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1 **Eocene volcanism during the incipient stage of Izu-Ogasawara arc: Geology and petrology of the**
2 **Mukojima Island Group, the Ogasawara Islands**

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18

19 Abstract

20 The Ogasawara Islands mainly comprise Eocene volcanic strata formed when the Izu-Ogasawara-Mariana
21 arc began. We present the first detailed volcanic geology, petrography and geochemistry of the Mukojima
22 Island Group, northernmost of the Ogasawara Islands, and show that the volcanic stratigraphy consists of
23 arc tholeiitic rocks, ultra-depleted boninite-series rocks, and less-depleted boninitic andesites which are
24 correlatable to the Maruberiwan, Asahiyama and Mikazukiyama Formations on the Chichijima Island
25 Group to the south. On Chichijima, a short hiatus is identified between the Maruberiwan (boninite, bronzite
26 andesite and dacite) and Asahiyama Formation (quartz dacite and rhyolite). In contrast, these lithologies
27 are interbedded on the Nakodojima of the Mukojima Island Group. The stratigraphically lower portion of
28 Mukojima is mainly composed of pillow lava, which is overlain by reworked volcanoclastic rocks in the
29 middle, whereas the upper portion is dominated by pyroclastic rocks. This suggests that volcanic activity
30 now preserved on Mukojima Island Group records growth of one or more volcanoes, beginning with quiet
31 extrusion of lava under relatively deep water followed by volcanoclastic deposition, and then changed into
32 moderately explosive eruptions that took place in shallow water or above sea level. This is consistent with
33 the uplift of the entire Ogasawara Ridge during the Eocene. Boninites from the Mukojima Island Group are
34 divided into three types on the basis of geochemistry. Type 1 boninites have high SiO_2 (>57.0 wt%) and
35 Zr/Ti (>0.022) and are the most abundant type in both Mukojima and Chichijima Island Groups. Type 2
36 boninites have low SiO_2 (<57.1 wt%) and Zr/Ti (<0.010). Type 3 boninites have 57.6-60.7 wt% SiO_2 and are
37 characterized by high $\text{CaO/Al}_2\text{O}_3$ (0.9-1.1). Both type 2 and 3 boninites are common on Mukojima but are
38 rare in the Chichijima Island Group.

39

40 Key words

41 Ogasawara (Bonin) Islands; Mukojima Island Group; subduction zone; volcanic geology; geochemistry;

42 petrography; boninite; arc tholeiite; pillow lava; pyroclastic rock

43

44 Introduction

45 Subduction zones play an essential role in producing continental crust and developing terrestrial
46 environment through material exchange between the Earth's interior and surface (e.g. Kelemen 1995;
47 Rudnick 1995; Tatsumi 2005; Kodaira *et al.* 2007; Tatsumi *et al.* 2008). Oceanic arc originally initiate in
48 an oceanic environment, causing a juvenile arc to form above them, which develops into a mature
49 arc-trench system (Stern 2010). However, it is poorly understood how immature arcs develop into mature
50 arcs and how subarc mantle evolves as a new subduction zone is established. The Izu-Ogasawara-Mariana
51 (Izu-Bonin-Mariana, or IBM) arc-trench system is an ideal site for addressing these issues because it
52 provides a complete volcanic record of the arc, which we can interpret to reveal the thermo-chemical
53 evolution of the wedge mantle from the beginning of subduction to the establishment of the stable
54 arc-trench system.

55 The Ogasawara (Bonin) Archipelago represents an emergent section of the
56 Izu-Ogasawara-Mariana fore-arc basement, which separates the Izu-Ogasawara-Mariana Trench from the
57 Ogasawara Trough and the active volcanic arc (Figs 1). Subduction of the Pacific plate started with
58 voluminous igneous activity, perhaps seafloor spreading, along the entire eastern margin of the overriding
59 Philippine Sea plate (Stern & Bloomer 1992). This is coincident with the change in plate motion in the
60 western Pacific at ca. 50 Ma (Sharp & Clague 2002; Wessel *et al.* 2006). Initial volcanism was MORB-like
61 basalt at 52-50 Ma (Reagan *et al.* 2010; Ishizuka *et al.* 2011), followed by arc tholeiite which was replaced
62 by boninite magmatism after 49 Ma (Cosca *et al.* 1998; Ishizuka *et al.* 2006). Boninite, a high-Mg andesite
63 with SiO₂ >52 wt%, MgO >8 wt% and TiO₂ <0.5 wt% (Le Bas 2000), is intimately associated with more
64 differentiated variety of rocks ranging in composition from bronzite andesite to quartz-bearing rhyolite
65 (Umino 1985; Umino & Nakano 2007). These boninite and related rocks are hereafter referred to
66 "boninite-series rocks". Two types of boninite series are recognized by distinct trends in major elements

67 and by trace element abundances. High-Si boninite-series rocks are distinguished from low-Si
68 boninite-series rocks by their higher SiO₂ at a given FeO*/MgO and severely depleted REEs (rare earth
69 elements) and HFSEs (high field strength elements). The initial boninite magmatism at 49-46 Ma is
70 represented by high-Si boninite-series rocks which include the “type” boninite of Chichijima. This
71 boninitic magmatism was followed by eruption of low-Si boninite and bronzite andesite associated with
72 calc-alkalic andesite and dacite, beginning at 45 Ma (Ishizuka *et al.* 2006). These lavas are widespread in
73 the Mikazuki-yama Formation of the Chichijima Island Group (Umino & Nakano 2007) (Figs 2a, 3) and on
74 the western scarp of the Ogasawara Ridge (Ishizuka *et al.* 2006). These activities are the transitional stage
75 from incipient to typical arc magmatism, which were followed by eruption of arc tholeiitic and
76 calc-alkaline magmas since 45 Ma (Ishizuka *et al.* 2006; unpubl. data, 2011). The progressive change in
77 magma compositions reflects the thermo-chemical evolution of the wedge mantle during the establishment
78 of the Izu-Ogasawara-Mariana subduction zone during the beginning ~10 myr of plate subduction (e.g.
79 Hussong *et al.* 1982; Ishii 1985; Bloomer & Hawkins 1987; Fryer *et al.* 1990; Arculus *et al.* 1992; Pearce
80 *et al.* 1992a, b; Cosca *et al.* 1998; Ishizuka *et al.* 2006) (Fig. 4).

81 Boninite-series volcanic rocks are widespread over the Ogasawara Ridge (Fig. 2a, 4). Besides the
82 Chichijima Island Group, including the type locality of boninite (Kikuchi 1890; Petersen 1891), the
83 Mukojima Island Group (Fig. 2b), the northernmost Ogasawara Archipelago, is also known to have
84 boninitic rock suites (Shiraki *et al.* 1979; Yuasa *et al.* 1981), which are similar to those of the Chichijima
85 Island Group (Fig. 3; e.g. Kuroda & Shiraki 1975; Maruyama & Kuramoto 1981; Umino 1985; Taylor *et al.*
86 1994; Umino & Nakano 2006; 2007). Boninite has also been recovered from the submarine Ogasawara
87 Ridge, inner slope of the Ogasawara Trench (Ishizuka *et al.* 2011) and Hahajima Seamount (Ishiwatari *et al.*
88 2006). Recently, ⁴⁰Ar/³⁹Ar ages of 48.04±0.17-44.3±0.3 Ma have been reported for the volcanic rocks
89 from the Mukojima Island Group (Ishizuka *et al.* 2011). These ages span the entire period of volcanic

90 activity on the Chichijima Island Group, which shows a wide spectrum of magma compositions from
91 boninite-series rocks to arc tholeiitic and calc-alkaline rocks. Likewise, the Mukojima Island Group is
92 expected to show a wide variety of magma compositions and variable style of volcanic products. However,
93 detailed volcanic geology, petrology and stratigraphic relationships between these volcanic suites are
94 poorly known.

95 This study provides the first detailed studies on the geology, petrography and geochemistry of the
96 Mukojima Island Group and discusses the style of volcanic activities, stratigraphic relationships among the
97 Ogasawara Islands and the genetic conditions of boninite magmas.

98

99 **Analytical techniques**

100 Preparation of bulk rock samples was conducted at Shizuoka University and the Geological Survey
101 of Japan. Normally 50 g of rock chips were ultrasonically cleaned and then soaked in distilled water at
102 80°C for 4 to 5 days to remove seawater contamination. The rock chips were then pulverized using an agate
103 mortar.

104 Whole rock major element abundances were determined by a Philips PW1404 XRF spectrometer at
105 the Geological Survey of Japan (GSJ, AIST) using glass beads prepared by fusion of 0.5-g rock with 5-g of
106 lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$). Analytical error is generally <2%.

107 Whole rock trace element compositions were determined by an inductively coupled plasma mass
108 spectrometry (ICP-MS) at the Geological Survey of Japan. About 100 mg of powder from each sample was
109 dissolved in a HF-HNO₃ mixture (5:1). After evaporation to dryness, the residues were re-dissolved with
110 2% HNO₃ prior to analysis. REEs, V, Cr, Rb, Sr, Y, Zr, Nb, Cs, Ba, Hf, Ta, Pb, Th and U concentrations
111 were analyzed by ICP-MS on a VG Platform instrument. Reproducibility is better than ±4% (2 σ) for REE
112 and better than ±6% (2 σ) for other elements.

113 Major elements of glass shards in pumice and scoria samples and constituent minerals (>0.4 mm
114 diameter) were analyzed by a JEOL JXA-8800 electron probe microanalyzer (EPMA) at Kanazawa
115 University. The accelerating voltage was 15 kV and the specimen current was 12 nA. Analyses of glass
116 followed the procedures of Noguchi *et al.* (2004) using broad beam diameters <30 μm . The corrections
117 were made using ZAF method.

118 Trace element compositions (REEs, V, Cr, Co, Ni, Li, B, Sc, Rb, Sr, Y, Zr, Nb, Cs, Ba, Hf, Ta, Pb,
119 Th and U) of glass were analyzed by laser ablation (193 nm ArF excimer: MicroLas GeoLas Q-plus)
120 inductively coupled plasma mass spectrometry (Agilent 7500S) (LA-ICP-MS) at Kanazawa University
121 (Ishida *et al.* 2004). Each analysis was performed by ablating spots of 100 μm in diameter at 5 Hz with
122 energy density of 8 J/m^2 per pulse. Signal integration times were 40 seconds for a gas background interval
123 and 30 seconds for an ablation interval. The NIST SRM 612 glass was used as the primary calibration
124 standard and was analyzed at the beginning of each batch of <3-5 unknowns, with a linear drift correction
125 applied between each calibration. The element concentration of NIST SRM 612 for the calibration is
126 selected from the preferred values of Pearce *et al.* (1997). Data reduction was facilitated using ^{29}Si as
127 internal standards for glass, based on SiO_2 contents obtained by EPMA analysis, and followed a protocol
128 essentially identical to that outlined by Longerich *et al.* (1996). Details of the analytical method and data
129 quality for the LA-ICP-MS system at Kanazawa University are described in Morishita *et al.* (2005a, b).

130

131 **Geology of the Mukojima Island Group**

132 Mukojima Island Group comprises three clusters of islands spread about 30 km northwest to
133 southeast: 1) Kitanoshima and Nakanoshima, and the adjacent reefs to the northeast (Ninoiwa and
134 Yon'noiwa; 2) Mukojima, Harinoiwa, Tatamiwa, Nakodojima; and 3) Yomejima (Fig. 2b). Total thickness
135 of volcanic strata of the Mukojima Island Group is more than 1900 m.

136

137 *1. Ninoiwa, Kitanoshima and Nakanoshima*

138 Ninoiwa, Kitanoshima and Nakanoshima are composed of altered aphyric tholeiitic andesite to
139 dacite.

140 Ninoiwa (Fig. 5) is the largest rocky reef among the islets in the northern end of the Ogasawara
141 Archipelago. It consists of altered agglutinate composed of densely welded ash- and lapilli-sized clasts of
142 aphyric andesite.

143 Kitanoshima, Nakanoshima and the surrounding reefs and islets form two volcanic edifices of
144 aphyric arc tholeiitic andesite to dacite similar to that of Ninoiwa (Figs 5, 6a). Nakanoshima is composed
145 of pillow lava (Fig. 7a) more than 180 m in thickness and dipping 20° to 54° to northeast. Pillows are
146 locally overlain by volcanic breccia above a SE-dipping erosional surface. Pillow lava sequences exposed
147 on reefs to the southeast of Kitanoshima also dip northeast, whereas pillows on the southeastern end of
148 Kitanoshima and the adjacent islet dip northwest, indicating an anticline plunging to the northeast. The
149 northwestern half of Kitanoshima and the surrounding reefs are composed of more than 660-m of
150 agglutinate consisting of densely to moderately welded lava clasts up to 10 cm in diameter (Fig. 7b, c),
151 which represents a proximal facies deposited very close to the source vent(s). The agglutinate is intruded
152 by dikes and overlain by 140 m of pillow lava on the southeast of Kitanoshima dipping 30°-52° SE, which
153 are underlain by the northwesterly dipping pillows forming the western limb of the anticline. All these
154 lavas on Kitanoshima, Nakanoshima and the surrounding reefs suffered low-temperature alteration and
155 weather reddish brown because of hematite and limonite covering surfaces and infillings of cracks in
156 pillow lobes. Bifurcating pillow lobes indicate flow directions to east on the north of Nakanoshima and
157 northwest on the southern Nakanoshima. The anticlinal structure affecting pillow lava on Nakanoshima and
158 adjacent reefs suggests that they reflect a pillowed ridge elongated northeast-southwest, which were

159 dissected and covered by the welded fall-out tephra and then by the uppermost pillow flows comprising
160 most of Kitanoshima.

161

162 *2. Yon'noiwa and Sasayojima*

163 Yon'noiwa (Fig. 5), a small reef 1.5 km north of Nakanoshima, consists of southwesterly dipping
164 bedded tuff breccia with intercalated sheet flows (<1 m thick) of porphyritic olivine-bronzite boninite.

165 Sasayojima (Figs 5, 6b), east off Nakanoshima, consists of pillow lava and tuff breccia of boninite and
166 bronzite andesite dipping 16°-22° west-southwest. The massive part of the tuff breccia includes lenticular
167 volcanic bombs, consisting of poorly vesiculated scoriae and lithic clasts. Well stratified tuff breccia
168 includes lapillistone and agglomerate lenses consisting of clasts several to tens of centimeters in diameter.

169 These tuff breccias are intruded by dikes of bronzite andesite that dip 85°-90° and strike NW. The interiors
170 of pillows and dikes are brecciated. The total thickness exceeds 55 m.

171

172 *3. Mukojima*

173 Mukojima (Figs 5, 6c), the largest island of the Mukojima Island Group, is mainly composed of
174 gently to moderately (12° to 40°) inclined boninite bedded tuff breccia and pillow lava. The total thickness
175 reaches 750 m. A south-southeasterly plunging anticline and a northerly plunging syncline are in the
176 northwest and east of the island, respectively. Faults with northwest-southeast strikes are dominant. The
177 lowest 297-m thick portion of the island is exposed in the northwest and consists of bedded tuff breccia
178 intercalated with partially brecciated pillows showing rare chilled margins and closely packed pillows with
179 thick chilled margins (Fig. 7d, e). The pillow lava and tuff breccia are type 3 high-Si boninites (to be
180 defined later) with the highest CaO/Al₂O₃ ratio (0.9-1.4) on the island. The middle portion consists of
181 316-m thick bedded tuff breccia with an intercalated 32-m thick pillow lava of porphyritic boninite which

182 includes clinoenstatite as long as 5 cm concentrated in the core of pillows. The bedded tuff breccias
183 include fragments of boninite pillows, coarse ash- to lapilli-sized poorly vesiculated scoria. The uppermost
184 portion consists of pillow flows of type 2 high-Si boninite (to be defined later), white tuffaceous
185 siltstone-sandstone-conglomerate (Fig. 8a, b), a boninite lobate sheet flow and massive tuff breccia (Fig.
186 7f), in ascending order. The uppermost massive tuff breccia is widely distributed in the center and east of
187 the island (Fig. 7g). The ubiquitous presence of volcanic bombs in the massive tuff breccia indicates the
188 products of middle strombolian eruptions, suggesting the eruptive center(s) was in the vicinity of the
189 island.

190

191 **4. Harinoiwa and Tatamiwa**

192 Harinoiwa (Figs 5, 6d) is located between Mukojima and Nakodojima and consists of NW-dipping
193 alternating beds of pillow lava, hyaloclastite and bedded tuff breccia of nearly aphyric bronzite andesite.
194 The total thickness attains 340 m. Pillow lobes are brecciated into glassy fragments and laterally changes
195 into hyaloclastite as the degree of fragmentation increases (Fig. 7h). Lenticular lava tongues show
196 subparallel arrangement embedded in hyaloclastite. The bedded tuff breccia comprises pillow fragments
197 and volcanic bombs which show graded bedding in the matrix of poorly vesiculated lithic clasts and
198 angular glassy fragments. Some dikes with undulating margins bud pillow lobes on the upper end, while
199 another dikes are short and closed at both ends within hyaloclastite and pillow lava (Fig. 7h).

200 Tatamiwa (Fig. 5) is a small reef composed of bronzite andesite lapilli tuff located in north off
201 Nakodojima.

202

203 **5. Nakodojima**

204 Nakodojima (Figs 5, 6e) is divided into the eastern, central and western blocks by faults running

205 NNE-SSW in the center of the island and N-S on the east of Tsurugiyama. The western block reaches 230
206 m in thickness and comprises boninite and bronzite andesite pillow lava overlain by quartz rhyolite
207 hyaloclastite. The central block moderately inclines toward south and has a thickness of 280 m and consists
208 of pillow lava of boninite and bronzite andesite in the lower part and hyaloclastite and lobate sheet flows
209 of nearly aphyric bronzite andesite with minor dacite and quartz rhyolite hyaloclastite in the upper part.
210 Boninite pillows are distributed in the lowermost part along the northern coast. Bronzite andesite forms
211 lobate sheet flows on the ridge behind the central embayment. The eastern block is composed of quartz
212 rhyolite hyaloclastite interbedded with bronzite andesite hyaloclastite. Brecciated pillow lava of bronzite
213 andesite and boninite occurs in the lowermost level below andesite hyaloclastite and in the upper level
214 beneath white pumice tuff (Fig. 8g) and quartz rhyolite hyaloclastite on the top of Byobuyama. The
215 lowermost brecciated pillow lava in the southeast of the island forms a composite flow of bronzite andesite
216 and boninite. Most boninite and andesite pillow lavas and quartz rhyolite lava are brecciated to glassy and
217 lithic fragments which grade into massive hyaloclastite (Fig. 7i). En echelon NW-trending alteration zones
218 are aligned in the central block, where lavas are hydrothermally bleached (Fig. 7j). A secondary
219 copper-bearing mineral deposit (Chrysocolla) is present in a narrow cove along the fault bounding the
220 central and the western block (Ishizuka *et al.* 2012). Nakodojima is considered to be a discrete volcanic
221 center, because the island is the only volcano that has felsic lava flows and fall deposits and intense
222 hydrothermal alteration and mineralization occurred associated with the rhyolite dikes.

223

224 6. Yomejima

225 Yomejima (Figs 5, 6f) is the southernmost of the Mukojima Island Group. Most of Yomejima
226 comprises bedded tuff breccia with intercalated pillow lava, up to 480 m thick. An E-W trending anticline
227 runs through the center of Yomejima and the adjacent Ushirojima, where stratigraphically lowest

228 composite pillow lavas of bronzite andesite and boninite are exposed beneath the bedded tuff breccia. The
229 northern limb of the anticline dips 9° - 30° N- to NW-, where the uppermost bedded volcanic breccia of
230 olivine-augite-bronzite andesite is distributed in the northwest of Yomejima. The southern limb of the
231 anticline is composed of composite pillow lava of boninite and bronzite andesite which is unconformably
232 overlain by tuff breccia, pillow lava, a surge deposit and welded fall-out scoria and volcanic bombs. The
233 surge deposit mainly consists of dense, glassy scoria, coarse ash and volcanic bombs of boninite. Poorly
234 vesiculated angular pyroclastic materials show finely stratified cross stratification, which is disturbed by
235 bomb sags. Weakly welded boninite agglomerate including dribblets and distorted spindle-shaped volcanic
236 bombs intercalated with boninite pillow flows, which grade laterally into pyroclastic N-S dikes, 50-328 cm
237 thick on the western coast of central Yomejima. A synform on the southern end of the island is formed by
238 northeasterly dipping pillow lava which abuts bedded tuff breccia dipping to the south. Polymict breccia
239 consisting of boninite and two-pyroxene andesite rest unconformably on the bedded tuff breccia on top of
240 the northwestern cliff of Yomejima.

241 Maejima southwest off Yomejima is composed of bedded volcanic and tuff breccia which are
242 weakly to moderately welded (Fig. 7k). Welded breccia surrounding an embayment of Maejima comprises
243 lenticular deposits of poorly vesiculated blocks and lapilli, which are considered to be a vent-filling talus
244 deposit. Intense Fe-Cu sulfide mineralization and quartz veining are pervasive throughout Maejima
245 (Ishizuka *et al.* 2012).

246 A number of dikes of boninite and altered bronzite andesite intruded into the tuff breccia in the
247 center of Yomejima and Maejima (Fig. 7l). The dikes show variable strikes, dipping 36° - 90° with an
248 average of 72° W. The thickness of measured 28 dikes vary from 11 cm to 800 cm, averaging 115 cm with a
249 median of 88 cm.

250

251 **Petrography**252 ***1. Boninite-series rocks***

253 Boninite was first described by Kikuchi (1890) and introduced by Petersen (1891) for rock
254 samples from Chichijima. The term “boninite” is defined as a feldspar-free andesite carrying bronzite as a
255 phenocryst and/or microphenocryst. Boninite is a compact, black gray rock and has abundant glass more
256 than 20% even in the core of a pillow and a dike, showing a vitreous fracture. Boninite-series rocks of
257 Chichijima are comprised of boninite, bronzite andesite, dacite and quartz-bearing dacite and rhyolite,
258 these form an almost continuous geochemical trend (Umino, 1985), although quartz-bearing dacite is
259 absent from the Mukojima Island Group lavas. Boninite-series can be readily distinguished from other
260 associated volcanic rock suites such as calc-alkalic and tholeiitic rocks as shown in the following chapters.

261 **1-1. Boninite**

262 Boninite occurs in Yon'noiwa, Sasayojima, Mukojima, Nakodojima and Yomejima as pillow lava,
263 clasts in bedded tuff breccia, scoriae and bombs in massive tuff breccia, and dikes. Generally, boninite
264 shows a bimodal or trimodal distribution in crystal size. Besides bronzite, olivine and clinoenstatite are
265 present as phenocrysts and/or microphenocrysts (Fig. 9a, b). Pyroxene phenocrysts form one millimeter to
266 a few centimeter thick prisms. Pyroxene microphenocrysts are several hundred μm to 2 mm-long prisms
267 and skeletal forms indicates relatively rapid growth. Small amounts of minute chrome spinel grains are
268 found as inclusions in phenocrysts and microphenocrysts of olivine, clinoenstatite and bronzite, and as
269 discrete equant crystals in the matrix glass. Groundmass consists of Ca-rich clinopyroxene microlites
270 embedded in glass (Fig. 9a, b).

271 In addition to the above general features, Mukojima boninites have some special features. Some
272 type 1 boninites (described later) have augite phenocrysts and microphenocrysts. Augite and hypersthene
273 phenocrysts are common in type 3 boninites (Fig. 9c), some of which have numerous inclusions of glass,

274 clinopyroxene, orthopyroxene and magnetite in a resorbed core surrounded by reversely zoned, euhedral
275 rim. Others show irregular, resorbed outlines. Rounded clots of plagioclase are rarely included. Clots of
276 subhedral augite without inclusions are present in some samples. Type 2 and 3 boninites commonly have
277 augite microphenocrysts (Fig. 9d).

278 Boninite from the upper central block of Nakodojima is nearly aphyric and have rare hypersthene
279 and augite phenocrysts which have resorbed, irregular shaped cores surrounded by more magnesian
280 bronzite rim.

281 1-2. Bronzite andesite

282 Bronzite andesite occurs in Sasayojima, Nakodojima, Harinoiwa, Tatamiwa and Yomejima as
283 massive tuff breccia (hyaloclastite), clasts in bedded tuff breccia, pillow lava and dikes. In addition to
284 bronzite, plagioclase, olivine, augite, hypersthene, magnetite and rare clinoenstatite occur as phenocrysts,
285 but some bronzite andesites lack some or most of these phenocrysts. Bronzite andesites from Harinoiwa,
286 Tatamiwa and the upper central block of Nakodojima are exclusively aphyric. Bronzite and augite are
287 common as microphenocrysts, and sometimes plagioclase and hypersthene are present. The groundmass is
288 generally glassy, and consists of microlites of plagioclase and clinopyroxene (Fig. 9e).

289 1-3. Dacite

290 Distribution of dacite is limited in Nakodojima and Yomejima as tuff breccia. Plagioclase, augite,
291 hypersthene and magnetite are present as phenocrysts and/or microphenocrysts (Fig. 9f). Glassy
292 groundmass consists of microlites of plagioclase and magnetite, and clinopyroxene may be present in some
293 samples.

294 1-4. Quartz rhyolite

295 Quartz rhyolite occurs in Nakodojima as tuff breccia and dikes, and rarely in Yomejima as dikes.
296 Quartz, plagioclase, hypersthene, augite and magnetite are present as phenocrysts and/or microphenocrysts

297 (Fig. 9g). The groundmass is almost holohyaline with rare plagioclase microlites, magnetite and
298 clinopyroxene, and shows aphanitic texture in some samples.

299

300 **2. Arc tholeiitic rocks**

301 Arc tholeiitic andesite to dacite occurs as welded tuff breccia in Ninoiwa, welded tuff breccia and
302 pillow lava in Kitanoshima and pillow lava in Nakanoshima. These rocks are generally aphyric, and small
303 amount of plagioclase and clinopyroxene are present as phenocrysts and microphenocrysts. Andesites have
304 rare olivine phenocrysts. Groundmass consists of plagioclase, magnetite and pyroxene. Some clasts in
305 welded tuff breccia of Ninoiwa have altered glassy groundmass. Most of these rocks suffered from
306 greenschist-facies metamorphism. The primary mineral assemblage is partially or completely replaced by
307 secondary minerals. Plagioclase is replaced by albite, epidote and quartz. Clinopyroxene is converted into
308 actinolite, chlorite, epidote, sphene, quartz and magnetite. Quartz, zeolites, epidote, chlorite, calcite,
309 apatite and magnetite occur as vesicle fillings and veins (Fig. 9h).

310

311 **Tephra from Mukojima and Nakodojima**

312 Because the Mukojima Island Group consists of several clusters of islands spread over 30 km
313 north-south, stratigraphic correlations among the islands are poorly constrained. Waterlain tephra deposits
314 from the upper Mukojima and Nakodojima correlate between the discrete two islands.

315 **1. Description of tephra**

316 Pumice and scoria tuff and lapillistone (M3-07) interbedded with boninite pillow lavas in a
317 stratigraphically high level are exposed on the eastern and southeastern coasts of Mukojima (Figs 6c, 8a, b).
318 They are 18 m in maximum thickness and are divided into three units; 1) a lower unit of pale green
319 sandstone 2 m thick. This unit is overlain by 6-m thick middle unit of turbiditic deposits consisting of 5- to

320 15-cm thick alternating beds of medium- to fine-grained tuff with 1 mm thick laminae (Fig. 8b). The upper
321 unit is 10 m thick and consists of 5-10 cm thick alternating beds of coarse tuff and lapillistone. Lapilli
322 generally show imbrication which indicates a paleo-current toward S50-88°E (Fig. 8b). Both the middle
323 and upper units are intruded by a boninite sheet lava which thins to the north.

324 The lapillistone in the upper unit and is relatively fresh and preserves original textures, although
325 most glass shards are completely palagonitized except some pumice and scoriae. Constituents of the
326 lapillistone (M3-07G, H; Fig. 8b) are white and gray woody pumice (~80 vol%) (Fig. 8c), black dense
327 scoria (~5 vol%) (Fig. 8d, e), fragments of orthopyroxene and quartz and trivial clinopyroxene and
328 plagioclase. Maximum grain size of pumice and scoria is 20 and 5 mm, respectively. Most pumice has
329 minor quartz, plagioclase and hypersthene phenocrysts set in a glassy matrix with a few microlites. Scoria
330 is of two types; one is crystal-free boninite scoria consisting of glass only (Fig. 8d), and the other is
331 porphyritic boninite scoria with 10-20 vol% orthopyroxene phenocrysts and microphenocrysts with rare
332 clinopyroxene phenocrysts in a glassy matrix with some clinopyroxene microlites (Fig. 8e). A few lithic
333 clasts have ~80 vol% groundmass minerals and phenocrysts. Coarse tuff is intervened by lenticular beds of
334 fine tuff in the upper part of the unit. The upper coarse tuff (M3-07I; Fig. 8b) is mainly composed of
335 woody pumice and fragments of orthopyroxene, quartz, clinopyroxene, and minor plagioclase. An agate
336 layer intercalates between the coarse tuff and the overlaying pillow lava.

337 On the northeastern coast of Mukojima, a ~~forty centimeter-thick~~ tuff (M2-06D) (Figs 6c, 8f) is
338 intercalated between overlaying massive boninite tuff breccia and underlying boninite pillow lava. The
339 lower half of the tuff is mainly composed of coarse ash-sized pumice, mineral fragments and minor scoria.
340 The upper half is alternating beds of lapillistone and coarse tuff. The lapillistone consists of white pumice
341 <15 mm in diameter and a small amount of scoria <3 mm in diameter and crystal fragments of
342 orthopyroxene, plagioclase, quartz and clinopyroxene. Glassy matrices of pumice and scoria are partially

343 and completely altered to clay minerals, respectively.

344 A pumice tuff layer (N2-09) (Figs 6e, 8g) is exposed in the eastern cliff of Nakodjima. The
345 pumice tuff about 2 m in maximum thickness is overlain by rhyolite tuff breccia and underlain by bronzite
346 andesite tuff breccia. Samples of the tuff were recovered from the top of a ridge south of Mt. Byobuyama
347 (Fig. 6e), where the pumice tuff becomes thinner to the north about 30 cm in thickness. Most of the
348 constituents are gray and white woody pumice <5 cm in diameter and minor amounts of orthopyroxene and
349 quartz fragments. Because pumice is nearly aphyric, mineral fragments are most likely derived from
350 phenocrysts from quartz rhyolite and boninite lavas. The majority of the pumice tuff is altered to clay
351 minerals.

352 2. *Glass and mineral compositions of tephtras*

353 Glass and mineral compositions are shown in Fig. 10, Table S1 and S2. The most magnesian glass
354 compositions from samples M3-07G and M3-07H were obtained for crystal-free boninite scoriae, which
355 contain 56.9 to 61.1 wt% SiO₂, 6.7 to 8.3 wt% MgO, 8.3 to 11.4 wt% CaO and 0.43 to 0.45 ppm Yb with
356 Zr/Ti ratio of 0.016. In contrast, the matrix glass of crystal-rich boninite scoriae has 58.2-63.6 wt% SiO₂,
357 5.4-5.9 wt% MgO, 8.2-10.5 wt% CaO, and 0.66-0.80 ppm Yb, with 0.021-0.023 Zr/Ti ratio (Fig. 10a, b).
358 Orthopyroxene phenocrysts and microphenocrysts in crystal-rich scoriae mostly range in Mg#
359 (Mg/(Mg+Fe)) from 0.85 to 0.90 and rarely from 0.66 to 0.78. Few clinopyroxene in the scoriae has Mg#
360 0.72 (Fig. 10c). Glass matrices of pumice have 68-82 wt% SiO₂, 0.1-2.1 wt% MgO and 0.62-1.48 ppm Yb
361 (Fig. 10a, b). The sample M3-07I includes pumice with a glass composition of 75.6-77.9 wt% SiO₂ and
362 1.0-1.7 wt% MgO (Fig. 10a).

363 Glass of scoriae in sample M2-06D was not analyzed due to severe alteration. Pumice contains
364 70.0-80.0 wt% SiO₂ and 0.1-2.3 wt% MgO (Fig. 10a).

365 Fragmental orthopyroxenes included in samples M3-07G, H, I and M2-06D have a similar

366 compositional range, which forms two clusters. Most orthopyroxene crystals have 0.77-0.91 Mg#, while
367 the rest has Mg# = 0.64-0.75. Samples M3-07G, H and M2-06D contain minor fragmental augite, while
368 M3-07I carries more common clinopyroxenes ranging from augite to sub-calcic augite and a lesser amount
369 of pigeonite. Sub-calcic augite has higher in Al₂O₃ content than augite (Fig. 10c). M2-06D commonly has
370 fragmental plagioclase, most of which ranges in An₈₃₋₉₀, whereas M3-07G, H and I rarely have plagioclase.

371 Glass compositions of pumice in N2-09 have narrow ranges from 77.1 to 78.7 wt% SiO₂, 0.3 to 0.5
372 wt% MgO and 0.91 to 1.1 ppm Yb (Fig. 10a, b). Fragmental orthopyroxenes have Mg#0.79-0.87 (Fig. 10c).

373 Trace element compositions of the pumice glass from Nakodojima and Mukojima cannot be
374 reconciled with those of the bulk quartz rhyolite by the addition and subtraction of plagioclase and
375 pyroxenes phenocrysts. Therefore, the pumice must have been derived from a different magma from that of
376 quartz rhyolite in Nakodojima.

377

378 **Whole rock geochemistry of Ogasawara Islands**

379 *1. Major elements*

380 Mukojima Island Group is composed of boninite and arc tholeiitic-rock series. Boninite-series
381 rocks are divided into high- and low-Si boninite series that form two distinct compositional trends. .
382 High-Si boninite-series rocks form the entire Yon'noiwa, Sasayojima, Mukojima, and main portions of
383 Nakodojima and Yomejima, while low-Si boninite-series rocks occur in Harinoiwa, Tatamiwa, the
384 uppermost Yomejima and also as andesite hyaloclastite in Nakodojima. Arc tholeiite-series rocks compose
385 Ninoiwa, Kitanoshima and Nakanoshima (Fig. 11; Table S3).

386 High-Si boninite-series rocks of the Mukojima Island Group consist of boninite, bronzite andesite,
387 dacite and quartz rhyolite, which range in SiO₂ from 54.6 to 77.1 wt%. In general, high-Si boninite-series
388 shows sharp bends around 60 wt% SiO₂ on MgO, Al₂O₃, CaO and FeO*/MgO vs. SiO₂ diagrams (Fig. 11;

389 Table S3). For example, with increasing SiO₂, MgO decreases and Al₂O₃ increases until 60 wt% SiO₂, and
390 both gradually decrease in higher (>60 wt%) SiO₂. These compositional range and characteristics are the
391 same as those of the Maruberiwan and Asahiyama Formations in the Chichijima Island Group (Umino 1985;
392 1986; Taylor *et al.* 1994; Umino & Nakano 2007), which is distinctive from arc tholeiitic and calc-alkalic
393 rocks from the Ogasawara Islands (Taylor & Nesbitt 1995; Yajima *et al.* 2001; Umino & Nakano 2007;
394 Haraguchi *et al.* 2008; Kanayama *et al.* 2010), Quaternary volcanic front (Taylor & Nesbitt 1998; Ishizuka
395 *et al.* 2007) and the Ogasawara forearc (Ishizuka *et al.* 2011). However, high-Si boninite-series rocks that
396 fall between 65 and 73 wt% SiO₂ (dacite) in the Mukojima island Group are very few, whereas boninite
397 series of the Maruberiwan Formation varies continuously from 54 to 78 wt% SiO₂. Some high-Si
398 boninite-series rocks with 60-64 wt% SiO₂ from the upper central block of Nakodojima form a distinct
399 trend which plots off the compositional trend of the main high-Si boninite-series rocks of the Ogasawara
400 Islands (Fig. 11). They plot on a tie line connecting a boninite with 60 wt% SiO₂ and a dacite with 64 wt%
401 SiO₂, suggesting magma mixing of these two end components. This is supported by the presence of
402 disequilibrium textures such as resorbed hypersthene and augite enclosed by magnesian bronzite.

403 Low-Si boninite series-rocks of the Mukojima Island Group consist of bronzite andesite with
404 57.9-60.9 wt% SiO₂. They have 0.26-0.41 wt% TiO₂, 5.5-4.1wt% MgO and 1.6-2.6 FeO*/MgO, which
405 generally plot within the compositional range of low-Si boninite series of the Mikazukiyama Formation
406 (Yajima & Fujimaki 2001; Umino & Nakano 2007) unconformably overlying the Maruberiwan and
407 Asahiyama Formations in the Chichijima Island Group (Umino & Nakano 2007) (Fig. 11; Table S3).
408 Compositional variations of these low-Si boninite-series rocks of the Ogasawara Islands partially overlap
409 with those of bronzite andesite from DSDP Site 458 (Meijer *et al.* 1981; Wood *et al.* 1981; Reagan *et al.*
410 2010). Such low-Si boninite-series rocks show intermediate compositional ranges between high-Si
411 boninite-series rocks in the Mukojima and Chichijima Island Groups and arc lavas of the Hahajima Island

412 Group.

413 Arc tholeiitic rocks of the Mukojima Island Group range from andesite to dacite with 58.3-71.0
414 wt% SiO₂, 0.43-0.76 wt% TiO₂, 6.0-9.2 wt% FeO*, 1.72-6.3 wt% MgO and 1.4-3.8 FeO*/MgO ratio (Fig.
415 11; Table S3). These rocks plot within a field of calc-alkaline rocks on the FeO*/MgO vs. SiO₂ diagram
416 (Fig. 11). However, these samples are severely altered under greenschist-facies metamorphism and SiO₂ is
417 significantly raised as indicated by pervasive quartz veins and vesicle fillings. Positive correlations of
418 immobile Ti and Zr indicating Ti enrichment with differentiation, as well as slight LREE-depleted REE
419 patterns are concordant with the view that they are primarily tholeiitic. They plot within the range of the
420 John Beach Volcanics in Chichijima (Umino & Nakano 2007; Ishizuka *et al.* 2012), except for extremely
421 low CaO (1.5-3.7 wt%) and high Na₂O (4.1-6.3 wt%) which can also be ascribed to greenschist-facies
422 alteration. Arc tholeiitic rocks of the Mukojima Island Group and the John Beach Volcanics
423 characteristically show lower P₂O₅ contents than the Hahajima Island Group lavas (Taylor & Nesbitt 1995;
424 Yajima *et al.* 2001; Kanayama *et al.* 2010) (Fig. 11).

425

426 2. Trace elements

427 High-Si boninite-series rocks from the Mukojima Island Group have 3.3-36.5 ppm Rb, 0.75-4.47
428 ppm Pb, 6.0-72.9 ppm Zr, 0.34-2.62 La ppm and 0.35-3.01 ppm Yb, which is similar to those of the
429 Maruberiwan and Asahiyama Formations in the Chichijima Island Group (Taylor *et al.* 1994) (Fig. 12a, b,
430 Table S3). The high-Si boninite-series rocks have characteristic highly depleted, U-shaped
431 chondrite-normalized REE patterns, positive anomaly of Zr and Hf (Zr/Ti=0.01-0.09) in spider diagrams
432 and higher LILE (large ion-lithophile element)/Nb (Ba/Nb=29-161, Th/Nb=0.21-0.87, Pb/Nb=1.53-10.6)
433 ratios compared with tholeiitic and calc-alkaline lavas of the Eocene and Quaternary volcanic front (Taylor
434 & Nesbitt 1995; 1998; Ishizuka *et al.* 2007; Yajima *et al.* 2001, Kanayama *et al.* 2010), which suggests

435 larger degrees of source depletion and the contribution of slab input (Fig. 12a, b, 13).

436 Low-Si boninite-series rocks from the Mukojima Island Group indicate flat REE and slightly
437 LREE-depleted patterns with 9.7-13.3 ppm Rb, 28.5-43.3 ppm Zr and 0.83-1.35 ppm Yb (Fig. 12c, d, Table
438 S3). LILE/Nb ratios (Ba/Nb=38-57, Th/Nb=0.24-0.40, Pb/Nb=2.24-2.81) are similar to or lower than the
439 high-Si boninite-series rocks and higher than the Hahajima arc tholeiitic and calc-alkaline rocks. These
440 rocks are similar to low-Si boninite-series rocks of the Mikazukiyama Formation in HREE, HFSE and LILE
441 abundances (Fig. 12c, d, 13). However, LREE-depleted REE patterns of the low-Si boninite-series rocks of
442 the Mukojima Island Group are similar to bonzite andesite from site 458 (Hickey & Frey 1981; Reagan *et*
443 *al.* 2010) rather than the U-shaped REE patterns of low-Si boninitic rocks of the Mikazukiyama Formation
444 (Fig. 12c, d).

445 Arc tholeiitic andesite and dacite of the Mukojima Island Group have compositions (1.78-9.11 ppm
446 Rb, 23.0-66.9 ppm Zr, 01.06-2.68 ppm Yb and La/Yb = 0.67-1.14) that are similar to or more depleted than
447 the John Beach Volcanics (Chichijima) (Fig. 12 e, f, Table S3). Highly scattered LILEs abundances such as
448 Cs, Rb and Ba for tholeiitic rocks from the Mukojima Island Group is most likely due to pervasive low
449 temperature alteration (Fig. 12e). Lower Nb/Yb (0.23-0.34) and higher LILE/Nb (Ba/Nb=47-396,
450 Th/Nb=0.25-0.41, Pb/Nb=1.26-2.17) ratios distinguish them from the Hahajima arc tholeiitic and
451 calc-alkaline rocks (Nb/Yb=0.28-1.49, Pb/Nb=0.21-1.38) (Fig. 13). LREE/HREE ratios of these tholeiites
452 from the Mukojima Island Group and the John Beach Volcanics are higher than those of MORB-like basalt
453 from the Ogasawara Trench (La/Yb=0.27-0.72; Ishizuka *et al.* 2011) (Fig. 12f).

454

455 **3. Classification of high-Si boninite**

456 High-Si boninite occurs in Yon'noiwa, Sasayojima, Mukojima, Nakodjima and Yomejima.
457 Boninite of Mukojima Island Group is divided into three types on the basis of major and trace element

458 characteristics (Fig. 14). Although REE abundances of type 1, 2 and 3 boninites are similar (e.g.,
459 $Yb=0.36-0.61$ ppm; Fig. 14c), significant differences are apparent especially for SiO_2 , CaO, Al_2O_3 , total
460 alkali (Na_2O+K_2O) contents, CaO/ Al_2O_3 , Zr/Ti and LILE/HREE ratios. Chemical characteristics of each
461 type are described as follows:

462 *Type 1 high-Si boninite* This comprises dikes, pillow lavas, massive and bedded tuff breccia in the
463 stratigraphically middle part of Mukojima as well as most boninite successions in the rest of the Mukojima
464 Island Group. They have high SiO_2 (>57.0 wt%), total alkali (>1.7 wt%), Zr/Ti (>0.022) and LILE/HREE
465 ($Ba/Yb>51$), medium to high Al_2O_3 (9.4-11.6 wt%), and low CaO (<8.0 wt%) and CaO/ Al_2O_3 (<0.8). They
466 plot within the range of “low-Ca boninite” of Crawford *et al.* (1989) that includes most boninites from the
467 Izu-Ogasawara-Mariana forearc. Type 1 high-Si boninites are similar to boninites from the Maruberiwan
468 Formation on Chichijima (“Type I, II and III boninites” of Umino (1986) and most boninites described by
469 Taylor *et al.* (1994)), Mariana Trench such as D28, D50 and site 1403 (e.g. Bloomer & Hawkins 1987),
470 Cape Vogel (e.g. Walker & Cameron 1983) and New Caledonia (Shiraki *et al.* 1984), however, they are
471 discriminated from boninites having lower SiO_2 (<56.7 wt%) contents from ODP Site 786 (Arculus *et al.*
472 1992; Pearce *et al.* 1992b), DSDP Site 458 (e.g. Hickey-Vargas 1989) and the Guam Facpi Formation (e.g.
473 Reagan & Meijer 1984).

474 *Type 2 high-Si boninite* forms pillow lava and pyroclastic rocks in the upper part of Mukojima.
475 This has lower SiO_2 (<57.1 wt%), total alkali (<1.4 wt%), Zr/Ti (<0.010) and LILE/HREE ($Ba/Yb<47$)
476 ratios, medium CaO (8.8-9.1 wt%) content and CaO/ Al_2O_3 (0.8) ratio, and high Al_2O_3 (>10.7 wt%). “Type
477 IV boninite” of Umino (1986) from the Maruberiwan Formation in Chichijima is geochemically and
478 petrographically identical to type 2 boninite. SiO_2 , FeO*, Zr/Ti and LILE/HREE ratios of this type are
479 similar to low-Si boninites of the Mikazukiyama Formation. However, CaO, Al_2O_3 , total alkali and trace
480 element concentrations are clearly lower, and MgO and CaO/ Al_2O_3 are higher than in the low-Si boninites.

481 Although $\text{CaO}/\text{Al}_2\text{O}_3$ and total alkali contents of type 2 boninite are similar to “high-Ca boninite” of
482 Crawford *et al.* (1989) of which reference site is the Troodos ophiolite (e.g. Cameron 1985), type 2 boninite
483 is readily distinguished from Crawford’s high-Ca boninite in terms of higher SiO_2 and FeO^* contents, and
484 lower Al_2O_3 and CaO contents. REE contents of Mukojima type 2 boninite is more depleted than the
485 Troodos boninite (e.g. Cameron 1985).

486 *Type 3 high-Si boninite* forms pillow lavas and bedded and massive tuff breccia of Mukojima. They
487 have remarkably high $\text{CaO}/\text{Al}_2\text{O}_3$ (0.9-1.1), medium to high CaO (7.8-9.8 wt%) and SiO_2 (57.6-60.7 wt%),
488 medium Zr/Ti (0.018-0.027) and LILE/HREE (Ba/Yb=36-76), and low to medium total alkali (1.2-1.9 wt%)
489 and Al_2O_3 (7.9-10.4 wt%) contents. Type 3 boninite has intermediate chemical compositions between type 1
490 and 2 except that type 3 has the highest $\text{CaO}/\text{Al}_2\text{O}_3$ and CaO and the lowest Al_2O_3 .

491

492 **Discussion**

493 *1. Volcanic activity of the Mukojima Island Group*

494 Common occurrence of pillow lava in the lower portion of Mukojima suggests quiet to moderate
495 eruptions at water depths more than several hundred meters. This agrees with the estimated water depth up
496 to 5000 m (as discussed below) for the lower Maruberiwan Formation on Chichijima, where pillow lava
497 dominates over a few pyroclastic interbeds. Increasingly pyroclastic deposits are found stratigraphically
498 higher on Mukojima suggests that the water depth of the source vent(s) shallowed as the volcanic edifice
499 grew. However, the common presence of poorly vesiculated scoria (<10 vol %) and water-chilled volcanic
500 bombs still indicates submarine eruptions.

501 Nakodjima andesite lavas have similar SiO_2 contents to the lower boninite lavas in Mukojima,
502 which form intact, close-packed pillows. However, hyaloclastic fragmentation of lava into glassy to
503 aphanitic clasts prevails on Nakodjima. Unlike boninite, hyaloclastic andesite lavas have abundant

504 plagioclase microlites in the groundmass. Fragmentation of lava into aa clinker may be caused by
505 plagioclase crystallization prior to extrusion, because the presence of plagioclase significantly increases
506 relaxation time of stress induced by cooling and shearing of erupting lava (Polacci *et al.* 1999). This
507 suggests that fragmentation of the Nakodojima lavas was caused by higher viscosities due to crystallization
508 of plagioclase enhanced by degassing under shallower water as well as accompanying fractionation of
509 mafic minerals. The pumice tuff on Nakodojima is composed of “woody pumice” with numerous tubular,
510 subparallel vesicles, suggesting a low vapor pressure during eruption such as under submarine environment
511 (Fisher & Schmincke 1984; Kato 1987). The presence of surge deposits on Yomejima also suggests that the
512 eruption took place about sea level because surges are turbulent low-density currents generally formed
513 above the water level.

514 Therefore, volcanic activities of the Mukojima Island Group began with quiet extrusion of pillow
515 lava under deep water at a depth of hundreds of meters. As the volcanic edifice grew, the activity changed
516 gradually into moderately explosive and produced pyroclastic rocks under shallow water or above sea level
517 and formed the upper succession of Mukojima, Nakodojima and the uppermost part of Yomejima. The
518 shallowing water depth of the Mukojima Island Group is consistent with the uplift of the entire Ogasawara
519 Ridge during the Eocene period (Fig. 4; Umino & Nakano 2007; Umino *et al.* 2009).

520

521

522 ***2. Correlation and emplacement of tephras***

523 Lower-MgO (<1 wt%) and higher-SiO₂ (>75 wt%) contents of pumice in M3-07G, H and M2-06D
524 from Mukojima and N2-09 from Nakodojima have similar glass composition, suggesting that these tephras
525 were derived from the same source, maybe the same eruption. Likewise, coincidence of major element
526 compositions of pumice glass with higher MgO (>1 wt%) and lower SiO₂ (<75 wt%) contents of M3-07G,

527 H, I and M2-06D indicates a similar origin (Fig. 8). Although pumice with higher MgO (>1 wt%) has not
528 been recovered from N2-09 in Nakodojima, limited sampling of Nakodojima tephra does not exclude this
529 as a possible source because it is the only island among Mukojima Island Group that yields felsic magmas.
530 Furthermore, the maximum size of pumice is several cm on Nakodojima, much larger than that on
531 Mukojima. It is very likely that Mukojima tephra was derived from volcano near Nakodojima. On the other
532 hand, scoriae included in M3-07G and H are low-Zr/Ti type 2 boninite. Presumably these were reworked
533 from pyroclastic deposits on Mukojima, which are the main constituent of the upper Mukojima sequence.

534 Mukojima pumice and scoriae were transported by turbidity currents toward S50-88°E as
535 indicated by imbrication of pyroclastic clasts. It is likely that pumices were erupted near the present site of
536 Nakodojima and were originally transported by currents northwards and deposited on the seafloor. Then, it
537 was transported by turbidity currents which reworked unconsolidated boninite scoriaceous deposits and
538 redeposited these as a mixture of pumice, scoriae, crystal and lithic clasts in the southeast of Mukojima.

539

540 *3. Correlation of Mukojima and Chichijima Island Group volcanic strata*

541 Volcanic rocks from the Mukojima Island Group are the same rock types that occur in the
542 Chichijima Island Group (Umino 1985; Umino & Nakano 2007). Major and trace element bulk
543 compositions and the differentiation trends of most high-Si boninite-series rocks of the Mukojima Island
544 Group are identical to those of the Maruberiwan and Asahiyama Formations of the Chichijima Island
545 Group (Figs 11, 12, 13). Radiometric dating Mukojima and Chichijima Island Groups boninitic rocks
546 indicate that high-Si boninitic magmatism were simultaneously active at both sites (Fig. 5; Ishizuka *et al.*
547 2006, 2011; Umino *et al.* 2009). We can make some estimates about the water depth at which these lavas
548 were erupted. The lowermost Maruberiwan Formation on Chichijima is dominated by pillow lava (Fig. 3;
549 Umino 1985; Umino & Nakano 2007). Although H₂O solubility in Maruberiwan boninite melt is

550 experimentally determined only for pressures >900 MPa (Umino & Kushiro 1989), these data plot on the
551 extrapolated solubility curve for a boninitic melt estimated by the method of Moore *et al.* (1998). Given a
552 primary water content of 2.2 wt% retained in the boninite lava upon extrusion (Dobson *et al.* 1995), the
553 water depth is estimated as 5000 m based on the calculated solubility of H₂O in the boninitic melt.
554 However, the middle to uppermost Maruberiwan Formation and the Asahiyama Formation have a larger
555 amount of pyroclastic deposits including scoriae, volcanic bombs and fragmentary lava clasts. These
556 pyroclastic rocks are overlain by the Mikazukiyama Formation including a subaqueous pyroclastic flow
557 deposit composed of well-vesiculated pumice (Fig. 3; Umino 1985; Umino & Nakano 2007). The
558 coincidental shallowing of eruption depths is ascribed to uplift of the entire Ogasawara Ridge during 48-44
559 Ma (Umino & Nakano 2007; Umino *et al.* 2009).

560 The above evidence suggests that most high-Si boninite-series volcanic strata on Mukojima
561 Island Group are likely to have been formed simultaneous with eruptions to form the Maruberiwan and
562 Asahiyama Formations on Chichijima Island Group (Fig. 5).

563 In Chichijima Island Group, erosional surfaces indicating obvious quiescent period are identified
564 between high-Si boninite, bronzite andesite and dacite of the Maruberiwan Formation and quartz dacite and
565 rhyolite of the Asahiyama Formation, and between the Asahiyama Formations and low-Si boninite series
566 and calc-alkaline rocks of the Mikazukiyama Formations (Umino 1985; Umino & Nakano 2007). However,
567 in Mukojima Island Group, high-Si boninite, bronzite andesite, dacite and quartz rhyolite lavas and
568 breccias alternate on Nakodajima, and radiometric ages for Nakodajima quartz rhyolite (48 Ma) is older
569 than that of Mukojima boninite (46.6 Ma), indicating that these magma types erupted about the same time
570 (Fig. 4, 5).

571 Whole rock compositions of low-Si boninite-series rocks of the Mukojima Island Group are
572 similar to 45-Ma low-Si boninite-series rocks of the Mikazukiyama Formation (Yajima & Fujimaki 2001;

573 Ishizuka *et al.* 2006; Umino & Nakano 2007) which occur between 48-46-Ma high-Si boninite and 45-40
574 Ma arc tholeiitic and calc-alkaline rocks in Hahajima (Ishizuka *et al.* 2006) (Figs 11, 12, 13). The low-Si
575 boninitic andesite breccia from the uppermost Yomejima is correlatable with the Mikazukiyama Formation
576 because of its radiometric age (44 Ma; Ishizuka *et al.* 2011) and isotopic ratios (Ishizuka, unpublished data,
577 2011) in addition to bulk major and trace element compositions (Fig. 5). In Nakodajima, low-Si
578 boninite-series andesite lava is presumably interbedded with high-Si boninite-series lavas, suggesting that
579 such transitional low-Si boninite magma and high-Si boninite magma are simultaneously active (Figs 4, 5).
580 Although radiometric ages and stratigraphic relationships of the low-Si boninitic andesite of Harinoiwa
581 and Tatamiwa with the other rock types are unknown, these low-Si boninitic andesites are probably
582 correlatable to the Maruberiwan or Mikazukiyama Formations.

583 Although radiometric dating has not been successful for John Beach Volcanics tholeiitic andesite
584 and dacite from Chichijima and Mukojima Island Groups, similar geochemical characteristics of these two
585 tholeiitic suites strongly suggest similar sources during pre-boninite volcanism (Fig. 3; Umino 1985;
586 Umino & Nakano 2007). Moreover, tholeiitic lavas and pyroclastics on Ninoiwa, Kitanoshima and
587 Nakanoshima suffered amphibolite-facies metamorphism, whereas Mukojima Island Group boninite-series
588 rocks are relatively fresh. The higher metamorphic grade of the tholeiitic rocks of the former islands is
589 consistent with the view that they are stratigraphic lower than and were once buried beneath boninite-series
590 rocks. Arc tholeiitic rocks of Mukojima Island Group and the John Beach Volcanics may be transitional
591 type between MORB-like and boninitic rocks, like tholeiitic lava of Site 458 and 459 (Figs 12, 13) (Hickey
592 & Frey 1981; Reagan *et al.* 2010).

593 Consequently, the Maruberiwan, Asahiyama and Mikazukiyama Formations in Chichijima Island
594 Group (Umino 1985; Umino & Nakano 2007) can be correlated with Mukojima Island Group volcanic
595 successions (Figs 4, 5).

596

597

598 **4. Petrogenesis of boninites from the Mukojima Island Group**

599 As shown in Fig. 14, vectors controlled by phenocrystic phases cannot reproduce chemical trends
600 of type 1 boninite by fractionation of type 2 boninite, and vice versa. Therefore, type 1 and 2 boninites are
601 derived from discrete parental magmas. Type 3 boninite has both normally zoned high-Mg# and reversely
602 zoned low-Mg# pyroxenes, and resorbed plagioclase in a single specimen. Therefore, it is likely that type 3
603 boninite is a mixing product of evolved magmas with augite, hypersthene and plagioclase and type 1 or 2
604 boninite magmas. However, no boninite-series and tholeiitic- and calc-alkaline rock-series lavas plot on
605 the extensions of postulated mixing lines connecting type 1 or 2 and 3 boninites. On the contrary, type 3
606 boninites can be reproduced by adding augite, hypersthene and plagioclase to type 1 boninite (Fig. 14).
607 Compositional variations among type 3 boninites can form by mixing type 1 boninite and the variable
608 proportions of augite, hypersthene and plagioclase. The presence of rare resorbed plagioclase clots in type
609 3 boninite suggest plagioclase dissolution in type 1 boninite magmas which are undersaturated with
610 plagioclase. The absence of evolved end member magma can be reconciled if captured crystals derived
611 from a mushy magma reservoir which were heated and partially remobilized by the supply of hot boninite
612 magma (e.g. Umino & Horio 1998; Costa *et al.* 2010; Huber *et al.* 2012).

613 Boninite-series rocks are geochemically characterized by their U-shaped REE patterns, depletion
614 in HFSEs (high-field-strength elements) and Nd isotope ratios, and enrichment in LILEs (e.g. Hickey &
615 Frey, 1982; Pearce *et al.* 1992a, b). Pearce *et al.* (1992a, b) and Taylor *et al.* (1994) concluded that trace
616 element and isotopic ratios of boninite from ODP Site 786 and those of the Chichijima Maruberiwan
617 Formation are explained by mixing three components: depleted mantle peridotite, hydrous melt resulted
618 from slab melting in the presence of residual amphibole, and typical slab dehydration fluids.

619 Type 1 boninite from Mukojima has the same range in trace element concentrations and ratios,
620 such as Zr/Ti and Sm/Zr, with most Maruberiwan Formation boninite (Type I, II and III boninites of Umino
621 (1986)) and low-Ca boninite of ODP Site 786 (Pearce *et al.* 1992a, b). In contrast, type 2 boninite has
622 markedly low Zr/Ti and high Sm/Zr ratios. Type 2 boninite is geochemically and petrographically identical
623 to Type IV boninite of Umino (1986) from the Chichijima Maruberiwan Formation, however, the
624 petrogenesis of type 2 has not been discussed by the previous studies.

625 Boninites are severely depleted in incompatible elements such as HFSEs and REEs, which are
626 inherited from a depleted source mantle. Production of MORB-like basalt may have depleted this source.
627 We will discuss the Zr/Ti versus Yb variations of type 1 and 2 boninites (Fig. 15) based on the model
628 calculation of melting of boninite source which is a mixture of 15%-batch melts of depleted peridotite (0 to
629 20% partial melts subtracted Depleted MORB Mantle (DMM: Workman & Hart 2005) before 15% melting)
630 and amphibolitic slab melt. The model calculations suggest that the degree of depletion of the source
631 mantle for type 1 and 2 boninites does not vary. This result indicates that boninite sources were
632 considerably more refractory than the sources for MORB and arc basalt such as those of Hahajima and the
633 Quaternary Izu-Ogasawara arc. The modeling also indicates that Zr enrichment of boninites can be
634 explained by contributions of partial melt of hydrated basaltic slab with amphibolite residue. Because Ti is
635 more compatible than Zr in amphibolite (Hilyard *et al.* 2000), melt in equilibrium with amphibolitic residue
636 has a high Zr/Ti. With the consensus that magmas of the Quaternary volcanic front of the Izu-Ogasawara
637 arc are produced by fluxing the mantle by fluids and melts derived from subducted sediments and oceanic
638 crust (Taylor & Nesbitt 1998; Ishizuka *et al.* 2007), the slab melting under amphibolite facies indicates a
639 much hotter shallow wedge mantle at ~48 Ma than in Quaternary time. This is consistent with the
640 suggestion of asthenospheric upwelling at the initiation of the Izu-Ogasawara subduction zone (Stern &
641 Bloomer 1992; Ishizuka *et al.* 2006, 2011; Reagan *et al.* 2010). The modeling also suggests that the

642 difference in Zr/Ti ratio between type 1 and 2 Mukojima boninites can be explained by different
643 proportions of amphibolitic slab melt added to a similar mantle source: Type 1 boninite with higher Zr/Ti
644 reflects more slab melt (7-15%), whereas type 2 boninite with lower Zr/Ti has less (4-5%). Maruberiwan
645 Formation boninite magma is considered to have been produced by partial melting of hydrous and highly
646 depleted mantle at shallow depths (0.8-1.2 GPa and 5% H₂O; Umino & Kushiro 1989; 0.3 GPa and 3% H₂O;
647 van der Laan *et al.* 1989). However, differences in major and trace element compositions between type 1
648 and 2 boninites require different melting conditions, such as temperature, pressure, water content, source
649 depletion, and degrees of melting. Petrogenetic models should explain both major and trace element
650 characteristics and differences of type 1 and 2 boninite magmas, which we will address in the future.

651

652 **Summary**

653 [Mukojima](#) Island Group consists of three clusters of islands from NNW to SSE: 1) Ninoiwa,
654 Yon'noiwa, Kitanoshima, Nakanoshima and Sasayojima in the north; 2) Mukojima, Harinoiwa, Tatamiiwa
655 and Nakodajima in the middle; and 3) Yomejima in the south. Kitanoshima, Nakanoshima and Ninoiwa in
656 the northern cluster consist of tholeiitic andesite and dacite, which form agglutinate and pillow and sheet
657 lava suffered from greenschist-facies alteration; these rocks are undated but are thought to be the oldest
658 strata on the Mukojima Island Group. The other two clusters of islands are composed of boninite-series
659 rocks that range in age from 48 to 44.3 Ma. Boninite and bronzite andesite mainly occur as pillow lava and
660 pyroclastic rocks, however, bronzite andesite lava exists as brecciated pillows and hyaloclastite.
661 Nakodajima dacite and quartz dacite occur as hyaloclastite and tephra. Hydrothermal alteration associated
662 with copper-bearing mineral deposits is present on Nakodajima and Maejima. Pumice-bearing tephra occurs
663 at stratigraphically upper levels in Nakodajima and Mukojima, which are correlated based on mineral and
664 glass compositions. Thicknesses of moderately undulating volcanic strata attains more than 830 m on

665 Kitanoshima and Nakanoshima, 750 m on Mukojima, 240 m on Nakodjima, and 480 m on Yomejima.
666 NW-SE and NNE-SSW trending faults dominate on Mukojima and Nakodjima, respectively. Ninoiwa,
667 Kitanoshima and Nakanoshima tholeiites are correlated with the John Beach Volcanics of Chichijima,
668 which is the lowermost unit Maruberiwan Formation. Other islands in the Mukojima Islands Group
669 comprising boninite-series rocks are correlated with the main part of the 48 to 46-Ma Maruberiwan and
670 Asahiyama Formations, and perhaps correlated with the 45-44 Ma Mikazukiyama Formation of Chichijima.
671 The uppermost Yomejima are correlated to the Mikazukiyama Formation. All boninite-series rocks from
672 boninite to dacite are interbedded on Nakodjima, indicating concurrent activity of these magma types.

673 Volcanic activity now preserved on the Mukojima Island Group began with quiet submarine
674 extrusion of pillow lava at a depth of hundreds of meters. As the volcanic edifice grew, the activity changed
675 gradually into moderately explosive eruptions that produced pyroclastic fall and flow deposits under
676 shallow water or above sea level; these sequences are preserved in the upper Mukojima and Nakodjima
677 and uppermost Yomejima strata. The shallowing water depth of volcanic sequences exposed in the
678 Mukojima Island Group is consistent with the uplift of the entire Ogasawara Ridge during the Late Eocene
679 period.

680 Most boninite-series rocks of the Mukojima Island Group belong to high-Si boninite series which
681 show the same major and trace element compositional ranges and differentiation trends as those of the
682 Maruberiwan and Asahiyama Formations of Chichijima. They have remarkably low TiO_2 , depleted
683 U-shaped REE patterns, higher LILE/Nb and Zr/Ti ratios. Major and trace element compositions of low-Si
684 boninitic andesites from Harinoiwa, Tatamiwa, Nakodjima and Yomejima plot within the ranges of low-Si
685 boninite series rocks from the Mikazukiyama Formation of the Chichijima Island Group, which are
686 intermediate between the high-Si boninite series and tholeiitic and calc-alkaline rocks from Hahajima
687 Islands. Tholeiitic rocks of the Mukojima Island Group resemble the John Beach Volcanics in terms of

688 major and trace elements. They are lower in P_2O_5 and Nb/Yb, and higher in LILE/Nb than the Hahajima
689 andesite and dacite.

690 Type 1 and 2 boninites have discrete parental magmas. Trace element modeling shows that type 1
691 and 2 boninites can be produced by partial melting of DMM which experienced 12 to 18 %-melt subtraction
692 before melting. This pre-melting source depletion is most plausibly the consequence of formation of the
693 MORB-like basalt that predates boninite magmatism in this region. The modeling also suggests that
694 difference in Zr/Ti between type 1 and 2 boninites can be explained by varying degrees of amphibolitic
695 slab-melt contribution, which is higher (7-15%) for type 1 boninite with higher Zr/Ti ratios and lower
696 (4-5%) for type 2 boninite with lower Zr/Ti ratios. Type 3 boninite does not represent a liquid composition
697 but is a contaminated type 1 boninite with xenocrysts of augite, hypersthene and plagioclase.

698

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706

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- 909

910 Figure 1 Map of the Philippine Sea Plate showing the location of the Ogasawara Ridge and some tectonic
911 features. Stars: borehole sites of Ocean Drilling Program.

912

913 Figure 2 (a) Enlarged rectangle in Fig. 1 showing the Ogasawara Island Groups. (b) Bathymetric map
914 (rectangle in Fig. 2a) showing the distribution of islands and reefs of the Mukojima Island Group.

915

916 Figure 3 Generalized volcanic stratigraphy of the Chichijima Island Group modified after Umino (1985)
917 and Umino & Nakano (2006, 2007). Data sources of radiometric ages are; a, Dobson (1986); b, Ishizuka *et*
918 *al.* (2006); c, Ishizuka *et al.* (2011).

919

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921 the Ogasawara Ridge. Stratigraphic data: Western scarp of the Ogasawara Ridge (Ishizuka *et al.* 2006),
922 Hahajima Island Group (Umino *et al.* 2009), Chichijima Island Group (Umino & Nakano 2007) and
923 Ogasawara Trench slope (Ishizuka *et al.* 2011). Radiometric ages are from Ishizuka *et al.* (2006; 2011).

924

925 Figure 5 Geological columns showing the stratigraphic relationships of the Mukojima Island Group.

926 Symbols are the same as those in Fig. 6. $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Ishizuka *et al.* (2011) are shown on the side of
927 the columns. Tholeiitic strata of Ninouiwa, Kitanoshima and Nakanoshima are presumably correlatable to
928 the John Beach Volcanics in the lowermost Maruberiwan Formation of Chichijima. High-Si boninite-series
929 rocks of Yon'noiwa, Sasayojima, Mukojima, Nakodjima and most of Yomejima are correlatable to the
930 Maruberiwan and Asahiyama Formations of Chichijima. Low-Si boninitic andesite of the uppermost part of
931 Yomejima is correlated to the Mikazukiyama Formation because of the younger $^{40}\text{Ar}/^{39}\text{Ar}$ ages for andesite
932 clast. Harinoiwa and Tatamiwa low-Si boninitic andesites may be correlated with the Maruberiwan and

933 Mikazukiyama Formations.

934

935 Figure 6 Geological maps and sampling localities of the Mukojima Island Group. (a) Kitanoshima and

936 Nakanoshima, (b) Sasayojima, (c) Mukojima, (d) Harinoiwa, (e) Nakodojima, (f) Yomejima.

937

938 Figure 7 Representative outcrops of the Mukojima Island Group. (a) Pillow lava of Nakanoshima. (b)

939 Northwestern cliff of Kitanoshima showing steeply inclined agglutinate layers to east. (c) Close-up view of

940 the agglutinate in b consisting of densely to moderately welded lava clasts up to 10 cm in diameter. Scale is

941 20 cm. (d) Pillow lava exposed on the southwestern cliff of Mukojima. (e) Western cliff of Torishima,

942 southwest of Mukojima. Bedded tuff breccia is underlain by pillowed boninite. (f) Volcanic bombs and

943 scoriae in massive tuff breccia of the uppermost Mukojima. (g) The uppermost massive tuff breccia is

944 widely exposed on central Mukojima. (h) Northeastern cliff of Harinoiwa. Andesite pillow lobes are

945 brecciated into glassy fragments and laterally change into hyaloclastite. Some dikes terminate within the

946 hyaloclastite and pillow lava. (i) South reef of Nakodojima. Bronzite andesite pillow lava on the right is

947 in-situ brecciated to glassy and lithic fragments which grade into massive hyaloclastite to the left. (j)

948 Western and central areas of Nakodojima. White alteration zones in front right and back left run northwest

949 in echelon in the central block. (k) Maejima, an islet southwest off Yomejima, is composed of bedded

950 volcanic and tuff breccia which are weakly to moderately welded. (l) Dike swarm of boninite and altered

951 bronzite andesite intruded into the tuff breccia in the center of Yomejima.

952

953 Figure 8 Tephras in Mukojima (M3-07 and M2-06D) and Nakodojima (N2-09). Sample localities are shown

954 in Fig. 3. (a) Pumice and scoria tuff and lapillistone (M3-07) are exposed on the east cliff of Mukojima. (b)

955 Columnar section at M3-07. (c)-(e) Microphotographs of (c) woody pumice, (d) crystal-free scoria and (e)

956 crystal-rich scoria in M3-07G and H. (f) Pumice and scoria tuff (M2-06) exposed on the east coast cliff of
957 Mukojima. (g) Pumice tuff (N2-09) lies between overlying quartz rhyolite and underlying bronzite andesite
958 tuff breccia on the eastern cliff of Nakodjima. N2-09 sample was recovered on the ridge to the left of the
959 photograph, where the pumice tuff becomes thinner to the north about 30 cm in thickness.

960

961 Figure 9 Microphotographs of volcanic rocks from the Mukojima Island Group. bz: bronzite, cpx:
962 clinopyroxene, cen: clinoenstatite, aug: augite, hyp: hypersthene, pl: plagioclase, qtz: quartz. (a) Typical
963 type 1 boninite. All boninite contain bronzite as a phenocryst and a microphenocryst, and clinopyroxene as
964 a groundmass mineral (plane-polarized light). (b) Clinoenstatite phenocryst in type 1 boninite
965 (plane-polarized light). (c) Type 2 boninite commonly has both augite and bronzite microphenocrysts
966 (crossed polars). (d) Irregular-shaped augite and reversely zoned hypersthene with glass inclusions in the
967 core in type 3 boninite (plane-polarized light). (e) Bronzite andesite resembles boninite in terms of mineral
968 assemblages but is distinguished by the presence of plagioclase laths in the vesicular groundmass
969 (plane-polarized light). (f) Dacite has small phenocrysts of plagioclase, augite, hypersthene and magnetite
970 embedded in a glassy groundmass with a small amount of microlites (plane-polarized light). (g) Quartz
971 rhyolite is similar to dacite but carries quartz as a phenocryst. The groundmass is holohyaline with
972 abundant microspherulites (plane-polarized light). (h) Tholeiitic andesite tuff breccia in Ninoiwa.
973 Groundmass crystal size differs from clast to clast. Plagioclase and pyroxene are mainly altered to albite,
974 epidote, chlorite, sphene and magnetite (plane-polarized light).

975

976 Figure 10 Glass and mineral compositions of tephra samples from Mukojima and Nakodjima. (a) SiO₂ vs.
977 MgO (wt%) of matrix glass of scoria and pumice in tephra. (b) Chondrite (Sun & McDonough
978 1989)-normalized REE patterns of matrix glass of scoria and pumice. (c) Pyroxene compositions of

979 phenocrysts and microphenocrysts in tephra.

980

981 Figure 11 Bulk major element compositions of Mukojima Island Group volcanic rocks. The line on the
982 FeO^*/MgO vs. SiO_2 diagram shows the boundary of tholeiitic and calc-alkaline series for the Quaternary
983 volcanic rocks from Izu-Hakone region after Miyashiro (1974). Data sources: boninite series rocks of the
984 Maruberiwan and Asahiya Formations of the Chichijima Island Group (Umino, 1986; Taylor *et al.* 1994;
985 Umino & Nakano 2007; original data), the John Beach Volcanics (Umino & Nakano 2007; Ishizuka *et al.*
986 2012), low-Si boninite series of the Mikazukiyama Formation (Yajima & Fujimaki 2001; Umino & Nakano
987 2007; original data), tholeiite and calc-alkaline rock series from the Hahajima Island Group (Taylor &
988 Nesbitt 1995; Yajima *et al.* 2001; Kanayama *et al.* 2010), MORB-like basalt from the Ogasawara (Ishizuka
989 *et al.*, 2011) and Mariana Trench (Reagan *et al.* 2010), bronzite andesite from Site 458 and tholeiitic rocks
990 from Site 458 and 459 (Meijer *et al.* 1981; Wood *et al.* 1981; Reagan *et al.* 2010).

991

992 Figure 12 Representative trace element compositions for volcanic rocks from the Mukojima Island Group.
993 Boninites, bronzite andesite, dacite and quartz rhyolite (a, b), bronzite andesite of low-Si boninite series (c,
994 d), arc tholeiitic rocks (e, f). (a, c, e) N-MORB-normalized trace element patterns. (b, d, f)
995 Chondrite-normalized REE patterns. Normalizing factors are after Sun & McDonough (1989). Data sources
996 for the gray hatched patterns are the same as in Fig. 11.

997

998 Fig 13 Bulk (a) Ba/Yb, (b) Th/Yb and (c) Pb/Yb vs. Nb/Yb diagrams of the Mukojima Island Group
999 volcanic rocks. Symbols and data sources are the same as those in Fig. 11.

1000

1001 Figure 14 Variation diagrams of bulk chemical compositions of type 1, 2 and 3 boninites. (a) Total alkali

1002 (Na₂O+K₂O) vs. SiO₂, (b) Al₂O₃ vs. CaO. Broken lines show CaO/Al₂O₃ = 0.6, 0.8, 1.0 and 1.2, (c) Zr/Ti
1003 ratio vs. Yb concentration, (d) Zr/Ti vs. Ba/Yb ratios. Gray thick arrows are compositional trends of 20
1004 wt% fractionation of olivine (OL, Fo₉₁), orthopyroxene (OPX, Mg#=0.91) and clinopyroxene (CPX,
1005 Mg#=0.90) from type 2 boninite. Fine arrows show vectors of 20 wt% addition of xenocrysts of OPX
1006 (Mg#=0.69) and CPX (Mg#=0.75) and An₇₅ plagioclase (PL) to type 1 boninite. Stars show the average
1007 compositions of CPX (Mg#=0.62-75) xenocrysts. Compositional fields enclosed by solid and broken lines
1008 show arc tholeiitic rocks and high-Si boninite series rocks (bronzite andesite, dacite, quartz rhyolite) from
1009 the Mukojima Island Group, respectively. Black and gray lines with ticks show postulated mixing lines of
1010 type 1 boninite and 0-100 wt% arc tholeiitic dacite and 0-100 wt% of quartz rhyolite, respectively. Data
1011 sources: Mariana Trench (D28,D50 and site 1403) (Hickey & Frey 1982; Bloomer & Hawkins 1987), Guam
1012 Facpi Formation (Reagan & Meijer 1984), Cape Vogel (Dallwitz *et al.* 1966; Walker & Cameron 1983),
1013 Chichijima Maruberiwan Formation (Umino 1986; Taylor *et al.* 1994), Leg 125 Hole 786A, B (Pearce *et al.*
1014 1992b), Troodos ophiolite (Cameron 1985; Flower & Levine 1987), Low-Si boninite of the Mikazukiyama
1015 Formation (Yajima & Fujimaki 2001; original data).

1016

1017 Figure 15 Zr/Ti vs. Yb for type 1 and 2 boninites. Also shown are mixing lines (black lines) between 15%
1018 batch melt of depleted MORB source mantle (DMM: Walkman & Hart 2005) and slab melt. Relative
1019 depletion of source mantle is shown by mixing lines (for example, “DMM-5%” means mixing line of slab
1020 melt and 15 wt% batch partial melt of residual DMM after 5 wt%-melt subtraction). Dashed lines are
1021 contours of iso-mixing-ratios of DMM and slab melts. Slab melt is calculated as 5% fractional melt of
1022 altered oceanic slab (average of Site 1149; Kelley *et al.* 2003) under amphibolite facies (clinopyroxene:
1023 amphibole: plagioclase=7:88:5). Partition coefficient for clinopyroxene-melt: Kelemen *et al.* (2003),
1024 amphibole-melt: Hilyard *et al.* (2000), plagioclase-melt: Smith & Asimow (2005). Hahajima basalts are

- 1025 from Taylor & Nesbitt (1995), Yajima *et al.* 2001, and Kanayama *et al.* (2010). Data source for low-Si
- 1026 boninite of the Mikazukiyama Formation is the same as in Fig. 14.

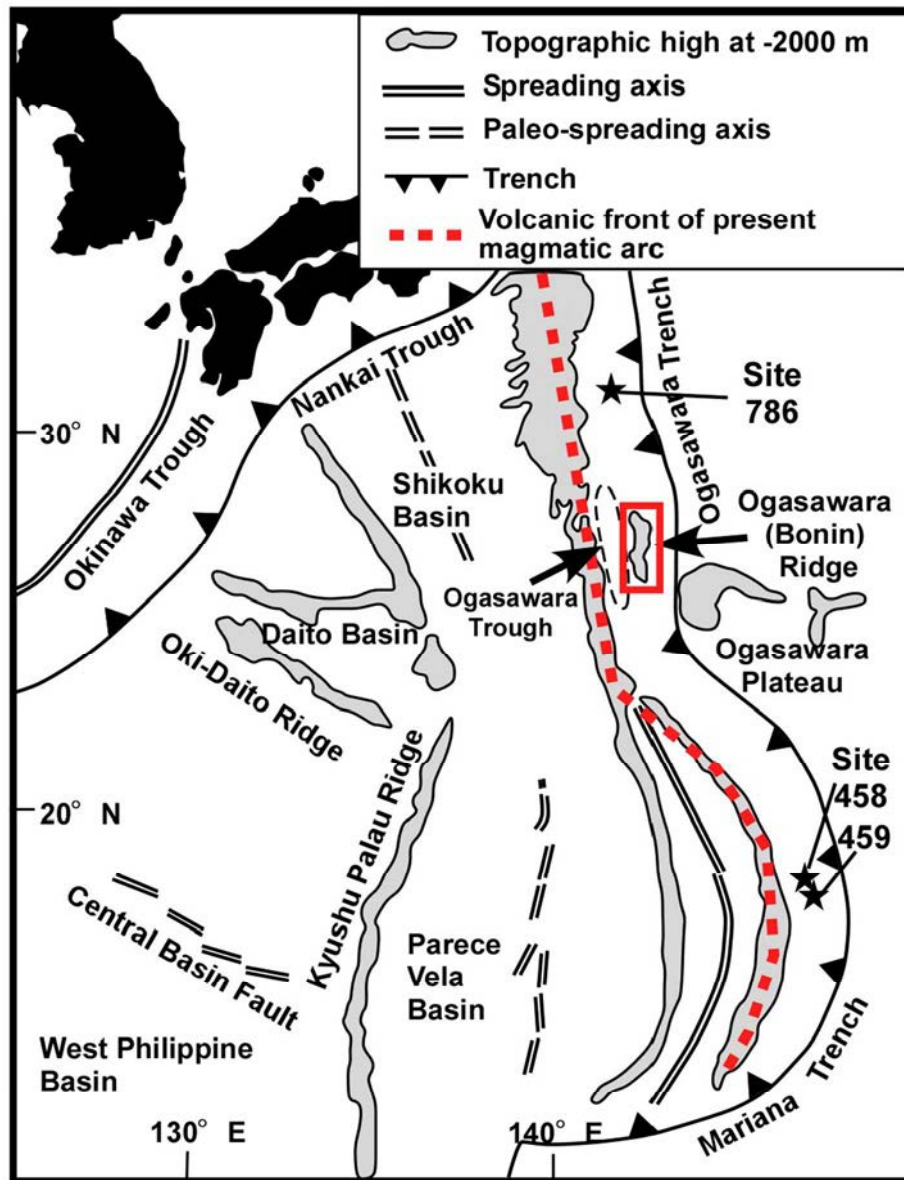


Figure 1 Map of the Philippine Sea Plate showing the location of the Ogasawara Ridge and some tectonic features. Stars: borehole sites of Ocean Drilling Program.

90x118mm (300 x 300 DPI)



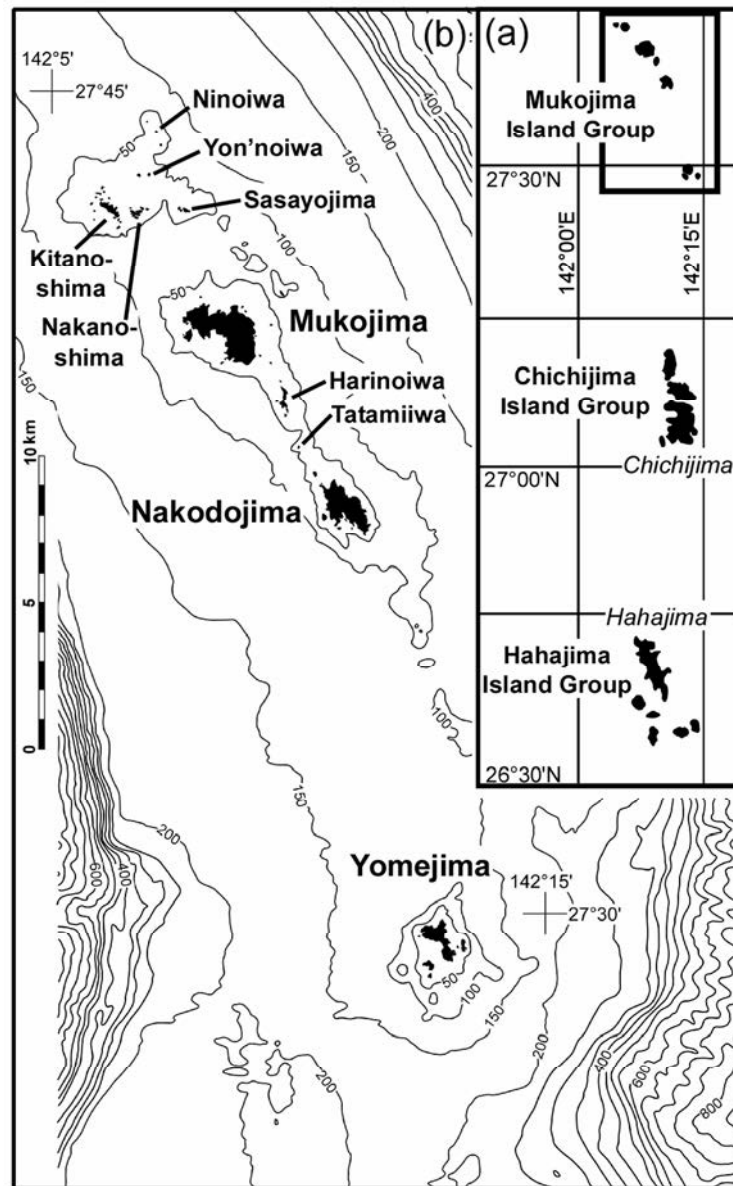


Figure 2 (a) Enlarged rectangle in Fig. 1 showing the Ogasawara Island Groups. (b) Bathymetric map (rectangle in Fig. 2a) showing the distribution of islands and reefs of the Mukojima Island Group. 86x139mm (300 x 300 DPI)



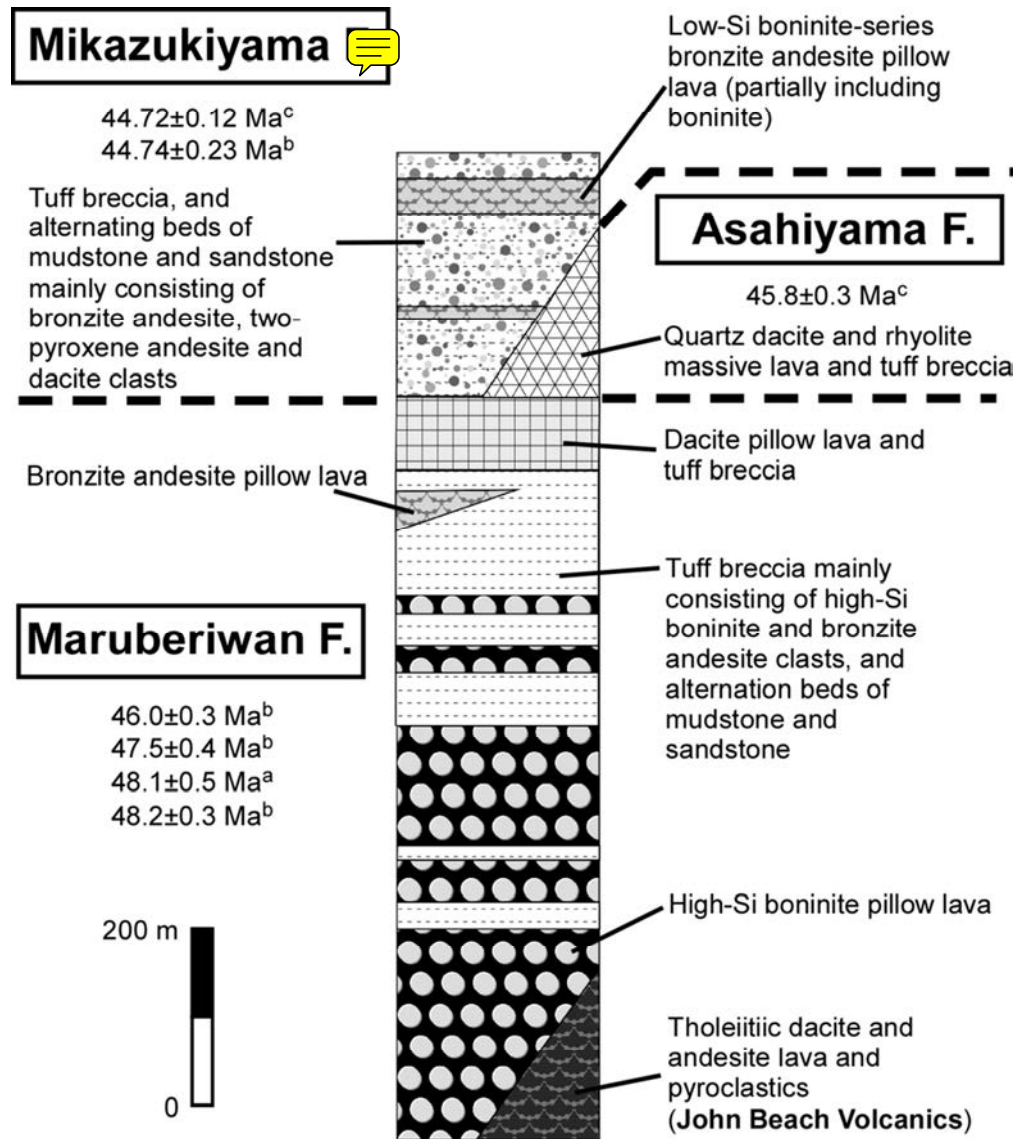


Figure 3 Generalized volcanic stratigraphy of the Chichijima Island Group modified after Umino (1985) and Umino & Nakano (2006, 2007). Data sources of radiometric ages are; a, Dobson (1986); b, Ishizuka *et al.* (2006); c, Ishizuka *et al.* (2011).
89x102mm (300 x 300 DPI)

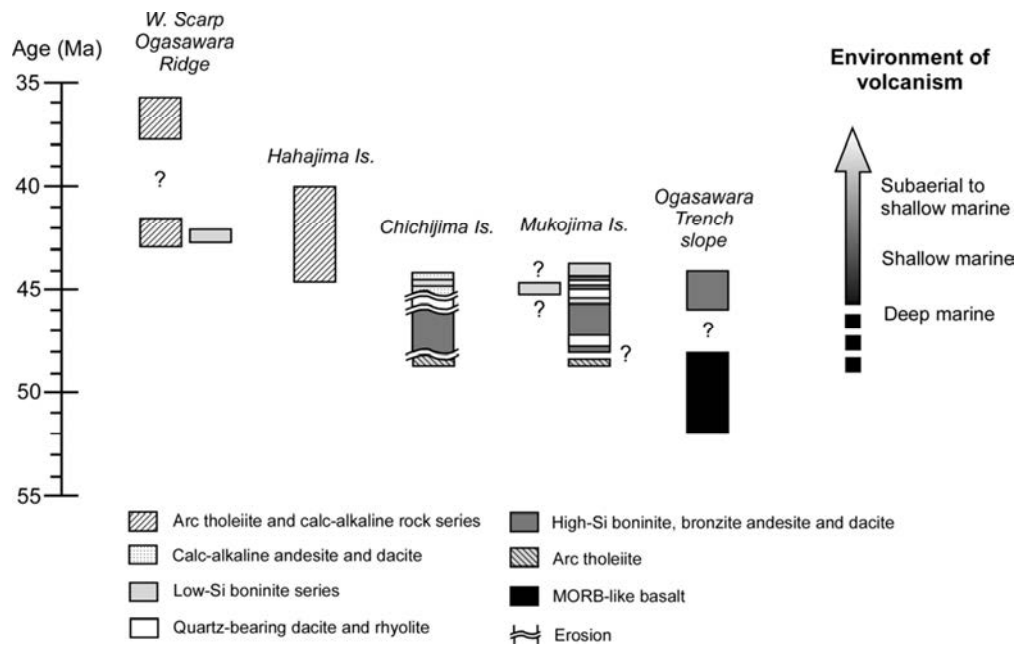


Figure 4 Summary of age, stratigraphic variations and environment of the Eocene-Oligocene volcanism on the Ogasawara Ridge. Stratigraphic data: Western scarp of the Ogasawara Ridge (Ishizuka *et al.* 2006), Hahajima Island Group (Umino *et al.* 2009), Chichijima Island Group (Umino & Nakano 2007) and Ogasawara Trench slope (Ishizuka *et al.* 2011). Radiometric ages are from Ishizuka *et al.* (2006; 2011). 91x57mm (300 x 300 DPI)

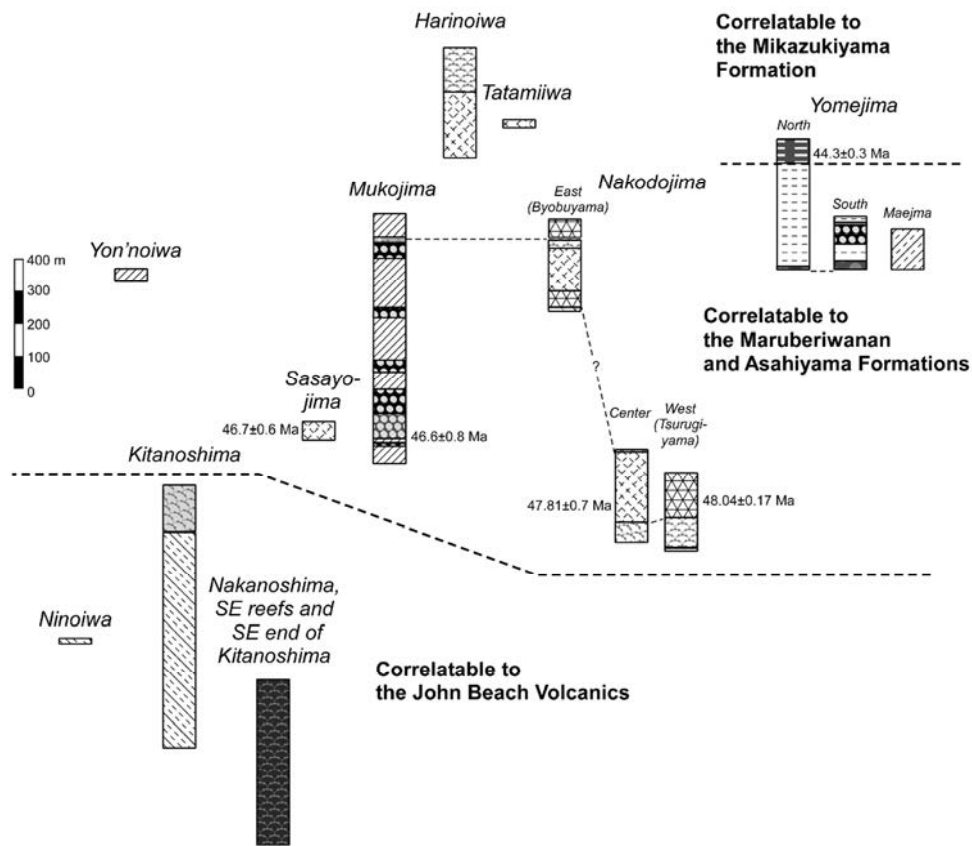


Figure 5 Geological columns showing the stratigraphic relationships of the Mukojima Island Group. Symbols are the same as those in Fig. 6. $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Ishizuka *et al.* (2011) are shown on the side of the columns. Tholeiitic strata of Ninoiwa, Kitanoshima and Nakanoshima are presumably correlatable to the John Beach Volcanics in the lowermost Maruberiwan Formation of Chichijima. High-Si boninite-series rocks of Yon'noiwa, Sasayojima, Mukojima, Nakodojima and most of Yomejima are correlatable to the Maruberiwan and Asahiyama Formations of Chichijima. Low-Si boninitic andesite of the uppermost part of Yomejima is correlated to the Mikazukiyama Formation because of the younger $^{40}\text{Ar}/^{39}\text{Ar}$ ages for andesite clast.

Harinoiwa and Tatamiwa low-Si boninitic andesites may be correlated with the Maruberiwan and Mikazukiyama Formations.

132x116mm (300 x 300 DPI)

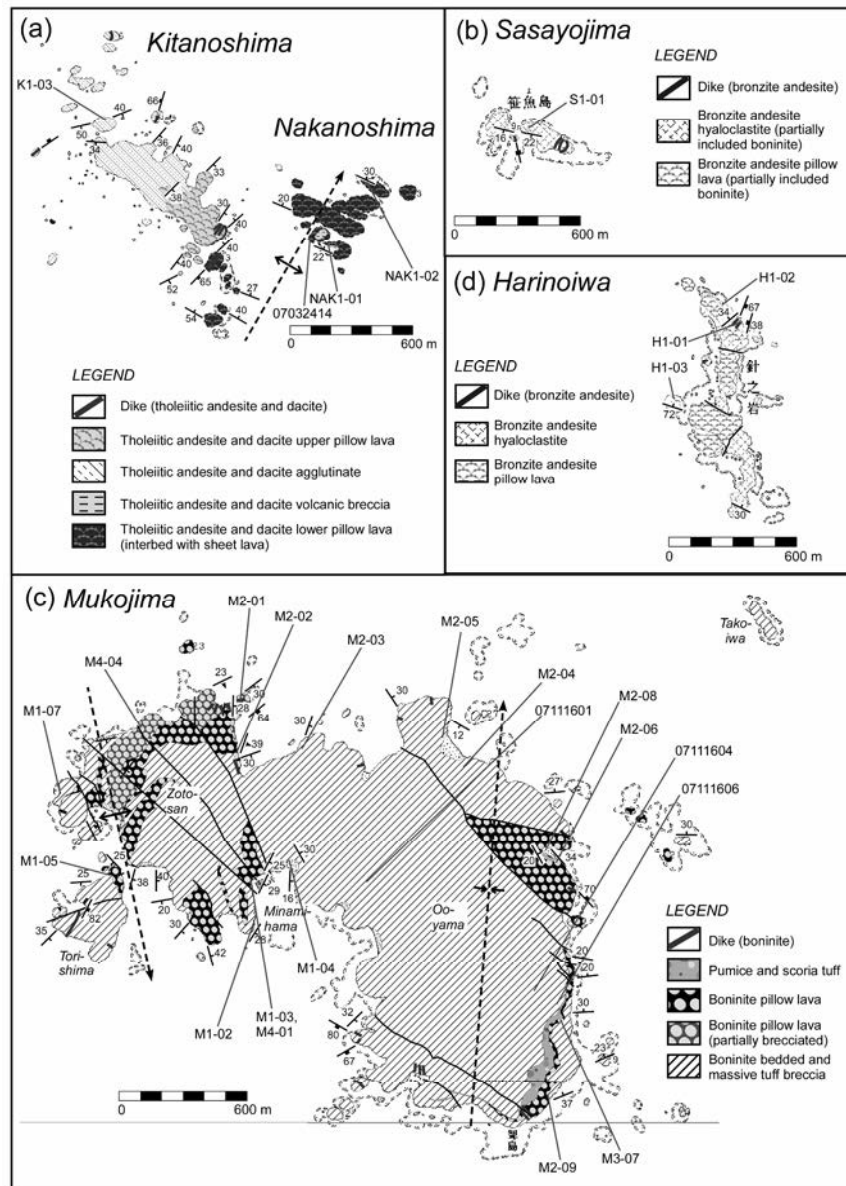
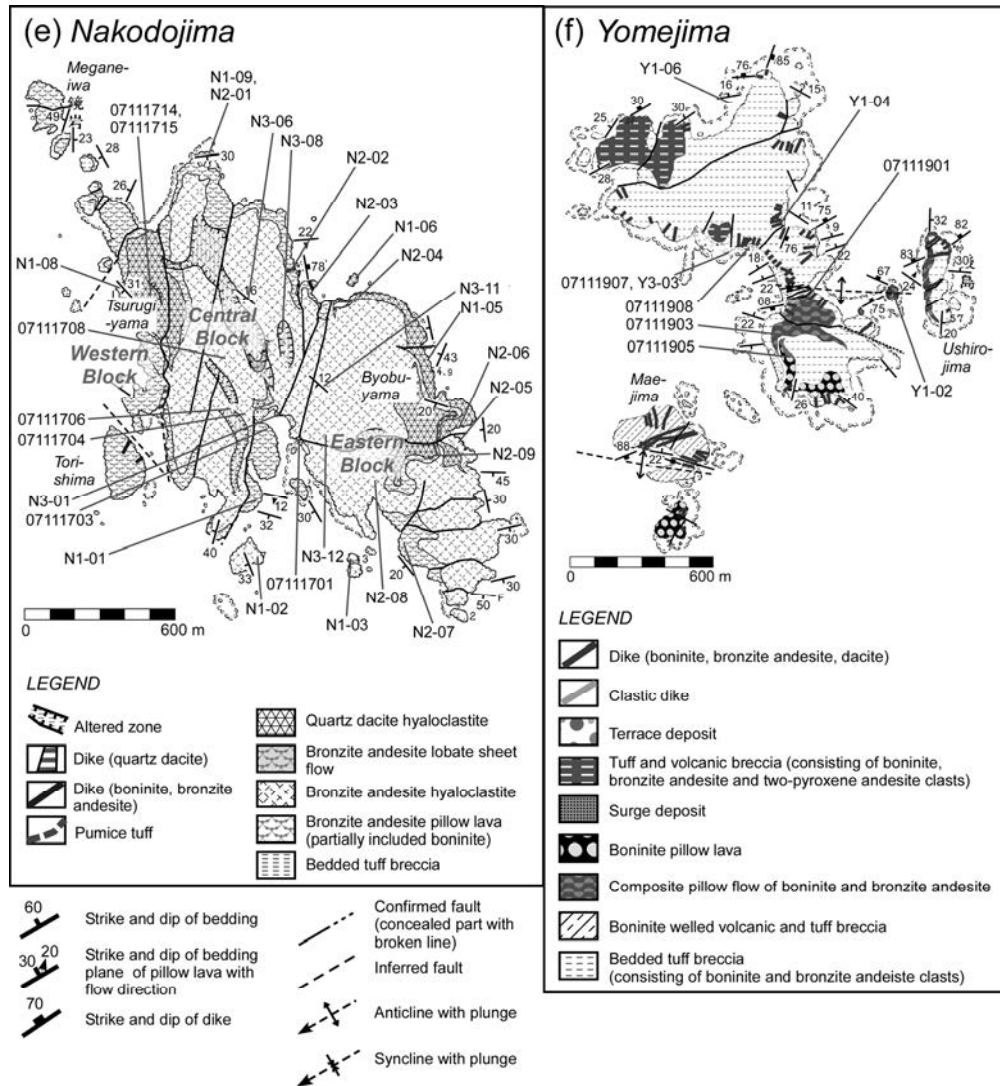


Figure 6 Geological maps and sampling localities of the Mukojima Island Group. (a) Kitanoshima and Nakanoshima, (b) Sasayojima, (c) Mukojima, (d) Harinoiwa, (e) Nakododjima, (f) Yomejima. 223x313mm (300 x 300 DPI)



(continued)
171x184mm (300 x 300 DPI)

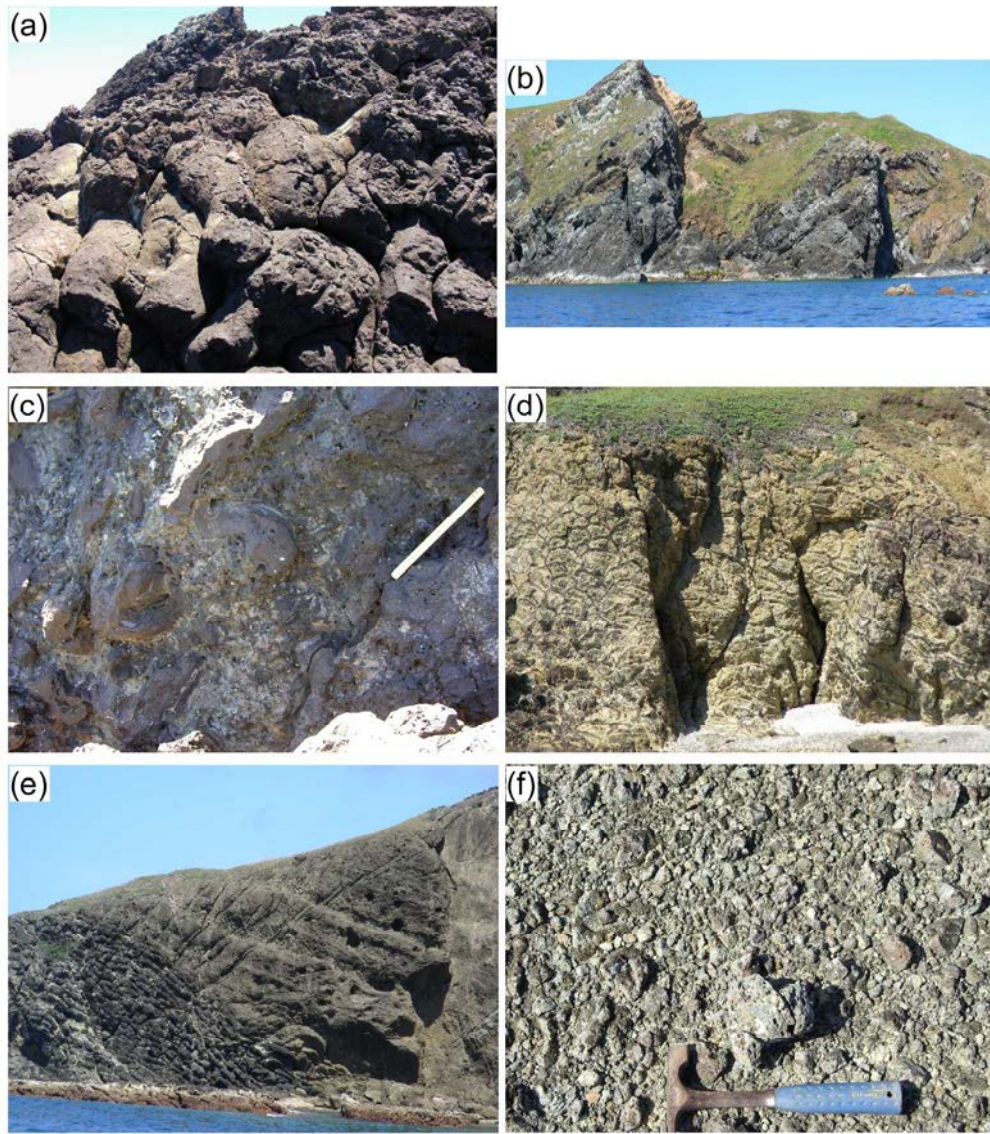
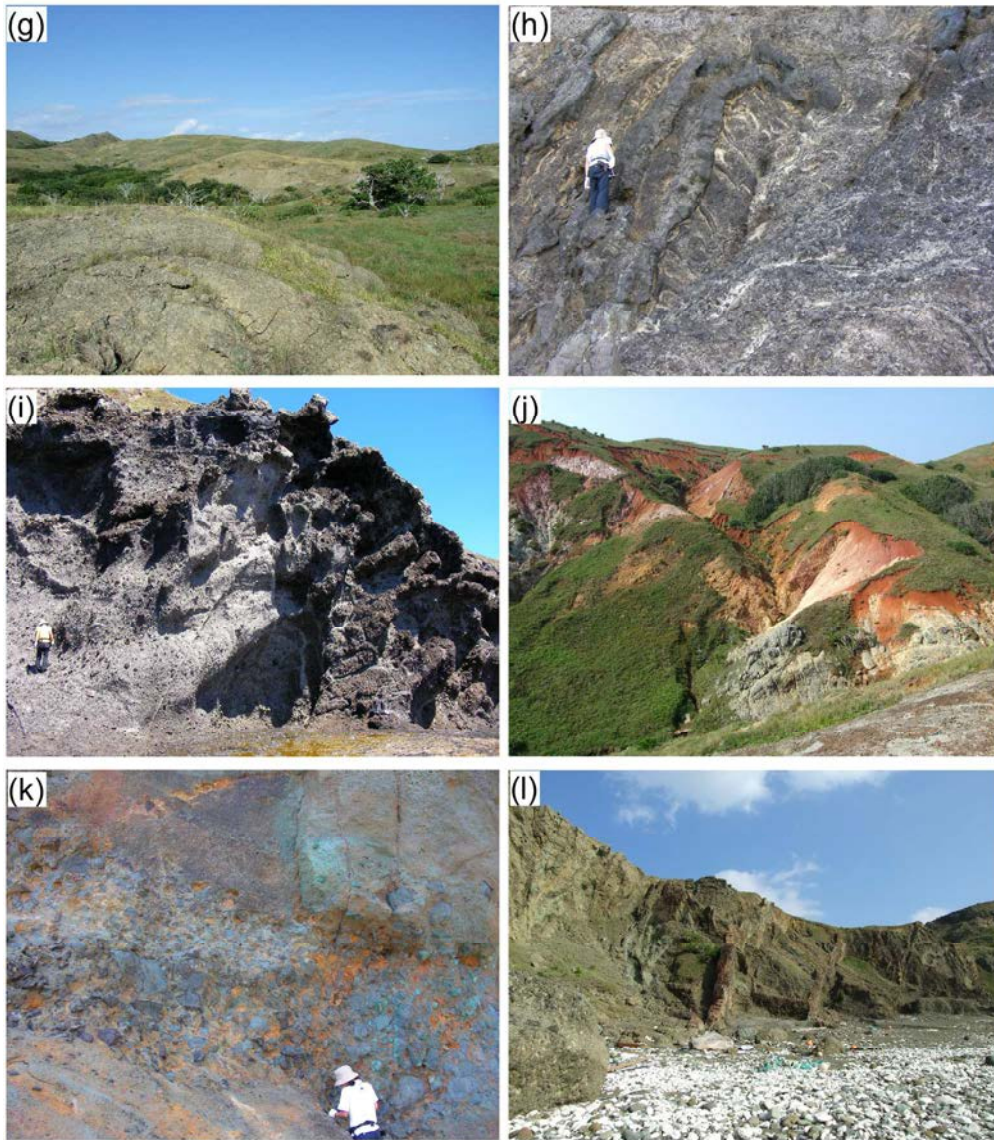


Figure 7 Representative outcrops of the Mukojima Island Group. (a) Pillow lava of Nakanoshima. (b) Northwestern cliff of Kitanoshima showing steeply inclined agglutinate layers to east. (c) Close-up view of the agglutinate in b consisting of densely to moderately welded lava clasts up to 10 cm in diameter. Scale is 20 cm. (d) Pillow lava exposed on the southwestern cliff of Mukojima. (e) Western cliff of Torishima, southwest of Mukojima. Bedded tuff breccia is underlain by pillowed boninite. (f) Volcanic bombs and scoriae in massive tuff breccia of the uppermost Mukojima. (g) The uppermost massive tuff breccia is widely exposed on central Mukojima. (h) Northeastern cliff of Harinoiwa. Andesite pillow lobes are brecciated into glassy fragments and laterally change into hyaloclastite. Some dikes terminate within the hyaloclastite and pillow lava. (i) South reef of Nakodojima. Bronzite andesite pillow lava on the right is in-situ brecciated to glassy and lithic fragments which grade into massive hyaloclastite to the left. (j) Western and central areas of Nakodojima. White alteration zones in front right and back left run northwest in echelon in the central block. (k) Maejima, an islet southwest off Yomejima, is composed of bedded volcanic and tuff breccia which are weakly to moderately welded. (l) Dike swarm of boninite and altered bronzite andesite intruded into the tuff breccia in the center of Yomejima.

182x209mm (300 x 300 DPI)



(continued)
182x211mm (300 x 300 DPI)

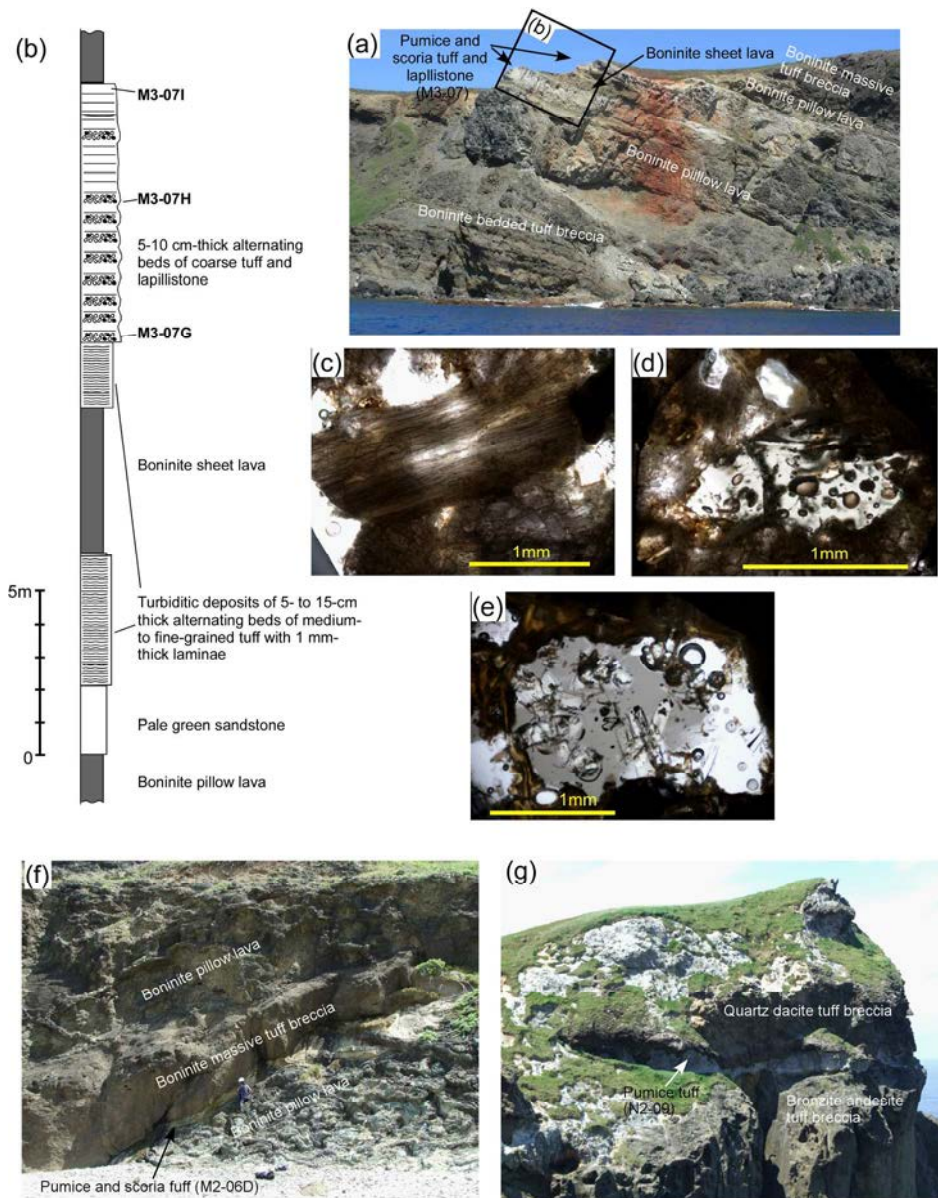


Figure 8 Tephra in Mukojima (M3-07 and M2-06D) and Nakodajima (N2-09). Sample localities are shown in Fig. 3. (a) Pumice and scoria tuff and lapillistone (M3-07) are exposed on the east cliff of Mukojima. (b) Columnar section at M3-07. (c)-(e) Microphotographs of (c) woody pumice, (d) crystal-free scoria and (e) crystal-rich scoria in M3-07G and H. (f) Pumice and scoria tuff (M2-06) exposed on the east coast cliff of Mukojima. (g) Pumice tuff (N2-09) lies between overlying quartz rhyolite and underlying bonzite andesite tuff breccia on the eastern cliff of Nakodajima. N2-09 sample was recovered on the ridge to the left of the photograph, where the pumice tuff becomes thinner to the north about 30 cm in thickness.
196x245mm (300 x 300 DPI)

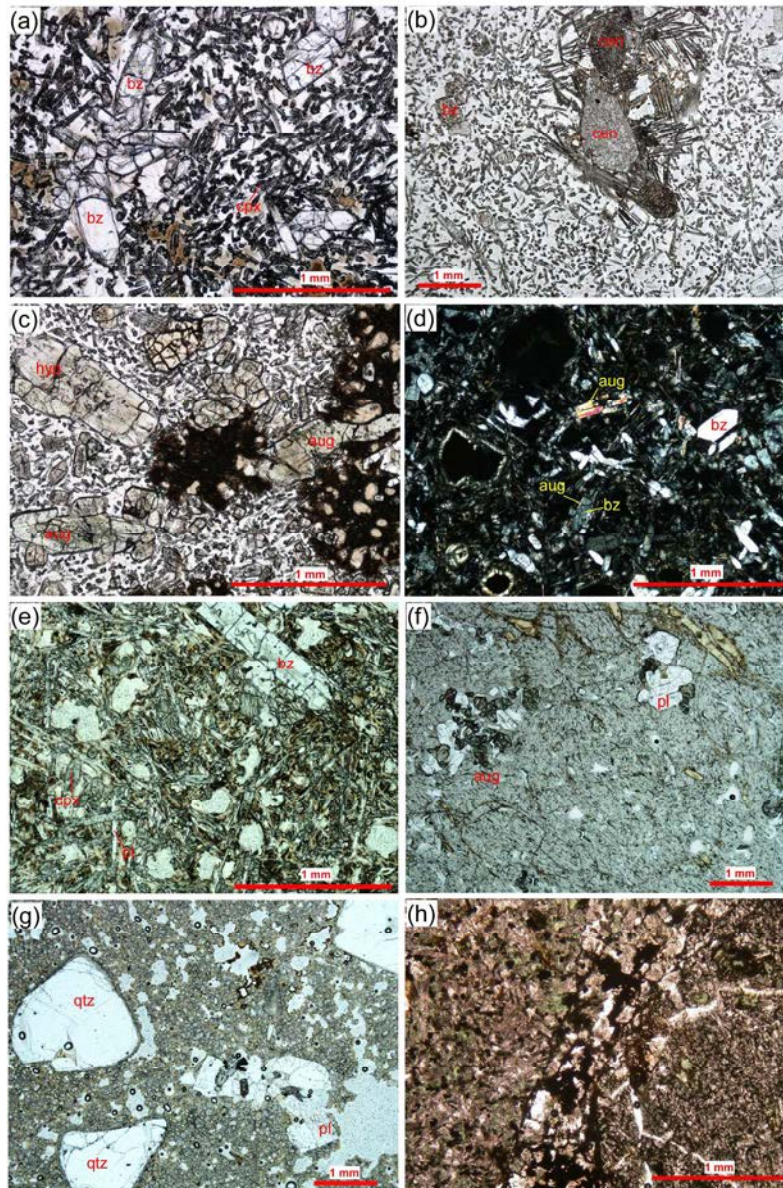


Figure 9 Microphotographs of volcanic rocks from the Mukojima Island Group. bz: bronzite, cpx: clinopyroxene, cen: clinoenstatite, aug: augite, hyp: hypersthene, pl: plagioclase, qtz: quartz. (a) Typical type 1 boninite. All boninite contain bronzite as a phenocryst and a microphenocryst, and clinopyroxene as a groundmass mineral (plane-polarized light). (b) Clinoenstatite phenocryst in type 1 boninite (plane-polarized light). (c) Type 2 boninite commonly has both augite and bronzite microphenocrysts (crossed polars). (d) Irregular-shaped augite and reversely zoned hypersthene with glass inclusions in the core in type 3 boninite (plane-polarized light). (e) Bronzite andesite resembles boninite in terms of mineral assemblages but is distinguished by the presence of plagioclase laths in the vesicular groundmass (plane-polarized light). (f) Dacite has small phenocrysts of plagioclase, augite, hypersthene and magnetite embedded in a glassy groundmass with a small amount of microlites (plane-polarized light). (g) Quartz rhyolite is similar to dacite but carries quartz as a phenocryst. The groundmass is holohyaline with abundant microspherulites (plane-polarized light). (h) Tholeiitic andesite tuff breccia in Ninowa. Groundmass crystal size differs from clast to clast. Plagioclase and pyroxene are mainly altered to albite, epidote, chlorite, sphene and magnetite (plane-

polarized light).
215x324mm (300 x 300 DPI)

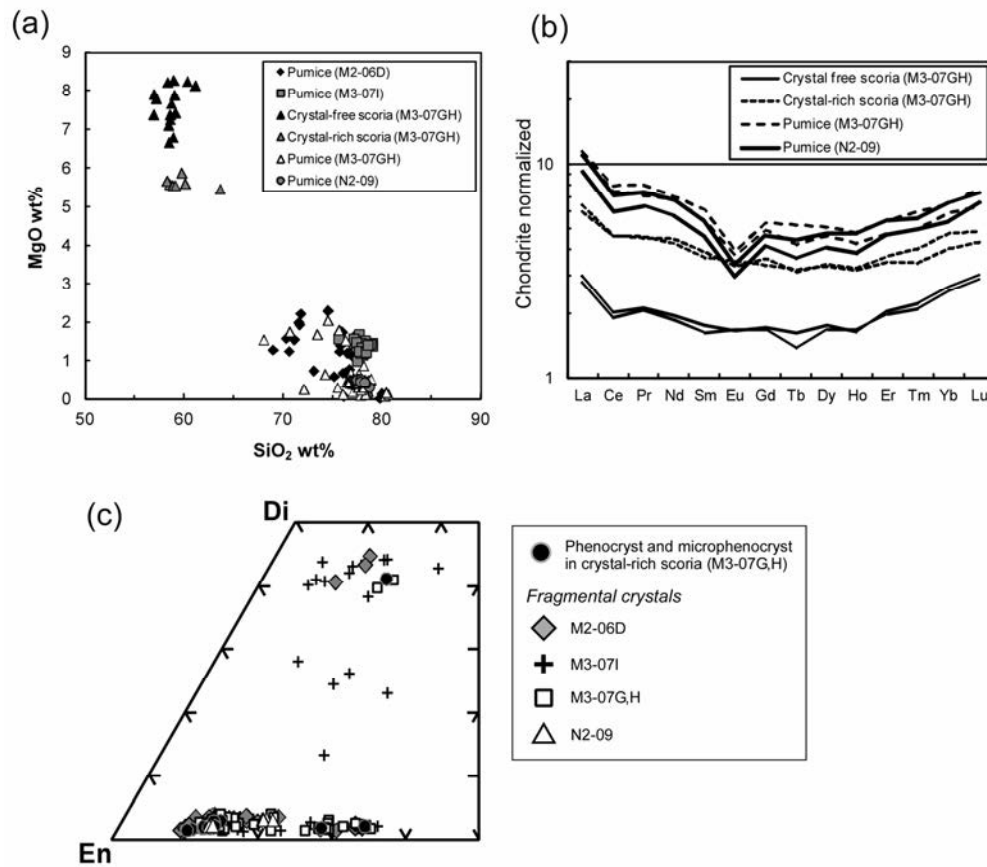


Figure 10 Glass and mineral compositions of tephra samples from Mukojima and Nakodjima. (a) SiO₂ vs. MgO (wt%) of matrix glass of scoria and pumice in tephra. (b) Chondrite (Sun & McDonough 1989)-normalized REE patterns of matrix glass of scoria and pumice. (c) Pyroxene compositions of phenocrysts and microphenocrysts in tephra.
138x121mm (300 × 300 DPI)

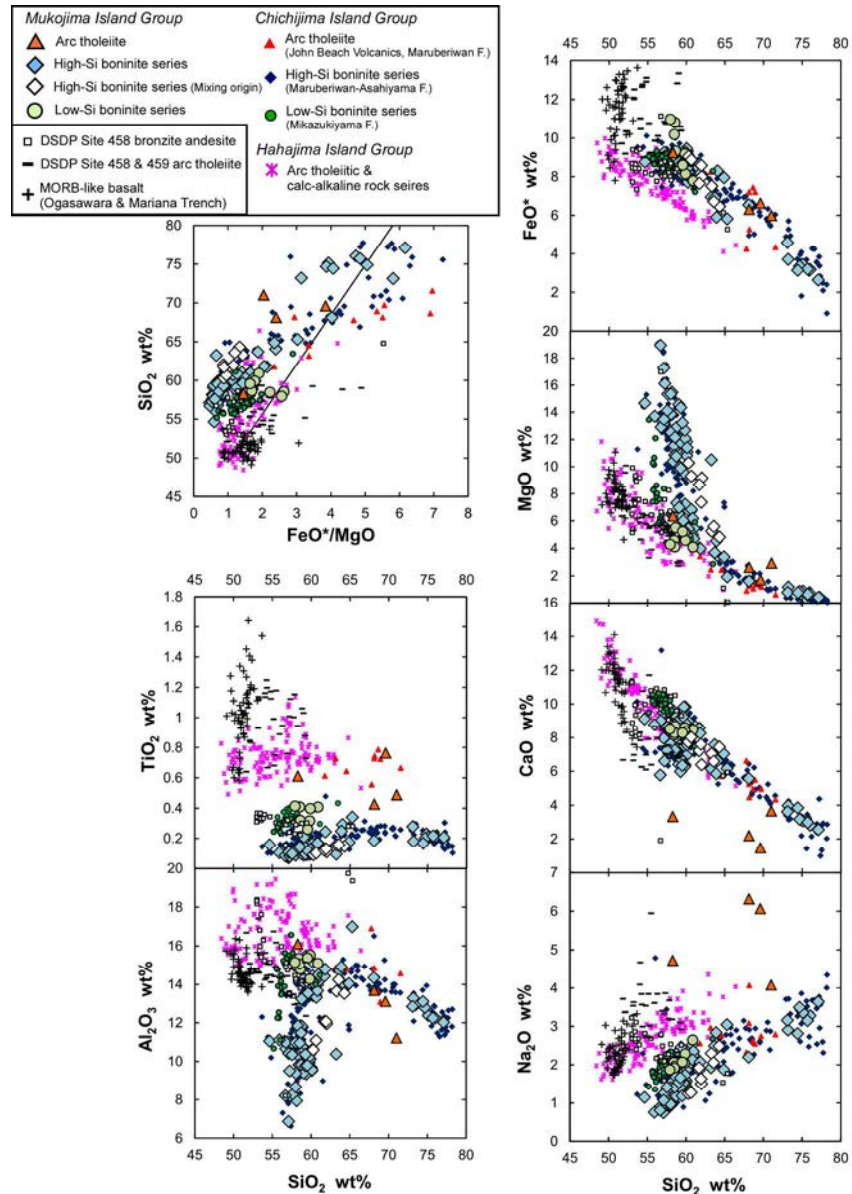


Figure 11 Bulk major element compositions of Mukojima Island Group volcanic rocks. The line on the FeO^*/MgO vs. SiO_2 diagram shows the boundary of tholeiitic and calc-alkaline series for the Quaternary volcanic rocks from Izu-Hakone region after Miyashiro (1974). Data sources: boninite series rocks of the Maruberiwan and Asahiya Formation of the Chichijima Island Group (Umino, 1986; Taylor *et al.* 1994; Umino & Nakano 2007; original data), the John Beach Volcanics (Umino & Nakano 2007; Ishizuka *et al.* 2012), low-Si boninite series of the Mikazukiyama Formation (Yajima & Fujimaki 2001; Umino & Nakano 2007; original data), tholeiite and calc-alkaline rock series from the Hahajima Island Group (Taylor & Nesbitt 1995; Yajima *et al.* 2001; Kanayama *et al.* 2010), MORB-like basalt from the Ogasawara (Ishizuka *et al.*, 2011) and Mariana Trench (Reagan *et al.* 2010), bronzite andesite from Site 458 and tholeiitic rocks from Site 458 and 459 (Meijer *et al.* 1981; Wood *et al.* 1981; Reagan *et al.* 2010).

221x316mm (300 x 300 DPI)

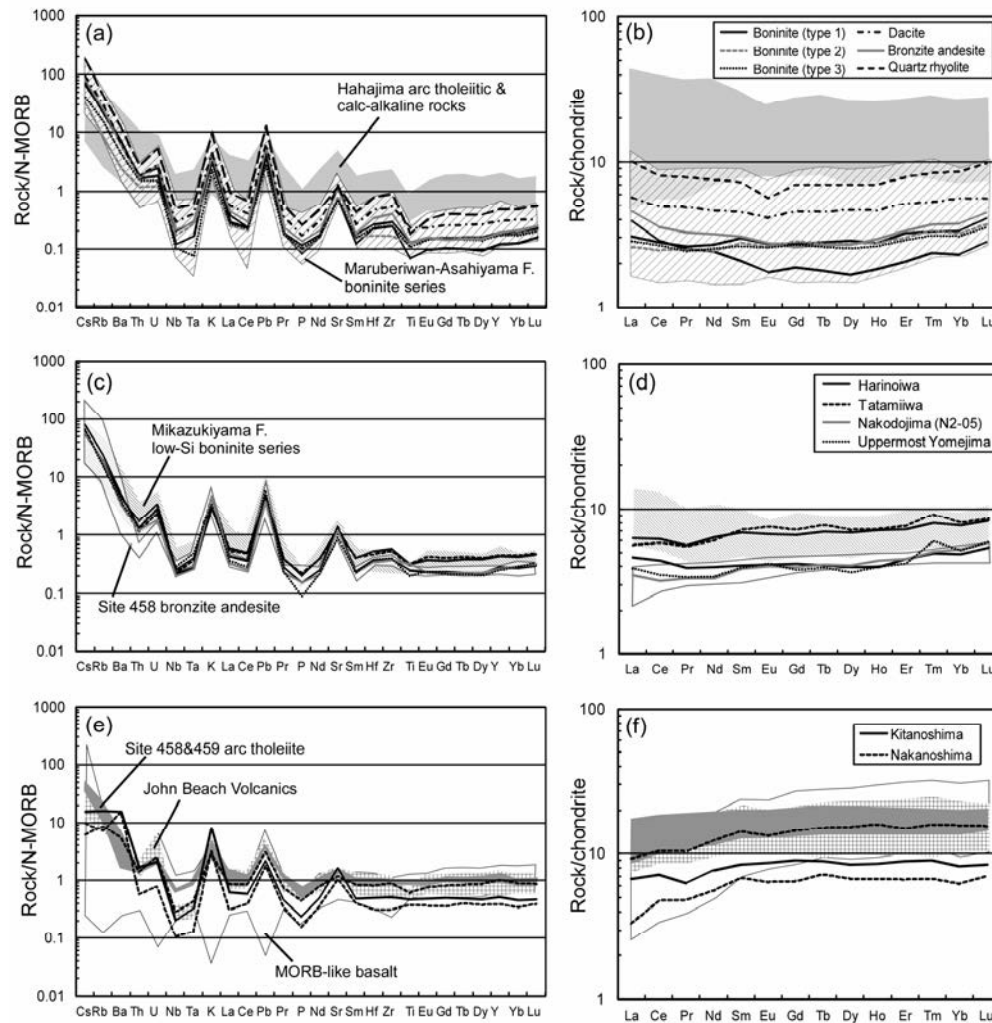


Figure 12 Representative trace element compositions for volcanic rocks from the Mukojima Island Group. Boninites, bronzite andesite, dacite and quartz rhyolite (a, b), bronzite andesite of low-Si boninite series (c, d), arc tholeiitic rocks (e, f). (a, c, e) N-MORB-normalized trace element patterns. (b, d, f) Chondrite-normalized REE patterns. Normalizing factors are after Sun & McDonough (1989). Data sources for the gray hatched patterns are the same as in Fig. 11.
163x169mm (300 x 300 DPI)

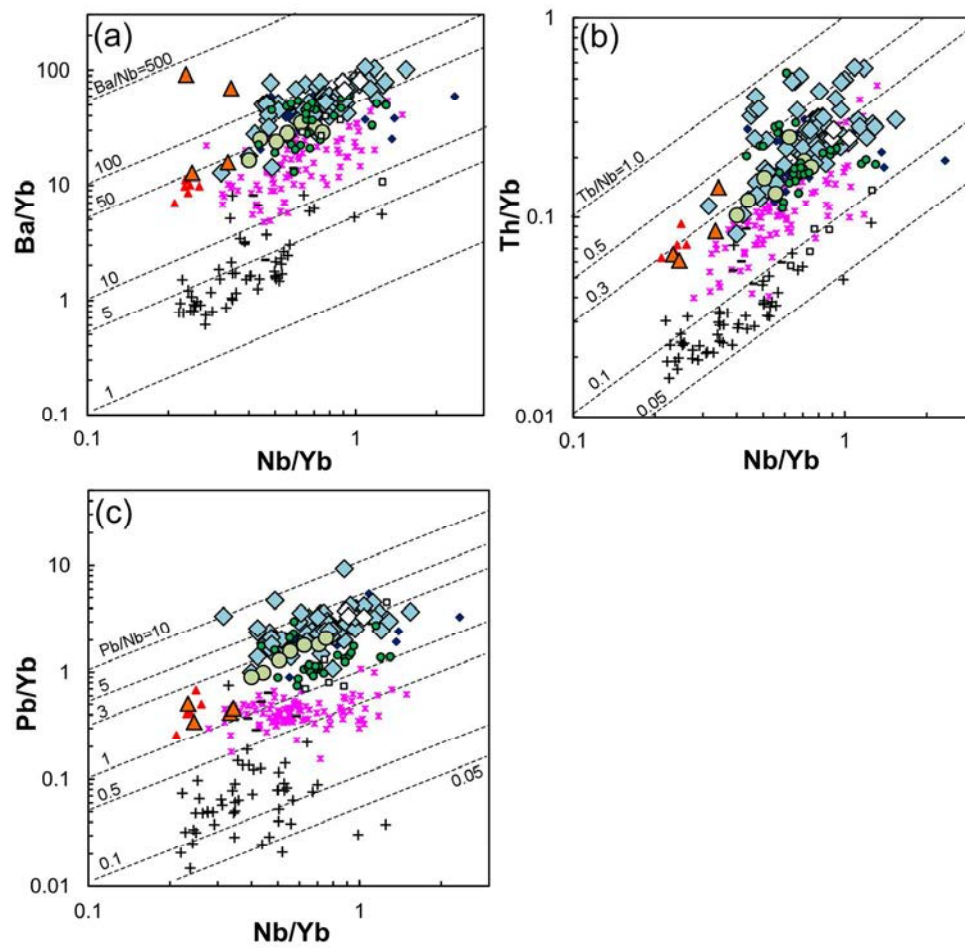


Fig 13 Bulk (a) Ba/Yb, (b) Th/Yb and (c) Pb/Yb vs. Nb/Yb diagrams of the Mukojima Island Group volcanic rocks. Symbols and data sources are the same as those in Fig. 11.
144x138mm (300 x 300 DPI)

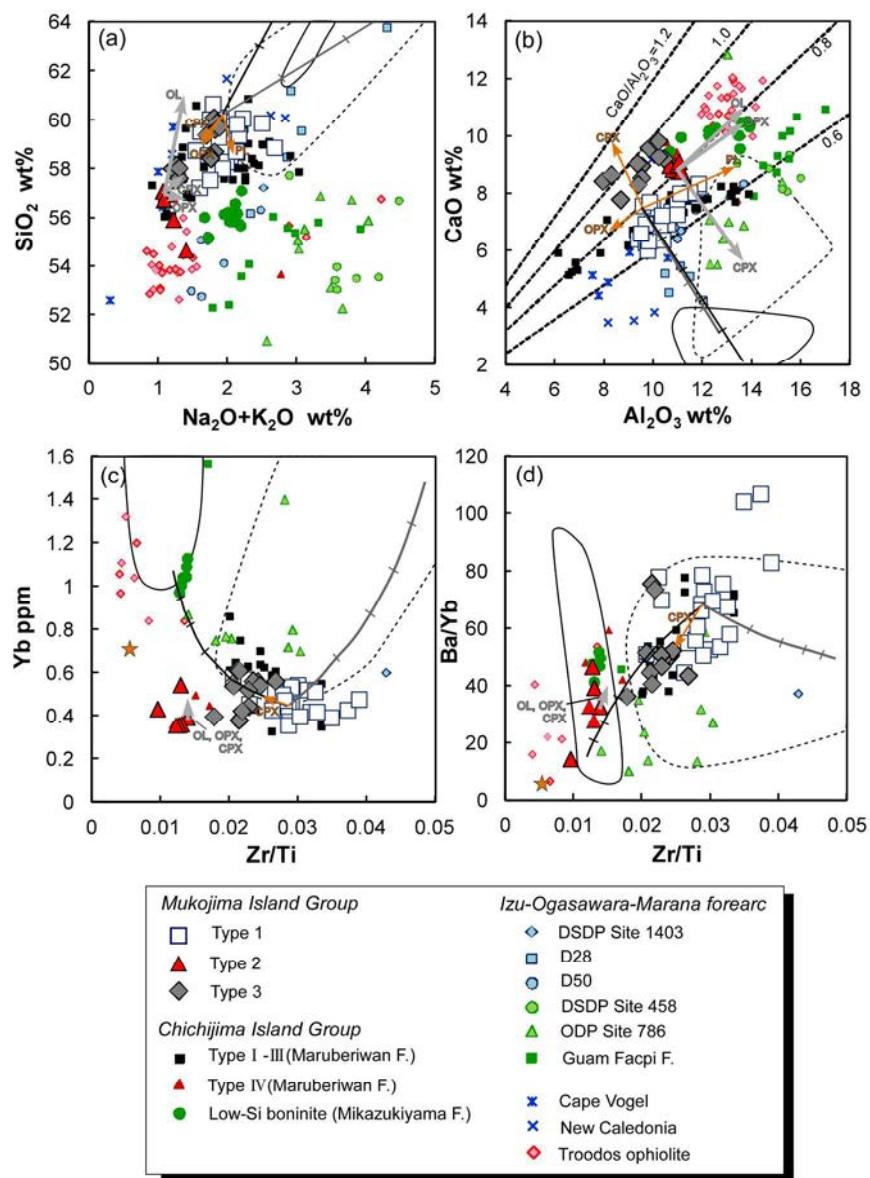


Figure 14 Variation diagrams of bulk chemical compositions of type 1, 2 and 3 boninites. (a) Total alkali ($\text{Na}_2\text{O}+\text{K}_2\text{O}$) vs. SiO_2 , (b) Al_2O_3 vs. CaO . Broken lines show $\text{CaO}/\text{Al}_2\text{O}_3 = 0.6, 0.8, 1.0$ and 1.2 , (c) Zr/Ti ratio vs. Yb concentration, (d) Zr/Ti vs. Ba/Yb ratios. Gray thick arrows are compositional trends of 20 wt% fractionation of olivine (OL, Fo_{91}), orthopyroxene (OPX, $\text{Mg}\#=0.91$) and clinopyroxene (CPX, $\text{Mg}\#=0.90$) from type 2 boninite. Fine arrows show vectors of 20 wt% addition of xenocrysts of OPX ($\text{Mg}\#=0.69$) and An_{75} plagioclase (PL) to type 1 boninite. Stars show the average compositions of CPX ($\text{Mg}\#=0.62-75$) xenocrysts. Compositional fields enclosed by solid and broken lines show arc tholeiitic rocks and high-Si boninite series rocks (bronzite andesite, dacite, quartz rhyolite) from the Mukojima Island Group, respectively. Black and gray lines with ticks show postulated mixing lines of type 1 boninite and 0-100 wt% arc tholeiitic dacite and 0-100 wt% of quartz rhyolite, respectively. Data sources: Mariana Trench (D28, D50 and site 1403) (Hickey & Frey 1982; Bloomer & Hawkins 1987), Guam Facpi Formation (Reagan & Meijer 1984), Cape Vogel (Dallwitz *et al.* 1966; Walker & Cameron 1983), Chichijima Maruberiwan Formation (Umino 1986; Taylor *et al.* 1994), Leg 125 Hole 786A, B (Pearce *et al.* 1992b), Troodos ophiolite

(Cameron 1985; Flower & Levine 1987), Low-Si boninite of the Mikazukiyama Formation (Yajima & Fujimaki 2001; original data).
220x303mm (300 x 300 DPI)

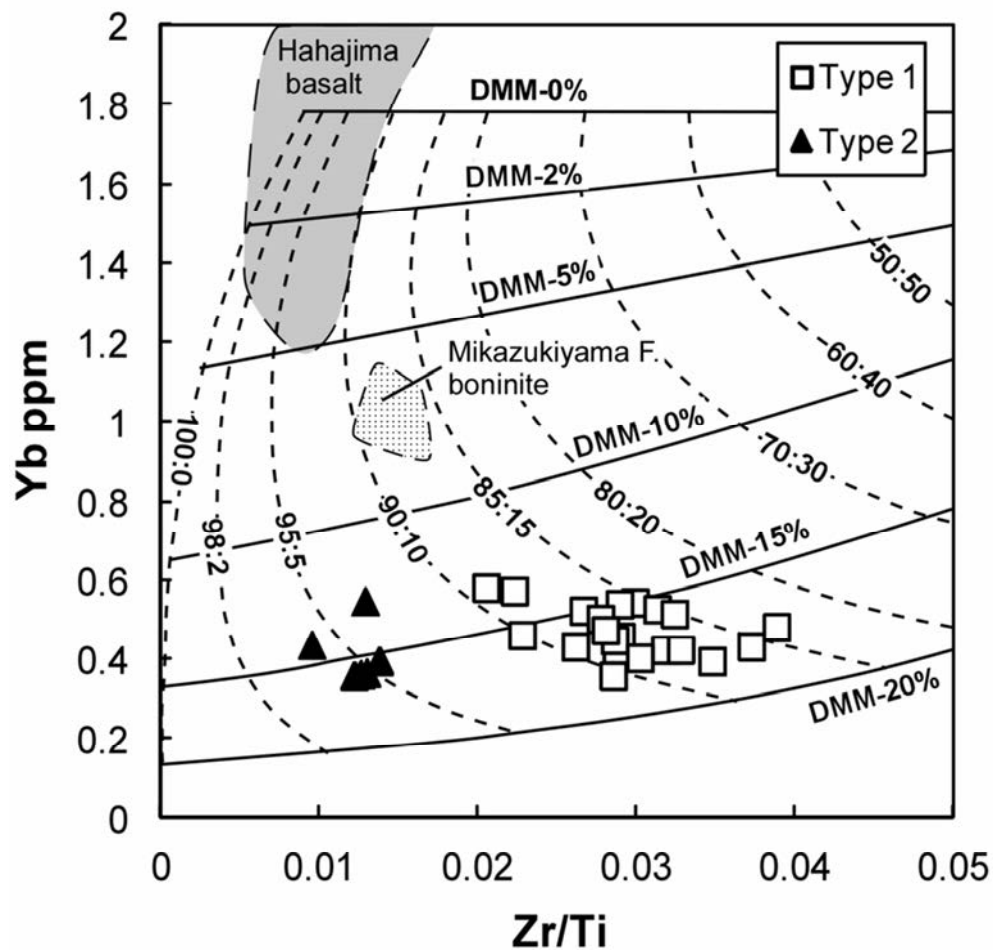


Figure 15 Zr/Ti vs. Yb for type 1 and 2 boninites. Also shown are mixing lines (black lines) between 15% batch melt of depleted MORB source mantle (DMM: Walkman & Hart 2005) and slab melt. Relative depletion of source mantle is shown by mixing lines (for example, "DMM-5%" means mixing line of slab melt and 15 wt% batch partial melt of residual DMM after 5 wt%-melt subtraction). Dashed lines are contours of iso-mixing-ratios of DMM and slab melts. Slab melt is calculated as 5% fractional melt of altered oceanic slab (average of Site 1149; Kelley *et al.* 2003) under amphibolite facies (clinopyroxene: amphibole: plagioclase=7:88:5). Partition coefficient for clinopyroxene-melt: Kelemen *et al.* (2003), amphibole-melt: Hilyard *et al.* (2000), plagioclase-melt: Smith & Asimow (2005). Hahajima basalts are from Taylor & Nesbitt (1995), Yajima *et al.* 2001, and Kanayama *et al.* (2010). Data source for low-Si boninite of the Mikazukiyama Formation is the same as in Fig. 14.

82x79mm (300 x 300 DPI)

Table S1 Representative glass compositions of scoria and pumice in tephra samples from Mukojima and Nakodjima

Sample ID	M3-07G	M3-07G	M3-07H	M3-07H	M3-07H	M3-07G	M3-07H	M3-07H	M3-07H	M3-07H	M3-07H	M3-07G	M3-07G	M3-07G	M3-07G	M3-07G	M3-07G	M3-07H	M3-07H
Type	Crystal-free scoria	Crystal-free scoria	Crystal-free scoria	Crystal-free scoria	Crystal-free scoria	Crystal-rich scoria	Crystal-rich scoria	Crystal-rich scoria	Crystal-rich scoria	Crystal-rich scoria	Crystal-rich scoria	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice
(wt% oxides on an anhydrous basis)																			
SiO ₂	57.17	56.96	58.59	58.32	58.71	63.64	58.54	58.24	58.85	59.09	59.74	80.30	78.02	74.23	77.76	77.88	77.61	77.09	76.74
TiO ₂	0.15	0.14	0.19	0.04	0.10	0.10	0.20	0.17	0.17	0.18	0.08	0.02	0.13	0.15	0.12	0.12	0.15	0.12	0.13
Al ₂ O ₃	13.30	13.33	14.04	12.81	13.39	13.24	13.87	13.95	13.60	13.32	13.72	11.99	12.26	11.64	12.02	11.87	11.80	12.37	11.95
FeO*	8.05	8.10	7.77	8.71	8.09	6.54	8.66	8.62	8.60	8.63	8.40	0.35	2.25	5.90	2.87	2.70	2.73	2.89	2.73
MnO	0.16	0.16	0.14	0.20	0.10	0.08	0.19	0.18	0.16	0.14	0.16	0.07	0.07	0.00	0.04	0.06	0.07	0.06	0.07
MgO	7.80	7.91	7.25	8.23	7.67	5.46	5.59	5.68	5.57	5.55	5.88	0.08	0.21	0.65	0.37	0.31	0.31	0.54	0.43
CaO	11.36	11.38	9.81	9.62	9.83	8.27	10.33	10.47	10.45	10.50	10.02	4.61	2.76	3.41	3.13	2.91	2.85	3.24	3.16
Na ₂ O	1.61	1.61	1.84	1.71	1.64	2.08	2.15	2.16	2.11	2.12	1.61	2.53	3.13	3.02	2.27	2.26	2.41	2.45	3.54
K ₂ O	0.28	0.27	0.37	0.28	0.43	0.56	0.40	0.45	0.44	0.42	0.36	0.06	1.18	0.99	1.40	1.87	2.06	1.21	1.22
FeO*/MgO	1.03	1.02	1.07	1.06	1.06	1.20	1.55	1.52	1.55	1.55	1.43	4.50	10.91	9.09	7.89	8.72	8.90	5.62	6.42
(ppm)																			
Li	7.2	7.3				9.9	6.8	6.7	6.8	6.9		0.2	1.6	1.5	37.1	0.9	0.6	16.0	1.2
B	10.2	12.0				25.2	10.5	10.9	10.5	10.1		38.7	35.3	31.1	21.6	21.7	21.2	30.5	31.7
Sc	47.0	47.1				36.3	41.8	41.5	41.4	41.9		14.1	12.9	13.6	24.5	11.6	12.3	17.1	13.1
Ti	627	626				937	1077	1087	1083	1079		810	713	744	1321	853	862	960	845
V	240	241				182	239	244	245	243		17	15	17	37	14	15	41	18
Cr	286	292				112	32	30	33	36		2	4	6	10	1	1	11	1
Co	40.6	41.3				27.0	34.8	35.0	35.5	35.2		3.9	3.3	4.1	14.9	3.4	3.6	6.9	4.1
Ni	73.4	74.8				66.0	24.3	24.2	24.7	24.6		1.0	1.0	3.6	53.4	0.7	0.6	10.4	1.0
Rb	8.7	9.1				15.1	10.4	10.3	10.4	10.2		29.1	30.1	27.4	30.4	45.7	34.0	29.2	31.5
Sr	66	67				76	117	117	118	117		88	79	82	99	96	89	98	94
Y	2.9	3.0				5.4	5.3	5.3	5.3	5.3		8.0	7.2	7.3	9.2	7.7	8.2	7.9	8.2
Zr	10	10				22	23	23	23	23		42	37	39	68	42	43	49	44
Nb	0.45	0.46				1.19	1.74	1.77	1.74	1.78		2.47	2.17	2.17	2.96	2.30	2.32	2.35	2.35
Cs	0.47	0.50				0.78	0.39	0.37	0.38	0.37		1.42	1.25	1.20	1.31	1.57	1.45	1.31	1.50
Ba	39	40				75	57	58	59	58		140	123	126	120	128	141	135	147
La	0.66	0.71				1.52	1.41	1.40	1.42	1.42		2.87	2.57	2.63	2.89	2.50	2.69	2.53	2.76
Ce	1.17	1.24				2.82	2.83	2.81	2.89	2.84		5.15	4.57	4.66	4.21	4.45	4.83	4.48	4.91
Pr	0.20	0.20				0.43	0.43	0.43	0.43	0.44		0.75	0.68	0.69	0.85	0.70	0.74	0.70	0.76
Nd	0.87	0.91				2.08	1.97	1.94	1.97	1.98		3.49	3.19	3.24	3.80	2.99	3.30	3.12	3.40
Sm	0.25	0.27				0.59	0.57	0.57	0.57	0.56		0.91	0.83	0.84	1.06	0.77	0.87	0.90	0.90
Eu	0.10	0.10				0.19	0.20	0.20	0.20	0.20		0.24	0.22	0.22	0.30	0.21	0.22	0.21	0.23
Gd	0.34	0.35				0.74	0.72	0.70	0.72	0.70		1.11	1.00	1.03	1.29	1.02	1.09	1.03	1.13
Tb	0.05	0.06				0.12	0.13	0.12	0.12	0.12		0.17	0.16	0.16	0.24	0.17	0.18	0.18	0.17
Dy	0.43	0.45				0.87	0.83	0.82	0.83	0.85		1.27	1.17	1.18	1.61	1.13	1.22	1.16	1.22
Ho	0.09	0.09				0.18	0.18	0.19	0.18	0.18		0.27	0.24	0.24	0.31	0.24	0.26	0.25	0.28
Er	0.33	0.34				0.62	0.58	0.57	0.59	0.58		0.86	0.78	0.79	1.06	0.82	0.86	0.84	0.89
Tm	0.05	0.06				0.10	0.09	0.09	0.09	0.09		0.14	0.13	0.12	0.19	0.12	0.14	0.14	0.14
Yb	0.43	0.45				0.80	0.67	0.66	0.67	0.68		1.10	1.00	1.02	1.48	0.90	1.01	0.99	1.06
Lu	0.07	0.08				0.12	0.11	0.11	0.11	0.11		0.18	0.16	0.16	0.26	0.16	0.18	0.18	0.19
Hf	0.29	0.28				0.64	0.62	0.60	0.62	0.61		1.26	1.10	1.13	2.05	1.15	1.26	1.43	1.34
Ta	0.03	0.04				0.09	0.11	0.10	0.11	0.10		0.18	0.16	0.16	0.24	0.14	0.17	0.19	0.18
Pb	1.93	2.11				3.66	1.49	1.45	1.49	1.48		7.74	7.11	6.08	11.89	8.75	7.09	7.61	7.29
Th	0.09	0.10				0.23	0.19	0.20	0.19	0.20		0.46	0.41	0.42	0.58	0.40	0.44	0.44	0.48
U	0.13	0.13				0.25	0.15	0.15	0.16	0.16		0.49	0.42	0.41	0.50	0.45	0.48	0.47	0.52
Zr/Ti	0.016	0.016				0.023	0.021	0.021	0.021	0.021		0.052	0.052	0.052	0.052	0.049	0.050	0.051	0.052

* Total Fe as FeO.

† BCR-2G reported value: Pearce et al. (1997)

Island Arc, For Peer Review

M3-07H	M3-07H	M3-07H	M3-07H	M2-06D	M2-06D	M2-06D	M2-06D	M2-06D	M3-07I	M3-07I	M3-07I	M3-07I	M3-07I	N2-09	N2-09	N2-09	N2-09	N2-09	N2-09
Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice	Pumice
76.75	77.56	77.67	76.68	79.96	75.63	71.79	74.53	71.58	77.75	77.33	77.51	77.72	75.63	77.21	77.14	77.38	77.85	77.30	77.46
0.13	0.12	0.14	0.12	0.06	0.02	0.08	0.09	0.03	0.06	0.00	0.07	0.06	0.03	0.16	0.16	0.17	0.15	0.15	0.21
12.08	12.17	11.97	12.05	13.39	15.15	15.67	14.92	14.15	14.57	14.78	13.96	14.54	15.24	12.25	12.06	12.27	11.92	12.03	12.30
2.73	2.84	2.79	2.87	0.08	0.96	2.77	1.96	3.96	0.07	0.04	0.12	0.17	0.83	2.32	2.22	2.15	2.10	2.05	2.13
0.05	0.09	0.04	0.07	0.06	0.13	0.18	0.10	0.06	0.04	0.05	0.01	0.01	0.04	0.04	0.05	0.04	0.04	0.05	0.10
0.43	0.44	0.66	0.45	0.14	1.56	2.22	2.30	2.00	1.50	1.40	1.00	1.67	1.57	0.50	0.51	0.47	0.45	0.42	0.51
3.06	3.21	2.96	3.17	2.53	2.76	3.13	2.95	3.89	1.62	1.59	1.48	1.95	2.36	2.79	2.71	2.79	2.66	2.60	2.79
3.69	2.42	2.29	3.47	3.41	2.79	2.81	1.85	3.45	2.68	3.12	4.46	2.66	2.87	3.53	3.92	3.54	3.62	4.20	3.29
1.04	1.12	1.45	1.13	0.32	1.01	1.34	1.28	0.86	1.69	1.68	1.34	1.21	1.43	1.17	1.19	1.16	1.18	1.19	1.20
6.42	6.55	5.23	6.45	0.53	0.61	1.25	0.85	1.98	0.05	0.03	0.13	0.10	0.53	4.65	4.46	4.62	4.64	4.87	4.17
17.5	39.2	16.5	3.0											4.4	3.7	3.5	2.9	8.7	3.2
31.3	34.1	31.9	30.0											18.5	22.2	24.5	24.1	26.5	36.8
18.2	26.1	17.6	12.7											11.7	13.7	13.3	9.9	18.9	14.0
1013	1278	1018	798											1007	1219	1179	1017	1451	811
46	67	37	18											45	43	45	36	52	42
19	30	8	2											22	24	15	3	58	17
8.0	14.4	7.7	3.8											4.7	4.3	4.4	3.6	5.5	4.7
12.7	28.4	10.9	0.7											6.4	6.3	4.6	1.1	13.3	7.5
31.2	31.0	33.2	27.4											29.4	34.6	35.8	33.5	35.8	27.9
101	107	103	90											70	81	79	73	83	61
8.2	7.8	8.3	7.8											7.1	8.4	8.5	7.9	8.8	6.5
51	62	51	42											61	77	76	62	102	52
2.45	2.88	2.57	2.12											1.41	1.79	1.73	1.45	2.22	1.30
1.40	1.36	1.47	1.28											1.42	1.61	1.73	1.65	1.72	1.32
142	126	150	133											92	110	107	106	109	81
2.63	2.42	2.69	2.53											2.17	2.59	2.62	2.38	2.72	2.02
4.67	4.27	4.85	4.49											3.69	4.39	4.38	4.12	4.38	3.60
0.72	0.66	0.76	0.69											0.61	0.71	0.72	0.68	0.72	0.55
3.25	2.96	3.29	3.04											2.69	3.22	3.24	3.01	3.23	2.47
0.99	0.85	0.94	0.80											0.70	0.83	0.82	0.76	0.81	0.67
0.22	0.21	0.23	0.22											0.17	0.20	0.20	0.19	0.20	0.16
1.06	1.00	1.09	0.98											0.85	0.96	1.05	0.95	1.07	0.75
0.19	0.17	0.19	0.17											0.14	0.17	0.17	0.16	0.16	0.13
1.22	1.18	1.28	1.16											1.03	1.22	1.25	1.15	1.23	1.00
0.27	0.25	0.27	0.25											0.22	0.27	0.26	0.26	0.28	0.23
0.87	0.87	0.90	0.82											0.78	0.91	0.95	0.89	0.96	0.73
0.15	0.14	0.15	0.13											0.13	0.14	0.15	0.14	0.15	0.12
1.04	1.07	1.11	0.96											0.92	1.13	1.12	1.06	1.10	0.98
0.19	0.19	0.20	0.17											0.17	0.19	0.19	0.19	0.20	0.15
1.44	1.74	1.58	1.21											1.66	2.02	2.12	1.73	2.77	1.43
0.19	0.23	0.20	0.15											0.11	0.14	0.14	0.12	0.18	0.11
8.24	11.50	9.10	6.26											4.40	5.28	5.54	4.58	5.20	3.83
0.47	0.49	0.49	0.41											0.36	0.42	0.43	0.39	0.50	0.32
0.52	0.54	0.55	0.44											0.34	0.40	0.39	0.35	0.42	0.27
0.050	0.048	0.050	0.052											0.061	0.063	0.064	0.061	0.070	0.064

N2-09		
Pumice	BCR-2G average [†]	σ
	n=9	
77.94	55.28	0.32
0.14	2.32	0.08
12.15	13.63	0.11
1.93	12.42	0.32
0.01	0.17	0.09
0.42	3.61	0.08
2.57	7.39	0.12
3.54	3.33	0.08
1.27	1.85	0.05
4.63		
	n=14	
2.9	9.1	0.2
40.3	12.2	2.8
11.1	34.9	0.7
847	13872	306
36	415	4
22	16.2	0.4
3.8	36.5	0.6
4.9	14.9	0.7
29.9	46.3	1.0
62	326	6
6.6	32.7	1.0
53	172	7
1.38	12.62	0.24
1.42	1.09	0.03
85	660	16
2.13	24.77	0.61
3.83	50.78	1.35
0.57	6.38	0.14
2.59	28.36	0.94
0.64	6.42	0.20
0.17	1.91	0.05
0.83	6.41	0.24
0.13	0.95	0.03
0.98	6.25	0.23
0.21	1.23	0.04
0.73	3.48	0.12
0.12	0.49	0.02
0.91	3.43	0.11
0.16	0.49	0.02
1.45	4.50	0.15
0.11	0.80	0.02
4.15	11.21	0.57
0.35	5.88	0.18
0.31	1.59	0.03
0.063		

Table S2 Representative microprobe analyses of minerals in tephra samples from Mukojima and Nakodjima

	Crystal-rich scoria Orthopyroxene								
Sample ID	M3-07G	M3-07G	M3-07G	M3-07G	M3-07G	M3-07H	M3-07H	M3-07H	M3-07H
(wt%)									
SiO₂	58.03	58.23	56.52	57.38	57.47	53.98	54.12	57.21	56.53
TiO₂	0.06	0.01	0.07	0.07	0.00	0.01	0.09	0.00	0.00
Al₂O₃	0.48	0.61	1.11	1.04	0.74	0.92	0.80	0.76	0.70
FeO*	7.86	6.49	8.86	8.24	8.72	17.85	21.26	6.85	6.49
MnO	0.20	0.25	0.23	0.11	0.21	0.37	0.48	0.13	0.20
MgO	32.95	33.74	31.09	31.20	32.05	25.60	23.05	33.60	34.26
CaO	1.13	0.83	1.59	1.54	1.19	0.99	1.11	0.93	0.88
Na₂O	0.00	0.00	0.02	0.02	0.04	0.00	0.03	0.00	0.03
K₂O	0.01	0.01	0.00	0.00	0.00	0.00	0.03	0.01	0.00
Cr₂O₃	0.26	0.41	0.71	0.63	0.48	0.25	0.17	0.65	0.56
Total	100.99	100.58	100.20	100.22	100.88	99.96	101.11	100.13	99.64
Cations									
O	6	6	6	6	6	6	6	6	6
Si	1.996	1.998	1.976	1.995	1.989	1.971	1.983	1.979	1.965
Ti	0.002	0.000	0.002	0.002	0.000	0.000	0.002	0.000	0.000
Al	0.020	0.025	0.046	0.043	0.030	0.040	0.035	0.031	0.029
Fe	0.226	0.186	0.259	0.240	0.252	0.545	0.651	0.198	0.189
Mn	0.006	0.007	0.007	0.003	0.006	0.011	0.015	0.004	0.006
Mg	1.690	1.726	1.621	1.617	1.653	1.393	1.259	1.733	1.776
Ca	0.042	0.030	0.060	0.057	0.044	0.039	0.043	0.035	0.033
Na	0.000	0.000	0.001	0.001	0.003	0.000	0.002	0.000	0.002
K	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Cr	0.007	0.011	0.020	0.017	0.013	0.007	0.005	0.018	0.015
Total	3.989	3.984	3.990	3.974	3.991	4.006	3.996	3.997	4.014
Mg#[†]	0.882	0.903	0.862	0.871	0.868	0.719	0.659	0.897	0.904
An	-	-	-	-	-	-	-	-	-

*Total Fe as FeO.

[†]Mg# = Mg / (Mg + Fe²⁺)

-, no data

Fragmental crystal									
Orthopyroxene									
M3-07G	M3-07G	M3-07G	M3-07G	M3-07H	M3-07H	M3-07H	M3-07H	M3-07H	M3-07I
57.17	54.00	57.50	57.26	55.77	54.05	57.00	57.84	57.53	54.55
0.01	0.00	0.04	0.02	0.03	0.08	0.00	0.00	0.01	0.07
1.03	1.02	0.79	0.65	1.23	1.00	0.54	0.32	0.45	0.91
8.56	18.24	10.60	9.03	13.05	18.60	9.73	8.33	8.28	16.83
0.27	0.37	0.31	0.24	0.36	0.53	0.15	0.14	0.19	0.37
31.46	25.11	30.03	31.37	28.18	25.17	31.85	32.41	32.05	26.17
1.88	1.35	1.36	1.72	2.12	0.80	0.81	1.54	1.67	1.41
0.00	0.02	0.00	0.00	0.01	0.02	0.02	0.00	0.04	0.02
0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.02	0.00
0.59	0.19	0.31	0.20	0.14	0.31	0.41	0.26	0.26	0.15
100.97	100.32	100.95	100.50	100.88	100.56	100.50	100.85	100.51	100.48
6	6	6	6	6	6	6	6	6	6
1.981	1.969	2.004	1.994	1.975	1.968	1.988	1.999	1.997	1.973
0.000	0.000	0.001	0.001	0.001	0.002	0.000	0.000	0.000	0.002
0.042	0.044	0.032	0.027	0.051	0.043	0.022	0.013	0.018	0.039
0.248	0.556	0.309	0.263	0.386	0.567	0.284	0.241	0.240	0.509
0.008	0.011	0.009	0.007	0.011	0.016	0.004	0.004	0.006	0.011
1.625	1.365	1.560	1.629	1.488	1.366	1.656	1.670	1.658	1.411
0.070	0.053	0.051	0.064	0.080	0.031	0.030	0.057	0.062	0.055
0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.000	0.003	0.001
0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.000
0.016	0.006	0.008	0.005	0.004	0.009	0.011	0.007	0.007	0.004
3.990	4.007	3.975	3.989	3.997	4.004	3.996	3.991	3.992	4.005
0.868	0.710	0.835	0.861	0.794	0.707	0.854	0.874	0.873	0.735
-	-	-	-	-	-	-	-	-	-

M3-07I	M3-07I	M3-07I	M3-07I	M3-07I	M3-07I	M2-06D	M2-06D	M2-06D	M2-06D
53.83	56.04	57.39	57.27	55.81	57.55	57.43	57.42	56.98	57.58
0.07	0.03	0.01	0.02	0.00	0.00	0.04	0.00	0.09	0.00
0.52	0.50	0.63	0.70	0.79	0.49	0.97	0.58	1.33	0.85
21.05	11.89	6.42	8.47	10.60	7.31	8.05	9.12	9.23	7.88
0.48	0.24	0.24	0.11	0.29	0.04	0.13	0.27	0.22	0.27
23.59	29.60	33.87	31.90	30.34	33.47	32.86	32.21	31.25	32.58
0.89	1.70	0.94	1.32	1.86	1.17	1.38	1.40	1.88	1.94
0.03	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.00	0.02
0.01	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.02
0.00	0.14	0.52	0.36	0.14	0.42	0.55	0.33	0.47	0.34
100.46	100.13	100.03	100.16	99.84	100.48	101.40	101.33	101.46	101.48
6	6	6	6	6	6	6	6	6	6
1.983	1.986	1.984	1.993	1.975	1.987	1.974	1.984	1.970	1.979
0.002	0.001	0.000	0.001	0.000	0.000	0.001	0.000	0.002	0.000
0.023	0.021	0.025	0.029	0.033	0.020	0.039	0.024	0.054	0.034
0.649	0.353	0.185	0.247	0.314	0.211	0.231	0.264	0.267	0.226
0.015	0.007	0.007	0.003	0.009	0.001	0.004	0.008	0.007	0.008
1.296	1.564	1.745	1.655	1.601	1.722	1.683	1.659	1.611	1.669
0.035	0.065	0.035	0.049	0.071	0.043	0.051	0.052	0.070	0.072
0.002	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.001
0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001
0.000	0.004	0.014	0.010	0.004	0.011	0.015	0.009	0.013	0.009
4.005	4.000	3.997	3.987	4.007	3.998	3.998	4.000	3.994	4.000
0.666	0.816	0.904	0.870	0.836	0.891	0.879	0.863	0.858	0.881
-	-	-	-	-	-	-	-	-	-

		Clinopyroxene					Plagioclase		
M2-06D	M2-06D	M3-07I	M3-07I	M3-07I	M3-07I	M3-07I	M2-06D	M2-06D	M2-06D
55.82	56.39	53.17	53.36	51.88	52.74	54.42	53.93	53.11	47.14
0.06	0.00	0.06	0.05	0.07	0.08	0.07	0.08	0.03	0.02
0.95	1.00	1.00	1.86	1.56	0.78	0.94	0.92	1.94	33.85
13.94	11.23	9.33	7.23	14.25	9.72	5.60	8.08	6.36	0.47
0.42	0.38	0.23	0.22	0.27	0.22	0.08	0.18	0.27	0.00
28.15	30.06	14.18	16.60	11.81	14.21	18.20	15.12	17.35	0.02
1.90	1.96	21.40	20.90	20.66	21.71	20.46	22.26	20.02	17.35
0.09	0.00	0.33	0.22	0.17	0.22	0.09	0.29	0.13	1.65
0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.03
0.12	0.27	0.00	0.25	0.00	0.00	0.46	0.00	0.27	0.07
101.44	101.28	99.71	100.73	100.66	99.66	100.32	100.87	99.48	100.60
6	6	6	6	6	6	6	6	6	8
1.974	1.973	1.987	1.952	1.962	1.979	1.978	1.983	1.955	2.157
0.002	0.000	0.002	0.001	0.002	0.002	0.002	0.002	0.001	0.001
0.039	0.041	0.044	0.080	0.070	0.034	0.040	0.040	0.084	1.825
0.412	0.329	0.292	0.221	0.451	0.305	0.170	0.249	0.196	0.018
0.012	0.011	0.007	0.007	0.009	0.007	0.002	0.006	0.008	0.000
1.484	1.568	0.790	0.906	0.665	0.795	0.986	0.829	0.952	0.001
0.072	0.074	0.857	0.819	0.837	0.873	0.797	0.877	0.789	0.850
0.006	0.000	0.024	0.016	0.012	0.016	0.007	0.021	0.009	0.146
0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.002
0.003	0.007	0.000	0.007	0.000	0.000	0.013	0.000	0.008	0.002
4.006	4.003	4.002	4.011	4.007	4.010	3.996	4.006	4.003	5.003
0.783	0.827	0.730	0.804	0.596	0.723	0.853	0.769	0.830	-
-	-	-	-	-	-	-	-	-	85.2

M2-06D	M2-06D	M2-06D	M2-06D
46.23	47.72	47.66	46.67
0.03	0.00	0.00	0.00
34.07	33.27	33.37	33.96
0.52	0.44	0.44	0.39
0.00	0.00	0.03	0.03
0.04	0.05	0.01	0.01
18.01	17.11	16.92	17.74
1.29	1.81	1.81	1.39
0.03	0.00	0.00	0.01
0.02	0.00	0.00	0.02
100.22	100.41	100.24	100.22
8	8	8	8
2.128	2.184	2.184	2.144
0.001	0.000	0.000	0.000
1.848	1.794	1.802	1.839
0.020	0.017	0.017	0.015
0.000	0.000	0.001	0.001
0.003	0.004	0.001	0.001
0.888	0.839	0.831	0.873
0.115	0.161	0.160	0.124
0.001	0.000	0.000	0.001
0.001	0.000	0.000	0.001
5.005	4.999	4.996	4.998
-	-	-	-
88.4	83.9	83.8	87.5

Table S3 Whole rock compositions of volcanic rocks from Mukojima Island Group

Locality	Yon'noiva	Sasayojima	Mukojima																									
Sample ID	Yon'noiva	S1-01A	S1-01B	M2-04A	M2-05A	M2-05B	07111601-2	M1-04	M2-01Aa	M4-01	M1-03Ca	M1-02C	M2-03	M2-09B	07111604	M2-06B	M2-06Aβ	M2-06Ac	M2-08	M1-05	M2-02	07111606-1	M2-06C	M2-01C	M1-07D	M1-07Cβ		
Rock type	Type1 boninite	Type1 boninite	Bronzite andesite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type1 boninite	Type2 boninite	Type2 boninite	Type2 boninite	Type2 boninite	Type2 boninite	Type2 boninite	Type3 boninite	Type3 boninite	Type3 boninite	Type3 boninite	Type3 boninite	Type3 boninite	Type3 boninite	
<i>(wt% oxides on an anhydrous basis)</i>																												
SiO ₂	57.56	59.28	59.62	59.05	59.39	59.88	59.83	60.05	59.63	60.13	59.75	58.88	60.06	54.65	55.92	56.74	57.07	56.97	56.75	58.14	57.62	58.01	58.03	59.39	58.43	58.53		
TiO ₂	0.10	0.09	0.11	0.09	0.09	0.09	0.11	0.10	0.14	0.10	0.10	0.11	0.16	0.16	0.10	0.08	0.08	0.08	0.08	0.10	0.11	0.09	0.09	0.13	0.13	0.14		
Al ₂ O ₃	10.35	10.36	13.54	9.39	10.26	10.40	9.67	9.67	9.52	9.56	9.94	10.75	10.58	11.05	11.12	10.66	10.78	11.01	10.99	7.94	8.29	8.66	9.37	9.34	9.82	10.22		
FeO*	8.71	8.61	8.60	8.40	8.43	8.50	9.09	9.45	8.63	9.17	9.18	9.01	9.04	8.76	9.00	8.84	8.82	8.87	9.00	8.45	8.52	8.70	8.83	8.47	8.54	8.62		
MnO	0.16	0.15	0.13	0.16	0.16	0.15	0.17	0.19	0.17	0.18	0.17	0.17	0.17	0.20	0.16	0.17	0.16	0.16	0.16	0.18	0.17	0.18	0.18	0.17	0.16	0.16		
MgO	14.12	9.88	6.01	14.57	12.78	12.08	12.69	11.83	11.11	11.41	11.34	11.01	10.81	14.66	13.70	13.46	13.15	13.02	12.91	15.48	15.32	15.35	13.86	11.72	11.54	11.27		
CaO	7.23	9.15	9.25	6.41	6.70	6.37	6.28	6.93	8.96	7.56	7.51	7.37	6.94	9.11	8.77	8.96	8.85	8.76	9.01	8.43	8.65	7.79	8.32	9.05	9.59	9.29		
Na ₂ O	1.41	1.66	2.21	1.45	1.62	1.33	1.37	1.45	1.35	1.33	1.72	1.58	1.14	0.76	0.87	0.88	0.92	0.91	0.95	0.94	0.97	1.04	1.36	1.25	1.43			
K ₂ O	0.35	0.80	0.50	0.46	0.55	0.88	0.80	0.38	0.37	0.52	0.65	0.96	0.64	0.25	0.46	0.21	0.19	0.19	0.18	0.32	0.35	0.24	0.26	0.33	0.51	0.31		
P ₂ O ₅	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02		
FeO*/MgO	0.62	0.87	1.43	0.58	0.66	0.70	0.72	0.80	0.78	0.80	0.81	0.82	0.84	0.60	0.66	0.66	0.67	0.68	0.70	0.55	0.56	0.57	0.64	0.72	0.74	0.77		
CaO/Al ₂ O ₃	0.70	0.88	0.68	0.68	0.65	0.61	0.65	0.72	0.94	0.79	0.76	0.69	0.66	0.82	0.79	0.84	0.82	0.80	0.82	1.06	1.04	0.90	0.89	0.97	0.98	0.91		
Na ₂ O/K ₂ O	1.75	2.46	2.71	1.91	2.17	2.50	2.14	1.75	1.82	1.87	1.98	2.68	2.22	1.40	1.22	1.08	1.82	1.12	1.09	1.26	1.30	1.20	1.30	1.69	1.76	1.75		
<i>(ppm)</i>																												
V	175	209	261	161	169	166	167	178	208	180	173	199	181	181	215	213	223	201	206	164	152	159	187	160	182	173		
Cr	1091	652	227	999	1037	823	795	635	592	559	631	748	575	1078	800	992	958	860	840	1092	961	985	926	722	801	700		
Rb	8.64	16.42	14.97	11.49	14.25	13.85	13.17	9.61	8.74	10.32	13.02	16.24	12.95	4.62	3.79	4.06	3.82	3.70	3.35	7.67	5.86	7.02	7.41	8.45	9.34	8.25		
Sr	57	67	102	68	77	74	99	77	67	88	102	70	119	72	118	47	43	46	43	61	55	51	59	65	70	77		
Y	3.5	4.2	5.2	3.4	3.7	4.2	4.0	3.8	5.1	4.2	3.8	4.5	5.3	4.8	3.1	2.4	2.3	2.3	2.4	4.3	3.6	3.2	3.5	4.8	5.3	5.0		
Zr	13.4	22.5	28.1	18.2	20.8	21.9	18.8	18.1	19.1	17.9	18.6	19.8	21.2	12.1	6.0	6.2	6.5	6.7	6.2	14.2	11.9	11.3	11.8	18.4	20.9	17.6		
Nb	0.42	0.63	0.95	0.46	0.47	0.48	0.31	0.33	0.25	0.27	0.27	0.36	0.28	0.39	0.21	0.24	0.24	0.26	0.23	0.23	0.19	0.39	0.41	0.24	0.27	0.28		
Cs	0.40	0.51	0.63	0.50	0.62	0.49	0.44	0.35	0.28	0.33	0.42	0.36	0.46	0.22	0.17	0.25	0.25	0.26	0.23	0.26	0.23	0.37	0.39	0.28	0.25	0.26		
Ba	32.0	38.7	62.6	40.7	45.9	39.6	33.0	33.1	28.4	30.5	31.7	28.6	44.6	15.1	6.2	16.8	14.2	12.8	11.7	20.8	14.4	28.9	31.3	26.5	24.5	27.8		
La	0.78	1.05	1.32	0.93	1.03	1.08	0.96	0.77	0.74	0.92	0.73	0.83	0.73	0.61	0.35	0.44	0.42	0.45	0.40	0.64	0.48	0.66	0.68	0.67	0.75	0.60		
Ce	1.53	2.10	2.66	1.76	2.02	2.11	1.72	1.55	1.67	1.63	1.45	1.73	1.71	1.51	0.77	0.96	0.94	0.99	0.92	1.27	1.12	1.29	1.31	1.62	1.71	1.38		
Pr	0.22	0.28	0.33	0.24	0.27	0.29	0.26	0.22	0.24	0.23	0.22	0.24	0.25	0.24	0.13	0.14	0.13	0.14	0.13	0.19	0.16	0.21	0.19	0.23	0.25	0.21		
Nd	1.06	1.33	1.67	1.14	1.17	1.31	1.13	1.09	1.23	1.13	0.99	1.20	1.26	1.14	0.64	0.63	0.62	0.68	0.64	0.98	0.83	0.92	0.93	1.18	1.31	1.13		
Sm	0.33	0.40	0.49	0.32	0.35	0.37	0.35	0.34	0.45	0.39	0.33	0.40	0.46	0.42	0.26	0.20	0.19	0.21	0.21	0.35	0.30	0.29	0.32	0.40	0.44	0.39		
Eu	0.13	0.13	0.17	0.10	0.12	0.12	0.12	0.13	0.15	0.15	0.12	0.14	0.16	0.15	0.09	0.10	0.08	0.08	0.08	0.13	0.10	0.11	0.12	0.15	0.17	0.13		
Gd	0.46	0.46	0.60	0.39	0.41	0.53	0.45	0.43	0.58	0.45	0.44	0.52	0.56	0.58	0.39	0.27	0.25	0.29	0.27	0.46	0.39	0.39	0.42	0.56	0.60	0.56		
Tb	0.07	0.09	0.11	0.07	0.07	0.08	0.08	0.08	0.10	0.08	0.08	0.08	0.09	0.11	0.10	0.07	0.04	0.04	0.05	0.05	0.08	0.08	0.07	0.10	0.11	0.10		
Dy	0.46	0.48	0.67	0.43	0.45	0.51	0.50	0.50	0.69	0.50	0.49	0.58	0.73	0.70	0.43	0.29	0.28	0.31	0.30	0.50	0.46	0.45	0.43	0.64	0.71	0.62		
Ho	0.12	0.12	0.16	0.10	0.11	0.12	0.11	0.12	0.16	0.13	0.12	0.13	0.16	0.16	0.10	0.07	0.07	0.07	0.12	0.11	0.10	0.11	0.15	0.16	0.15	0.15		
Er	0.37	0.40	0.53	0.34	0.37	0.38	0.38	0.39	0.47	0.39	0.37	0.43	0.53	0.50	0.32	0.26	0.28	0.26	0.25	0.39	0.36	0.33	0.34	0.48	0.50	0.47		
Tm	0.08	0.07	0.09	0.06	0.06	0.07	0.08	0.06	0.08	0.09	0.06	0.08	0.08	0.09	0.06	0.06	0.05	0.05	0.05	0.07	0.06	0.06	0.06	0.08	0.09	0.09		
Yb	0.46	0.49	0.62	0.39	0.43	0.48	0.42	0.45	0.56	0.44	0.42	0.54	0.57	0.54	0.43	0.36	0.36	0.39	0.36	0.45	0.40	0.38	0.42	0.52	0.56	0.54		
Lu	0.09	0.09	0.12	0.07	0.08	0.09	0.08	0.09	0.09	0.08	0.08	0.08	0.10	0.10	0.09	0.08	0.07	0.06	0.07	0.08	0.07	0.07	0.07	0.09	0.10	0.10		
Hf	0.37	0.50	0.72	0.46	0.50	0.53	0.48	0.48	0.50	0.47	0.47	0.47	0.54	0.34	0.18	0.17	0.17	0.19	0.18	0.34	0.29	0.31	0.32	0.47	0.49	0.45		
Ta	0.033	0.060	0.090	0.039	0.038	0.041	0.027	0.028	0.017	0.037	0.021	0.035	0.006	0.009	0.010	0.010	0.010	0.010	0.008	0.026	0.007	0.032	0.036	0.010	0.030	0.022		
Pb	1.94	1.46	2.27	1.43	1.46	1.66	1.51	1.61	1.05	1.33	1.37	1.10	1.19	0.80	2.04	0.76	0.76	0.96	0.82	0.80	0.75	1.53	1.68	0.87	0.87	1.08		
Th	0.18	0.14	0.19	0.22	0.24	0.24	0.11	0.11	0.18	0.08	0.09	0.12	0.20	0.14	0.05	0.18	0.18	0.14	0.17	0.08	0.16	0.09	0.20	0.18	0.08	0.13		
U	0.13	0.14	0.18	0.12	0.14	0.13	0.11	0.11	0.08	0.09																		

Hannawa																										Tatamiwa									
M2-01B Type3 boninite	M2-01A Type3 boninite	M1-07Ca Type3 boninite	M4-04 C Type3 boninite	M4-04 A Type3 boninite	H1-03A Bronzite andesite	H1-03B Bronzite andesite	H1-01Aβ Bronzite andesite	H1-01 Bα Bronzite andesite	T1-01 Bronzite andesite	N1-06C Type1 boninite	N2-08B Type1 boninite	N1-06B Type1 boninite	N2-03B Type1 boninite	N2-07 Type1 boninite	N2-02a Type1 boninite	N2-01Aα Type1 boninite	N3-10B Type1 boninite	N1-03C Type1 boninite	N3-11 Type1 boninite	N3-06B Type1 boninite	N2-10A Bronzite andesite	N1-09Aβ Bronzite andesite	07111706 Bronzite andesite	N1-08C Bronzite andesite	07111708-2 Bronzite andesite	N2-01Bβ Bronzite andesite									
60.11	59.63	58.70	59.71	59.90	58.62	59.83	60.89	58.46	59.90	59.30	58.01	58.74	59.52	58.72	58.30	58.80	62.01	60.29	61.70	60.66	60.68	59.85	61.94	60.23	63.57	58.79									
0.14	0.14	0.15	0.15	0.16	0.32	0.32	0.41	0.32	0.40	0.12	0.12	0.10	0.09	0.12	0.12	0.12	0.11	0.09	0.12	0.10	0.15	0.13	0.13	0.16	0.16	0.14									
9.52	9.52	10.44	10.21	10.12	14.79	14.27	15.10	15.35	15.52	9.77	10.98	9.83	9.79	11.48	11.84	11.82	11.95	10.60	12.07	11.09	13.32	13.52	12.07	13.41	14.24	13.24									
8.61	8.63	8.55	8.50	8.55	9.32	9.18	7.78	10.19	8.14	8.43	8.64	9.01	9.24	8.61	8.83	8.72	7.99	9.05	7.65	8.87	7.85	8.37	8.57	8.03	6.71	8.87									
0.16	0.17	0.16	0.16	0.17	0.12	0.13	0.12	0.15	0.13	0.16	0.15	0.17	0.16	0.15	0.17	0.15	0.13	0.16	0.13	0.15	0.13	0.13	0.15	0.13	0.08	0.14									
11.08	11.11	10.96	9.54	9.41	5.51	5.16	4.09	4.58	4.57	14.34	12.53	12.90	13.23	10.76	10.39	10.20	9.16	10.28	8.66	9.30	6.83	7.23	7.37	6.78	5.60	7.31									
8.55	8.96	9.21	9.83	9.83	8.67	8.58	8.46	8.15	8.35	5.99	7.62	7.71	6.34	8.03	8.33	8.24	6.39	7.73	7.22	8.01	8.44	8.40	7.60	8.59	6.59	9.28									
1.42	1.45	1.45	1.53	1.51	1.97	2.05	2.65	2.06	2.29	1.40	1.40	1.17	1.18	1.68	1.57	1.52	1.50	1.24	1.92	2.06	1.85	1.63	2.10	2.06	1.72										
0.38	0.37	0.36	0.36	0.34	0.65	0.45	0.46	0.73	0.66	0.48	0.53	0.36	0.42	0.44	0.42	0.40	0.73	0.55	0.49	0.53	0.52	0.51	0.51	0.54	0.96	0.49									
0.03	0.02	0.02	0.02	0.02	0.03	0.04	0.05	0.03	0.05	0.03	0.03	0.01	0.02	0.03	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.03									
0.78	0.78	0.78	0.89	0.91	1.69	1.78	1.90	2.22	1.78	0.59	0.69	0.70	0.70	0.80	0.85	0.85	0.87	0.88	0.88	0.95	1.15	1.16	1.16	1.18	1.20	1.21									
0.90	0.94	0.88	0.96	0.97	0.59	0.60	0.56	0.53	0.54	0.61	0.69	0.78	0.65	0.70	0.70	0.70	0.53	0.73	0.60	0.72	0.63	0.62	0.63	0.64	0.46	0.70									
1.80	1.82	1.81	1.88	1.85	2.62	2.49	3.10	2.79	2.53	2.94	1.88	1.93	1.54	1.61	1.99	1.92	2.24	1.79	2.41	2.58	2.36	2.15	2.64	3.02	2.20										
159	168	187	191	196	467	286	390	256	164	186	188	160	209	205	216					196	216	256	212	224	212	231									
726	743	739	487	499	95	59	4	59	878	794	901	997	595	659	584					486	300	334	295	265	295	247									
9.26	8.74	9.52	7.77	8.15	10.69	13.33	10.00	9.65	10.84	13.61	10.96	14.32	11.44	11.08	11.42					13.14	12.75	16.50	13.19	13.11	13.19	12.11									
73	67	80	71	72	125	115	114	105	64	100	52	51	70	60	60					72	98	72	81	96	81	75									
5.0	5.1	5.2	5.2	5.5	8.1	12.5	6.8	12.7	3.5	3.8	3.4	2.6	4.0	3.9	4.1					3.8	4.9	4.7	4.1	4.9	4.1	4.5									
20.0	19.1	21.0	19.9	19.8	28.5	43.3	30.9	39.7	18.5	20.0	19.2	15.9	22.4	19.5	19.2					19.9	27.0	26.2	24.1	27.4	24.1	20.7									
0.25	0.25	0.29	0.29	0.32	0.52	0.58	0.55	0.54	0.27	0.38	0.35	0.31	0.42	0.40	0.41					0.47	0.51	0.52	0.52	0.51	0.52	0.44									
0.25	0.28	0.28	0.28	0.29	0.37	0.55	0.39	0.45	0.45	0.56	0.45	0.47	0.50	0.51	0.50					0.62	0.56	0.70	0.60	0.54	0.60	0.50									
28.3	28.4	28.3	24.9	27.5	28.9	33.0	24.5	22.2	19.2	28.7	24.5	23.5	28.0	28.1	28.7					34.7	34.1	36.9	40.4	33.9	40.4	27.9									
0.62	0.74	0.76	0.68	0.76	1.10	1.50	0.85	1.33	0.60	0.65	0.67	0.46	0.81	0.75	0.73					0.75	1.09	0.85	0.91	1.06	0.91	0.76									
1.45	1.67	1.70	1.61	1.69	2.71	3.81	1.96	3.59	1.22	1.37	1.33	0.87	1.54	1.42	1.46					1.38	2.17	1.78	1.70	2.12	1.70	1.50									
0.22	0.24	0.24	0.23	0.27	0.37	0.54	0.30	0.52	0.17	0.20	0.18	0.12	0.23	0.22	0.21					0.21	0.30	0.23	0.26	0.31	0.26	0.22									
1.15	1.23	1.29	1.19	1.25	1.86	2.96	1.53	2.83	0.83	1.01	0.87	0.60	1.04	0.96	1.03					0.97	1.47	1.17	1.14	1.48	1.14	1.14									
0.39	0.45	0.44	0.46	0.44	0.63	1.06	0.53	1.09	0.26	0.30	0.27	0.14	0.32	0.32	0.32					0.31	0.46	0.37	0.36	0.44	0.36	0.34									
0.13	0.15	0.17	0.16	0.16	0.24	0.39	0.22	0.44	0.08	0.11	0.10	0.06	0.11	0.10	0.11					0.09	0.14	0.13	0.12	0.15	0.12	0.12									
0.53	0.58	0.59	0.58	0.61	0.87	1.37	0.71	1.47	0.35	0.39	0.33	0.26	0.42	0.38	0.43					0.38	0.59	0.48	0.47	0.57	0.47	0.49									
0.09	0.10	0.11	0.11	0.11	0.15	0.26	0.14	0.29	0.06	0.07	0.06	0.05	0.07	0.07	0.07					0.07	0.10	0.08	0.08	0.10	0.08	0.08									
0.63	0.69	0.70	0.66	0.69	1.02	1.75	0.92	1.80	0.41	0.47	0.41	0.32	0.49	0.47	0.48					0.46	0.64	0.54	0.49	0.65	0.49	0.56									
0.14	0.16	0.16	0.15	0.17	0.22	0.40	0.23	0.41	0.11	0.12	0.10	0.08	0.13	0.12	0.13					0.12	0.15	0.13	0.12	0.15	0.12	0.15									
0.45	0.47	0.52	0.51	0.52	0.75	1.19	0.65	1.26	0.33	0.36	0.33	0.26	0.41	0.38	0.42					0.40	0.51	0.45	0.42	0.52	0.42	0.46									
0.08	0.08	0.09	0.09	0.10	0.13	0.20	0.11	0.24	0.06	0.07	0.06	0.05	0.08	0.07	0.08					0.07	0.09	0.09	0.07	0.09	0.07	0.09									
0.54	0.56	0.56	0.61	0.61	0.83	1.31	0.78	1.35	0.43	0.47	0.42	0.36	0.52	0.50	0.52					0.51	0.61	0.61	0.50	0.62	0.50	0.61									
0.09	0.09	0.10	0.11	0.11	0.14	0.21	0.13	0.22	0.07	0.08	0.08	0.07	0.09	0.10	0.10					0.09	0.11	0.11	0.09	0.11	0.09	0.11									
0.47	0.50	0.49	0.53	0.46	0.78	1.08	0.76	0.98	0.43	0.46	0.40	0.36	0.52	0.46	0.49					0.47	0.67	0.57	0.57	0.68	0.57	0.51									
0.018	0.017	0.031	0.013	0.015	0.036	0.053	0.041	0.049	0.013	0.025	0.042	0.037	0.030	0.032	0.032					0.037	0.038	0.046	0.042	0.036	0.042	0.035									
1.28	1.05	0.98	1.28	1.25	1.49	1.29	1.41	1.22	0.84	1.12	1.02	0.97	1.33	1.38	1.43					1.73	1.56	1.44	1.63	1.57	1.63	1.44									
0.13	0.18	0.09	0.08	0.08	0.21	0.16	0.15	0.14	0.10	0.14	0.09	0.08	0.16	0.16	0.16					0.14	0.19	0.11	0.12	0.19	0.12	0.17									
0.08	0.08	0.09	0.08	0.08	0.16	0.13	0.11	0.11	0.07	0.08	0.08	0.06	0.09	0.08	0.09					0.10	0.12	0.11	0.13	0.12	0.13	0.09									
45.9	38.1	37.2	36.4	36.2	26.2	22.0		16.7	31.7	43.9	36.8	51.4	34.8	37.3	39.1					46.2	31.3	43.2	44.3	31.9	44.3	36.9									
52.3	50.4	50.6	40.7	44.7	34.7	25.1		16.4	44.7	60.8	58.1	66.3	53.6	56.1	55.1					67.6	56.2	60.8	81.4	54.8	81.4	45.5									
0.024	0.023	0.024	0.021	0.021	0.015	0.018		0.017	0.026	0.028	0.033	0.029	0.031	0.028	0.027					0.032	0.030	0.033	0.031	0.029	0.026	0.025									

																										Yomejima	
07111704-1	N3-12	N3-08	N1-01Aβ	N1-01Bβ	N2-03C	N1-01Aα	N2-01Bβ	N1-09Bβ	N1-09Aα	N1-09Bα	N2-08C	07111714-1	N2-05B	N2-05A	07111701-1	07111701-2	N1-02Aα	N2-04	N1-09C	07111715-1	N1-03B	N2-06	N1-05A	N1-08B	07111703-1	07111903-2	
Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Dacite	Dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Quartz dacite	Type1 boninite
60.83	59.03	64.30	61.02	60.21	63.30	60.84	60.29	59.37	60.82	60.97	60.16	63.69	57.93	58.53	64.05	65.30	73.19	74.68	75.12	74.44	76.05	75.72	74.88	73.11	77.10	56.67	
0.17	0.15	0.15	0.16	0.16	0.16	0.17	0.15	0.17	0.15	0.15	0.16	0.15	0.41	0.41	0.29	0.34	0.18	0.20	0.21	0.21	0.22	0.23	0.28	0.21	0.08		
13.67	14.12	13.53	14.17	14.46	13.65	13.98	14.08	15.50	14.31	14.51	15.19	14.70	15.14	15.05	14.07	16.99	13.28	12.79	12.38	13.11	12.24	12.25	12.71	12.85	12.02	8.21	
7.84	8.45	6.46	7.69	7.71	7.51	7.86	8.20	8.15	7.96	7.78	8.44	6.92	10.98	10.81	8.29	5.82	3.70	3.35	3.44	3.14	3.18	3.20	3.41	4.58	2.64	9.07	
0.13	0.12	0.11	0.11	0.11	0.11	0.13	0.13	0.11	0.12	0.12	0.10	0.11	0.15	0.16	0.11	0.02	0.06	0.06	0.06	0.05	0.05	0.05	0.06	0.08	0.01	0.17	
6.18	6.51	4.82	5.46	5.42	5.26	5.44	5.44	5.11	4.99	4.71	4.89	3.69	4.28	4.10	3.46	1.92	1.18	0.86	0.87	0.77	0.67	0.66	0.68	0.79	0.43	18.96	
8.51	8.99	7.44	8.42	9.00	7.04	8.66	8.98	8.32	8.32	8.77	8.41	7.58	8.51	8.27	6.62	6.16	3.98	3.17	3.08	3.84	2.81	2.99	3.15	3.62	2.55	5.78	
2.13	1.99	2.49	2.25	2.26	2.30	2.31	2.16	2.46	2.52	2.35	1.88	2.49	1.87	1.91	2.43	3.04	2.90	3.50	3.36	2.81	3.28	3.15	3.43	3.16	3.64	0.81	
0.52	0.63	0.66	0.69	0.64	0.64	0.58	0.55	0.79	0.78	0.62	0.73	0.63	0.70	0.71	0.62	0.39	1.47	1.34	1.44	1.63	1.46	1.72	1.40	1.46	1.39	0.23	
0.03	0.02	0.05	0.03	0.03	0.04	0.03	0.03	0.02	0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.02	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.06	0.07	0.02	0.02
1.27	1.30	1.34	1.41	1.42	1.43	1.45	1.51	1.60	1.60	1.65	1.73	1.87	2.57	2.64	2.40	3.03	3.14	3.87	3.93	4.07	4.73	4.85	5.06	5.82	6.17	0.48	
0.62	0.64	0.55	0.59	0.62	0.52	0.62	0.64	0.54	0.58	0.60	0.55	0.52	0.56	0.55	0.47	0.36	0.30	0.25	0.25	0.29	0.23	0.24	0.25	0.28	0.21	0.70	
2.65	2.62	3.15	2.95	2.90	2.93	2.89	2.70	3.25	3.29	2.97	2.61	3.12	2.56	2.63	3.06	3.43	4.38	4.84	4.80	4.45	4.74	4.88	4.82	4.62	5.03	1.04	
231	216				233	251	236	243	233	252	204	229	275	500	426		102	27	34	58	39	32	26	34	27	148	
262	159				197	172	157	23	107	105	28	54	31	6	9		14	17	33	12	31	16	12	5	14	1441	
13.49	15.47				17.75	13.67	15.45	12.55	16.14	16.62	19.63	18.55	10.50	11.40	16.31		26.92	26.16	30.63	28.52	28.79	29.52	23.79	25.01	36.53	5.98	
98	88				99	100	82	109	112	107	100	102	107	116	107		89	92	100	92	95	108	110	113	94	46	
5.1	8.6				5.7	5.3	5.4	4.9	5.2	5.6	5.8	6.4	7.6	7.9	8.5		9.0	12.5	13.3	8.8	13.0	29.3	13.3	13.5	12.0	4.4	
28.6	26.6				34.7	29.4	25.4	34.4	31.6	35.9	29.5	35.7	27.8	29.1	39.3		56.0	58.5	65.4	54.1	66.7	72.9	66.3	61.2	67.1	10.8	
0.55	0.47				0.62	0.49	0.52	0.56	0.49	0.58	0.56	0.74	0.45	0.49	0.67		1.10	1.02	1.03	1.01	1.15	1.27	1.16	1.07	1.25	0.25	
0.55	0.63				0.83	0.57	0.68	0.63	0.61	0.63	0.59	0.87	0.38	0.38	0.65		1.35	1.06	1.23	1.35	1.22	1.22	1.25	1.08	0.92	0.32	
38.0	27.5				55.2	36.9	39.0	31.3	39.8	41.6	29.7	55.5	21.4	24.7	39.1		79.9	72.3	79.8	83.8	77.9	83.7	73.1	68.5	78.5	17.0	
1.09	1.53				1.21	1.08	0.98	0.92	1.13	1.30	1.11	1.45	0.83	0.87	1.37		1.99	2.19	2.28	2.13	2.26	2.62	2.39	2.23	1.41	0.67	
2.27	1.60				2.37	2.20	1.99	2.01	2.42	2.68	1.73	2.64	1.96	2.06	3.00		3.93	4.70	4.83	4.18	4.76	5.08	4.98	4.76	1.97	0.91	
0.31	0.36				0.34	0.31	0.28	0.28	0.32	0.34	0.31	0.42	0.32	0.31	0.46		0.58	0.66	0.69	0.63	0.67	0.87	0.75	0.70	0.39	0.22	
1.45	1.69				1.52	1.50	1.34	1.35	1.52	1.61	1.46	1.90	1.56	1.62	2.16		2.57	3.29	3.23	2.76	3.24	4.42	3.53	3.50	1.78	1.03	
0.45	0.52				0.47	0.47	0.41	0.41	0.43	0.50	0.43	0.50	0.59	0.61	0.69		0.73	0.98	0.99	0.77	1.01	1.44	1.12	1.09	0.62	0.34	
0.16	0.15				0.15	0.16	0.13	0.15	0.15	0.16	0.13	0.18	0.23	0.25	0.24		0.20	0.28	0.31	0.23	0.28	0.37	0.33	0.35	0.33	0.14	
0.62	0.74				0.56	0.54	0.54	0.51	0.56	0.61	0.59	0.66	0.82	0.85	0.94		0.87	1.29	1.25	0.92	1.22	2.30	1.45	1.41	0.90	0.46	
0.10	0.13				0.10	0.10	0.10	0.09	0.10	0.10	0.10	0.12	0.16	0.15	0.17		0.16	0.23	0.24	0.16	0.22	0.44	0.26	0.26	0.18	0.08	
0.66	0.80				0.67	0.68	0.64	0.59	0.65	0.67	0.65	0.76	1.03	1.07	1.19		1.10	1.53	1.59	1.09	1.50	3.14	1.78	1.74	1.40	0.56	
0.16	0.20				0.17	0.17	0.16	0.15	0.16	0.16	0.16	0.19	0.25	0.24	0.26		0.25	0.36	0.37	0.27	0.36	0.81	0.40	0.42	0.37	0.13	
0.52	0.68				0.54	0.56	0.52	0.49	0.51	0.55	0.56	0.60	0.75	0.75	0.86		0.83	1.16	1.18	0.89	1.15	2.61	1.31	1.28	1.36	0.43	
0.09	0.12				0.10	0.09	0.10	0.08	0.09	0.10	0.09	0.11	0.13	0.14	0.14		0.14	0.20	0.21	0.15	0.20	0.45	0.21	0.24	0.24	0.09	
0.63	0.77				0.70	0.64	0.67	0.61	0.64	0.66	0.64	0.77	0.90	0.88	0.96		0.99	1.33	1.36	1.03	1.31	3.01	1.47	1.53	1.76	0.54	
0.11	0.14				0.12	0.11	0.12	0.11	0.11	0.12	0.11	0.14	0.15	0.14	0.14		0.17	0.23	0.22	0.18	0.22	0.51	0.25	0.25	0.28	0.11	
0.70	0.68				0.83	0.70	0.65	0.82	0.72	0.80	0.71	0.85	0.71	0.70	0.96		1.31	1.37	1.48	1.33	1.52	1.66	1.58	1.47	1.64	0.30	
0.043	0.034				0.059	0.038	0.040	0.047	0.042	0.053	0.039	0.059	0.034	0.041	0.052		0.071	0.071	0.081	0.076	0.077	0.092	0.077	0.070	0.091	0.021	
1.45	1.35				2.63	1.72	1.82	2.04	1.96	1.86	1.66	2.76	1.16	1.37	1.91		4.47	3.79	3.75	4.34	3.61	4.20	3.79	3.47	1.90	0.98	
0.16	0.17				0.17	0.20	0.18	0.18	0.17	0.18	0.18	0.17	0.14	0.12	0.22		0.30	0.32	0.29	0.26	0.30	0.31	0.32	0.32	0.32	0.07	
0.11	0.08				0.17	0.13	0.11	0.11	0.13	0.15	0.09	0.17	0.08	0.08	0.13		0.28	0.22	0.24	0.26	0.23	0.25	0.24	0.23	0.28	0.06	
35.0	18.0				45.8	34.2	39.6	33.9	35.2	32.1	26.8	38.3	25.7	28.3	28.6		40.2	32.9	35.1	39.4	34.4	31.9	30.6	30.8	55.7	25.6	
59.9	35.9				79.3	57.5	58.4	51.4	62.0	63.1	46.3	72.5	23.8	28.2	40.7		81.0	54.5	58.9	81.3	59.4	27.8	49.6	44.8	44.5	31.8	
0.028	0.030				0.037	0.029	0.028	0.034	0.034	0.039	0.030	0.041	0.011	0.012	0.023		0.052	0.049	0.052	0.054	0.052	0.056	0.048	0.037	0.054	0.021	

Nakanoshima																
07111905-1	07111908-8	Y1-04A	07111907	Y3-03C	Y1-02Aa	Y1-06A	Y1-02Ba	07111903-1	07111901-1	K1-03	07032414-3	NAK1-01	NAK1-02	JB2		
Type1 boninite	Type1 boninite	Type1 boninite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Bronzite andesite	Dacite	Tholeiitic andesite	Tholeiitic dacite	Tholeiitic dacite	Tholeiitic dacite	average	σ	
57.23	57.12	58.55	59.08	59.55	59.90	61.83	61.72	64.89	68.11	58.29	71.01	68.14	69.60	52.91		
0.08	0.11	0.14	0.21	0.26	0.13	0.24	0.13	0.17	0.18	0.61	0.49	0.43	0.76	1.17		
9.50	10.41	10.96	14.30	15.37	14.27	14.79	14.43	14.04	14.35	16.10	11.22	13.69	13.11	14.70		
8.69	9.25	9.02	8.75	8.59	9.26	8.18	8.63	7.95	6.54	9.24	5.99	6.31	6.63	14.05		
0.16	0.17	0.16	0.14	0.14	0.14	0.12	0.12	0.12	0.02	0.12	0.11	0.10	0.12	0.20		
16.12	13.47	12.17	6.97	5.22	5.17	3.98	4.04	3.38	1.62	6.36	2.94	2.63	1.72	4.63		
6.61	7.96	7.26	8.57	8.28	8.89	8.25	8.56	7.03	5.57	3.34	3.66	2.19	1.47	9.84		
1.26	1.07	1.41	1.54	2.07	1.73	2.08	1.86	1.87	2.20	4.73	4.08	6.32	6.07	2.00		
0.33	0.42	0.31	0.40	0.51	0.49	0.49	0.49	0.52	1.36	1.17	0.46	0.17	0.41	0.42		
0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.02	0.05	0.05	0.04	0.03	0.10	0.09		
0.54	0.69	0.74	1.26	1.65	1.79	2.05	2.14	2.35	4.03	1.45	2.04	2.40	3.85			
0.70	0.76	0.66	0.60	0.54	0.62	0.56	0.59	0.50	0.39	0.21	0.33	0.16	0.11			
1.59	1.49	1.72	1.94	2.58	2.23	2.56	2.34	2.40	3.56	5.90	4.54	6.49	6.47			
															n=6	
169		229	249	272	279	278	283	222		303	285	306	163	573	12	
1280		812	223	52	97	55	49	21		10	5	8	1	24.3	1.7	
8.78		9.30	8.25	8.75	14.53	13.11	13.12	13.55		9.11	3.98	1.78	4.85	6.04	0.16	
54		54	72	81	83	83	77	75		146	94	115	108	178	4	
2.7		4.3	5.8	7.0	4.6	7.6	4.5	5.6		14.6	10.9	10.2	28.4	24.6	0.3	
14.7		17.6	23.8	29.9	21.7	28.8	23.0	26.4		38.8	23.0	30.4	66.9	45.3	0.9	
0.45		0.43	0.58	0.66	0.62	0.69	0.79	0.91		0.48	0.25	0.36	0.66	0.43	0.02	
0.45		0.52	0.45	0.46	0.78	0.72	0.75	0.70		0.11	0.07	0.05	0.04	0.80	0.03	
27.7		29.5	28.7	24.9	46.5	40.7	46.6	42.3		98.5	98.2	16.8	34.2	213	6	
0.69		0.81	0.92	0.93	1.15	1.23	1.06	1.17		1.59	0.80	0.89	2.19	2.14	0.02	
1.30		1.60	2.01	2.14	2.11	2.61	2.08	2.39		4.41	2.93	3.19	6.42	6.41	0.15	
0.19		0.22	0.30	0.32	0.28	0.37	0.28	0.33		0.60	0.46	0.38	0.98	1.03	0.04	
0.83		1.10	1.37	1.61	1.26	1.77	1.23	1.64		3.59	2.63	2.27	5.72	5.95	0.16	
0.24		0.37	0.52	0.60	0.40	0.58	0.35	0.44		1.30	1.05	0.90	2.17	2.16	0.08	
0.08		0.12	0.18	0.24	0.13	0.20	0.13	0.15		0.51	0.37	0.35	0.78	0.78	0.06	
0.33		0.47	0.70	0.78	0.50	0.77	0.44	0.59		1.86	1.33	1.19	2.96	2.99	0.16	
0.05		0.08	0.12	0.15	0.09	0.15	0.08	0.11		0.33	0.27	0.24	0.57	0.57	0.02	
0.39		0.56	0.77	0.93	0.59	0.94	0.53	0.72		2.16	1.72	1.55	3.93	3.89	0.07	
0.09		0.14	0.18	0.23	0.14	0.23	0.12	0.16		0.49	0.38	0.33	0.91	0.87	0.02	
0.30		0.44	0.62	0.70	0.48	0.74	0.45	0.59		1.49	1.10	1.03	2.50	2.53	0.05	
0.06		0.08	0.11	0.15	0.09	0.13	0.10	0.10		0.23	0.17	0.16	0.41	0.41	0.02	
0.40		0.58	0.73	0.87	0.64	0.87	0.62	0.76		1.40	1.06	1.06	2.68	2.53	0.05	
0.07		0.10	0.14	0.15	0.12	0.15	0.12	0.14		0.21	0.18	0.17	0.40	0.39	0.01	
0.41		0.44	0.59	0.76	0.57	0.68	0.55	0.68		1.05	0.64	0.76	1.68	1.39	0.04	
0.046		0.037	0.052	0.064	0.050	0.055	0.073	0.075		0.044	0.017	0.033	0.057	0.034	0.002	
1.28		1.42	1.83	1.82	2.10	1.89	1.95	1.87		0.64	0.54	0.45	0.92	5.07	0.45	
0.11		0.16	0.16	0.16	0.22	0.20	0.18	0.19		0.20	0.07	0.09	0.16	0.27	0.05	
0.11		0.10	0.14	0.14	0.16	0.17	0.17	0.16		0.10	0.04	0.07	0.12	0.13	0.01	
40.4		36.6	31.1	26.9	40.3	33.1	43.7	36.1		61.8	123.4	18.8	15.6			
69.6		51.0	39.3	28.5	72.6	46.8	75.0	55.8		70.6	92.2	15.8	12.7			
0.030		0.021	0.019	0.019	0.028	0.020	0.030	0.025		0.011	0.008	0.012	0.015			