evolution of the volcano. The Hachijo-Fuji volcano represents a typical stratovolcano similar to the famous Fuji volcano (Figure 10), and the 3D structure is simple.
The submarine volcanic basement of the Mihara-yama volcano consists of altered volcanic and volcanoclastic rocks, dated by K-Ar methods at 2.12 Ma (Kaneoka et al. 1970) and 2.27 ± 0.07 Ma (NEDO 1993). Marine volcanoclastic rocks were deposited at the foot of the submarine volcano with buttress unconformity and fragments of altered volcanic rocks are included within the lowermost marine volcanoclastic strata overlying the basement. The above 2.12 Ma K-Ar age by Kaneoka et al. (1970) was obtained from a sample of such a volcanic clast. The field relationships show that the original submarine basement ediﬁce had been uplifted and emerged above sea level when the marine volcanoclastic rocks were accumulated.

The date of the lower glassy tuff correlated to the Ata-Torihama tephra is 0.24 Ma, and the lower tuff is slightly above the marker basaltic lava flow stratigraphically (Figure 5, Figure 6a–d). This terrestrial basaltic volcanism (dated by K-Ar method at 0.22 ± 0.06 Ma by NEDO 1993; Figure 3) mostly comprising lava ﬂows began at about this time of 0.24 Ma, and these horizons conformably overlie terrestrial tuffs but locally abut the altered volcanic basement near the eruption center with unconformity (see Figure 3). The basaltic marker horizon underlies marker submarine scoriaceous tuff in outcrops of the Shiomi and Aigae coasts, which might be a precursor of voluminous terrestrial scoria and pumice ﬂows and falls.

Shortly after eruption of the marker basaltic lava ﬂows, the Ata-Torihama tephra of 0.24 Ma derived from the Ata caldera, Kyushu (Figure 10), was deposited and intercalated in the pumice ﬂows derived from the Mihara-yama volcano. A later tephra of the Kikai-Tozurahara at 0.095 Ma was derived from the Kikai caldera, Kyushu (Figure 10), and also intercalated in the pumice ﬂows derived from the Mihara-yama volcano. The thickness of scoria and pumice tuffs between the two tephra horizons is <170 m, and the deposition rate is estimated of <1.14 mm/y. This accumulation rate is an order of magnitude faster than that of the Lake Suigetsu sediments (McLean et al. 2020, p. 0.65 mm/y) and the Lake Biwa sediments (Yoshikawa and Inouchi 1993, p. 0.35 mm/y), but may be reasonable for volcanic- pyroclastic successions. Note that the Kikai-Tozurahara tephra observed at the front of the Sokodo port is 2 m in thick (Figure 6c,d), possibly a drift of ash. Whereas the city of Tokyo is also distant from Kyushu calderas (Figure 10), the ﬁeld observations presented herein suggest that hazards associated with such long distance ash drift should be considered.

We observed SSE vergent asymmetric folds (and a thrust fault associated with a NW-vergent asymmetric fold) and NNW-SSE trending conjugate sets of normal faults, that suggest NNW-SSE shortening. NNW-SSE shortening may be driven by the collision of the Izu-Bonin arc with the central Japan arc (Suga 1998). O-shima island (Figure 1a) at the northern end of the Izu-Bonin arc closest to the collision region lacks contractional structures. However, parasitic cones are aligned NNW-SSE, suggesting fisure eruptions along the NNW-SSE-striking fractures associated with a NNW-SSE maximum horizontal stress axis (Nakamura 1969; note that Fuji and Hakone volcanoes are associated with similar parasitic cones). The Izu peninsula is characterized by a conjugate set of NNW-SSE sinistral and WNW-ESE dextral faults, which also suggests the collision-related NNW-SSE shortening (Nakamura 1969).

After the effusive and explosive volcanism of Mihara-yama ceased, a scoria cone was formed at the SW foot of the Mihara-yama, and formed the Kurozuna scoria. The Kando-yama tuff cone that formed offshore and NW of Mihara-yama also deposited scoria.

Margin of the Mihara-yama volcano was eroded by wave action so that a sea cliff formed surrounding the volcanic island. To the NW there was shallow sea, and the drill hole No. 1 cored unconsolidated marine volcanoclastics there (associated consolidated strata at the bottom; Figure 3). Above this unit, the core exhibits unconsolidated terrestrial volcanoclastics, that covered the marine sediments as a precursor to the main stage Hachijo-Fuji volcanism and ﬁlled the shallow sea (Figure 3). The main lava ﬂows accumulated to form the Hachijo-Fuji stratovolcano, and some lavas abutted the preexisting Mihara-yama sea cliff and the Kando-yama tuff cone.

The emergence of Hachijo-jima above sea level as an island took place by ca. 0.24 Ma when deposition of the terrestrial tuff and its intercalated Ata-Torihama tephra began. However, marine volcanoclastic rocks abutted the altered volcanic basement along a buttress unconformity, and the basement may have been uplifted to form a subaerial summit between 2.12 Ma and 0.24 Ma. This earlier uplift history may have been driven by shortening, or alternatively by basal intrusions as proposed for the Madeira Archipelago at the eastern end of the Atlantic hot spot track (Ramalho et al. 2015) and for the Santa Maria Island in the Azores Archipelago near the Mid-Atlantic Ridge (Ramalho et al. 2017). The emergence time is thus not well constrained, but if we apply the above estimated sedimentation rate of 1.14 mm/y to the 750 m layer between the base of marker basaltic lava and the base of marine volcanoclastic rocks (Figure 3), the duration of
5.4. Implications for genesis of the Troodos ophiolite

Although trace element and isotopic data are lacking for the Mihara-yama basalt as well as the Hachijo-Fuji basalts, the present geological and chronological data allows comparison with other island arc terranes, including those interpreted as supra subduction zone ophiolites (e.g. Stern and Bloomer 1992; Shervais 2001; Pearc 2003; Whatam and Stern 2011), and facilitates comparisons of the genesis of units such as the Troodos ophiolite of Cyprus (Osozawa et al. 2012b).

A part of deep-sea sediment cover over the Troodos pillow lavas is called the Kainanuiv Formation consisting of silicic tuff (Robertson 1977; Osozawa and Okamura 1993). The silicic tuff might have derived from a mature island arc distinct from the nascent suprasubduction-zone setting (Robertson 1977). The basin of the Coast Range ophiolite of California, that has suprasubduction zone geochemical affinity (e.g. Shervais and Kimbrough 1985; Shervais et al. 2004) is also overlain by volcano-pelagic strata including silicic tuff that is significantly younger than the basalt, and has been ascribed to a different magmatic source (Wakabayashi and Dilek 2000; Hopson et al. 2008). Caribbean oceanic plateau basalt accreted to the Colombian margin is associated with terrestrial lapilli tuff (Buchsa et al. 2018). On IODP Expedition 352, frontal Bonin ridge, the four sites U1439-U1442 drilled through the Ata-Torihama tephra in superficial sediments (Kutterolf et al. 2017) overlying volcanic basement that includes boninite (Reagan et al. 2017) at 100 m depth (U1440-1442) and 200 m depth (U1439). The Mihara-yama succession, including tholeiitic lavas formed in a young immature island arc, contains the exotic calc-alkaline tephras derived from the Kyushu calderas of a mature volcanic arc, a relationship similar to the cover of the Troodos ophiolite. Alteration of the Hachijo lavas and Troodos lavas is negligible, and those rocks are unaffected by penetrative deformation such as pressure solution cleavage. Hachijo-jima volcanic rocks are deformed by an ENE-WSW-trending syncline and outcrop scale asymmetrical folds. By comparison, a WNW-ESE-trending anticlinal dome has been documented in the Troodos ophiolite (Osozawa et al. 2012b). The structures at both localities may reflect pre-collisional shortening that developed as an immature subduction zone approached a mature one at a trench-trench triple junction.

6. Conclusions

The erosionally-dissected Mihara-yama volcano was built on 2.12 Ma submarine volcanic basement. The deposition of volcaniclastic strata over this basement by buttress unconformity began in submarine conditions at < 1.8 Ma, and was succeeded by terrestrial pyroclastic flows and a tholeitic-lava flow from 0.24 Ma onward. Emergence of the Mihara-yama volcano above sea level took place prior to 0.24 Ma (ca. 0.89 Ma). The Ata-Torihama tephra (Ata-Th; 0.24 Ma; U-Pb age < 0.46 Ma) and Kikai-Tozurahara tephra (K-Tz; 0.095 Ma; U-Pb age < 0.24 Ma) from giant calderas of Ata and Kikai of Kyushu (calc-alkaline) are intercalated with terrestrial scoriaceous-pumice tuffs of the Mihara-yama volcano (tholeiitic). Adjacent to the southwestern paleo seaciff of this old volcano, a shallow marine basin was formed at < 0.26 Ma. Subaerial scoria and tuff cones were also formed as small-scale lateral volcanoes. Tholeiitic lava flows built the subaerial Hachijo-Fuji stratovolcano over the shallow marine basin, and two major volcanoes were connected to form a present, single Hachijo-jima island. The island deformed by NNW-SSE shortening, reflecting the Izu-Bonin collision with the central Japan arc, similar to the NNE-SSW shortening observed for the Troodos ophiolite. The silicic tuff cover of the Troodos ophiolite may have been derived from an adjacent but more mature volcanic arc.

Highlight

The erosionally-dissected Mihara-yama volcano was built on 2.1 Ma altered volcanic basement.

Deposition of volcanic strata over this basement buttress unconformity began in submarine conditions at < 1.8 Ma, followed by subaerial pyroclastic flows and a tholeitic-lava flow from 0.24 Ma onward. Emergence of the Mihara-yama volcano above sea level was > 0.24 Ma.

The Ata-Torihama tephra (Ata-Th; 0.24 Ma; U-Pb age < 0.46 Ma) and Kikai-Tozurahara tephra (K-Tz; 0.095 Ma; U-Pb age < 0.24 Ma) from giant calderas of Ata and Kikai of Kyushu (calc-alkaline) are intercalated in the terrestrial scoriaceous-pumice tuffs derived from the Mihara-yama volcano (tholeiite). Previous correlations to the Aia-Tn tephra (Aira-Tanzawa; AT; 0.0275 Ma) are not viable.
Adjacent to the northwestern paleo sea cliff of this old volcano, a shallow marine basin was formed at < 0.26 Ma. Subaerial scoria and tuff cones were also formed as small-scale lateral volcanoes. 

Tholeiitic lava flows built the subaerial Hachijo-Fuji strato-volcano over the shallow marine basin, and two major volcanoes were connected to form a single Hachijo-jima island. The island deformed by NNW-SSE shortening, reflecting the Izu-Bonin collision towards the central Japan arc.

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Competing interests

The authors declare no competing interests.

References

Aoki, K., Irino, T., and Oba, T., 2008, Late Pleistocene tephrostratigraphy of the sediment core MD01-2421 collected off the Kashima coast, Japan: The Quaternary Research, v. 47, no. 6, p. 391–407. (in Japanese with English abstract) 10.4116/jaquja.37.391.

Asaki, T., and Yoshida, T., 1999, Alteration of basalts from the Shimanto belt in southern Tokushima Prefecture, Southwest Japan: Japanese Journal of Petrology, Mineralogy, and Economic Geology, v. 94, no. 1, p. 11–36. (in Japanese with English abstract) 10.2465/ganko.94.11.

Bacon, C.D., McKenna, M.J., Simmons, M.P., and Wagner, W.L., 2012, Evaluating multiple criteria for species delimitation: An empirical example using Hawaiian palms (Arecaceae: Pritchardia): BMC Evolutionary Biology, v. 12, no. 1, p. 1–18. 10.1186/1471-2148-12-23.

Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Baumgartner-Mora, C., and Ulianov, A., 2010, Late Cretaceous arc development on the SW margin of the Caribbean Plate: Insights from the Golfito, Costa Rica, and Azuero, Panama, complexes: Geochemistry Geophysics Geosystems, v. 11, no. 7, p. Q07S24. 10.1029/2009GC002901.

Buchs, D.M., Irving, D., Coombs, H., Miranda, R., Wang, J., Coronado, M., Arrocha, R., Lacerda, M., Goff, C., Almengor, E., Portugal, E., Franceschi, P., Chichaco, E., and Redwood, S.D., 2019, Volcanic contribution to emergence of Central Panama in the Early Miocene: Scientific Reports, v. 9, no. 1, p. 1417. 10.1038/s41598-018-37790-2.

Buchsa, D.M., Kerr, A.C., Brims, J.C., Zapata-Villada, J.P., Correa-Restrepo, T., and Rodríguez, G., 2018, Evidence for subaerial development of the Caribbean oceanic plateau in the Late Cretaceous and palaeo-environmental implications: Earth and Planetary Science Letters, v. 499, p. 62–73. 10.1016/j.epsl.2018.07.020.

Busby, C.J., Putirka, K., Melosh, B., Renne, P.R., Hagan, J.C., Gambis, M., and Wesoloski, C., 2018, A tale of two Walker Lane pull-apart basins in the ancestral Cascades arc, central Sierra Nevada, California: Geosphere, v. 14, no. 5, p. 1–50. 10.1130/GEOS1398.1.

Crowley, J.L., Schoene, B., and Bowring, S.A., 2007, U-Pb dating of zircon in the Bishop Tuff at the millennial scale: Geology, v. 35, no. 12, p. 1123–1126. 10.1130/G24017A.1.

Danbara, T., 1995, Towards precise measurement of zircon and glass fission-track geochronology for Quaternary tephras: The Quaternary Research, v. 34, no. 3, p. 221–237. (in Japanese with English abstract) 10.4116/jaquja.34.221.

Danbara, T., Yamashita, T., Iwano, H., Takemura, K., and Hayashida, A., 2010, Chronology of the 1400-m core obtained from Lake Biwa in 1982–1983: Re-investigation of fission-track ages and tephra identification: The Quaternary Research, v. 39, no. 3, p. 101–119. (in Japanese with English abstract) 10.4116/jaquja.49.101.

Domitsu, H., Nishi, H., Uchida, J., Oda, M., Ogane, K., Taira, A., and Aoike, K., Shimokita Microfossil Research Group, 2010, Age model of core sediments taken by D/V CHIKIYU during the shakedown cruises off Shimokita Peninsula: Fossils, v. 87, p. 47–64. (in Japanese with English abstract).

Ewart, A., Collerson, K.D., Regelous, M., Wendt, J., and Niu, Y., 1998, Geochemical evolution within the Tonga–Kermadec–Lau arc–back-arc systems: The role of varying mantle wedge composition in space and time: Journal of Petrology, v. 39, no. 3, p. 331–368. 10.1093/petrology/39.3.331.

Farris, D.W., Cardona, A., Montes, C., Foster, D., and Jaramillo, C., 2017, Magmatic evolution of Panama Canal volcanic rocks: A record of arc processes and tectonic change: PLoS One, v. 12, no. 5, p. e0176010. 10.1371/journal.pone.0176010.

Fisher, R., 1961, Proposed classification of volcanioclastic sediments and rocks: Geological Society of America Bulletin, v. 72, no. 9, p. 1409–1414. 10.1130/0016-7606(1961)72[1409:PCOVSA]2.0.CO;2.

Furusawa, A., 1995, Identification of tephra based on statistical analysis of refractive index and morphological classification of volcanic glass shards: Journal of Geologic Society of Japan, v. 101, no. 2, p. 123–133. (in Japanese with English abstract) 10.5575/geosoc.101.123.

Guillon, M., von Quadt, A., Sakata, S., Peytcheva, I., and Bachmann, O., 2014, LA-ICP-MS Pb-U dating of young zircons from the Kos-Nisyros volcanic centre, SE Aegean arc: The Journal of Analytical Atomic Spectrometry, v. 29, no. 6, p. 963–970. 10.1039/C4JA00009A.
Heads, M., and Grehan, J.R., 2021, The Galápagos I slands: Biogeographic patterns and geology: Biological Reviews, v. 96, no. 4, p. 1160–1185. 10.1111/brv.12696.

Hopson, C.A., Mattinson, J.M., Pessagno, E.A., Jr., and Luyendyk, B.P., 2008, California Coast Range ophiolite: Composite Middle and Late Jurassic oceanic lithosphere, in Wright, J.E., and Shervais, J.W., eds., Ophiolites, Arcs, and Batholiths: A Tribute to Cliff Hopson, Geological Society of America Special Paper, no. 438, p. 1–101.

Hoshi, H., 2018, Kanto Syntaxis: When did it began to grow?: Journal of Geological Society of Japan, v. 124, no. 10, p. 805–817. (in Japanese with English abstract) 10.5575/geosoc.2018.0023.

Ikehara, A., 2016, Zircon: the Chemical, and isotopic constraints: Earth and Planetary Science Letters, v. 250, no. 1–2, p. 385–401. 10.1016/j.epsl.2006.08.007.

Ikehara, A., and Geshi, N., 2018, Geochemical map of Hachijojima Volcano: Geological Map of volcanoes, v. 20, Geological Survey of Japan, AIST.

Isshiki, N., 1959, Geology of the Hachijojima district. quadrangle series scale 1: 50,000, Geological Survey of Japan, 58pp. (in Japanese with English abstract)

Ito, H., 2014, Zircon U–Th–Pb dating using LA-ICP-MS: Simultaneous U–Pb and U–Th dating on the 0.1 Ma Toya Tephra, Japan: Journal of Volcanology and Geothermal Research, v. 289, p. 210–223. 10.1016/j.jvolgeores.2014.11.002.

Ito, H., and Danisik, M., 2020, Dating late Quaternary events by the combined U-Pb LA-ICP-MS and (U-Th)/He dating of zircon: A case study on Omachi Tephra suite (central Japan): Terra Nova, v. 32, no. 2, p. 134–140. 10.1111/ter.12452.

Ito, H., Nanayama, F., and Nakazato, H., 2017a, Zircon U–Pb dating using LA-ICP-MS: Quaternary tephras in Boso Peninsula, Japan: Quaternary Geochronology, v. 40, p. 12–22. 10.1016/j.quageo.2016.07.002.

Ito, H., Uesawa, S., Nanayama, F., and Nakagawa, S., 2017b, Zircon U–Pb dating using LA-ICP-MS: Quaternary tephras in Yakushima Island, Japan: Journal of Volcanology and Geothermal Research, v. 338, p. 92–100. 10.1016/j.jvolgeores.2017.02.003.

Kaneoka, I., Isshiki, N., and Zashu, S., 1970, K-Ar ages of the Izu-Bonin Islands: Geochemical Journal, v. 4, no. 2, p. 53–60. 10.2343/geochemj.4.53.

Kasama, T., and Shiioi, H., 2019, Stratigraphic subdivision of the Pleistocene Miyata Formation based on lithology and unconformity, Miura Peninsula, with special reference to the radiometric age of the intercalated Funakubo Tuff: Bulletin of Kanagawa Prefecture Museum (Natural Sciences), v. 48, p. 1–12. (in Japanese with English abstract).

Kosaka, H., Miwa, A., Imaizumi, T., Inagaki, H., Hashimoto, S., Kagohara, K., and Sasaki, A., 2014, Fault exposure of Dainenjyama fault across urban district of Sendai City, Northeast Japan: Journal of the Japan Society of Engineering Geology, v. 55, no. 4, p. 166–176. (in Japanese with English abstract) 10.5110/jjseg.55.166.

Kutterolf, S., Schindelbeck, J.C., Robertson, A.H.F., Avery, A., Baxter, A.T., Petronotis, K., and Wang, K.L., 2017, Tephrostratigraphy and provenance from IODP Expedition 352, Izu-Bonin arc: Tracing tephra sources and volumes from the Oligocene to recent: Geochemistry, Geophysics, Geosystems, v. 19, no. 1, p. 150–174. 10.1002/2017GC007100.

Le Pichon, X., Iiyama, T., Bouglé, J., Charvet, J., Faure, M., Kano, K., Lallemant, S., Okada, H., Rangin, C., Taira, A., Urabe, T., and Uyeda, S., 1987, Nankai Trough and Zenisu Ridge: A deep-sea submersible survey: Earth and Planetary Science Letters, v. 83, no. 1–4, p. 285–299. 10.1016/0012-821X(87)90072-0.

Ludwig, K.R., 2012, User’s Manual for Isoplot 3.75: A geochronological Toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication, v. 5, p. 75.

Machida, H., and Arai, F., 2003, Atlas of tephra in and around of Japan: Tokyo, Tokyo University Press, 336 p. (in Japanese).

McLean, D., Albert, P.G., Suzuki, T., Nakagawa, T., Kimura, J.I., Chang, Q., et al., 2020, Constraints on the timing of explosive volcanism at Aso and Aira calderas (Japan) between 50 and 30 ka: New insights from the Lake Suigetsu sedimentary record (SG14 core): Geochemistry, Geophysics, Geosystems, v. 21, no. 8, p. e2019GC008874. 10.1029/2019GC008874.

Meffre, S., Falloon, T.J., Crawford, T.J., Hoernle, K., Hauff, F., Duncan, R.A., Bloomer, S.H., and Wright, D.J., 2012, Basalts erupted along the Tongan fore arc during subduction initiation: Evidence from geochronology of dredged rocks from the Tonga fore arc and trench: Geochemistry Geophysics Geosystems, v. 13, no. 12, p. Q12003. 10.1029/2012GC004335.

Miller, J.S., Matzel, J.E.P., Miller, C.F., Burgess, S.D., and Miller, R.B., 2007, Zircon growth and recycling during the assembly of large, composite arc plutons: Journal of Volcanology and Geothermal Research, v. 167, no. 1–4, p. 282–299. 10.1016/j.jvolgeores.2007.04.019.

Montes, C., Bayona, G., Cardona, A., Buchs, D.M., Silva, C.A., Morón, S., Hoyos, N., Ramírez, D.A., Jaramillo, C.A., and Valencia, V., 2012, Arc-continent collision and orocline formation: Closing of the Central American seaway: Journal of Geophysical Research: Solid Earth, v. 117, no. B4. 10.1029/2011JB008959.

Montes, C., Cardona, A., Jaramillo, C., Pardo, A., Silva, C., Valencia, V., Ayala, C., Perez-Angel, J.C., Rodriguez-Parra, L.A., Ramírez, V., and Nino, H., 2015, Middle Miocene closure of the Central American Seaway: Science, v. 348, no. 6231, p. 226–229. 10.1126/science.aaa2815.

Nagashashi, Y., and Kataoka, K.S., 2014, Tephrostratigraphy (part 5): Major element composition of volcanic glass shards and tephra beds correlation: The Quaternary Research, v. 53, no. 5, p. 265–270. (in Japanese with English abstract) 10.4116/jaqua.53.265.
null
Island (Azores)- The conundrum of uplifted islands revisited: Geological Society of Bulletin, v. 129, no. 3–4, p. 372–391. 10.1130/B31538.1.
Reagan, M.K., Pearce, J.A., Petronotis, K., Almees, R.R., Avery, A.J., Carvallo, C., et al., 2017, Subduction initiation and ophiolite crust: New insights from IODP drilling: International Geology Review, p. 1–12. 10.1080/00206814.2016.1276482.
Robertson, A.H.F., 1977, The Kannaviou Formation, Cyprus: Volcanoclastic sedimentation of a probable Late Cretaceous volcanic arc: Journal of the Geological Society of London, v. 134, no. 3, p. 269–292. 10.1114/gsjgs.134.3.0269.
Sakata, S., 2018, A practical method for calculating the U-Pb age of Quaternary zircon: Correction for common Pb and initial disequilibria: Geochemical Journal, v. 52, no. 3, p. 281–286. 10.2343/geochemj.2.0508.
Schmitz, M.D., and Bowring, S.A., 2001, U-Pb zircon and titanite systematics of the Fish Canyon Tuff: An assessment of high-precision U-Pb geochronology and its application to young volcanic rocks: Geochimica et Cosmochimica Acta, v. 65, no. 15, p. 2571–2587. 10.1016/S0016-7037(01)00616-0.
Shervais, J.W., 2001, Birth, death, and resurrection: The life cycle of supra subduction zone ophiolites: Geochemistry, Geophysics, Geosystems, v. 2, Paper number 2000GC000080.
Shervais, J.W., and Kimbrough, D.L., 1985, Geochemical evidence for the tectonic setting of the Coast Range ophiolite: A composite island arc-oceanic crust terrane in western California: Geology, v. 13, no. 1, p. 35–38. 10.1130/0091-7613(1985)13<0035:GEFTTS>2.0.CO;2.
Shervais, J.W., Kimbrough, D.L., Renne, O., Hanan, B.B., and Murchey, B., 2004, Multi-stage origin of the Coast Range Ophiolite, California: Implications for the life cycle of supra-subduction zone ophiolites: International Geology Review, v. 46, no. 4, p. 289–315. 10.2747/0020-6814.46.4.289.
Sláma, J., Kosler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., and Whitehouse, M.J., 2008, Plešovice zircon – A new natural reference material for U-Pb and Hf isotopic microanalysis: Chemical Geology, v. 249, no. 1–2, p. 1–35. 10.1016/j.chemgeo.2007.11.005.
Sterr, R.J., and Bloomer, S.H., 1992, Subduction zone-infanat: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of America Bulletin, v. 104, no. 12, p. 1621–1636. 10.1130/0016-7606(1992)104<1621:SZIEAT>2.3.CO;2.
Sterr, R.J., and Scholl, D.W., 2010, Yin and yang of continental crust creation and destruction by plate tectonic processes: International Geology Review, v. 52, no. 1, p. 1–31. 10.1080/00206810903332322.
Suga, K., 1994, Volcanic history of Higashiyama, Hachijojima: Bulletin of the Volcanological Society of Japan, Second series, v. 38, p. 115–127. (in Japanese with English abstract).
Suga, K., 1998, The evolution process and its characteristics in the Hachijojima volcanic group, Izu-Bonin Arc: The Quaternary Research, v. 39, no. 2, p. 59–75. (in Japanese with English abstract).
Suga, K., 1997, A few remarks on the growth history of Hachijojima Volcano, Izu-Bonin Islands: Bulletin of the Volcanological Society of Japan, Third series, v. 42, no. 227–231. (in Japanese with English abstract).
Suganuma, Y., Aoki, K., Kanamatsu, T., and Yamazaki, T., 2006, Tephrostratigraphy of deep-sea sediments in the northwestern Pacific and its implications for the chronology of the past 300 kyr: The Quaternary Research, v. 45, no. 6, p. 435–450. (in Japanese with English abstract) 10.4116/jaqua.45.435.
Sugihara, S., 1998, Tephrochronological study of Higashiyama Volcano at Hachijojima, Izu Islands: Journal of Geography, v. 107, no. 3, p. 390–420. (in Japanese with English abstract) 10.5026/geography.107.3.390.
Sugihara, S., and Shimada, S., 1998, Stratigraphy and eruption ages of deposits at the southeast side of Nishiyama volcano, Hachijo Island during the last 2,500 years: Journal of Geography, v. 107, no. 5, p. 695–712. (in Japanese with English abstract) 10.5026/geography.107.5.695.
Taira, A., Saito, S., Aoike, K., Morita, S., Tokuyama, H., Suyehiro, K., Takahashi, N., Shinozuka, M., Kiyokawa, S., Naka, J., and Klaus, A., 1998, Nature and growth rate of the Northern Izu-Bonin (Ogasawara) arc crust and their implications for continental crust formation: Island Arc, v. 7, no. 3, p. 395–407. 10.1111/j.1440-1738.1998.00198.x.
Takarada, S., and Hoshizumi, H., 2020, Distribution and eruptive volume of Asō-4 pyroclastic density current and tephra fall deposits, Japan: A M8 super-eruption: Frontiers in Earth Science, v. 8, p. 170. 10.3389/feart.2020.00170.
Tamura, Y., Busby, C.J., Blum, P., Guérin, G., Andrews, G.D.M., et al., 2015, Expedition 350 summary, in Tamura, Y., Busby, C.J., and Blum, P., eds., the expedition 350 scientists, proceedings of the International Ocean Discovery Program, Expedition 350, College Station, TX (International Ocean Discovery Program), Izu-Bonin-Mariana Rear Arc.
Tamura, Y., Ishizuka, O., Sato, T., and Nichols, A.R.L., 2019, Nishinoshima volcano in the Ogasawara Arc: New continent from the ocean?: Island Arc, v. 28, no. 1, p. e12285. 10.1111/iar.12285.
Tamura, Y., Sato, T., Fujiwara, T., Shuichi Kodaira, S., and Nichols, A., 2016, Advent of continents: A new hypothesis: Scientific Reports, v. 6, no. 1, p. 33517. 10.1038/srep33517.
Tsukui, M., and Hoshino, K., 2002, Magmatic differentiation of Hachijo-Nishiyama volcano, Izu Islands, Japan: Bulletin of the Volcanological Society of Japan, Second series, v. 47, p. 57–72. (in Japanese with English abstract).
Tsukui, M., Morizumi, M., and Suzuki, M., 1991, Eruptive history of the Higashiyama Volcano, Hachijo Island during the last 22,000 years: Bulletin of the Volcanological Society of Japan, Second series, v. 36, p. 345–356. (in Japanese with English abstract).
Tsukui, M., Morizumi, M., and Suzuki, M., 1993, Evolution of magma plumbing system of Hachijō-Higashiyama volcano in the last 30,000 years: Bulletin of the Volcanological Society of Japan, Second series, v. 38, p. 199–212. (in Japanese with English abstract).
Wakabayashi, J., and Dilek, Y., 2000, Spatial and temporal relationships between ophiolites and their metamorphic soles: A test of models of forearc ophiolite genesis, in Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A., eds., Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program, Geological Society of America Special Paper no. 349, p. 53–64.

Whattam, S.A., Montes, C., and Stern, R.J., 2020, Early central American forearc follows the subduction initiation rule: Gondwana Research, v. 79, p. 283–300. 10.1016/j.gr.2019.10.002.

Whattam, S.A., and Stern, R.J., 2011, The ‘subduction initiation rule’: A key for linking ophiolites, intra-oceanic forearcs, and subduction initiation: Contributions to Mineralogy and Petrology, v. 162, no. 5, p. 1031–1045. 10.1007/s00410-011-0638-z.

Yamamoto, H., and Aoki, K., 2002, Late Quaternary tephrostratigraphy in piston cores collected during “Mirai” MR00–K05 cruise: AMSTECR, v. 46, p. 29–36. (in Japanese with English abstract).

Yoshikawa, S., 1976, The volcanic ash layers of the Osaka Group: Journal of the Geological Society of Japan, v. 82, no. 8, p. 497–515. (in Japanese with English abstract) 10.5575/geosoc.82.497.

Yoshikawa, S., and Inouchi, Y., 1993, Middle Pleistocene to Holocene explosive volcanism revealed by ashes of the Takashima-oki core samples from Lake Biwa, Central Japan: The Association for the Geological Collaboration in Japan, v. 467, p. 97–109. (in Japanese with English abstract).